National Seismological Network in India for Real-Time Earthquake Monitoring

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Abstract

The National Seismological Network (NSN) of India has a history of more than 120 yr. During the last two decades, the NSN has gone through a significant modernization process, involving installation of seismic stations equipped with a broadband seismograph (BBS) and a strong-motion accelerograph (SMA). Each station has a very-small-aperture terminal connectivity for streaming data in real time to the central receiving station (CRS) in New Delhi. Seismic data recorded by the network are analyzed continuously on 24 × 7 basis to monitor the earthquakes in India and its adjoining regions. In this article, we present details of BBS and SMA network configurations; data streaming from the field seismic stations to the CRS for analysis; and the automatic and manual publication of the earthquake parameters including location coordinates, focal depth, time of occurrence, and magnitude, etc. Details of historically significant analog seismic charts and the seismic catalog, which includes more than 34,000 events with magnitude M_w 1.7–9.3 since 1505, are provided. The national network of India has been strengthened over the years and is now capable of estimating the main earthquake source parameters within ∼5–10 min with an average of about 8.0 min. The spatial analysis of minimum magnitude of completeness further indicates a significant enhancement in minimum threshold magnitude detection capability of the network in recent decades.

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Supplemental Material

Introduction

The tectonics of the Indian subcontinent are very complex and are categorized into three major physiographic divisions: the Himalaya, the Indo-Gangetic plains, and the Peninsular India (Valdiya, 2015). The Himalayan belt is seismically the most active region owing to continental convergence between the Indian and Eurasian plates. The convergence initiated about 55 million years ago (Patriat and Achache, 1984; Garzanti *et al.*, 1987) and completed in 40 million years. This convergence not only caused the genesis of the Himalaya but also formed an active seismic belt stretching about 2500 km along the common plate margin, having the potential to generate large to great earthquakes from the Kashmir Himalaya in the northwest to the Arunachal Himalaya in the northeast. Almost half of the Himalayan mountain belt has ruptured in the last 120 yr or so, and at least three great earthquakes ($\mathbf{M} \geq 8.0$) occurred in 1897, 1934, and 1950 (Fig. 1). The Kangra earthquake, which was initially considered to be in the category of great earthquakes, is not included in the list because the magnitude of this earthquake was revised to $M_w \sim 7.8$ (Bilham, 2019). These historical earthquakes caused major destruction to properties and loss of human lives, flora, and fauna, and so forth in different parts of the country.

Based on the seismicity, the intensity experienced, and the geologic and tectonic settings of different areas, the Bureau of Indian Standards has grouped the country into four seismic zones: II–V; with zone V having high hazard and zone II the least (Bureau of Indian Standards [BIS], 2002). The seismicity of the Indo-Burmese arc and the Andaman–Nicobar Islands are intricately related to the subduction of the Indian plate beneath the Myanmar microplate that makes the region seismically the most hazardous (zone V), on par with the Himalayan collision zone in the north and the Kachchh seismic zone in the western part of India. The western Indian Peninsula witnessed a strong historical earthquake on 16 June 1819, the Allah Bund earthquake (M_w 7.8), which devastated the region and resulted in uplift of ∼3–6 m of the hanging wall along the fault (Oldham, 1928; see Data and Resources). However, in the northeast region, the Great Shillong earthquake of 12 June 1897 (M_s 8.7) is considered to be one of the largest events in recorded history and was caused by the continent–continent collision beneath the Himalayas (Oldham, 1899; Verma and Bansal, 2013).

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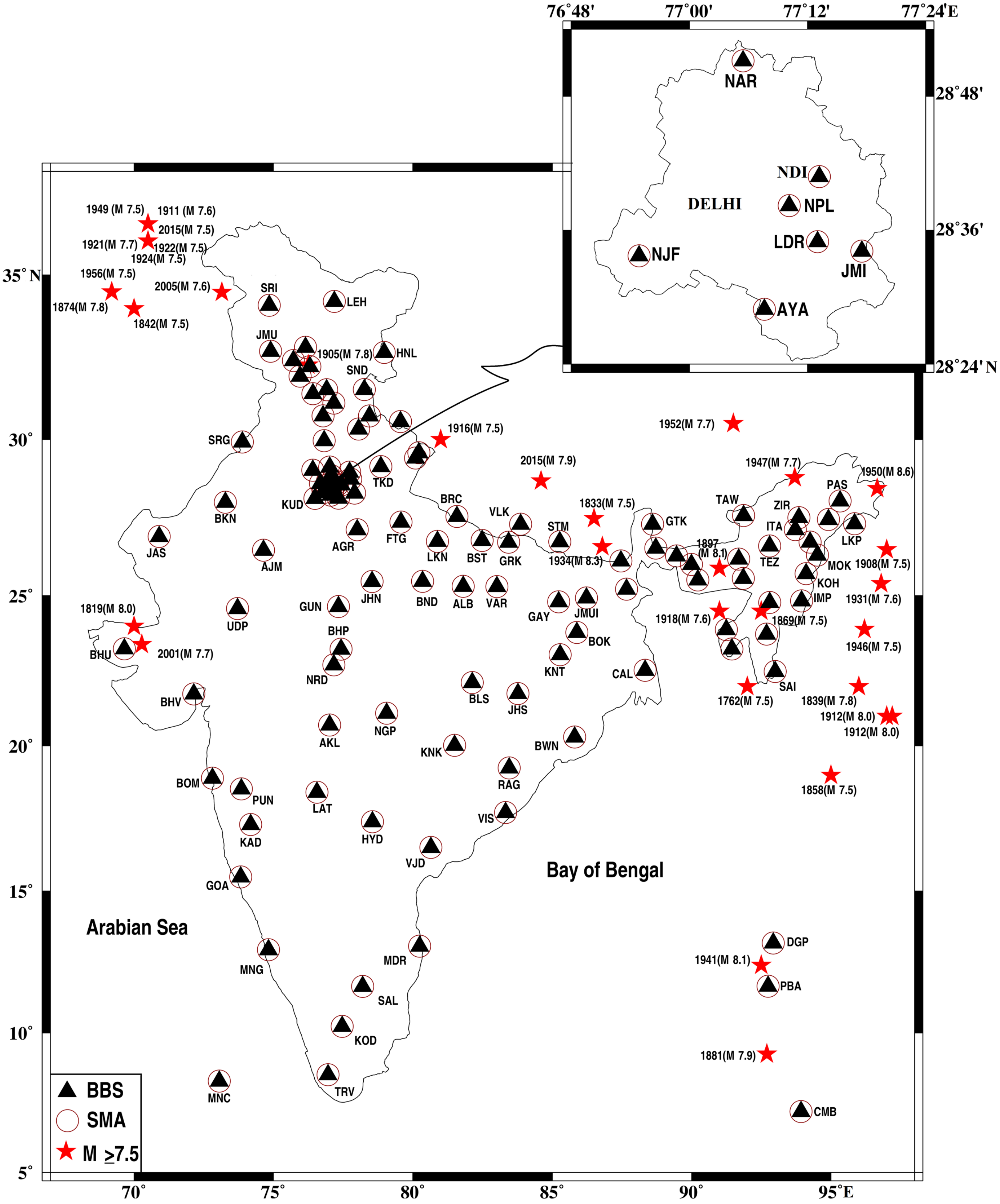

Figure 1. Map showing the locations of seismic stations of the National Seismological Network (NSN) maintained by the National Centre for Seismology. The network consists of 115 seismic stations having broadband seismometers (BBSs) and strong-motion accelerographs (SMAs). Stars represent the earthquakes of magnitude **M** ≥ 7.5 since 1505. (Inset) Locations of the seismic stations established within the National Capital Territory, Delhi. The color version of this figure is available only in the electronic edition.

In addition, instrumentally recorded significant earthquakes in the Himalayan arc from west to east are, namely, the 1905 M_w 7.8 Kangra, 1916 M_s 7.5 Dharuchula, 1934 M_s 8.3 Bihar–Nepal, 1947 M_w 7.7 Assam, and 1950 M_w 8.6 Assam earthquakes (Fig. 1). The Andaman–Sunda arc connecting to the southern tip of the Burmese arc has been associated with several damaging earthquakes, and in some cases, a tsunami was also generated (Bilham *et al.*, 2005). The largest among these are mainly the historical earthquakes of 1881 (M_w 7.9) and 1941 (M_w 8.1), also depicted in Figure 1. However, in recent times, the 26 December 2004 megathrust earthquake (M_w 9.3) along the Indian plate near Andaman–Nicobar Islands has been the most devastating event in the region; it also generated a destructive tsunami in the Indian Ocean that killed about 0.2 million people and caused damage to property worth a few billion dollars (Synolakis *et al.*, 2005; Titov *et al.*, 2005).

In the recent past, the peninsular India has experienced more than 100 earthquakes of magnitude ≥ 5 (National Centre for Seismology [NCS] catalog), several of which were damaging. Chronologically, these are the 1993 Killari (M_w 6.2, intensity VIII+) and 1997 Jabalpur (M_w 5.8, intensity VIII) earthquakes in central India and the 2001 Bhuj earthquake (M_w 7.7, intensity X+) in the western part of the peninsular shield region. These earthquakes changed the long-held belief of slight seismicity in the Indian Peninsula (Chandra, 1977; Bansal and Verma, 2013). Consequently, the seismicity in the Indian subcontinent needed to be studied rigorously because even the moderate earthquakes caused damage across large areas and small events created panic among the public.

The NCS, established in August 2014 under the Ministry of Earth Sciences (MoES), is a nodal agency of the Government of India, for near-real-time earthquake monitoring across the country. The NCS was set up by bringing all of the seismological activities of the India Meteorological Department (IMD) and MoES under one umbrella, to address nationwide earthquake related issues. The NCS established regional as well as local networks to cover the most seismically active regions such as the Himalaya, northeast region, Andaman–Nicobar subduction zone, and parts of the Peninsular India. During the last 6 yr, a major expansion and modernization of the seismic equipment and network in the country has occurred (Fig. 1). This article highlights details of the progression of the seismological network in India from the past to the current stage, including state-of-the-art equipment deployed for earthquake monitoring, seismic data streaming from the seismic stations to the central receiving station (CRS) at the NCS, real-time analysis capabilities, and dissemination of earthquake information, earthquake catalog, and seismological bulletins. We also analyzed the NCS catalog to obtain the spatial variation of the minimum magnitude of completeness over time to understand the network performance.

Progression of Network and Its Performance

The National Seismological Network (NSN) in India has a history of more than 120 yr in earthquake studies. Instrumental earthquake observation in India dates back to 1898, with the first seismological observatory of the country established at Alipore (Calcutta) [Now, Kolkata] on 1 December 1898 after the Great Shillong earthquake of 12 June 1897. The occurrence of catastrophic earthquakes, such as Bihar–Nepal (1934), Assam (1950), and so on, necessitated building up the NSN gradually from a scanty six seismic stations in 1940 to eight in 1950, followed by 15 in 1960 and 18 in 1970 (see Fig. S1, available in the supplemental material to this article). Subsequently, the network was strengthened, and now consists of 115 seismic stations. Prior to the upgrade, all of the analog observatories were equipped with Milne–Shaw, Press–Ewing, and Hagiwara seismographs. The early 1960s witnessed an extensive landmark in the history of earthquake monitoring, when the World Wide Standardized Seismic Network (WWSSN) stations started functioning globally. There were three-component seismic stations located at Kodaikanal, New Delhi, Pune, and Shillong that became part of the WWSSN during 1962–1963 with the installation of matched short-period and long-period seismograph systems. The seismology division of the IMD (now the NCS) in the early 1960s started manufacturing Wood–Anderson and electromagnetic seismographs. With similar instruments, an observatory was established at the National Geophysical Research Institute, Hyderabad on 11 December 1967, and at nearly in the same time, an L-shaped seismic array was established at Gauribidanur by the Bhabha Atomic Research Centre.

The seismological network, prior to 1990, primarily consisted of a conventional analog type of seismograph systems with either photographic, smoke, or ink recording devices, and separate short-period and long-period sensors were used to record the near as well as distant events, respectively. Following the deadly Latur earthquake of 1993, 10 analog observatories located mostly in the peninsular shield region were upgraded to the standards of the Global Seismograph Network in April 1997. These were the first series of digital seismographs inducted in the NSN. Subsequently, 14 more analog observatories were upgraded with similar digital broadband seismographs (BBSs) during 1999–2000. Bhattacharya and Dattatrayam (2000) and Srivastava *et al.* (2003) gave a detailed overview of the history and developments in seismic instrumentation in India covering the period through the end of the last millennium. At present, the NCS maintains the NSN having 115 digital seismological observatories (BBS and strong-motion accelerograph [SMA]) spread over the entire length and breadth of the country (Fig. 1; Table 1). Each station is equipped with a force balance-type broadband seismometer, accelerometer, six-channel 24-bit digital recording system, and

TABLE 1

Details of the Seismic Stations Installed with Broadband Seismometers (BBSs) and Strong-Motion Accelerographs under the National Seismological Network of India Including the Date of Installation and Local Surface Geology

Serial Number	Station	Code	Latitude (°)	Longitude (°)	Elevation (m)	Installation Date (yyyy/mm/dd)	Samples per Second*	Surface Geology
1	Campbell Bay	CMB	7.19	93.93	10	2008/02/13	100	Gondwana and Vindhyan
2	Diglipur	DGP	13.18	92.93	30	2008/01/27	100	Gondwana and Vindhyan
3	Port Blair	PBA	11.66	92.75	79	1957/04/22	100	Gondwana and Vindhyan
4	Vijayawada	VJD	16.52	80.65	18	1998/09/27	40	Precambrian
5	Visakhapatnam	VIS	17.72	83.33	82	1961/05/27	100	Precambrian
6	Itanagar	ITA	27.15	93.72	214	2010/12/23	40	Recent Pleistocene
7	Pasighat	PAS	28.06	95.33	167	2010/12/22	40	Precambrian
8	Tawang	TAW	27.60	91.87	297	2011/06/04	40	Cuddapah
9	Ziro	ZIR	27.53	93.85	160	2011/03/30	40	Tertiary
10	Dhubri	DHU	26.02	89.99	33	2010/12/16	40	Recent Pleistocene
11	Dibrugarh	DIB	27.47	94.91	90	2010/12/05	40	Recent Pleistocene
12	Guwahati	GUW	26.19	91.69	88	2011/04/18	40	Precambrian
13	Jorhat	JOR	26.74	94.25	79	2010/12/04	40	Tertiary
14	Lekhapani	LKP	27.33	95.85	139	1977/05/18	40	Deccan Trap
15	Silchar	SIL	24.78	92.80	18	2011/04/03	40	Tertiary
16	Tezpur	TEZ	26.62	92.80	83	2011/03/28	40	Recent Pleistocene
17	Gaya	GAY	24.80	85.24	101	2018/03/26	40	Recent Pleistocene
18	Jamui	JMUI	24.93	86.22	79	2018/03/21	40	Recent Pleistocene
19	Jogbani	ARI	26.14	87.47	38	2018/03/08	40	Recent Pleistocene
20	Sitamarhi	STM	26.75	85.27	55	2018/03/11	40	Recent Pleistocene
21	Valmiki Nagar	VLK	27.32	83.87	100	1993/08/01	40	Recent Pleistocene
22	Bilaspur	BLS	22.13	82.13	398	1983/08/28	40	Deccan Trap
23	Kanker	KNK	20.02	81.50	387	2018/04/08	40	Precambrian
24	Ayanagar	AYA	28.48	77.13	220	2001/03/13	40	Recent Pleistocene
25	Lodi Road, New Delhi	LDR	28.58	77.22	200	1964/01/01	40	Recent Pleistocene
26	Najafgarh (Ujwa) Delhi	NJF	28.56	76.92	218	2017/12/22	40	Recent Pleistocene
27	Narela Delhi	NAR	28.85	77.09	210	2017/12/01	40	Recent Pleistocene
28	Ridge, Delhi	NDI	28.68	77.22	230	1960/12/01	40	Recent Pleistocene
29	Jamia University	JMIU	28.57	77.29	189	2017/11/17	40	Recent Pleistocene
30	National Physical Laboratory, New Delhi	NPL	28.64	77.17	215	2017/11/27	40	Recent Pleistocene
31	Goa	GOA	15.49	73.83	58	1964/06/06	100	Deccan Trap

*Accelerometers are operating at 100 samples per second in continuous mode and at 200 samples per second in triggered mode. The BBS samples per second is provided in the table.

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TABLE 1 (continued)

Details of the Seismic Stations Installed with Broadband Seismometers (BBSs) and Strong-Motion Accelerographs under the National Seismological Network of India Including the Date of Installation and Local Surface Geology

Serial Number	Station	Code	Latitude (°)	Longitude (°)	Elevation (m)	Installation Date (yyyy/mm/dd)	Samples per Second*	Surface Geology
32	Bhavnagar	BHV	21.75	72.14	182	2002/07/16	40	Deccan Trap
33	Bhuj	BHU	23.26	69.66	80	1979/06/25	100	Gondwana and Vindhyan
34	Bahadurgarh	BHG	28.67	76.94	214	2000/09/12	40	Recent Pleistocene
35	Ganaur	GNR	29.14	77.02	228	2017/11/21	40	Recent Pleistocene
36	Jhajjar	JHJ	28.62	76.69	234	2018/01/09	40	Recent Pleistocene
37	Kundal	KUD	28.15	76.49	227	2000/12/05	40	Recent Pleistocene
38	Kurukshetra	KKR	29.96	76.82	250	2000/09/14	40	Recent Pleistocene
39	Palwal	PAW	28.15	77.33	194	2017/12/05	40	Recent Pleistocene
40	Rohtak	RTK	29.03	76.42	220	2000/09/21	40	Recent Pleistocene
41	Sohna	SON	28.25	77.06	180	2000/09/13	40	Recent Pleistocene
42	Pataudi	PTD	28.33	76.78	229	2018/04/23	40	Recent Pleistocene
43	Bhakra	BHK	31.42	76.42	410	1959/07/12	100	Precambrian
44	Kalpa	KLP	31.55	78.26	2724	1985/05/12	40	Gondwana and Vindhyan
45	Sundernagar	SND	31.54	76.91	927	1968/01/01	40	Gondwana and Vindhyan
46	Tissa	TSS	32.84	76.15	1781	2018/05/27	40	Gondwana and Vindhyan
47	Dharamshala	DHR	32.25	76.31	1995	2007/12/25	100	Tertiary
48	Shimla	SML	31.13	77.17	2200	1975/01/01	100	Precambrian
49	Jammu	JMU	32.72	74.90	360	1982/05/01	40	Tertiary
50	Hanley	HNL	32.68	78.97	4320	2018/06/08	40	Gondwana and Vindhyan
51	Alchi (Leh)	LEH	34.22	77.19	3135	2018/06/06	40	Gondwana and Vindhyan
52	Srinagar	SRI	34.10	74.85	1587	1982/04/30	40	Gondwana and Vindhyan
53	Bokaro Thermal	BOK	23.80	85.89	282	1954/12/29	40	Tertiary
54	Khunti	KNT	23.06	85.29	644	2018/01/16	40	Precambrian
55	Sahibganj	SHB	25.22	87.67	37	1995/09/15	40	Recent Pleistocene
56	Mangalore	MNG	12.94	74.82	31	1984/01/18	40	Precambrian
57	Thiruvananthapuram	TRV	8.51	76.96	64	1966/08/15	100	Precambrian
58	Minicoy	MNC	8.28	73.06	2	1984/02/07	100	Recent Pleistocene
59	Narmadanagar	NRD	22.72	77.17	292	2018/01/31	40	Gondwana and Vindhyan
60	Guna	GUN	24.65	77.33	488	2018/04/19	40	Deccan Trap
61	Bhopal	BHP	23.24	77.43	520	1994/02/26	100	Deccan Trap
62	Akola	AKL	20.70	77.02	310	1983/04/25	40	Deccan Trap
63	Karad	KAD	17.31	74.18	582	1970/01/01	40	Deccan Trap
64	Latur	LAT	18.42	76.56	620	1993/12/20	40	Deccan Trap

*Accelerometers are operating at 100 samples per second in continuous mode and at 200 samples per second in triggered mode. The BBS samples per second is provided in the table.

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TABLE 1 (continued)

Details of the Seismic Stations Installed with Broadband Seismometers (BBSs) and Strong-Motion Accelerographs under the National Seismological Network of India Including the Date of Installation and Local Surface Geology

Serial Number	Station	Code	Latitude (°)	Longitude (°)	Elevation (m)	Installation Date (yyyy/mm/dd)	Samples per Second*	Surface Geology
65	Mumbai	BOM	18.90	72.81	6	1899/01/01	40	Deccan Trap
66	Nagpur	NGP	21.10	79.06	311	1988/12/08	40	Deccan Trap
67	Pune	PUN	18.53	73.85	560	1949/01/01	40	Deccan Trap
68	Imphal	IMP	24.83	93.95	792	1977/06/01	100	Tertiary
69	Tura	TUR	25.52	90.23	406	1975/06/01	40	Tertiary
70	Shillong	SHL	25.57	91.86	1600	1952/01/01	100	Tertiary
71	Aizawal	AZL	23.78	92.69	969	2011/04/05	40	Tertiary
72	Saiha	SAI	22.50	93.00	729	2012/01/06	40	Tertiary
73	Kohima	KOH	25.72	94.11	1353	2010/12/17	40	Tertiary
74	Mokokchung	MOK	26.32	94.52	1353	2010/12/19	40	Recent Pleistocene
75	Bhubaneswar	BWN	20.30	85.81	46	1995/02/18	40	Precambrian
76	Jharsuguda	JHS	21.76	83.77	213	2015/12/30	40	Precambrian
77	Rayagada	RAG	19.25	83.46	255	2015/12/13	40	Precambrian
78	Talwara	TLW	31.96	75.96	480	1963/09/01	40	Precambrian
79	Thein Dam	THN	32.43	75.72	621	1986/05/01	40	Precambrian
80	Jaisalmer	JAS	26.93	70.90	223	2002/01/18	40	Recent Pleistocene
81	Bikaner	BKN	28.02	73.28	228	2018/03/16	40	Recent Pleistocene
82	Sriganganagar	SRG	29.92	73.89	187	2017/11/27	40	Recent Pleistocene
83	Udaipur	UDP	24.58	73.71	578	2018/02/02	40	Precambrian
84	Ajmer	AJM	26.48	74.64	540	1976/11/01	40	Precambrian
85	Gangtok	GTK	27.32	88.60	1348	1999/03/25	40	Recent Pleistocene
86	Kodaikanal	KOD	10.23	77.47	2345	1931/01/01	40	Precambrian
87	Chennai	MDR	13.07	80.25	15	1952/06/21	100	Recent Pleistocene
88	Salem	SAL	11.65	78.20	278	1999/09/22	40	Precambrian
89	Hyderabad	HYB	17.40	78.55	510	2007/12/12	100	Precambrian
90	Agartala	AGT	23.89	91.25	18	1975/06/10	40	Tertiary
91	Belonia	BEL	23.25	91.45	20	2011/01/20	40	Tertiary
92	Chandigarh	CGR	30.73	76.78	334	2018/02/28	40	Precambrian
93	Allahabad	ALB	25.31	81.81	107	1985/09/07	40	Recent Pleistocene
94	Asaura	ASO	28.76	77.77	160	2000/09/15	40	Recent Pleistocene
95	Bahraich	BRC	27.57	81.58	123	2015/11/25	40	Recent Pleistocene
96	Banda	BND	25.47	80.35	126	1981/08/01	40	Recent Pleistocence
97	Basti	BST	26.80	82.49	81	2018/01/20	40	Recent Pleistocence

*Accelerometers are operating at 100 samples per second in continuous mode and at 200 samples per second in triggered mode. The BBS samples per second is provided in the table.

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TABLE 1 (continued)

Details of the Seismic Stations Installed with Broadband Seismometers (BBSs) and Strong-Motion Accelerographs under the National Seismological Network of India Including the Date of Installation and Local Surface Geology

Serial Number	Station	Code	Latitude (°)	Longitude (°)	Elevation (m)	Installation Date (yyyy/mm/dd)	Samples per Second*	Surface Geology
98	Bisrakh	BIS	28.57	77.44	200	2000/09/17	40	Recent Pleistocene
99	Farrukhabad	FTG	27.39	79.58	138	2018/01/22	40	Recent Pleistocene
100	Gorakhpur	GRK	26.74	83.44	63	2018/01/19	40	Recent Pleistocene
101	Jhansi	JHN	25.47	78.54	250	1987/11/18	40	Recent Pleistocene
102	Lucknow	LKN	26.77	80.88	117	2018/01/17	40	Recent Pleistocene
103	Meerut	MER	28.98	77.74	212	2015/10/30	40	Recent Pleistocene
104	Thakurdwara	TKD	29.15	78.86	204	2017/12/09	40	Recent Pleistocene
105	Unchagaon	UNC	28.31	77.91	237	2001/04/27	40	Recent Pleistocene
106	Varanasi	VAR	25.30	83.02	88	1968/03/25	40	Recent Pleistocene
107	Agra	AGR	27.14	78.01	160	2000/09/16	40	Recent Pleistocene
108	Joshimath	JOS	30.56	79.56	1889	2002/04/09	40	Gondwana and Vindhyan
109	Lohaghat	LGT	29.42	80.10	1700	1985/11/24	40	Gondwana and Vindhyan
110	Pithoragarh	PTH	29.58	80.22	1669	1981/01/01	40	Gondwana and Vindhyan
111	Uttarkashi	UTK	30.73	78.45	1150	2018/03/27	40	Recent Pleistocene
112	Dehradun	DDI	30.32	78.06	682	1953/04/01	100	Recent Pleistocene
113	Coochbehar	COB	26.30	89.46	39	2018/03/13	40	Recent Pleistocene
114	Kolkata	CAL	22.54	88.33	6	1898/01/01	40	Recent Pleistocene
115	Jalpaiguri	JPG	26.55	88.72	75	2018/02/08	40	Recent Pleistocene

*Accelerometers are operating at 100 samples per second in continuous mode and at 200 samples per second in triggered mode. The BBS samples per second is provided in the table.

very-small-aperture terminal (VSAT)-based communication facility for high-speed data transmission. The Global Positioning System (GPS) time synchronization available with these modern digital systems facilitated an improvement in time resolution necessary for the accurate estimation of hypocentral parameters. With due progression of the network, the estimation time of earthquake source parameters, namely, epicenter, origin time, and magnitude, has reduced substantially from over an hour (prior to 1997) to ~5–10 min with an average time of 8 min. Upon comparison with the best global seismological networks, the dissemination time of the estimated focal parameters using the NSN is found to be comparable. The U.S. Geological Survey (USGS) releases an initial estimate of earthquake parameters within ~20 min for earthquakes occurring outside the United States. However, an earthquake in the state of California is located within ~2.5 min due to a dense seismic network in the area. In the case of an event in the United States, excluding the state of California, the information is typically posted within 8 min. The European-Mediterranean Seismological Centre operates an earthquake notification service that disseminates email/SMS/fax and so forth to the registered end users within an of average 20–30 min after the event. Another agency, the National Earthquake Information Center, targets a 20 min release time for the specific events having threshold magnitudes $\mathbf{M} \geq 5.0$.

Soon after the 2004 Great Sumatra earthquake, seven BBSs and 35 SMAs were installed by the Indian National Centre for Ocean Information Services, in Andaman–Nicobar Islands, where three seismological observatories have been functioning under the NSN. The seismic activity along the Indo-Burmese arc and in the Andaman–Nicobar region is effectively monitored with 20 dedicated telemetered BBS stations in the Northeast region and 10 BBS stations in the Andaman region (Fig. 1). The NSN, which monitors the earthquakes in the entire country and its adjoining region through a centralized 24 × 7 continuous monitoring system, is capable of locating earthquakes of magnitude down to M_w 3.0 (Fig. 2).

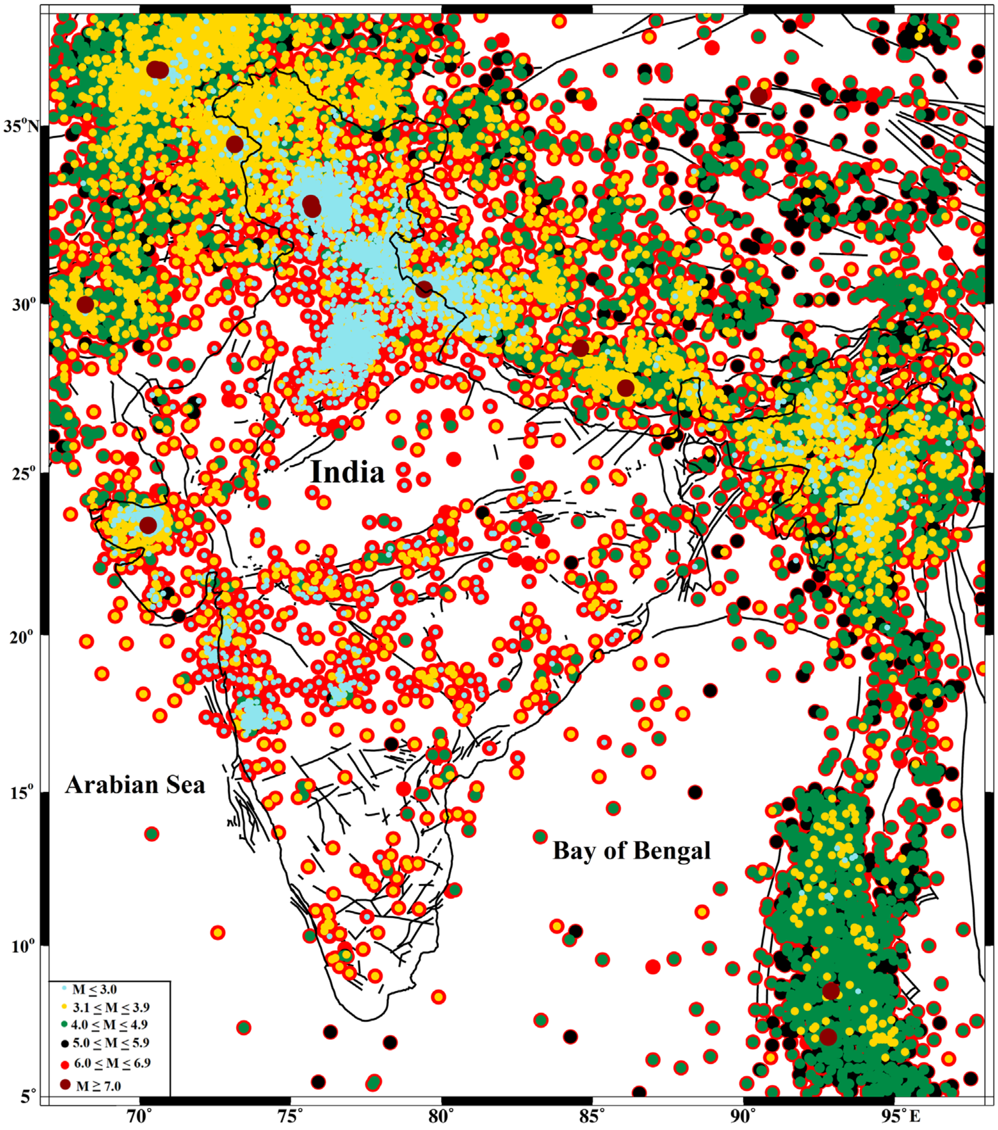

Figure 2. Map depicting spatial distribution of the earthquakes since 1990 in an area covered within latitude 5°–38° N and longitude 67°–98° E. The identified faults and lineaments are also overlaid. The magnitude scale is shown in the lower left corner. The color version of this figure is available only in the electronic edition.

In addition to the national network of the NCS, several seismological stations are also being operated and maintained by various state and central government organizations, Universities, research and development (R&D) institutions, and other agencies in the country for specific purposes and as per their requirement. About 500 seismic stations under the Incorporated Research Institutions for Seismology (IRIS) also contribute to the network for locating earthquakes outside India and its region.

Field Observatory Setup

The network establishment and upgrade took place in different phases, so the instrumentation at different field observatories varies. The 17 stations established under the Real-Time Seismic Monitoring Network (RTSMN) system for tsunami warning are composed of a 24-bit Taurus/Trident digitizer connected to Trillium-240 broadband seismometers (frequency range 240 s to 32 Hz) and an accelerometer (Metrozet Model Number TSA-100S) with an external GPS unit. Each station is powered with external 12 V batteries and solar panels. Although 20 seismic stations under the Northeast Telemetry network are composed of broadband seismometers (RefTek 151-120) and accelerometers (131A-02/3) with a six-channel digitizer (RefTek 130-01/6), the remaining 78 stations under the Optimum Seismological Network are instrumented with broadband seismometers (RefTek 151B-120), accelerometers (147A-01/3), and six-channel digitizers (130S-01/06). All 115 observatories under the NSN are operating at different sampling rates (samples per second), and they are linked to the CRS at New Delhi through VSAT communication for real-time transmission of data from the remote stations (Fig. 3). In the case of strong-motion recording, the seismic waveforms are recorded at the rate of 100 samples per second in continuous mode and 200 samples per second in triggered mode. The sampling rate for the weak-motion recording is mostly configured at 40 samples per second; however, at a few seismic stations 100 samples per second recording is also carried out. Details of sensors and acquisition system including sampling rates at each seismic station are provided in Table 1. To minimize the local noise level, we ensured that the BBS stations are located away from residential areas, highways, industries, high tension power lines, generator sets, machinery creating ground vibrations, and so forth. These sites are located over diverse geological formations (Table 1). In a recent study, performed during the nationwide lockdown due to the COVID-19 pandemic, the

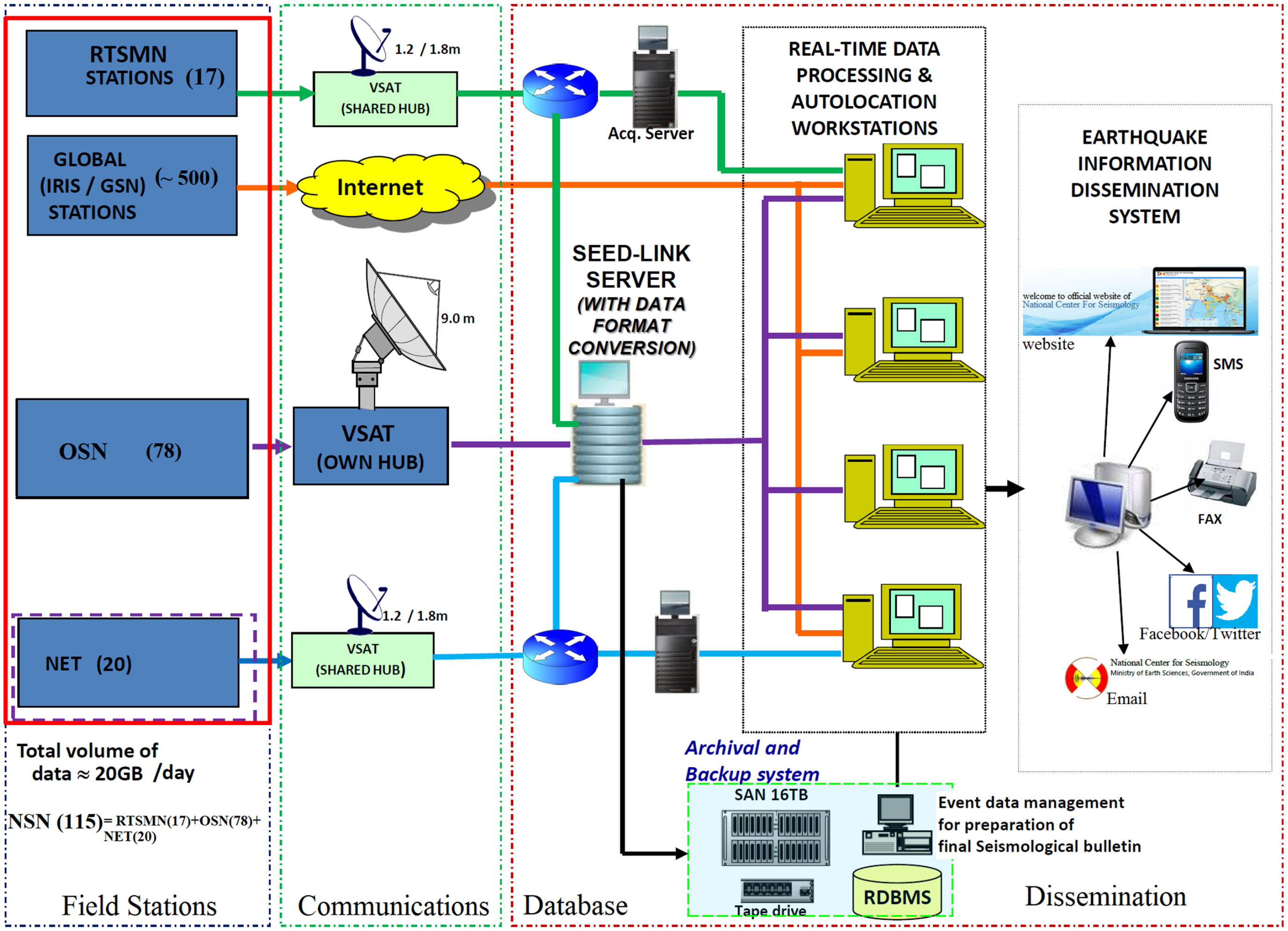

Figure 3. A schematic diagram showing data flow from the field seismic stations to the data center and dissemination of earthquake information to the publication media. GSN, Global Seismographic Network; IRIS, Incorporated Research Institutions for Seismology; NET, Northeast Telemetry; OSN, Optimum Seismological Network; RTSMN, Real-Time Seismic Monitoring Network; VSAT, very-small-aperture terminal. The digits shown in the brackets indicate the number of seismic stations. All data stored in the SAN 16 TB server is managed using the Relational Database Management System (RDBMS). The color version of this figure is available only in the electronic edition.

seismic background noise levels observed at the national network stations diminished by ~10–12 dB in urban areas at period <1.0 s; however, the noise wavefields remained unchanged in the remote areas (Pandey *et al.*, 2020).

The Figure S2 shows a schematic diagram of the seismic pillar used at observatories, which is constructed using a mixture of cement, sand, and stone chips in the ratio of 1:2:4 without using any iron material. Also, the floor of the observatory room is separated from the pillar through a moat. A permanent seismological observatory under the NSN is, generally, set up in a vault with seismic instruments housed in a two-room double walled concrete shed (Fig. S3). The seismic sensors are placed in one room, and all other accessories such as electronic parts, cables, power supply, GPS for time lock, and so forth are kept in the other room. The seismic sensors are installed on a seismic pillar and covered with thermal insulation to partially isolate them from variations in the atmospheric pressure and temperature.

Data Flow and Analysis

Continuously recorded seismic data are transmitted in real time using VSAT from remote seismic stations to the central data receiving Hubs located at Hyderabad and New Delhi; the data flows into the Data Center (DC) and then to the CRS for analysis (Fig. 3). The data received in the CRS are stored using acquisition software configured to each model of digitizer and transferred to one platform through the SEEDLINK protocol. Data are then converted into a common format "miniSEED" (mSEED) and fed into the autolocation software "SeisComP3" (Weber *et al.*, 2007) for real-time autolocation of the events. Further, the continuous data in mSEED format are permanently archived in ring buffers. As an example, the waveform traces of the SMA and BBS recorded at the KOH station for the recent Manipur earthquake (M_w 6.7) of 3 January 2016

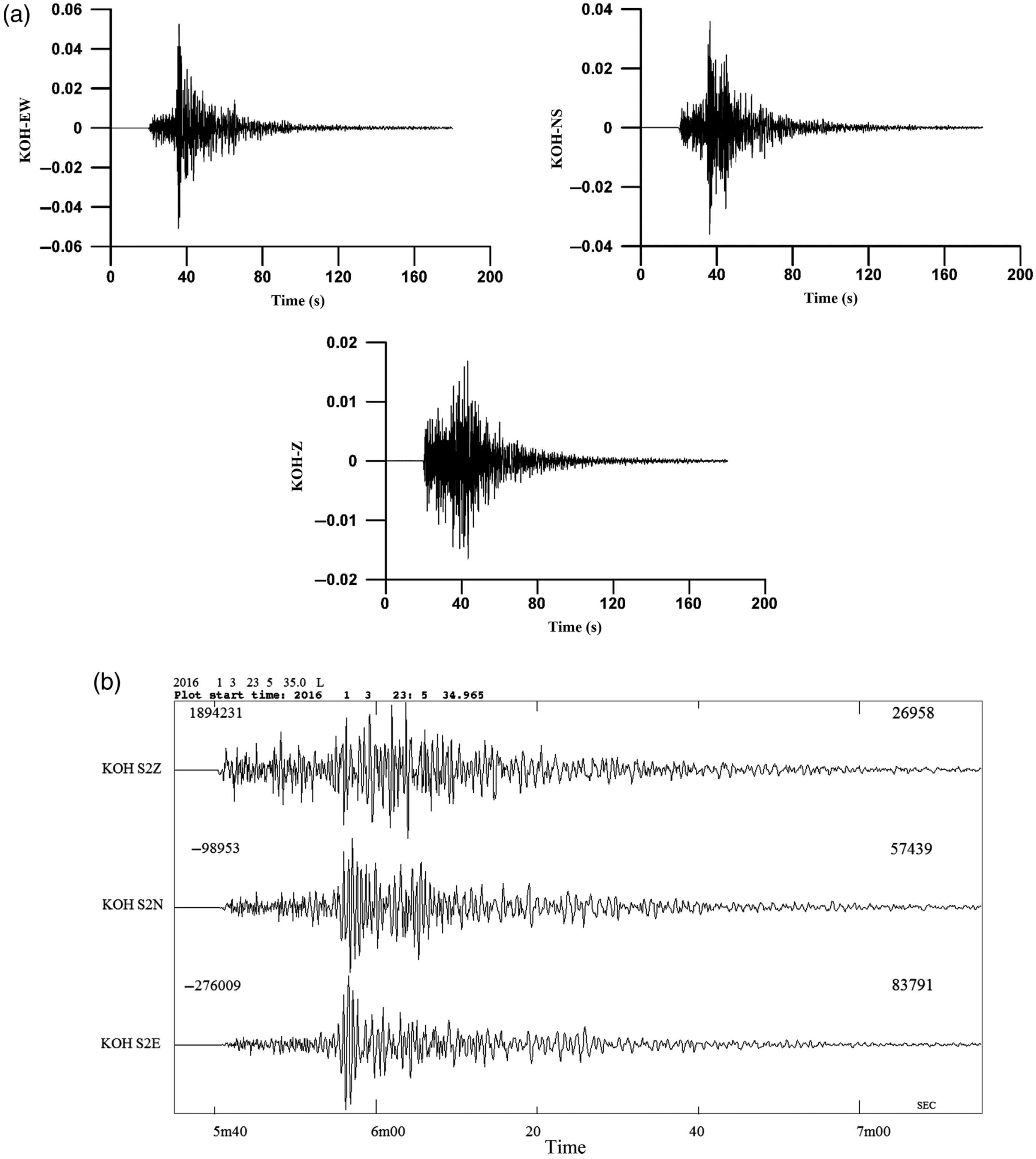

Figure 4. (a) An example of the waveforms of the 3 January 2016 (**M** 6.7) earthquake in Manipur, India, that was recorded by an SMA at the KOH station. (b) An example of the seismogram (three components) recorded by a BBS at the KOH station for the same event mentioned in (a).

are illustrated in Figure 4a,b. The "SeisComP3" software preliminarily estimates earthquake parameters within a shortest possible time, that is, within 60–100 s after the arrival of seismic phases, which is further reviewed by a seismologist (on duty) before its dissemination to the public and concerned authorities. Various steps of data flow, activities under CRS seismological operations, dissemination of information, and so forth are depicted in Figure 3.

The reviewed earthquake information is disseminated to user agencies including public information channels, media, press, and the concerned states and central government authorities through different modes of communications, such as Mobile-app (Realtime Information System for Earthquake [RISEQ]; now named as BhooKamp), SMS, FAX, Email, official website (see Data and Resources) with value added products, and social media platforms such as WhatsApp, Twitter, and Facebook for relief and rehabilitation measures, if found necessary. However, specific criteria are framed based on the magnitude cutoff level, for disseminating information to different parts of the country. The earthquake information is also populated on the NCS webpage in near-real time (see Data and Resources). RISEQ is an official mobile application of the NCS for informing the public about countrywide earthquakes. Later, "Monthly Seismological Bulletins" (MSB) are prepared by re-analyzing waveform data of all of the significant earthquakes in and around the country, using SEISAN software (Havskov and Ottemöller, 1999) and considering appropriate crustal velocity models.

Events with improved focal parameters and identified phases form part of the MSB and are used for research purposes within the country as well as globally. The "SeisComP3" software is configured to automatically locate events in near-real time only. However, the autolocated events are manually reviewed using SeisComP3 prior to dissemination. The MSB contains refined locations of the event as well as the phase data, root mean square (rms) errors, errors in depth, magnitude, latitude, and longitude in the standard Nordic format. The HYPOCENTER location package of SEISAN software is used to locate the earthquakes locally, regionally, and globally. The earthquake waveform data received from different field stations are normally compiled, processed, and analyzed for estimation of the hypocentral parameters, and subsequently the information is archived in the DC. On comparison of earthquake locations estimated by the NSN with that of USGS, for moderate-to-large earthquakes in India and its region, an average difference in location is found to be ~0.02°. The rms error varies in the 0.10–1.63 range for the USGS network; it is <1.0 for events located within the NSN and <2.0 for events in the boundary region. The difference in location between the NSN real-time system and the MSB is approximately $<0.1°$ for local and $<0.5°$ for regional events.

The Hypo-71 program used in the MSB analysis requires arrival times of recorded seismic phases at seismic stations, accurate station coordinates, and a reasonable crustal velocity model (Lee and Lahr, 1972). For the network, different velocity models have been used for locating the events including the Jeffreys–Bullen model (Jeffreys and Bullen, 1940), iasp91 model (Kennett and Engdahl, 1991), and ak135 model (Kennett *et al.*, 1995). In the autolocation software "Response Hydra" of the RTSMN system "ak135" velocity model has been used. However, at present, the real-time data processing using SeisComP3 software is performed considering the "iasp91" velocity model for locating regional (1000–2000 km) and teleseismic (>2000 km) events. This model is also used by several global seismological agencies for detecting and reporting earthquakes worldwide. This software provides analysts with the ability to process the trace data for picks and associate picks that are used in the determination of the initial location of the events and to insert all of the data into the Oracle database for further processing. It is emphasized that local velocity models are also used for parts of the country, namely, the Delhi region, northwest Himalaya, northeast region, and Andaman–Nicobar region.

A precise estimation of focal depth is often a problem for want of depth phases from nearby seismic stations. Nevertheless, using digital broadband records, it is possible to identify the depth phases after applying a suitable filter; these are otherwise not very clear in the narrowband analog seismograms. As an example, the focal depth of the 1997 M_w 5.8 Jabalpur earthquake was accurately determined using *sPn* phase that was identified on low-pass-filtered (at 2 Hz) waveform. We mention that the uncertainty in the focal depth estimation further increases with the increase in epicentral distance of the event from the nearest seismograph. The error in focal depth is observed to be 6–10 km for events within the network; however, it is ~13 km in the border region. On comparison with USGS estimates for moderate-to-large events, a variation of about ±5.0 km is observed in the focal depths.

Depending on the epicentral distances of the earthquakes, different types of magnitudes such as M_L, m_b, M_s, M_D, M_c, and M_w are estimated using the waveforms amplitude, period, and coda duration. The estimated magnitudes for moderate-to-large earthquakes ($\mathbf{M} \geq 5.0$) are found to be similar to those estimated by different global agencies. Normally, a variation in magnitude for a value ±0.1 is observed between the NCS and USGS networks.

Other important information such as "Dos and don'ts" during an earthquake, focal mechanism, estimated intensity map, seismology glossary, historical earthquakes, analog seismograms, and so forth are also provided on the NCS webpage for public awareness. More than 100,000 people have visited the NCS webpage since its inception in 2019, which reflects tremendous enthusiasm among people for acquiring earthquake information. Real-time data are also sent to the IRIS from three seismic stations, namely, PBA (Port Blair), SHL (Shillong), and MNC (Minicoy). Data from some of the temporary stations, maintained and operated by different research institutions in project mode, are also received in the DC.

In addition to the permanent national network, mobile seismic equipment (BBS) is deployed in specific areas from time to time to monitor aftershocks and swarm activity. The seismological data from the entire national network, including those operated by other agencies supported by the MoES, are compiled, processed, analyzed, and archived systematically in the DC in standard SEED format, which could be retrieved successfully as and when required. The DC is equipped with data acquisition modules, SEEDLINK server for the real-time data exchange, data storage, networking and data access infrastructure with regional centers, offline data exchange, and information management. Data recovery in case of system failure is warranted not only by providing enough redundancy in the infrastructure, but also through different modes of data transmission. All of the data collected at the New Delhi data hub are mirrored at Hyderabad data hub to ensure data availability in case something goes wrong at either location.

Earthquakes Catalog and Seismological Bulletin

Waveform data from all field stations relating to earthquakes occurring in India and its region, encompassing an area between latitude (5°–40° N) and longitude (60°–100° E), and significant earthquakes **M** 6.0 and above in any part of the world are routinely analyzed. However, the catalog is prepared by compiling the earthquakes occurring in India and its adjoining regions (5°–40° N and 60°–100° E) only. It includes information on the origin time, location (region), focal depth, and magnitude of the earthquakes. From the analysis, the completeness of the catalog for magnitude is found to be M_s 5.0 through the early 1980s. However, with deployment of more digital BBSs in the network in late 1980s, the completeness magnitude of the catalog improved to **M** 3.0.

Further, an MSB is prepared by re-analyzing the waveform data of all significant earthquakes detected by the national network in a particular month, using SEISAN software (Havskov and Ottemöller, 1999) and considering appropriate crustal velocity models. The MSB contains refined earthquake parameters including the phase data, rms errors, and so forth in standard Nordic format. Such seismological bulletins have been prepared since 1998. India, represented by the NCS, is a permanent member of the International Seismological Centre, United Kingdom. This monthly bulletin of the NCS, which contains information on the earthquakes that occurred across the globe, is shared regularly with the world research community.

Historically Significant Analog Seismic Charts

Over the past 120 yr, a wealth of seismological data has been generated from across the seismological network using analog and digital seismographs. The historical analog seismic charts number more than a million. These charts, containing earthquake records, were made on photographic smoke recording and heat sensitive recording devices. These precious charts, being quite old, needed the safest mode of preservation. Accordingly, raster scanning of 100,000 historical analog charts and vector digitization of 5000 significant earthquake waveforms have been documented. The goal is to achieve long-term preservation of invaluable information contained in these historical charts in electronic form to bolster research opportunities for the seismological community. As an example, a historical analog chart of the 1950 Assam earthquake recorded at the Delhi seismic observatory by a WWSSN seismograph and its digitized waveform is depicted in Figure 5.

Minimum Magnitude Detection Capability of the Network

Any seismological network in a country is recognized based on its performance for detecting smaller earthquakes (D'Alessandro *et al.*, 2011). The NSN of India has been operating for a long time, starting with a single seismic station in 1898 and now having 115 seismic stations. Here, an effort is made to understand the progression in the spatial variability of the minimum magnitude of completeness (M_c) over this time period in four time windows, viz., 1898–1989, 1990–2000, 2001–2010, and 2011–2020 (Fig. 6). We determined M_c using ZMAP software (Wiemer, 2001), considering the Maximum Curvature method (Wyss *et al.*, 1999) and goodness-of-fit test (level of fit: 90%–95%) in the analysis. The algorithm compared the observed Gutenberg–Richter distribution with the synthetic ones and estimated the goodness of fit. In the analysis, we used local, regional, and global regression equations (Baruah *et al.*, 2012; Weatherill *et al.*, 2016; Kumar *et al.*, 2020) and converted different types of magnitudes into a single homogenized moment magnitude (M_w) for the complete NCS catalog. The homogenized catalog is subsequently considered in the analysis for obtaining spatial distribution of M_c in four selected time windows. The lower minimum threshold can easily be correlated with the progressive expansion of the national seismic network. Figure 6 clearly depicts the improvement in M_c over time in many parts of the country, which may be attributed to increased seismic stations in the network with good azimuthal coverage in these areas as well as to the enhanced technology and methodology used in the network operation. In the last two decades, the M_c has improved substantially for most parts of the country including the south-central (peninsular) region (Fig. 6). The detection level of the earthquake magnitude is observed to be **M** 3.0 and above in the northeast region, **M** 3.5 and above in the Peninsular and extra Peninsular region, **M** 2.5 and above in Delhi and the surrounding region, **M** ≥ 3.5 in the Andaman–Nicobar region, and **M** 4.0 and above in the border areas. Evidently, the completeness of the earthquake catalog in space and time for any specific region provides very useful information for visualizing the capability of the seismological network. The NCS catalog is compiled for the period from 1505 (Oldham, 1899, 1928; Kanamori, 1977; Quittmeyer and Jacob, 1979) to date including the data recorded in the "digital era" that started in 1997. We mention that the earthquake information in the catalog for the preinstrumental era is mostly compiled from previous works. These are based on the inferences drawn from the intensity details as well as the effects of ground motion on the people, land, structures, and so forth. Such assessments are often qualitative and sometimes prone to serious errors.

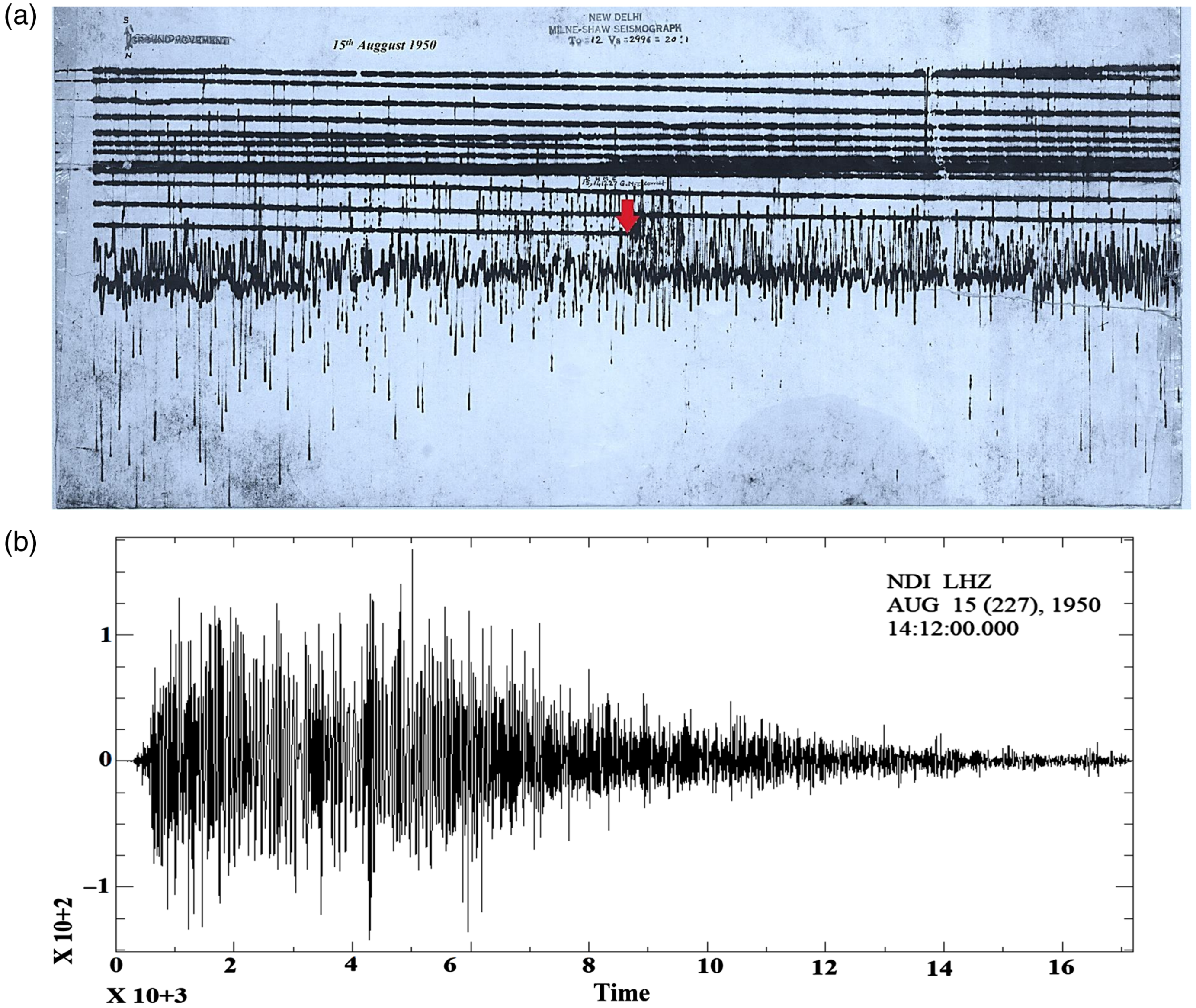

Figure 5. Preserving the historical earthquakes waveform by the analog charts and digitizing: an example of the 15 August 1950 M_w 8.6 Assam earthquake. (a) The historical analog chart and (b) the corresponding digitized seismogram of the Delhi seismic station. The arrow in the analog chart shows the onset of event at Delhi station. The color version of this figure is available only in the electronic edition.

Concluding Remarks

The NSN of the NCS is well capable of precisely monitoring earthquakes in and around India in near-real time on a continuous 24 × 7 basis, by recording the ground motions on the occurrence of earthquakes using state-of-the-art seismic equipment at the seismic stations. The events are quickly located within a few minutes after their occurrence, using autolocation software “SeisComP3.” Subsequently, the events are reviewed in the shortest possible time (5–10 min) for improved location by minimizing the errors, and the reviewed earthquake parameters are populated over the official website and app and are disseminated to concerned authorities in the center and state governments using other modes of communication, such as SMS, telefax, email, and so on. Eventually, the waveform data recorded for individual events are archived in the DC for further application and research. We emphasize that the seismic data generated at the NCS are exchanged with various national and international monitoring organizations as well as institutions for further R&D in different fields of seismological study. Further, high-quality seismic data over a broad magnitude and distance range are provided to users and the engineering community on request to facilitate geo-scientific problems. Currently, 115 seismic stations are maintained across the entire country, co-equipped with both highly sensitive BBS as well as robust SMA equipment, and are networked through VSAT.

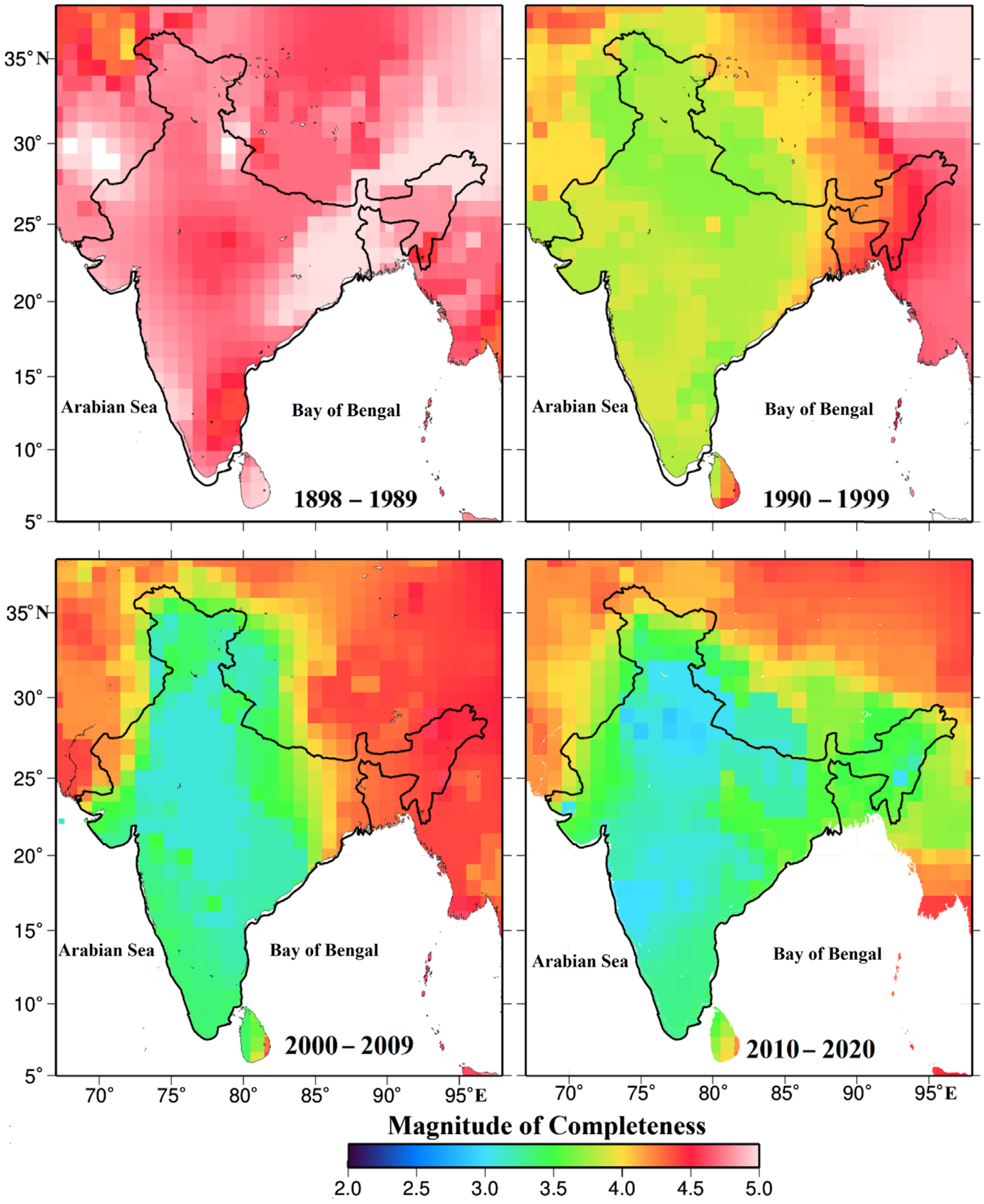

Figure 6. Map showing spatial variation of the minimum magnitude of completeness in India from 1898 to 2020 in four time windows, viz., 1898–1989, 1990–1999, 2000–2009, and 2011–2020. The scale bar is shown at the bottom. The color version of this figure is available only in the electronic edition.

Continuously recorded weak-motion data are transmitted from the remote stations to the CRS at the NCS in real time using VSAT communication for quick analysis and interpretation. In addition to these, 35 more seismic stations are being installed to cover the gap areas, increasing the total number of stations to 150 by 2020. Further, the network is planned to be strengthened in the near future by augmenting an additional 300 observatories into it. Such a proposed expansion of the NSN would help greatly in improving earthquake detection capabilities to a new threshold down to **M** 2.5 for the entire country. The spatial variation in the minimum magnitude of completeness for the entire country clearly indicates a significant enhancement in the detection capability of the network in the last two decades. We mention that a powerful and much efficient dissemination mechanism under the NSN is also in development for quickly disbursing earthquake information in the public domain that would significantly improve awareness among the people about the earthquake activity in and around the country.

Data and Resources

The earthquake catalog and Monthly Seismological Bulletins (MSB) are available at https://seismo.gov.in/seismological-data (last accessed December 2020). The near-real-time earthquake location data can be accessed at https://seismo.gov.in/MIS/riseq/earthquake/archive/ (last accessed December 2020). Data ascribed to the National Centre for Seismology (NCS), Ministry of Earth Sciences, India, can be requested from Director, NCS. Details of the services can be obtained from the NCS official website at http://www.seismo.gov.in. Some figures were prepared using the public domain Generic Mapping Tools v.4.5.9 (www.soest.hawaii.edu/gmt, last accessed May 2020; Wessel and Smith, 1998). Supplemental material for this article includes a history of the upgrades of the National Seismological Network (NSN), construction of a seismic pillar, and an example of a permanent seismological observatory.

Declaration of Competing Interests

The authors acknowledge that there are no conflicts of interest recorded.

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