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Review

Urban Seismic Networks: A Worldwide Review

Salvatore Scudero *, Antonio Costanzo and Antonino D'Alessandro

Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Nazionale Terremoti, 00143 Rome, Italy; antonio.costanzo@ingv.it (A.C.); antonino.dalessandro@ingv.it (A.D.)
* Correspondence: salvatore.scudero@ingv.it

Abstract: Seismic networks in urban areas today represent key infrastructure to better address the tasks of earthquake preparation and mitigation in the pre-event phase, and are an important knowledge tool supporting disaster risk management during seismic crises and post-disaster recovery. In the last fifteen years, a decrease in instrumentation costs and the development of new low-cost devices have enhanced the deployment of several monitoring and experimental networks worldwide. This paper conducts a review of scientific work that refer to the deployment of Urban Seismic Networks (USN) in order to define the current state of the art. We collected a list of more than one hundred USNs worldwide that were operative within the period from 1994–2023. For each USN, we report the locations and objectives along with information about the timing, coverage, geometry, and technical characteristics (sensors and transmission). By reviewing all these aspects, this paper offers important insights to provide guidelines for new implementations, bearing in mind that the interest in monitoring urban areas is expected to continue to increase in the near future driven by population growth in urbanized areas.

Keywords: seismic monitoring; urban seismic network; earthquake monitoring

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1. Introduction

Spreading seismic instrumentation to obtain diffuse earthquake observations is considered among the main technical achievements of seismology since the mid-20th century [1–3], with seismic networks starting to develop worldwide. At their beginning, networks for seismic monitoring implemented at a local-scale and targeted to urbanized area were normally employed exclusively for short-term seismological studies or experiments. The planning and possibility of building permanent or at least long-term seismic networks within an urban environment fundamentally began in the mid-1990s. These possibilities have been greatly favored by the opportunities offered by new technological devices such as digital systems for acquisition and transmission, and their development has been further influenced by the modern transformation of urban centers into great metropolitan areas worldwide. Moreover, the increasing trend of population growth in urban areas is expected to become accentuated even more in the near future; it has been estimated that more than 60% of the world's population will live in urban areas by 2030 [4]. The growth of urban centers is the main reason that the number of people killed or injured due to earthquakes has increased in the last century and is expected to increase further in the future [5,6]. In several recent earthquakes, the effects have been destructive in precisely the most highly vulnerable urbanized areas (e.g., China in 2008, Italy in 2009 and 2016, Haiti in 2010 and 2021, Nepal in 2015, and Turkey–Syria in 2023). Many of these earthquakes caused disproportionate damage and casualties with respect to the size of their shocks [5,7].

Therefore, the increased consciousness of seismic risk in certain urban centers has resulted in likewise increased attention to monitoring of these areas, with particular attention focused on the most vulnerable and most exposed locations. Networks especially designed for earthquake monitoring may reveal crucial tools for other tasks to connected with seismic

phenomena, such as scientific studies, earthquake warning, and decision support systems. In this work, we refer to such infrastructure as "Urban Seismic Networks" (USN).

The purposes of USNs is generally different than "traditional" country scale-networks. The latter typology is usually intended for earthquake observation and seismological studies on a broad scale. Although both types of networks can be integrated, each has its own characteristics and peculiarities while sharing the objective of earthquake risk reduction, as suggested by D'Alessandro et al. (2019) [8]. In particular, urban-scale networks have distinct characteristics with respect to country-scale networks in terms of their coverage areas and density of nodes, which may even differ to some order of magnitude. The technical choices about the type of sensors and data transmission may differ as well.

As the number of USNs, regardless the specific application, has been increasing over the last two decades, we recognize the importance of providing a complete picture on the topic of USNs, looking in particular at their design and at their technical characteristics and how these are related to the specific objectives of each urban network. For this purpose, we retrieved information on 105 USNs implemented worldwide. These networks' objectives and technical characteristics have been categorized to make for an easier synthesis.

USNs represent crucial infrastructure because of the practical and scientific challenges they support, which is even more the case looking to the future perspective. This work can represent a reference and a practical guideline for future planners of urban networks.

2. USN Catalogue

We collected information about 105 different USNs. The collection criteria were basically two: (i) the earthquake network should mainly cover an urbanized area (town, city, or metropolitan area) and (ii) it should have been active at least for some months. Moreover, measurements encompassing the systematic repositioning of sensors rather than their simultaneous recording as a proper network were excluded. We did not include deployments of sensors in different non-contiguous urban areas. Such situations do not describe independent and complete networks with characteristics that can be easily quantified (e.g., number of sensors or covered area). As an example, what are often referred as citizen–based or community-based networks usually show a patchy distribution over many different urban areas and even different countries [9–11].

Several characteristics are reported in this review paper to characterize the purposes related to the deployment of each USN: the position, number of nodes, area covered, main objective, and secondary objectives (where indicated). Moreover, specific network-related characteristics such as the timing (start, duration, and end of recording), type of sensors, and transmission system were summarized.

It is worth pointing out that all information was retrieved as-is from the listed references without making any critical interpretations of the details provided by the authors. All the desires information was retrieved from the paper(s) or websites describing the networks. Unfortunately, sometimes details about the data transmission were not reported (16% of the USNs). Furthermore, certain USNs evolved over time, in these cases, we report the most up-to-date information available.

To provide a detailed framework of the USNs, general information, i.e., location, objectives, and sources, are reported in Table 1, whereas specific characteristics such as operating time, coverage, density, and technical features of the instruments are reported in Table 2. Moreover, in the following sub-paragraphs we describe and analyze each of these aspects characterizing the USNs.

2.1. Geographical Distribution

The worldwide distribution of USNs (Table 1) is shown in Figure 1a. The networks are not uniformly distributed around the world; North America and the Euro-Mediterranean region are the two zones where most of the USNs are located (Figure 1b,c). A total of 37 different countries are present in the catalogue. The USA, Italy, and Turkey are the most represented, with 13, 9, and 7 USNs, respectively. Several cities represented the target for

more than one urban network over the time, mainly driven by their high seismic hazard. These include Istanbul (Turkey), Bursa (Turkey), Quito (Ecuador), Bishkek (Kyrgyzstan), Bucharest (Romania), Gyeongju (South Korea), Los Angeles (USA), and Bogotà (Colombia), to mention only some of them.



Figure 1. (**a**) Global distribution of the USNs collected in this review. Detailed maps are provided for North America (**b**) and Europe (**c**), where USNs are the most common.

The distribution of USNs roughly follows the global seismic hazard zoning (Figure 2); however, there is not a clear correlation. In Figure 2, the colour shades represent the global earthquake hazard as proposed by [12]; in particular, they indicate the expected Peak Ground Acceleration (PGA) with 10% of excedance in 50 years. Most USNs are located along the Pacific Ocean coasts, both western and eastern, where the probability of excedance of the ground motion is high (PGA > 4 m/s^2) according to [12]. Several others are in areas where the expected ground motion is generally between 2 and 5 m/s^2, e.g., in southern Europe and south-eastern Asia. Only few USNs are located in regions with lower hazard, e.g., northern Europe and eastern North America, where the expected shaking is

characterised by PGA < 2 m/s^2. Finally, some USNs even fall into very low hazard zones with PGA < 0.5 m/s^2.

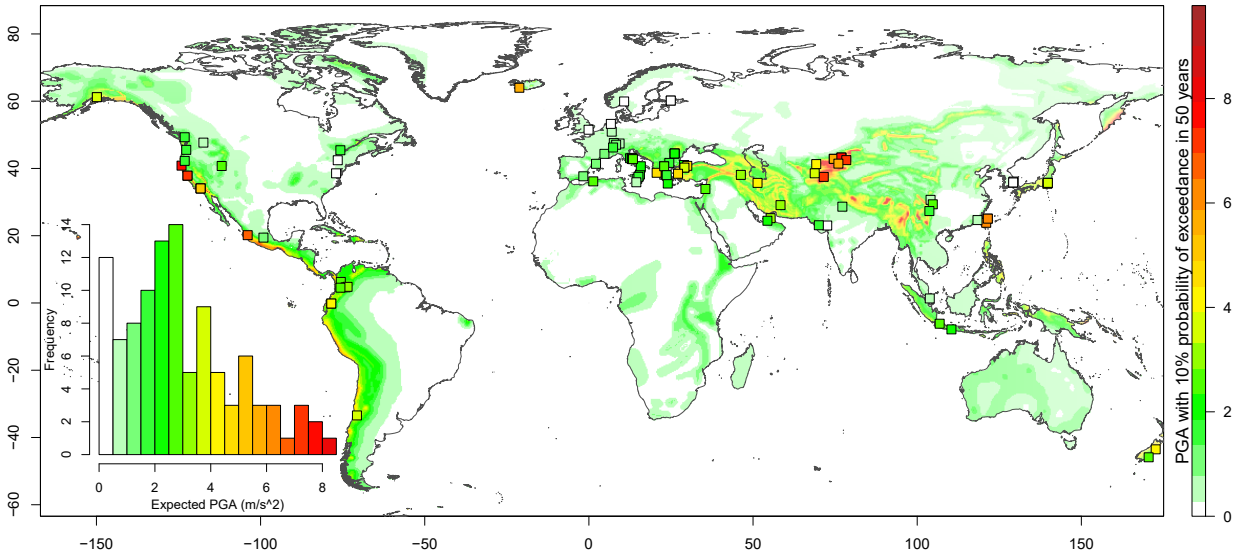


Figure 2. Global seismic hazard map from [12] and locations of urban seismic networks (USNs). The histogram indicates the frequency of expected PGA (m/s^2) corresponding to the USN locations.

Table 1. General information of the collected USNs.

ID	Country	City-Met. Area	Objective 1	Objective 2	Objective 3	Source (s)
1	Turkey	Bursa	Site effect research			[13]
2	Greece	Thessaloniki	Site effect research			[14]
3	USA	Anchorage	Earthquake monitoring	Site effect research		[15,16]
4	Colombia	Medellin	Earthquake monitoring	Early warning		[17]
5	Netherlands	Groningen	Earthquake monitoring	Other		[18–21]
6	Japan	Yokohama	Seismic intensity mapping	Earthquake monitoring	Post Event damage assessment	[22–24]
7	USA	Oakland	Seismic intensity mapping			[25]
8	Colombia	Bogotà	Site effect research	Post Event damage assessment	Seismic intensity mapping	[26,27]
9	Colombia	Armenia	Earthquake monitoring			[28,29]
10	Turkey	Izmit	Earthquake monitoring			[30]
11	Greece	Athens	Earthquake monitoring			[31,32]
12	Kazakhstan	Almaty	Earthquake monitoring			[33]
13	Germany	Cologne	Site effect research			[34]
14	Usa	Spokane	Earthquake monitoring			[35]
15	Turkey	Istanbul	Post Event damage assessment	Early warning	Seismic intensity mapping	[36,37]
16	Canada	Ottawa	Site effect research	Earthquake monitoring		[38]
17	Romania	Bucharest	Seismic intensity mapping	Earthquake monitoring		[39]
18	Turkey	Bursa	Earthquake monitoring			[40]
19	Romania	Bucharest	Earthquake monitoring	Site effect research		[41]
20	Canada	Vancouver	Seismic intensity mapping	Site effect research		[42]
21	Japan	Tokyo	Other	Seismic intensity mapping	Site effect research	[43–45]
22	USA	Anchorage	structural monitoring	Site effect research		[46–49]
23	Iran	Bam	Site effect research			[50]
24	Italy	Potenza	Site effect research			[51]
25	Iran	Tabriz	Site effect research			[52]
26	Iran	Tehran	Earthquake monitoring			[53]
27	USA	Portland	Site effect research			[54]
28	Switzerland	Basel	Earthquake monitoring	Other	Site effect research	[55–58]
29	Mexico	Mexico City	Earthquake monitoring	Site effect research		[59]
30	Colombia	Bogotà	Earthquake monitoring			[29]
31	Indonesia	Yogyakarta	Site effect research			[60]
32	Lebanon	Beirut	Site effect research			[61]
33	India	Delhi	Site effect research			[62–65]
34	Iceland	Hveragerdi	Earthquake monitoring	Site effect research		[66]
35	Taiwan	Taipei	Site effect research	Earthquake monitoring		[67]

Table 1. *Cont.*

ID	Country	City-Met. Area	Objective 1	Objective 2	Objective 3	Source (s)
36	Japan	Tokyo	Early warning			[68]
37	Turkey	Istanbul	Site effect research	Earthquake monitoring		[37]
38	China	Chengdu	Earthquake monitoring	Seismic intensity mapping		[69]
39	Chile	Santiago de Chile	Site effect research			[70]
40	India	Anjar	Site effect research	Earthquake monitoring		[71]
41	Turkey	Izmir	Seismic intensity mapping	Site effect research	Post Event damage assessment	[72]
42	Kyrgyzstan	Bishkek	Site effect research			[73–75]
43	Turkey	Istanbul	Early warning			[76,77]
44	Canada	Vancouver	structural monitoring	Post Event damage assessment		[78]
45	Italy	Norcia	Site effect research			[79,80]
46	Uzbekistan	Tashkent	Site effect research			[75]
47	Tajikistan	Dushanbe	Site effect research			[75,81]
48	Ecuador	Quito	Earthquake monitoring	Site effect research		[82]
49	Taiwan	Taiwan	Early warning	Seismic intensity mapping		[83–85]
50	New Zealand	Christchurch	Earthquake monitoring	Site effect research		[86,87]
51	USA	Los Angeles	Seismic intensity mapping	structural monitoring	Early warning	[88,89]
52	Mexico	Jalisco	Earthquake monitoring			[90]
53	Kyrgyzstan	Karakol	Site effect research			[75,91]
54	China	Zhaotong	Early warning			[92]
55	UAE	Dubai	Seismic intensity mapping			[93]
56	Tajikistan	Khorog	Site effect research			[75]
57	China	Fujian	Early warning			[94]
58	Greece	Lefkada	Seismic intensity mapping	Site effect research		[95,96]
59	UAE	Abu Dhabi	Post Event damage assessment	structural monitoring		[97,98]
60	Switzerland	St. Gallen	Earthquake monitoring			[99]
61	Kyrgyzstan	Naryn	Site effect research			[75,100]
62	Indonesia	Jakarta	Other			[101]
63	Malta	Malta	Earthquake monitoring			[102]
64	Greece	Kalochori	Earthquake monitoring	Site effect research	structural monitoring	[103]
65	Kazakhstan	Almaty	Site effect research			[75]
66	USA	Washington	Site effect research			[104]
67	Algeria	Chlef	Site effect research			[105]
68	USA	Los Angeles	structural monitoring	Post Event damage assessment	Site effect research	[106]
69	United Kingdom	London	Other			[107]
70	USA	Ithaca	Earthquake monitoring			[108]
71	Italy	Perugia-Foligno	Earthquake monitoring	Seismic intensity mapping		[109]
72	Ecuador	Quito	Site effect research			[110]
73	New Zealand	Dunedin	Earthquake monitoring	Other		[111]
74	South Korea	Gyeongju	Early warning	Earthquake monitoring		[112]
75	Italy	Acquasanta Terme	Site effect research	Earthquake monitoring		[113,114]
76	France	Rhône Velley	Site effect research			[115]
77	South Korea	Gyeongju	Earthquake monitoring			[112]
78	USA	Uni. Cal. Berkeley	Earthquake monitoring	Early warning		[116]
79	USA	Los Angeles	structural monitoring	Post Event damage assessment		[117]
80	Greece	Chania	Other	Seismic intensity mapping		[118]
81	China	Zigong	Site effect research			[119]
82	Taiwan	Taipei	Site effect research	Earthquake monitoring		[120]
83	India	Ahmedabad	Site effect research			[121]
84	Spain	Lorca	Seismic intensity mapping			[122]
85	USA	Humboldt State Uni.	Earthquake monitoring	Early warning		[116]
86	Japan	Tokio	Earthquake monitoring			[123]
87	Macedonia	Ohrid	Site effect research	structural monitoring		[124]
88	South Korea	Pohang	Earthquake monitoring			[125]
89	South Korea	Gyeongju	Earthquake monitoring			[126]
90	Italy	Acireale	Seismic intensity mapping	structural monitoring		[127,128]
91	Italy	Catania	Early warning	structural monitoring	Seismic intensity mapping	[129–131]
92	Italy	Ragusa	Seismic intensity mapping	structural monitoring		[8,132]
93	Italy	Messina	Seismic intensity mapping	structural monitoring		[8,132]
94	USA	Salt Lake City	Other			[133]
95	Finland	Helsinki	Earthquake monitoring	Other		[134]
96	Singapore	Singapore	Earthquake monitoring			[135]
97	Greece	Athens	Earthquake monitoring			[32]
98	Spain	Barcelona	Other			[136]
99	Switzerland	Lucerne	Site effect research			[137]
100	Finland	Helsinki	Earthquake monitoring	Other		[138]
101	Romania	Bucharest	structural monitoring			[139]
102	Switzerland	Sion	Earthquake monitoring	Site effect research		[140]
103	Italy	Camerino	Post Event damage assessment	Seismic intensity mapping	Site effect research	[141,142]
104	Norway	Oslo	Earthquake monitoring			[143]
105	Kyrgyzstan	Bishkek	Early warning			[144]

Table 2. Details of the collected USNs.

ID	Nodes	Area km^2	Density Log (nodes/km^2)	Start Year	Duration Years	Sensor Type	Transmission
1	6	375	−1.80	1992	5.9	Force Balance Accelerometer	No trasmission
2	10	28	−0.45	1993	0.25	Velocimeter	No trasmission
3	37	500	−1.13	1995	28	Force Balance Accelerometer	Real-time
4	32	800	−1.40	1996	21	Force Balance Accelerometer	No info
5	163	1600	−0.99	1997	26	Velocimeter and accelerometer	No info
6	159	600	−0.58	1997	13.5	Force Balance Accelerometer	Real-time
7	13	120	−0.97	1998	7	Force Balance Accelerometer	Near real-time
8	32	500	−1.19	1999	3	Force Balance Accelerometer	Real-time
9	10	19,000	−3.28	1999	19	Velocimeter and accelerometer	Real-time
10	10	3600	−2.56	1999	0.17	Velocimeter	No trasmission
11	8	200	−1.40	1999	0.27	Velocimeter and accelerometer	No trasmission
12	15	400	−1.43	2000	10	Force Balance Accelerometer	No info
13	44	660	−1.18	2001	0.14	Velocimeter	No trasmission
14	6	130	−1.34	2001	0.08	Velocimeter	No info
15	110	1500	−1.13	2002	5	Force Balance Accelerometer	Near real-time
16	14	720	−1.71	2002	NA	Force Balance Accelerometer	Real-time
17	13	45	−0.54	2003	8	Force Balance Accelerometer	Near real-time
18	11	5000	−2.66	2003	0.5	Velocimeter	No info
19	34	620	−1.26	2003	0.8	Velocimeter	No trasmission
20	21	60	−0.46	2004	NA	Force Balance Accelerometer	Near real-time
21	3800	3100	0.09	2004	19	MEMS Accelerometer	Real-time
22	43	2	1.33	2004	19	Velocimeter and accelerometer	Real-time
23	8	10	−0.10	2004	0.14	Velocimeter	No trasmission
24	11	12	−0.04	2004	0.66	Velocimeter	No trasmission
25	11	70	−0.80	2004	0.23	Velocimeter	No info
26	24	4100	−2.23	2004	14	Velocimeter	No info
27	16	320	−1.30	2005	13	Force Balance Accelerometer	No info
28	21	75	−0.55	2005	12.2	Force Balance Accelerometer	Real-time
29	28	3700	−2.12	2006	17	Velocimeter	Real-time
30	9	720	−1.90	2006	17	Velocimeter	Real-time
31	15	1650	−2.04	2006	0.25	Velocimeter	No trasmission
32	10	20	−0.30	2006	0.5	Velocimeter	No trasmission
33	20	1550	−1.89	2007	6.9	Force Balance Accelerometer	Real-time
34	14	3	0.67	2007	15.2	MEMS Accelerometer	Near real-time
35	12	330	−1.44	2008	12	Force Balance Accelerometer	Real-time
36	39	360	−0.97	2008	3	Velocimeter and accelerometer	Near real-time
37	13	25	−0.28	2008	8	Force Balance Accelerometer	Real-time
38	80	18,000	−2.35	2008	6	Force Balance Accelerometer	Real-time
39	8	0.3	1.43	2008	0.16	Velocimeter	No trasmission
40	3	0.15	1.30	2008	0.25	Velocimeter	No trasmission
41	16	1000	−1.80	2008	10	Velocimeter and accelerometer	Real-time
42	19	1000	−1.72	2008	0.25	Velocimeter	No trasmission
43	20	20	0.00	2009	2	MEMS Accelerometer	Real-time
44	170	15,000	−1.95	2009	6	MEMS Accelerometer	Real-time
45	15	20	−0.12	2009	0.38	Velocimeter	No trasmission
46	5	300	−1.78	2009	0.25	Velocimeter	No trasmission
47	45	280	−0.79	2009	0.6	Velocimeter	No trasmission
48	18	570	−1.50	2009	13.25	Force Balance Accelerometer	No trasmission
49	636	36,200	−1.76	2010	13	Low cost MEMS	Near real-time
50	180	2250	−1.10	2010	2.5	Low cost MEMS	Near real-time
51	500	1400	−0.45	2011	12	Low cost MEMS	Near real-time
52	28	65,000	-3.37	2011	6	Velocimeter	Real-time
53	16	240	−1.18	2011	0.29	Velocimeter	No trasmission
54	12	0.1	2.08	2012	1	MEMS Accelerometer	Real-time
55	5	320	−1.81	2012	10.7	Force Balance Accelerometer	Real-time
56	12	20	−0.22	2012	0.27	Velocimeter	No trasmission
57	125	120,000	−2.98	2012	10.1	Velocimeter and accelerometer	Real-time
58	21	9	0.37	2013	9	Low cost MEMS	Real-time
59	61	970	−1.20	2013	2	Force Balance Accelerometer	Real-time
60	7	350	−1.70	2013	1.4	Force Balance Accelerometer	Real-time
61	16	24	−0.18	2013	0.33	Velocimeter	No trasmission
62	96	500	−0.72	2013	0.41	Velocimeter	No info
63	8	315	−1.60	2014	9	Velocimeter	Real-time
64	7	13	−0.27	2014	3	Force Balance Accelerometer	Real-time
65	16	800	−1.70	2014	0.25	Velocimeter	No trasmission
66	27	170	−0.80	2014	0.8	Velocimeter	No info
67	9	10	−0.05	2014	0.82	Velocimeter	No trasmission
68	300	480	−0.20	2015	8	Low cost MEMS	Near real-time
69	5	15	−0.48	2015	0.15	Velocimeter	No trasmission
70	12	30	−0.40	2015	1	Velocimeter	No trasmission
71	20	1000	−1.70	2016	5	Low cost MEMS	No trasmission
72	20	330	−1.22	2016	2.16	Velocimeter	No trasmission
73	14	110	−0.90	2016	0.13	Velocimeter	No trasmission
74	6	50	−0.92	2016	0.08	Low cost MEMS	Real-time
75	5	3	0.22	2016	0.58	Velocimeter and accelerometer	Real-time
76	3	5	−0.22	2016	0.85	Velocimeter	No info

Table 2. *Cont.*

ID	Nodes	Area km^2	Density log (nodes/km^2)	Start Year	Duration Years	Sensor Type	Transmission
77	27	1200	−1.65	2016	0.3	Velocimeter	No trasmission
78	9	1.5	0.78	2016	2	Low cost MEMS	Real-time
79	220	1	2.34	2017	6	Low cost MEMS	Real-time
80	11	35	−0.50	2017	6	MEMS Accelerometer	Real-time
81	8	0.15	1.73	2017	2	Force Balance Accelerometer	No info
82	140	3450	−1.39	2017	6	Velocimeter	Real-time
83	12	320	−1.43	2017	0.08	Velocimeter	No info
84	11	15	−0.13	2017	5.8	Low cost MEMS	Real-time
85	13	0.8	1.21	2017	2	Low cost MEMS	Real-time
86	300	12000	−1.60	2017	5.7	Force Balance Accelerometer	Real-time
87	8	1.5	0.73	2017	0.5	Force Balance Accelerometer	No info
88	13	45	−0.54	2017	1.4	Velocimeter	No info
89	200	3600	−1.26	2017	3.3	Velocimeter	Real-time
90	7	2	0.54	2018	2	Low cost MEMS	Near real-time
91	20	5	0.60	2018	3	MEMS Accelerometer	Real-time
92	12	3	0.60	2018	5	Low cost MEMS	Near real-time
93	5	1	0.70	2018	5	Low cost MEMS	Near real-time
94	32	3	1.03	2018	0.09	Velocimeter	No info
95	112	200	−0.25	2018	0.3	Velocimeter	No trasmission
96	88	1000	−1.06	2019	0.08	Velocimeter	No trasmission
97	6	325	−1.73	2019	0.08	Velocimeter	No info
98	19	10	0.28	2019	1	Velocimeter and accelerometer	Near real-time
99	9	17	−0.28	2019	0.67	Velocimeter	No trasmission
100	113	450	−0.60	2019	0.7	Velocimeter	No trasmission
101	15	25	−0.22	2020	2.5	Low cost MEMS	Real-time
102	6	21	−0.54	2020	2.13	Velocimeter and accelerometer	Real-time
103	14	10	0.15	2021	2	Low cost MEMS	Near real-time
104	NA	450		2021	2	Low cost MEMS	Real-time
105	32	150	−0.67	NA	NA	Low cost MEMS	Real-time

2.2. Objectives

The implementation of USNs enables several tasks, particularly those related to the management of the seismic risk and applications related to civil engineering problems. However, other applications in the broad field of monitoringare gaining interest as well (c.f. [145]).

Each USN is established to accomplish a clear objective. This main objective can sometimes be followed by secondary objectives. Therefore, logistic and technological choices of each USN are properly conceived to cope with these objectives. We identified six recurring objectives among the collected USNs:

- *Earthquake early warning*. USNs are usually designed to provide a warning in the very first moments after the occurrence of a strong earthquake. Such systems are based on the early processing of the seismic signals recorded at the network nodes by means of opportune algorithms. The two possible approaches to this task are the "network- or regional-based" and the "on site (or single station)" approaches. The on-site approach is the one most commonly adopted by USNs devoted to earthquake early warning. It does not require an extended network, and the alert time is reduced compared to the regional approach, which need not necessarily include the accurate location of the event. For this reason, unlike the regional approach, low-cost sensors can be employed and transmission can even be neglected [146]. In particular, on-site early warning systems are based on the detection of P-wave arrivals and estimation of the intensity of the incoming ground shaking in a few fractions of second, which is done by taking advantage of the difference in velocity between the P and S waves [147–149].
- *Earthquake monitoring*. USNs are frequently established to monitor earthquakes in urban areas. they are sometimes implemented as permanent networks, while other times they are expressly temporary and established only after the main earthquake of a sequence with the main objective of monitoring any following aftershocks.
- *Post-event damage assessment*. This group of networks includes those specially planned for the implementation of systems that function to estimate earthquake damage, casualties, or losses in short time after an earthquake [150,151]. They are often referred to as "rapid response systems" because they account for their task immediately after an earthquake. They can quickly support the creation of basic seismic intensity maps.

- *Seismic intensity mapping*. Under this definition, we have grouped the networks which provide measurements of the ground motion intensity at the nodes of the urban network after an earthquake. These measurements can be straightforwardly used to map the distribution of the peak ground shaking for a given event as well as to produce products known as *shakemaps*. These depict the spatial distribution of peak ground motion, usually taking into account the recorded peak ground acceleration (PGA) or peak-ground velocity (PGV) together with information about the event source (e.g., magnitude, location) and the local site amplification and attenuation laws [152,153]. The distribution of ground motion shaking intensity is a very useful parameter for evaluating the potential damage. While this objective may partially overlap with the previously listed objectives, it is distinguished by its timing, as the action need not necessarily take place immediately after the earthquake.
- *Site effect research*. Among the factors that control the expected ground motion (i.e., the seismic hazard), site effects play a major role. Site effects can be generally defined as alterations to the earthquake's characteristics in terms of amplitude, frequency, and duration of the wave field due to specific stratigraphic or topographic conditions [154]. Such effects can be significant, and can be evaluated with a variety of sensors and methods [155–158]. Their assessment is critical in the built environment, and is the reason behind the implementation of several USNs (usually temporary ones) worldwide.
- *Structural health monitoring*. Earthquakes can affect the state of health of buildings and structures in general. Certain structures can be considered strategic because of their function or value. Networks conceived to monitor the vibrations of such strategic buildings and their behaviour over time represent fundamental tools to establish protection strategies and preserve their functions, and possibly their cultural value, in case of damaging earthquakes [8].

Moreover, grouped under *"other"*, we classified USNs with less common objectives such as the implementation of decision support systems [43,45,118], seismological studies [101,107,133,136], and monitoring of geothermal stimulation, mines, or other industrial activities [18,55,134,138]. For each record in Table 1, the main objective is reported along with any secondary ones where provided.

The temporal trends of the objectives indicate that not all the objectives are prominent in the same way or within the same period (Figure 3). For instance, USNs for earthquake monitoring and seismic site response have been adopted all along the analysed period, while USNs for earthquake early warning have been implemented only since 2008, and their number has increased relatively quickly (c.f. [159]).

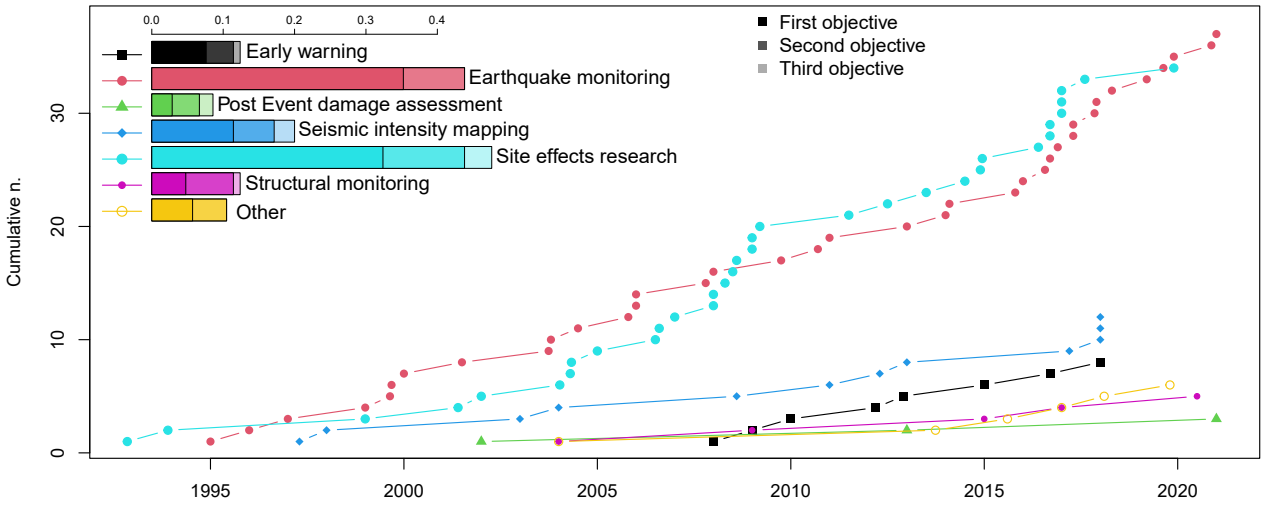


Figure 3. Temporal trends of the main objective adopted by USNs (c.f. Table 1) and frequency of occurrence of all the objectives.

The frequency of occurrence of the various objectives, distinguishing between the main and the secondary ones, is reported in Figure 3. Considering only the main objective, one-third of the considered USNs were established for earthquake monitoring; the study of site effects and the assessment of ground motion intensity are the second- and third-most frequent objectives, respectively. Considering the primary and secondary tasks together, earthquake monitoring and site effects make up the objectives for more than 40% of the collected USNs.

2.3. Duration

The date of starting observation (year, and sometimes month and day) is provided for all the USNs except for a single one. Conversely, the exact date of ending observation is provided only for the fixed-term networks. Certain USNs have been planned as permanent monitoring infrastructure, and remain active at present. For other networks, the authors did not provide any clues as to whether the networks were established as fixed-term or permanent ones. In many of these cases, we have been able to find further references providing information about the activity of the networks. Therefore, for these USNs, the duration reported in Table 2 actually indicates a "minimum duration", i.e., the time span between the starting of the network and the last evidence of activity. For the active networks, the duration is considered to be current until 2023.

The corresponding temporal bar for each of the collected networks is reported in Figure 4. The first urban networks were implemented in the early 1990s, and until the early 2000s there were only a few networks. Subsequently, the number of new operating USNs has steadily increased for about fifteen years. This trend has been sharply increasing since 2016-17, with the relatively lower number of USNs reported in the last few years ascribed to the most recent networks still being unpublished. In addition, Figure 4 reports the frequency density distribution of the duration. About 40% of the USNs have a duration shorter than one year, and 60% last for less than five years. Only approximately the 20% of the networks have been continuously operating for more than ten years.

The operating time of a network is tightly constrained by its objective(s). Of course, other factors may influence on the duration, most of all the economic resources needed to keep a network working. The duration as a function of the main objective is displayed in Figure 5. For a given objective, the duration may span a wide range of years. Part of this dispersion is due to limits in the assessment of the exact duration, as explained above. However, differences between various objectives are recognizable, even though no universal conclusions can be derived.

Networks for earthquake monitoring include the widest range of durations, as they comprise both USNs designed for seismic surveillance (i.e., long-term monitoring) and USNs conceived to monitor only a single seismic sequence or seismic swarm. Although the durations cover more than a decade, the networks for site effects are clearly clustered, as is predictable, towards the shortest duration (even less than one year). Conversely, no short-duration networks are targeted to report ground motion intensity. The networks for structural health monitoring have variable duration, and are mostly implemented as permanent infrastructure.

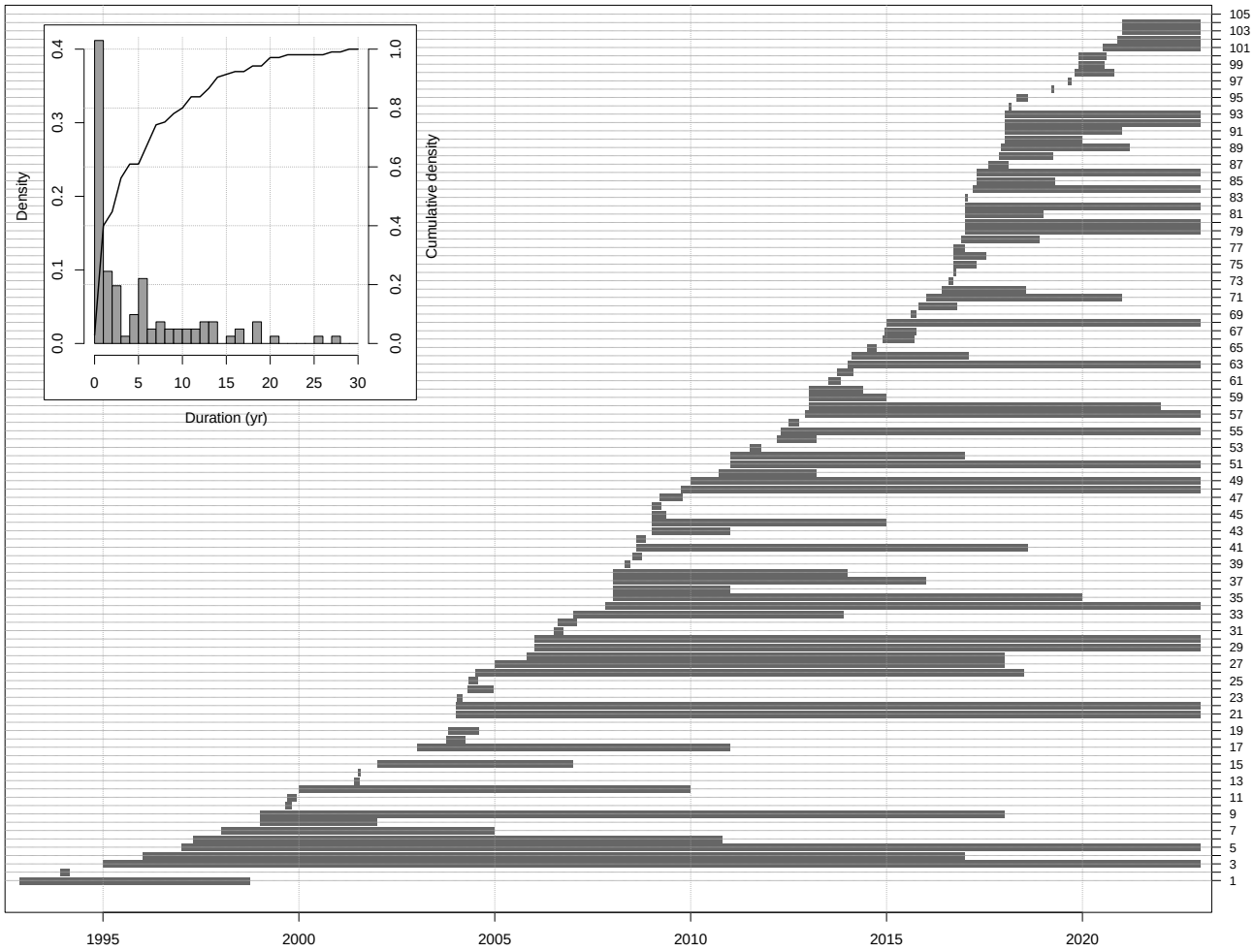


Figure 4. Temporal bar graph of the collected USNs; the inset displays the frequency density distribution of USN durations.

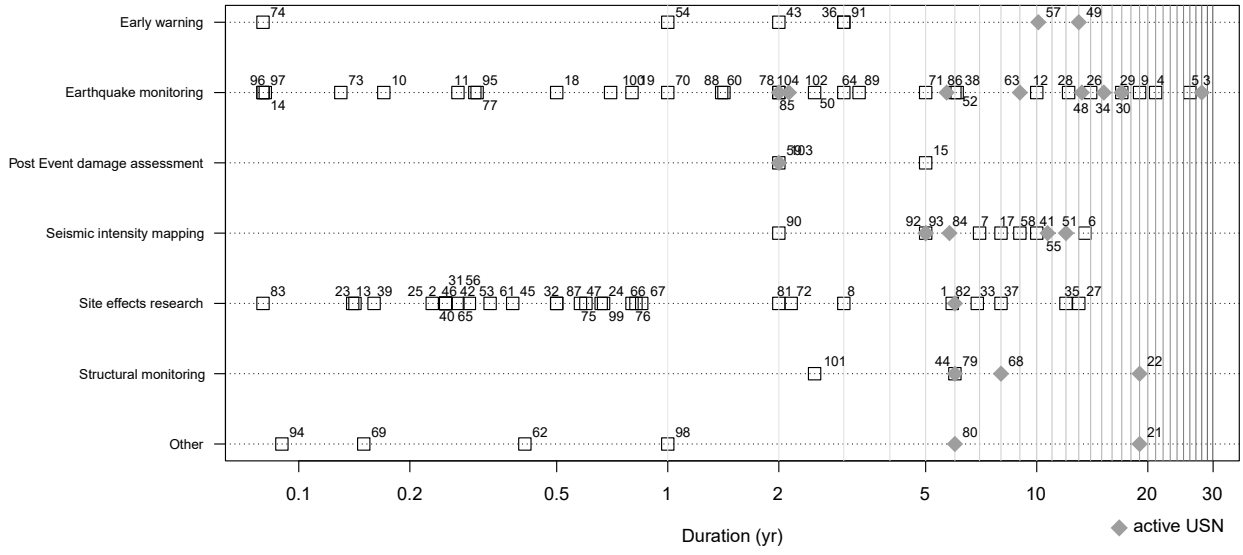


Figure 5. Operating times of USNs grouped according to their main objective. The temporal axis is in logarithmic scale and the numbers refer to the IDs in Tables 1 and 2.

2.4. Coverage

With regard to the number of nodes and the area covered by each USN, the catalogue includes a very wide range of combinations; both factors span several orders of magnitude, and their their ratio (i.e., number of nodes per unit area) likewise covers a wide range of density values.

The number of nodes forming a USN depends on several factors. Usually, these factors result from the combination of the objectives to be accomplished and the area being monitored, although the logistical needs and available financial resources can contribute to quantifying the sensor nodes to be installed, as some networks can be integrated over time, especially permanent ones. Most of the USNs have some tens of nodes, with only sixteen of them having more than a hundred sensors. USNs usually extend between some tens and few thousands of km^2 (see Figure 6). It is worth highlighting that the size of the area covered by a USN often does not appear to be strictly related to the extension of the corresponding urban/metropolitan area where it is located, and might depend on the network's purpose as well. Sometimes the target of an USN is only a portion of a given urban area, e.g., a campus, historic center, or neighborhood, while sometimes it extends to the far outskirts of the urbanized territory, and may include different contiguous urban centers under a single network. In these latter cases, USNs can extend up to 10^4–10^5 km^2, representing real regional-scale networks. As far as density is concerned, the densest USNs count even more than 100 nodes per km^2, while in the loosest networks a single monitoring site covers a surface greater than 1000 km^2. However, most USNs have densities ranging between 0.01 and 1 nodes/km^2 (Figure 6).

D'Alessandro et al. (2019) [8] classified only those seismic networks characterized by specific combinations of values of area and density as "urban-scale networks" (the solid grey contour in Figure 6b,c). Actually, only a few USNs in our collection fall within this definition; these fourteen USNs all fall within a limited part of it. Therefore, the definition of a USN provided by [8] is too restrictive from the point of view of the covered area and too inclusive when it postulates very-high-density networks over relatively large areas. This is due to the very limited collection underlying their observations, as they reported only five USNs implemented in Italy).

Our catalogue helps to better define USNs in terms of the combination of covered area, number of nodes, and their ratio. Most USNs lie within the red region in Figure 6b, which can be considered the typical combination of covered area and number of nodes for a USN: a few tens of nodes spread over a surface of 10–1000 km^2. Moreover, we found that when considering all the USNs and including all the objectives, the density of the USN decreases linearly on a log–log scale when the covered area increases (see Figure 6c). This scale relationship is very clear, and can be used as a guideline when planning new USNs. This relation may suggest the indicative number of sites necessary to establish a new network over an urban area of a given extension, or conversely, can provide indications of the maximum extension achievable by the network when a given number of sensors is available. Of course, the final plan of a new network must support all its specific targets, which are peculiar and unique for each case. However, exploiting the indications from a vast collection of other applications can represent decisive support as well as a measure of comparison with the state of the art.

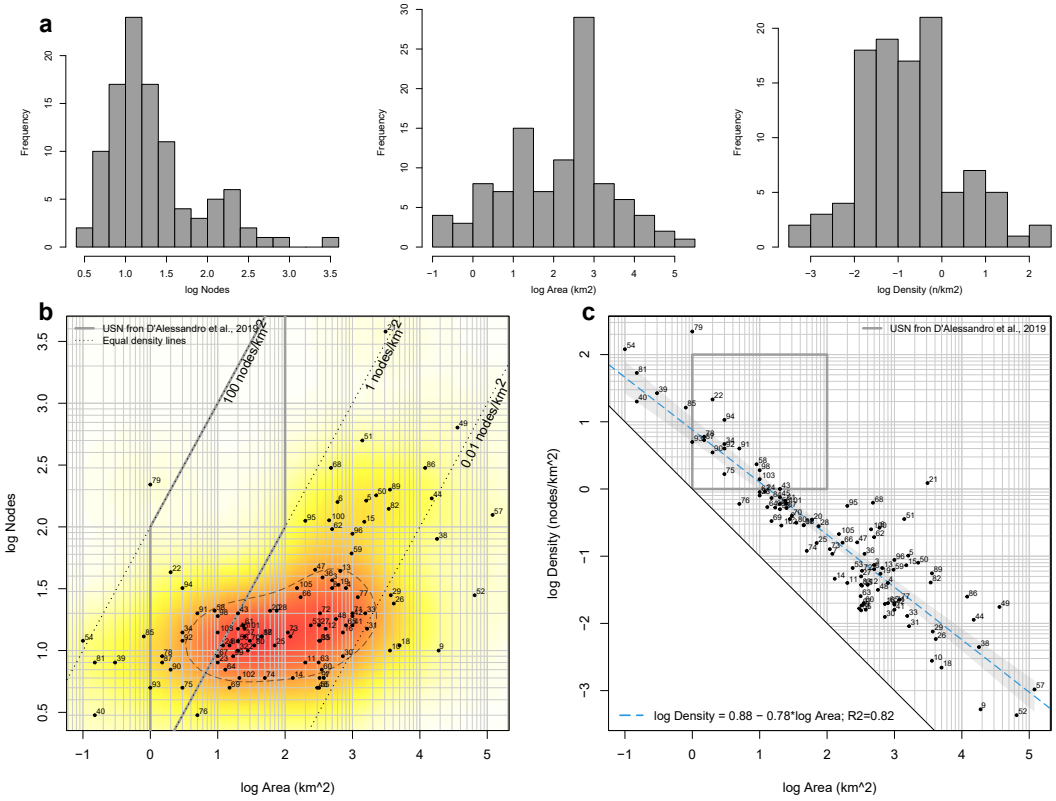


Figure 6. (**a**) Histograms for number of nodes, covered area, and network density. (**b**) Scatter plots of node number versus covered area; the coloured shades represent the intensity of observations and the dashed line encloses the area with greatest intensity. (**c**) Scatter plots of network density versus covered area; the blue dashed line and the shaded region indicate the regression line and the 95% confidence interval, respectively. The numbers refer to the IDs in Tables 1 and 2.

2.5. Technical Characteristics

This subparagraph resumes the information concerning the type of sensors employed in the USNs and their transmission systems. The network geometry is another important feature of the monitoring networks that we have investigated. We provide considerations about this latter aspect in a devoted paragraph.

2.5.1. Sensors

The type of sensors employed in the network is a key feature of each USN. We classified the sensors adopted by each USN into five different types: (i) velocimeter, (ii) force balance accelerometer, (iii) both velocimeter and accelerometer, (iv) MEMS accelerometer, and (v) low-cost MEMS.

The balanced use of velocimeters and accelerometers at different nodes is sometimes adopted to exploit the advantages of both types of sensors; therefore, a dedicated group has been considered to cover this case. For other combinations of sensors, which are far less frequent, the prevalent typology is considered. The distinction between short-period and broad-band sensors is not reported at this stage, though considerations are provided in the text. The most widely employed sensors (in more than 40% of USN) are velocimeters; force balance accelerometers and low-cost MEMS occur less frequently, being encountered in about 20% of the USNs, and the two remaining groups are even less frequent (Figure 7).

The main difference between the two MEMS (micro-electro-mechanical systems) groups is the cost for a single device, though this obviously carries a number of implications. This distinction concerns the performance of the sensors as well, in particular the self-noise level, the type of output (usually analog for better sensors), and the stability against environmental conditions. The literature has largely investigated the performance

of several models of MEMS sensors [116,160–165]. In terms of self noise spectral density, a level in the order of 10^{-5} m $\cdot$ s$^{-2}/\sqrt{\text{Hz}}$ in the band 1–10 Hz can been considered as a rough boundary between the two groups of MEMS sensors.

In the selection of appropriate sites to establish a seismic network, considerations about the background seismic noise play a role. The seismic noise affects the detection capability; thus, sites should be as quiet as possible. A great portion of the noise power, especially at high frequencies, is related to human activities (so-called urban or cultural noise). Inevitably, urban areas suffer strong levels of seismic noise, and these noisy areas are unsuitable to host networks only conceived and designed to locate earthquakes. These conditions represent a relevant limitation for USNs, and are the most usual reason for poorly performing sensors (especially in terms of self-noise and bandwidth), particularly for certain objectives. On the other hand, cheaper sensors allow applications with higher density at equal cost, which could desirable for USNs. These are among the reasons that lower quality devices such as MEMS sensors and even low-cost MEMS can be suitable for seismological applications and employed in a variety of applications in the broad field of seismology, including in USNs [166–168]. Their use started only about fifteen years ago, and has been increasing sharply over the last decade (Figure 7). During the first decade of their development, USNs were mainly strong-motion networks based essentially on accelerometers (Figure 7).

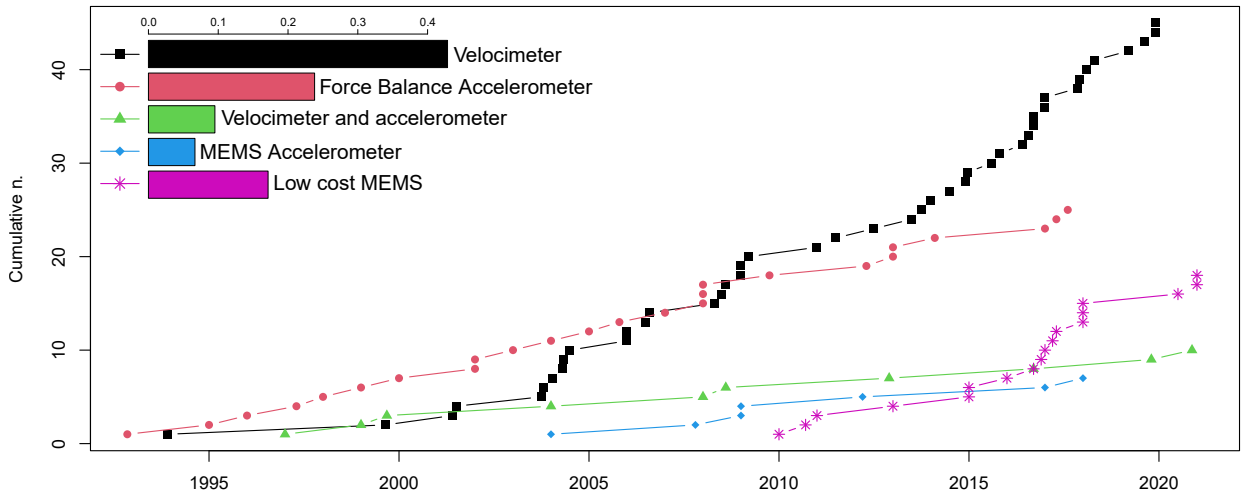


Figure 7. Temporal trends of the types of sensors adopted by USNs listed in Table 2 and their frequency of occurrence.

The choice of sensor typology is typically made based on the main objective; in fact, a coupling of the sensor type and main objective occurs very frequently, e.g., velocimeters for earthquake monitoring and site effect assessment, while several other combinations never occur (Figure 8). Both force-balance accelerometers and low-cost MEMS can be profitably employed in many different applications [167,169]

Other secondary aspects regarding sensors include the sampling rate, type of installation (surface, borehole), and natural period for velocimeters (short period, broad band, etc). This information is not always declared for the selected USNs; moreover, as our aim is to provide a schematic view of the solutions adopted for USNs, taking these aspects into account would be an unproductive complication.

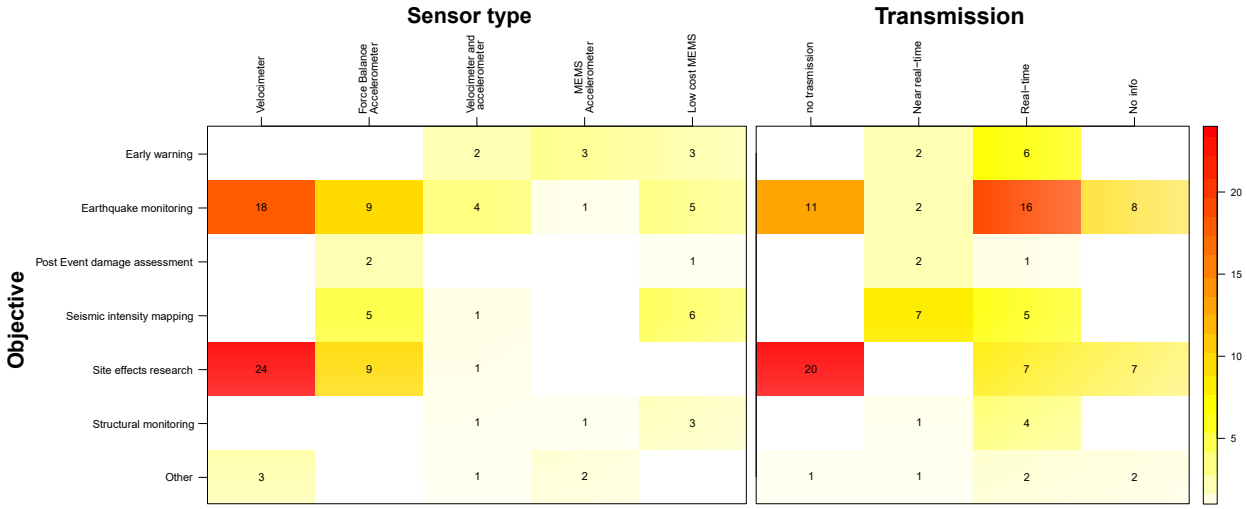


Figure 8. The numbers and color bar indicate the frequency of occurrence of combinations between the main objective and the sensor type (**left**) and transmission type (**right**). Data retrieved from Tables 1 and 2.

2.5.2. Transmission

Concerning data transmission, we identified three classes: (i) real-time transmission; (ii) near-real-time transmission; and (iii) no transmission. For certain USNs, it was not possible to retrieve any information about the transmission type; these are classed as "no info".

The difference between real-time and near-real-time can be subtle, and we were not able to verify whether different authors adopted the same definitions. We only gathered the information as it was provided, without performing any type of validation. Real-time transmission is the most commonly adopted choice, being implemented in almost the 40% of USNs; about one third of the networks were designed without any data transmission (Figure 9). Real-time (or even near-real time) transmission may have represented a limit for early USNs, while today technical solutions are easily feasible via internet connections (Figure 9), especially in urbanized areas. For this reason, the choice of transmission is not strictly and exclusively imposed only by the final objective of the USN, although a correspondence certainly exists (Figure 8); in fact, for the realization of certain objectives, e.g., site effect studies or characterization of structural health states, data transmission may be a non-essential requirement and local data storage may represent a rather more agile solution. For other objectives, however, such as earthquake monitoring and earthquake early warning, collecting data in real time is a fundamental prerequisite. In particular, reliable real-time transmission is indispensable for network-based early warning systems. Real-time transmission can additionally be useful for remote control of the correct functioning of acquisition stations without needing to reach the sites, at least periodically.

A summary of the main features for both the sensor and transmission types, recalling their pros and cons, is reported in Table 3. When planning a USN, these features should be evaluated together with the objective(s) of the network.

Table 3. Summary of the main features of the various sensor and transmission types applicable for the implementation of a USN.

	Type	Pros	Cons
SENSORS	Velocimeters	Wide range of devices (short-period to broad-band) and versatility. Generally higher sensitivity and lower self-noise level. High robustness and durability, suitable for long-term applications. Reliable reconstruction of the waveform in a wide frequency range.	Expensive and unaffordable for the implementation of a dense USN. Usually require quieter sites for the installation (vaults or post-hole configurations would be preferable, especially for broad-band sensors). Signals can saturate in case of strong motion.
	Force Balance Accelerometers	High sensitivity. High robustness and durability: suitable for long-term applications. Signals do not saturate in case of strong motion.	Relatively expensive. Poor capability to record weak motions.
	MEMS sensors	Low unit cost, small size, and light weight, make them suitable for implementing a dense USN with a high number of sensors. Possible digital output; no need for a datalogger. Suitable for installations in noisy sites or buildings.	Generally low sensitivity and resolution and higher self-noise level. Usually limited durability and need for greater maintenance and replacement of non-functioning parts.
TRANSMISSION	No transmission	Agile solution. No extra power consumption. Easier installations. No need for remote acquisition system. Suitable for temporary observations.	Fixed storage capacity. Periodic on-site maintenance to gather data. No telemetry of the monitoring sites. Early on-site elaborations can be exploited only locally. No possibility of checking the correct functioning of the system, without on-site visits.
	Near or real-time	Immediate availability of data for end users. Extendable remote storage capacity. Possibility to share early on-site elaborations. Possibility of using the telemetry of the monitoring sites. Data back-up.	Higher power consumption. Remote storage infrastructure is required. Costs for data transmission can be relevant for large amounts of data, i.e., numerous devices with continuous recording at high sampling rates and for a long time.

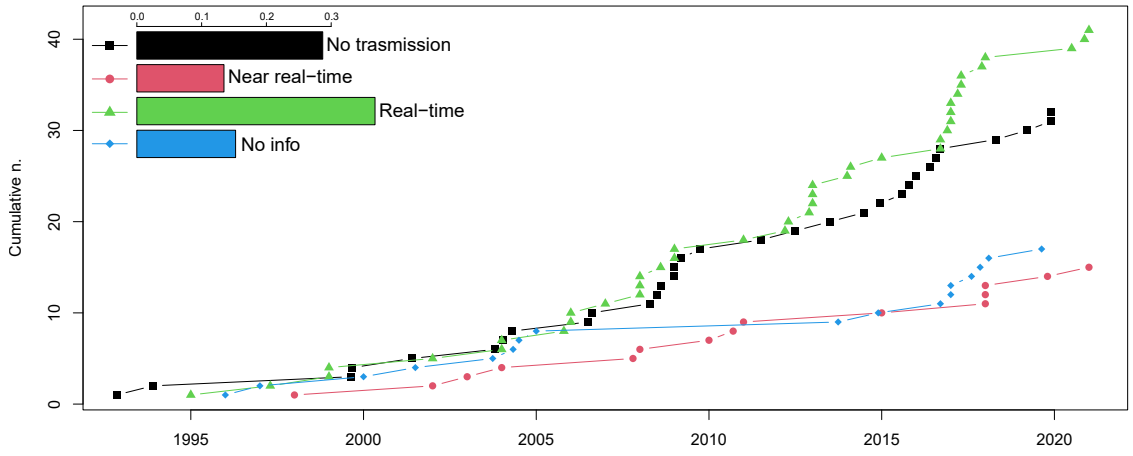


Figure 9. Temporal trends of the types of transmission adopted by the USNs listed in Table 2 and their frequency of occurrence.

2.6. Network Geometry

The design of a network in an urban context represents a trade-off between external fixed geometrical constraints, high levels of noise, and the cost of preparing the sites [170]. Therefore, the geometry is a crucial aspect; however, it cannot be entirely planned.

The geometry affects the results in relation to the objective of the network. This is especially valid for networks designed to detect and locate earthquakes, as the results derive from the combination of observations at several different nodes. For this reason, the

geometry plays a critical role in the precision and accuracy of the hypocentre locations as well as in estimation of the the magnitude [171,172]. The relevance of a planned geometry is relatively decreased for networks in which the observations are treated independently on a site-by-site basis (e.g., on-site early warning, assessing site effects, seismic intensity mapping), even though the geometry may affect the later data interpolation or modelling. Finally, other networks, such as those designed for structural health monitoring, are completely unaffected by geometry, as the observations at a given site are never combined with observations from other sites.

We have not classified the types of geometry in the USN catalogue. Although the positions of the nodes are sometimes provided, it was not possible to assess a metric to clearly and unambiguously support the grouping of USNs into distinct classes of geometries. However, we provide an overview of the various typologies of geometrical arrangements adopted by the USNs (Figure 10). From the reported examples, it is clear that the transition between regular and irregular geometries may not be sharp enough to define clear boundaries between these classes.

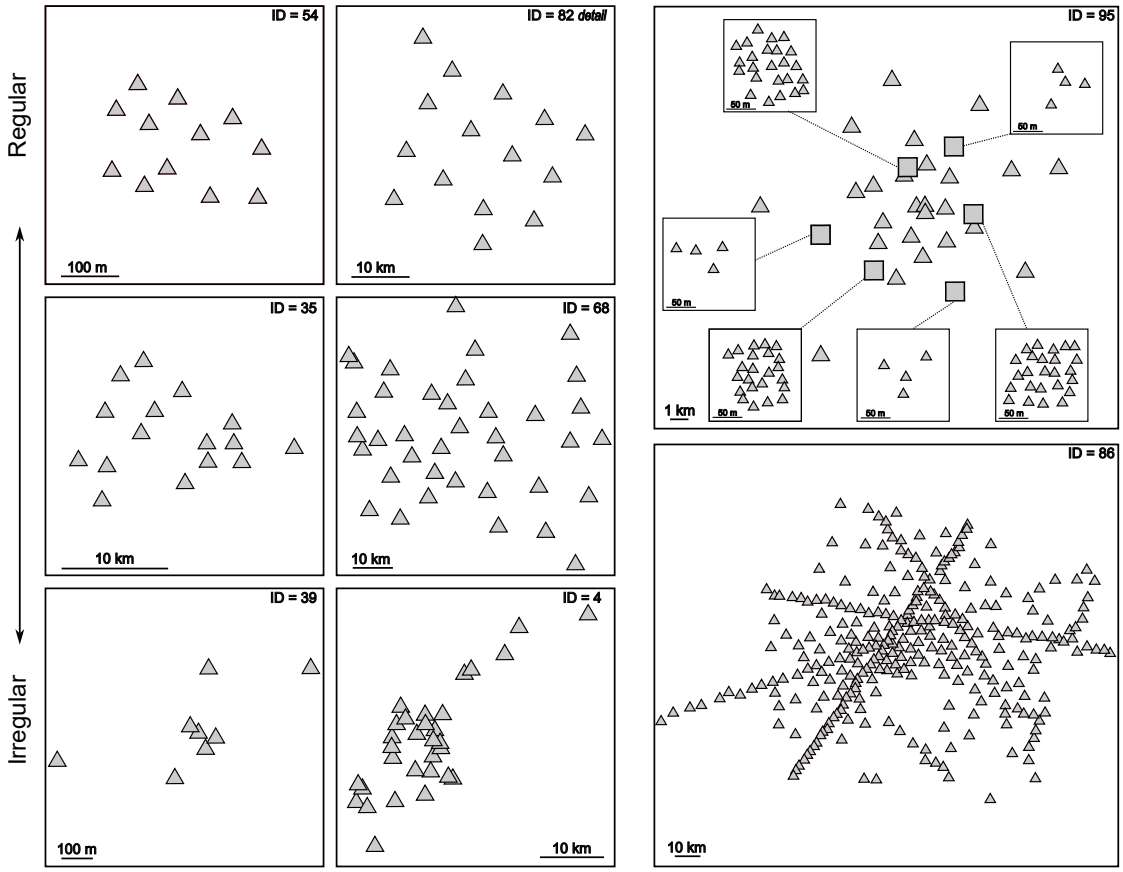


Figure 10. Examples of network geometries with different degrees of regularity. In the right column, examples of USNs including station arrays: six arrays in Helsinki [134] and five linear arrays in Tokyo [123].

In most cases, the choice of the geometry is mainly aimed towards providing uniform coverage of the target urban area. However, geographical boundaries (e.g., coastlines), geological boundaries (the need to sample all soil types), and sometimes even administrative boundaries or permission issues can represent constraints when planning the geometry of a network. For all of these reasons, there are few networks in which the geometry can be deliberately designed. In certain cases, the networks are the results of superpositions of other sub-networks with different geometries, resulting in articulated final arrangements [39].

Regular networks forming grids with regular meshes are ideal solutions; however, they are hard to implement [92,120]. The arrangement sometimes aims to ensure homogeneous coverage with equally spaced nodes, even if through an irregular pattern [67,88] (Figure 10). In certain cases, part of the network is designed to form specific geometrical patterns, i.e., arrays (Figure 10), with several identical sensors deployed regularly (or almost regularly) at different scales [123,134,138]. Arrays enhance the seismic signals, allowing the detection of weaker signals and characterization of the wavefield. Finally, a few USNs include vertical arrays, with the deployment of several sensors in a given location at different depths [37,46,48,49,134]. Arrays are mostly used for seismological experiments, and mainly fall within the group of "other" objectives.

3. Concluding Remarks

The idea of focusing an earthquake monitoring network on a single urban areas has been widely exploited in the last decades, and has became a tool for a variety of different tasks.

USNs can be settled in a relatively short time compared to traditional large-scale networks, and the costs for their maintenance in the case of long-term applications are comparatively constrained. Of course, for certain specific objectives USN performance can be reduced with respect to large-scale networks, especially compared to those designed for seismic surveillance. However, in most cases USNs represent an excellent solution in the trade-off between time and costs on the one hand and performance and reliability on the other. In this review, we provide an overview of the application of this tool, focusing in particular on the technical characteristics. In addition, we aim to provide strategies for the planning and development of USNs (presented in Table 4). Each USN objective, together with any possible secondary tasks, entails numerous possible combinations between technical and operational elements. Tables 3 and 4 provide recommendations on a wide range of such choices.

Although often designed as single-task infrastructure, USNs may enable multiple functions, especially in case of strong earthquakes. USNs can represent the core of an entire chain of actions, starting in the very early aftermath of earthquake detection (early warning systems) and revealing decisive information in the short term when supporting decision-making and rescue operations is crucial (post-event damage assessment, seismic intensity mapping), while other actions may only performed later (seismic site response, structural monitoring).

It is very likely that in the near future the interest in monitoring urban areas will continue to increase, driven by the expansion of urban centers and the consequent need to arrange mitigation and prevention actions [173,174]. The capabilities of new sensing networks based on fiber-optic cables have been explored and developed in the last few years [175–183]. A network based on distributed acoustic sensing (DAS) represents the ideal candidate for the future generation of USNs. At this early stage for this technology, the cost for DAS interrogation units are remarkable; conversely, the possibility of exploiting existing communication infrastructure and the contained costs for cable maintenance help to balance the overall cost. Such systems are very sensitive; they allow high spatial (sub-metric) and temporal (up to kHz) resolutions. The waveforms can be reconstructed with high fidelity in the band from 0.02 to 30 Hz, making their performance comparable to broadband seismometers [178,182,184]. In general, the main advantages are the possibility of exploiting expanding communication infrastructure and the potentially huge amount of high quality data.

According to Allen and Stogaitis (2022) [159], seismic networks are evolving from research-oriented projects into public safety infrastructure. From this perspective, in the near future USNs could be integrated with other networks as components of a multi-scale and multi-parametric system in a smart city context. Such a system could carry out several roles in the disaster cycle, not only involving earthquakes, both in the pre-event (preventions) and post-event (recovery) phases. Such integration includes the possibility

of sharing crucial data during the phase of post-disaster decision-making (e.g., structural monitoring, power and water grids, transportation, energy, etc.) as well as with regard to climate and environmental parameters [185]. Stakeholders, civil protection authorities, decision-makers, the scientific community, and the whole of society are among the potential beneficiaries of the outcomes of this integrated multi-scale system for the reduction of seismic risk.

Table 4. Schematic guidelines for the implementation of a USN according to the planned objective.

Objective	Sensors	Transmission	Duration	Notes
Early Warning	All types can be theoretically used. The literature indicates that, due to their characteristics (c.f. Table 3), MEMS sensors are preferable.	Real-time transmission is necessary for more reliable systems based on the "on-site" approach. It is indispensable for the "network-based" approach.	To be planned as an open-ended application.	USNs are suitable for implementing the "on-site" early warning approach in urban areas and for critical infrastructure.
Earthquake Monitoring	Velocimeters are the most commonly employed sensors. According to specific purposes (e.g., the monitoring of strong local seismicity), force balance accelerometers or MEMS sensors can be suitable for integrating surveillance networks.	Data transmission is always recommended, especially for long-term monitoring campaigns (see Table 3).	Months to years, as well as a long-term task according to the specific USN's needs.	Integration between the capabilities of different types of sensors at different nodes, or even at the same sites, can be exploited.
Post-Event Damage Assessment	Accelerometers are the most adapted to measuring strong motion.	Transmission is required.	To be planned as an open-ended application.	Regular geometries are recommended.
Seismic Intensity Mapping	Accelerometers are the most adapted to measuring strong motion.	Data transmission is required.	To be planned as an open-ended application.	Transmission can be essential for generating real-time *shakemaps*.
Site Effects Research	Velocimeters are usually adopted. The natural period of the sensor affects the bandwidth of the results.	Data transmission is not essential, though it can be useful for the reasons listed in Table 3.	The USN can be planned as a short-term application.	The distribution of USN nodes must be homogeneous and representative of the soil types and stratigraphic conditions.
Structural Health Monitoring	MEMS sensors are the most widely adopted; they represent a good trade-off between cost and quality. A free-field installation as a reference is recommended.	Data transmission is recommended.	To be planned as an open-ended application.	Critical infrastructure (bridges, distribution networks, etc.) and/or strategic buildings (hospitals, schools, fire stations, etc.) should represent the primary targets.

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Abbreviations

The following abbreviations are used in this manuscript:

USN	Urban Seismic Networks
MEMS	Micro-Electro-Mechanical Systems
DAS	Distributed Acoustic Sensing

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