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ORIGINAL PAPER

Tsunami in the last 15 years: a bibliometric analysis with a detailed overview and future directions

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Abstract

In the last fifteen years, tsunami science has progressed at a rapid pace. Three major tsunamis: The Indian Ocean in 2004, the 2011 Tohoku tsunami, and the 2018 Palu tsunami were significant landmarks in the history of tsunami science. All the three tsunamis, as mentioned, suffered from either no warning or poor reception of the alerts issued. Various lessons learned, consequent numerical models proposed, post-2004 tsunami damage findings manifested into solutions. However, the misperceived solutions led to a disastrous impact of the 2011 Tohoku event. In the following years, numerous improvements in warning systems and community preparedness frameworks were proposed and implemented. The contributions and new findings have added multi-fold advancements to tsunami science progress. Later, the 2018 Palu tsunami happened and again led to a massive loss of life and property. The warning systems and community seemed un-prepared for this non-seismic tsunami. A significant change is to take place in tsunami science practices and solutions. The 2018 tsunami is one of the most discussed and researched events concerning the palaeotsunami records, damage assessment, and source findings. In the new era, using machine learning and deep learning prevails in all the fields related to tsunami science. This article presents a complete 15-year bibliometric analysis of tsunami research from Scopus and Web of Science (WoS). The review of majorly cited documents in the form of a progressing storyline has highlighted the need for multidisciplinary research to design and propose practical solutions.

Keywords Scopus · Web of science (WoS) · Bibliometric · DART · NOAA · Indian Ocean · Japan

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1 Introduction

A tsunami is one of the most unfortunate and hazardous events described as a series of waves caused by the displacement of an enormous water volume. This tragic and deadly event has drastically impacted both humans and nature. The scientific community has surged forward to find practical and effective solutions that can help in real-time predictions. Such predictions can empower humanity to be well prepared and implement defensive measures to minimize the damage caused by similar life-threatening events.

Tsunami, apart from being a water displacement event, can be potentially caused by earthquakes, volcanic eruptions, and meteorite impacts. One of the oldest tsunamis occurred in 1957. Initially, only tide-gauges recorded the tsunami; scientists used water equations to understand the tsunami run-ups (Stoneley 1963). However, various other factors have been identified with time, as documented by Mulia et al. (2020). The authors have used radar altimeter, Global Navigation Satellite Systems (GNSS) receiver, and drones assimilated data to design an airborne-based forecasting system.

Repeated or even a single occurrence of a tsunami has affected various countries like India, Sri Lanka, Japan, Thailand, and Indonesia worldwide. Therefore, scientists and practitioners have taken cues from pre- and post-analysis of various precursors of tsunami events and thus proposed several algorithms, methods, simulations, and models describing the occurrence, prediction, or impact of such events. Röbke and Vött (2017) suggested a need for progress in tsunami science, where the solutions paving various disciplines, viz. sedimentology, geophysics, and ecology, could be more effective when required. The state-of-the-art till 2015, as studied by Okal (2015), highlighted that the two significant tsunamis, viz. 2004, Sumatra and Indonesia, and 2011, Tohoku had a different impact on tsunami science history. The past studies have pointed out substantial weaknesses in warning systems and inconsistencies in planning and community preparedness. The research field's significant contributions started since the most famous South Asian tsunami in 2004 and the Tohoku tsunami in 2011, with a particular trend rising since the 2018 Palu tsunami.

Bibliometric or Scientometric analysis is a discipline that studies literature and science in a particular field quantitatively, thus providing a platform for future research (Blümel and Schniedermann 2020). Such analysis creates a timeline or an outline of a specific area that can identify particular research gaps. The identified gaps can provide ways to conduct probabilistic research and present certain results. In the last 5 years, various fields have experienced contributions relating bibliometric analysis like green supply chain management (Fahimnia et al. 2015), labs in education (Heradio et al. 2016), business impacts (Albort-Morant and Ribeiro-Soriano 2016), smart cities, Industry 4.0 (Muhuri et al. 2019), bitcoin scientific production (Merediz-Sola and Bariviera 2019), fuzzy in big data (Shukla et al. 2020).

Few articles that have performed a bibliometric analysis in tsunami research are by Chiu and Ho (2007) and Dahdouh-Guebas and Jayatissa (2009), which covered tsunami impact on vegetation. Another contribution by Anil et al. (2017) covered only the Scopus database from 1997 to 2008. A detailed document type-based analysis that presents the 154 covering the last 15 years of scientific data is a first. Such assessment has spanned the three most massive tsunamis of Indonesia (2004), Tohoku (2011), and Palu (2018) in the form of a storyline discussing findings, impact assessment, disaster resilience, and experiences of the victims that have contributed to progress in tsunami science. This article contributes to the respective field as a platform for primary probabilistic research and open gap analysis.

The significant contributions of the paper are:

1. A detailed bibliometric analysis for "Tsunami" from the most generally used scientometric database, viz. Scopus and WoS.
2. Top 30 journals from WoS and Scopus that are actively publishing in the field of tsunami research are listed having total citations (TC) and total documents (TD) published since 2005 (inclusive).
3. Field study focused on several parameters: major funding agencies, most influential authors, and most publishing countries, actively promoting tsunami research.
4. We present the top 10 articles published in the area of the tsunami from both WoS and Scopus.
5. To highlight the top conference and book series titles from Scopus.
6. Explore a total of 154 Scopus and WoS documents outlining the top-keywords and the top-cited papers. We present a review that demonstrates progress from 2005 to date.

The summary outlines the existing problems and available research datasets that the current scientific community (geologists, sedimentologists, seismologists, and researchers) can work for future innovations. The recent data sets highlight the need for multidisciplinary research where novel and well-worked methods can be implemented or further enhanced to combat both theoretical and practical aspects, giving new results. Smart systems supported by robust algorithms can solve the current and prevailing problem of the unpredictability of tsunamis.

2 Data: collection and description

This contribution initially starts with a detailed bibliometric analysis of data mined from two of the most widely used databases: Scopus and Web of Science (WoS), followed by a state-of-the-art-study. The data was extracted from both databases using a keyword-based search of "tsunami" in the *Title, Abstract, and Keywords* fields of both the databases. We have used Title, Abstract, and Keywords as searching fields include all documents that may not involve tsunami in *Title* and probably its potential precursors such as Earthquake and Landslides. However, the research focus of such articles would mostly be tsunami directly or indirectly. Both databases have provided bibliographic, and citation information for every article for the search performed on 20th April 2020. A total of 11,915 documents were collected from the search carried out. Further, these documents are classified as Articles (61%), Conference Paper (27%), Review (5%), Short Survey (1%), Book Chapter (2%), Editorial (2%), and Note (2%). Here Article refers to the documents published in a respective journal. WoS database returned 11,711 documents categorized as Articles (87%), Conference Paper (4%), Review (4%), Editorial (4%) and Book Chapter (1%). Figure 1a and b summarizes the percentage-wise distribution, as mentioned above. The contribution to the journal article in both databases is essential in numbers. Scopus indexed conferences have also contributed a relatively greater number of documents compared to just WoS indexed.

For the analysis, the following are the parameters which have been extracted and calculated:

- *Total Documents (TD):* This parameter refers to the entire documents (of all types) from the given database.
- *Total Citations (TC):* It is the total citations captured by a selected publication

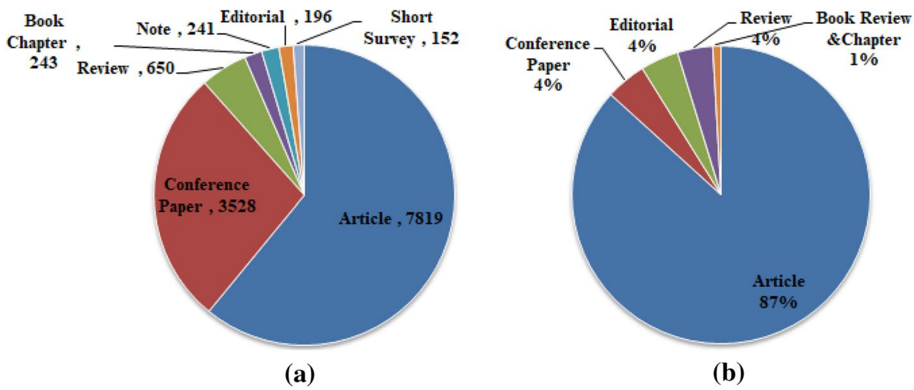

Fig. 1 **a**, **b** "Document Type" division from Scopus and WoS databases on "Tsunami"

- *Average citations per Document:* Citation impact factor or (ACPD) calculated using the above two parameters gives the average number of citations for a given research unit. Here research unit refers to the documents extracted using the "Tsunami" keyword. As summarized by Waltman (2016), it is better to compare journals on average citations per document as a size-independent indicator.

The following sections give a detailed bibliometric analysis:

3 Bibliometric analysis

3.1 Research trends: 2004–2015

Tsunami study and its aftermath have gained a great deal of attention since the Indian Ocean tsunami mishap in 2004. State-of-the-art finds this to be one of the worst tsunamis to occur. Since then, the scientific community has been highly interested in directly or indirectly researching the incidence and post-occurrence effects of this incident. The total documents (TD) extracted from Scopus and WoS from 2005 until April 2020 are shown in Fig. 2a, b. The figure also shows the number of documents in the year 2004 to study and compare the consequent trend.

Figure 2 shows that the TD in the Scopus database has increased almost six times, from 2004 to 2005, whereas in WoS the increase was many-fold, i.e., from 1 in 2004 to 236 in 2005. In recent years, consistent growth has peaked with a peak in 2010 (Scopus) and 2011, while for WoS, it mostly fell in 2011–12. The observation stems from the fact that, in the early months of 2011, the second most destructive tsunami struck Japan. The Scopus peak in 2010 is due to a worldwide international conference held in the same year under a consortium of US nationals and Canada that alone contributed 774 articles. Figure 3 depicts the TC trend. With a growing but varying pattern, the old documents from 2005 to 2012 have many citations. In the following years, the field witnessed major contributions, receiving a reasonable number of citations.

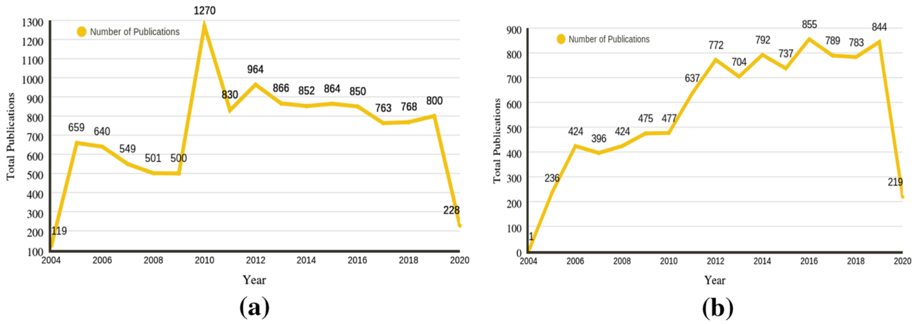

Fig. 2 **a**, **b** Number of Publications (2004–2020) filtered over keyword "Tsunami" from Scopus Database

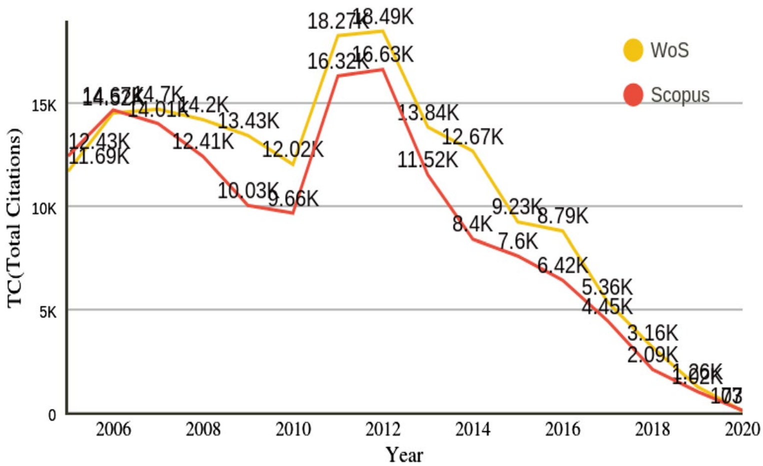

Fig. 3 Citation overview from 2005 to 2020 of both Scopus and WoS

3.2 Citation overview

Figure 3 presents the citation overview of the documents extracted from the databases with two peaks, where one is in 2006, and the other is in 2011–12. These are the two immediate years after the two most significant tsunamis in the history of the world. The majority of early field survey studies, responses, and observations, which are still obtaining citations, have been published this year. For example, of the 11,915 documents extracted from Scopus, Japan appears as a keyword in 1477 documents. Out of these documents, 227 and 247 documents were published in 2011, and 2012, respectively. Contributions have shown a decreasing trend in the last five years, perhaps because they are relatively new documents in this area. In recent years, however, the citation count has a wide range, clearly showing the extent of scientific research happening in this area with an impact across all disciplines.

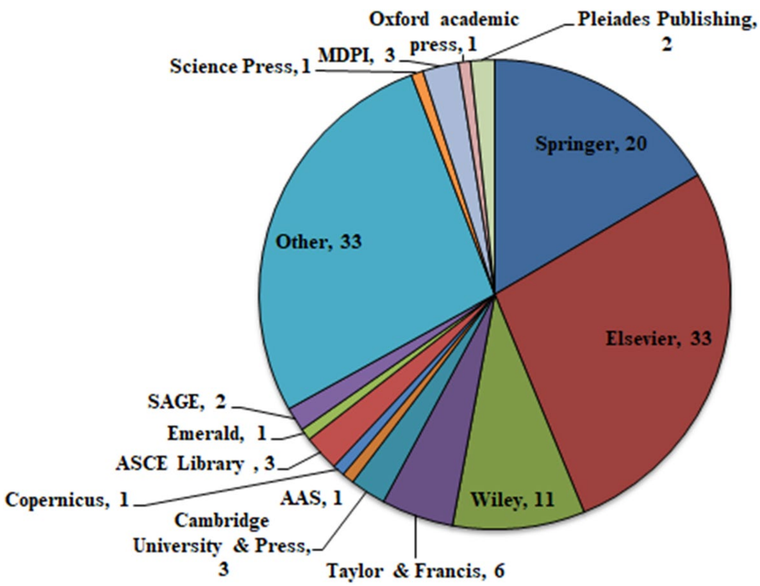

Fig. 4 Publisher wise analysis of the top 121 journals indexed in Scopus and WoS both

3.3 Top source journals

To explore the existing documents contributed by various active researchers, we have followed a "true blue" approach that exemplifies a particular assumption. The assumption is that certain scientific journals from specific publishers and indexing like Science Citation Index-Expanded (SCI-E), the Social Science Citation Index (SSCI), and Emerging Social Science Citation Index (E-SCI) serve as the "real McCoy" for summarizing a particular topic. Hence, the majority of documents for review are from such indexed sources. However, this assumption is limited to this article review only.

Considering the Scopus database's broader acceptability, we prepare a master list of 121 journals from Scopus on a certain threshold. This threshold here is 10. In the past 15 years, each of the 121 journals has contributed TD ≥ 10 papers. A publisher wise analysis was performed and presented in Fig. 4. Elsevier tops this list with 33 journals, followed by Springer (20), Wiley (11), and Taylor & Francis (6), significantly contributing to this field.

Table 1 shows the top 30 journals extracted from Scopus and WoS both. The list is an intersection of source titles obtained from both databases, where in terms of TD, some had the same rank (in the respective top 30 journal list), and some differed. For example, with TD = 155, Marine Geology published by Elsevier occupies the 5th rank in WoS, while in Scopus, it has a much larger TD = 192 count. Similarly, another journal: Natural Hazards and Earth System Sciences, has 279 documents in WoS while its TD = 186 in Scopus.

In terms of TD, Pure and Applied Geophysics (TD = 376), Natural Hazards (TD = 262), Geophysical Research Letters (TD = 244), Marine Geology (TD = 192), Science (TD = 144) are the most productive journals in Scopus. In the top five journals in WoS, the top four journals remain the same, with another journal named Natural Hazards and Earth system sciences (TD = 279). In terms of TC, the highest citations in these 15 years were obtained by Geophysical Research Letters with TC = 8008 from Scopus and TC = 8611 from WoS.

Table 1 Top source journals from Scopus and WoS

Journal name	Publisher	Scopus				WoS			
		TD	TC	ACPD	NHCP	TD	TC	ACPD	NHCP
Pure and applied geophysics	Springer	376	5233	13.92	78	390	4841	12.41	76
Natural hazards	Springer nature	262	4313	16.46	65	380	4972	13.08	72
Geophysical research letters	Springer	244	8008	32.82	124	283	8611	30.43	137
Marine geology	Wiley	192	6187	32.22	97	234	6112	26.12	98
Nature	Springer Nature	144	3652	25.36	33	41	2236	54.54	13
Science	American association	120	6163	51.36	39	59	3607	61.14	24
Coastal engineering	Elsevier	115	2485	21.61	33	130	2390	18.38	35
Journal of disaster research	Fuji technology press	114	471	4.13	5	96	3792	24.46	24
Natural hazards and earth system science	Copernicus	186	3853	20.71	68	279	4465	16	82
Geophysical journal international	Oxford university press	104	2275	21.87	38	146	2799	19.17	46
Journal of coastal research	Coastal education and research foundation, Inc	100	1081	10.81	9	155	1426	9.2	15
Earth planets and space	Springer nature	94	2904	30.89	38	130	3468	26.68	46
Plos one	Public library of science	91	1558	17.12	23	73	1004	13.75	15
Sedimentary geology	Elsevier	91	3750	41.21	54	100	3570	35.7	51
Journal of geophysical research solid earth	Wiley-Blackwell	88	2420	27.5	36	162	4139	25.55	62
Coastal engineering journal	Taylor & Francis	84	1705	20.30	21	94	1472	15.66	20
Journal of geophysical research oceans	Wiley-Blackwell	76	2527	33.25	38	87	2305	26.49	38
Earth and planetary science letters	Elsevier	75	2499	33.32	40	105	3402	32.4	57
Ocean engineering	Elsevier	69	953	13.81	17	78	845	10.83	12
Earthquake spectra	Earthquake engineering research institute	68	1429	21.01	29	75	1184	15.79	21
Prehospital and disaster medicine	Cambridge university press	61	464	5.27	6	27	145	5.37	2
Journal of waterway port coastal and ocean engineering	ASCE	58	1538	26.52	21	47	884	18.81	8
Bulletin of the seismological society of America	Seismological society of America	55	2053	37.33	28	83	1697	20.45	27
Disasters	Wiley-Blackwell	52	988	19	19	79	1102	15.74	18

Table 1 (continued)

Journal name	Publisher	Scopus				WoS			
		TD	TC	ACPD	NHCP	TD	TC	ACPD	NHCP
Science of tsunami hazards	Tsunami society	52	230	4.42	2	–	–	–	–
Journal of earthquake and tsunami	World scientific	51	219	4.29	1	104	615	5.91	7
Geology	Geological society of America	48	1673	34.85	31	62	2031	37.76	42
International journal of disaster risk reduction	Elsevier	41	458	11.17	7	105	795	7.57	9
Earth science reviews	Elsevier	37	930	25.13	18	27	1041	38.56	17
Lancet	Elsevier	36	797	22.14	8	29	404	13.93	–

Table 2 Top conference proceedings

Conference Title	TD	TC	ACPD
9th US national and 10th Canadian conference on earthquake engineering (2010)	774	38	.0490
Proceedings of the international offshore and polar engineering conference	205	300	1.46
Iop conference series earth and environmental science	176	135	.767
Proceedings of the coastal engineering conference	173	533	3.08
Proceedings of the international conference on offshore mechanics and arctic engineering OMAE	59	105	1.77

Table 3 Most influential books on tsunami

Book Title	TD	TC	ACPD
Advances in natural and technological hazards research	34	96	2.82
Engineering geology for society and territory volume 4 marine and coastal processes	7	18	2.57
Handbook of coastal disaster mitigation for engineers and planners	7	26	3.71
Developing tsunami resilient communities: the national tsunami hazard mitigation program	6	67	11.16
Coastal and marine hazards, risks, and disasters	5	22	4.4

Waltman (2016) has discussed various size-independent factors to analyze journals. One is ACPD already described in Sect. 2. Another is the number of highly cited papers (NHCP) used under any citation count threshold to compare two journals in a field by counting their number of highly cited articles. The threshold here is TC ≥ 20. For example, Marine Geology from Wiley has NHCP = 97 and 98 from both the databases. Geophysical Research Letters has the highest NCHP among the top 30 source journals. In terms of ACPD, in both databases, Science multidisciplinary journal tops, followed by Sedimentary Geology (ACPD = 41. 21) and Nature (ACPD = 54.54), respectively, from Scopus and WoS.

The top 10 source titles indexed by Scopus included four conference proceedings. Table 2 lists the top five proceedings from Scopus. The 9th US National and 10th Canadian Conference on Earthquake Engineering in 2010 has contributed the most with TD = 774. Also, the maximum citations of TC = 533 in Scopus and ACPD of 3.08 were obtained by the Proceedings of the Coastal Engineering Conference, followed by the Proceedings of the International Offshore and Polar Engineering Conference with TC = 300.

Tsunami research has seen several related book publications across multiple disciplines. Table 3 lists the top 5 books from Scopus due to its wider acceptability. Advances in Natural and Technological Hazards Research have contributed to the highest number of chapters with TD = 34. However, two books, viz. Developing Tsunami Resilient Communities: The National Tsunami Hazard Mitigation Program and Coastal and Marine Hazards, Risks, and Disasters from Scopus, have received maximum ci citations over small document contribution with ACPD = 11.16 and 4.4, respectively. The chapters highlighting the tsunami risk mitigation and community preparedness aspects are being read and cited the most.

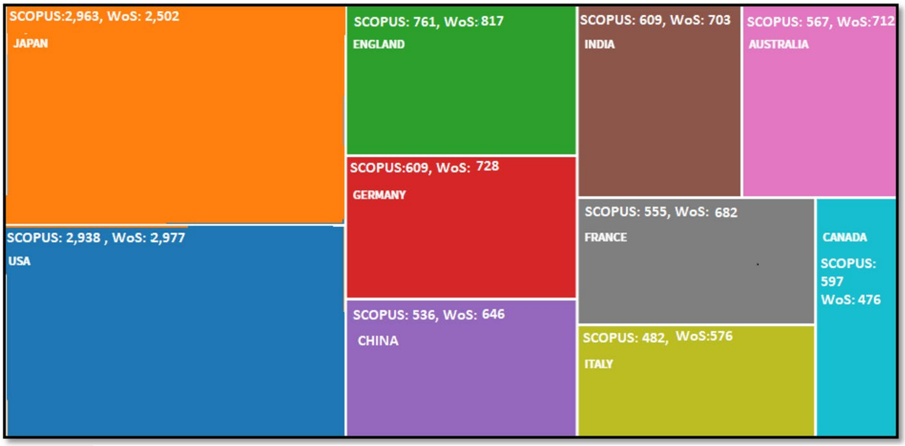

Fig. 5 Top Countries contributing to Tsunami Research since 2005 in Scopus and WoS

3.4 Most publishing countries

Figure 5 shows the top 10 countries contributing to tsunami research since 2005. The data extracted from both Scopus and WoS is analyzed. Here, Japan has contributed the maximum to this field with TD = 2963 followed by USA (TD = 2938), England (TD = 761), Germany (TD = 609) and India (TD = 609). Figure 5 is a treemap with decreasing Scopus-based order of TD along with WoS-obtained TD values. Out of the total, Japan contributed 24.8% of documents in Scopus and 21.3% in WoS. One of the possible explanations may be that after Japan experienced one of the world's worst tsunamis in 2011, scientists made fairly substantial contributions from the respective country, in the form of case studies, field surveys, and group interview results. The USA is the second most published country in Scopus. In the WoS database, however, it has contributed more documents than Japan. The likely explanation (concluded from Sect. 3.6

) here is that three of the top 10 funding organizations that support tsunami research are procuring major documents from the USA.

3.5 Top productive authors with influence

Table 4 shows the ten most productive authors extracted from Scopus with their corresponding WoS contributions. Three parameters, as discussed in Sect. 2, have been extracted. We have used second names to address the authors. In Scopus, Satake (TD = 114), Koshimura (TD = 97), Imamura (TD = 92) are the top three authors. While in WoS, following are the top three authors: Satake (TD = 114), Imamura (TD = 114) and Goff (TD = 86). As shown in Table 4,there are also significant contributions to WoS by the most productive Scopus authors. The other three authors occurring in top 10 list of WoS database are Lay (TD = 55, TC = 2411), Supassri (TD = 54, TC = 876), and Chague Coff (TD = 50, TC = 1842). Among the top 10 productive authors, Satake, Goto, and Imamura are the most influential Scopus authors. In WoS, Lay (ACPD = 43.83), Chague (ACPD = 36.84) and Satake (ACPD = 29.82) are the most influential authors. Clearly, out

Table 4 Top 10 productive and their influence based on data from both WoS and Scopus

Author name	Author affiliation	Scopus			WoS		
		TD	TC	ACPD	TD	TC	ACPD
Satake, Kenji	University of Tokyo, Japan	114	4151	36.41	114	3399	29.82
Koshimura, Shunichi	Tohoku university, Japan	97	1520	15.67	69	1222	17.71
Imamura, Fumihiko	Tohoku university, Japan	92	2241	24.35	114	2466	21.63
Goff, James	University of New South Wales Sydney, Australia	75	2025	27	86	2166	25.19
Nistor, Ioan	University of Ottawa, Canada	73	907	12.42	44	411	8.93
Goto, Kazuhisa	Tohoku university, Japan	64	2011	31.42	79	2093	26.49
Okal, Emile. A	Northwestern university, United States	50	1150	23	58	1119	18.45
Tinti, Stefano	Alma Mater Studiorum Università di Bologna, Italy	50	1113	2.26	58	857	13.82
Shibayama, T	Waseda university, Tokyo, Japan	48	670	13.96	31	348	11.23
*Pelinovsky Efim	Nizhny Novgorod State technical university, Nizhny Novgorod, Russian federation	47	672	14.29	46	572	10.4

*Author has multiple affiliations, Maximum period affiliation is taken

Table 5 Top 5 funding organizations from both WoS and Scopus

Funding organization/council	Scopus		WoS		Headquarters	Founded
	TP	TC	TP	TC		
Japan society for the promotion of science	371	5533	496	6,986	Tokyo, Japan	1932
National science foundation	334	7432	596	13,324	Virginia, USA	1950
National natural science foundation of China	183	1309	315	2,027	Beijing, China	1986
Ministry of education, culture, sports, science and technology	164	2964	719	12,100	Tokyo, Japan	2001
Russian foundation for basic research	101	1191	174	1211	Russia	1992

of the top 10 productive authors in Scopus and WoS, 50% of them are affiliated to Japan's universities.

3.6 Top funding organizations

Table 5 presents the top five funding (common to both the databases) organizations with decreasing Scopus-based order of TD. There are two organizations from Japan in the top five. Japan Society for the Promotion of Science (JSPS) has the highest contribution with TD = 371 in Scopus and TD = 496 in WoS. However, the National Science Foundation (NSF) has the highest and consistent citation impact factor (ACPD here) across both the databases (Scopus: 22.25 and WoS: 22.35). Further, the National Natural Science Foundation of China (NSFC) also has a considerable contribution; however, its ACPD is 7.15 and 6.43 in Scopus and WoS, respectively.

Table 6 Top 10 affiliations from Scopus

Affiliation	TD	TC	ACPD
Tohoku university, Japan	508	8379	16.49
University of Tokyo, Japan	453	8444	18.64
Kyoto university, Japan	226	3313	14.65
Russian academy of sciences, Russia	190	1951	10.26
United States geological survey, USA	184	6825	37.09
University of Washington, Seattle	175	3151	18.00
CNRS, France	174	3303	18.98
NOAA	168	3911	23.27
Japan agency for marine- earth science and technology	158	3076	19.46
University of southern California, USA	152	4222	27.77

Table 7 Top 10 affiliations from WoS

Affiliation	TD	TC	ACPD
Tohoku university, Japan	565	9112	16.13
University of Tokyo, Japan	487	8635	17.73
Russian academy of sciences, Russia	395	3789	9.59
CNRS, France	388	9296	23.96
University of California, USA	299	8704	29.11
United States department of the interior, USA	284	9518	33.51
United States geological survey, USA	282	9502	33.7
Kyoto university, Japan	219	4446	20.3
Helmholtz association	213	3828	17.97
NOAA	191	5032	26.35

3.7 Institution/affiliation wise analysis

Tables 6 and 7 present the institution or affiliation wise analysis for the data extracted from Scopus and WoS. Two universities from Japan top the contribution chart in terms of TD. Tohoku University, Japan, with TD = 508 in Scopus and TD = 565 in WoS, is the first. Followed by the University of Tokyo, Japan, with TD = 453 and TD = 487 in Scopus and WoS. In terms of ACPD, which gives the citation impact factor, organizations from the USA have the maximum ACPD. The United States Geological Survey with ACPD = 37.09 and the United States Department of the Interior with ACPD = 33.51, are among the top two. Followed by the University of Southern California, USA, with ACPD = 27.77 in Scopus. NOAA (National Oceanic and Oceanic Administration) is the next most influential organization.

3.8 Top keywords

This section presents the top occurring keywords using the widely used software: Vosviewer given by Van and Waltman (2010). Figures 6 and 7 provide the top keywords obtained from Scopus and WoS data between 2005 and 2020 (inclusive). An interesting

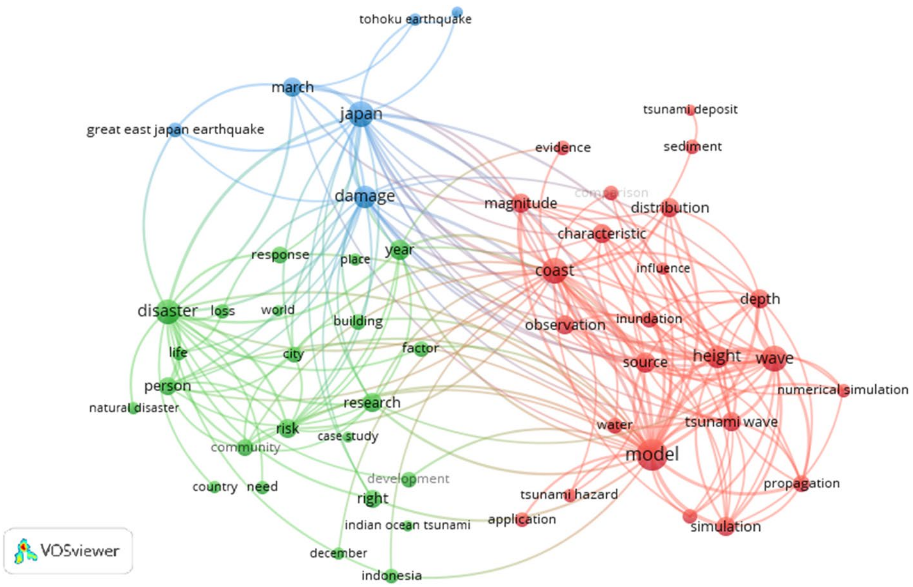

Fig. 6 Most commonly used keywords for Tsunami research extracted from Scopus

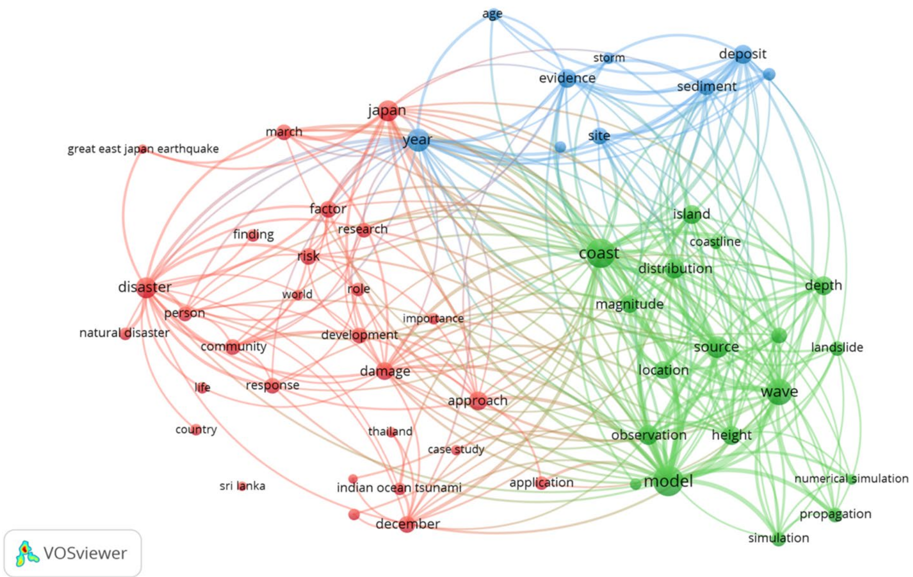

Fig. 7 Most commonly used keywords for Tsunami research extracted from WoS

observation in top keywords is that both databases have shown three clusters. In Scopus, the three clusters are divided as- where one is talking about the 2011 Japan tsunami, the second cluster about the Indian Ocean tsunami. The third cluster consists of the keywords outlining tsunami sources through numerical models, simulations, and wave models.

Sediments and deposit findings as a source of the 2004 and 2011 major tsunami event and their impact factors falling into two different clusters make an essential contribution to WoS.

The later sections of this paper cover the study of about 15 years indexed through these top keywords in the given clusters.

3.9 Top 10 influential papers

Table 8 shows the top ten cited documents prepared in decreasing order of citation extracted from the Scopus database. As per the true blue approach discussed before, the list presents the top ten Scopus documents with their corresponding WoS citations. Out of the top ten cited, six are present in the WoS top ten cited as well. The rest of the four highly cited papers from the top ten of WoS documents are Janda and Abbott (2010): TC = 797, Cisternas et al. (2005): TC = 337, Chlieh et al. (2007): TC = 321 and Kathiresan and Rajendran (2005): TC = 321.

4 Tsunami: overview of last 15 Years

In this section, we address the scientific and scholarly perspective of tsunami research. The findings from 154 papers contributed in the last 15 years have been summarized. This review includes the top 10 cited papers from Scopus and WoS (also shown in Table 7). The next 142 papers contain the most cited, coming from the highly occurring examination of keywords carried out on the full scholarly database.

4.1 Overview of tsunami

Humanity was affected in different forms by the December 2004 tsunami. Therefore, scientists began investigating the physical cause behind it. Stevenson et al. (2005) gave one of the early papers in 2005 explaining tsunami generation and propagation phenomena through descriptive wave equations. Another related field observing large contributions is probable precursors of a tsunami, identified as earthquakes (Satake et al. 2007), landslides (Masson et al. 2006), and volcanic eruptions. Relevant papers were also part of the literature (Kapila et al. 2005) that covered post-tsunami impact analysis and addressed topics such as health evaluations, policy restoration, and better rebuilding, in addition to researching physical phenomena.

Further, Wahlstrom et al. (2005) have highlighted the need to identify gaps between the relief and recovery phase to help humanity cope with after-effects. One of the interesting observations that came from the impact analysis of the Asian tsunami was vegetation's role in reducing these forceful oceanic waves along the shorelines, as reported by Danielsen et al. (2005). In the concluding months of the year 2005, Harinarayana and Hirata (2005) spoke in a letter-article (in the concluding months of 2005) that the scientific community's lessons from post-event recovery could provide a platform for implementation to improve the current early warning systems. Several ideas, such as Taubenböck et al. (2009), began to emerge a few years later. The need to interlink remote sensing data and the resulting numerical model impact analysis became a need for successful disaster risk management, evaluation, and reduction.

Table 8 Top 10 influential documents from Scopus, including WoS top 6 cited

Authors	Title	Year	Source title	TC	
				Scopus	WoS
Lay et al. (2005)	The great Sumatra–Andaman earthquake of 26 December 2004	2005	Science	759	315
Alongi (2008)	Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change	2008	Estuarine, coastal and shelf science	743	651
Simons et al. (2011)	The 2011 magnitude 9.0 Tohoku-Oki earthquake: Mosaicking the megathrust from seconds to centuries	2011	Science	488	470
Danielsen et al. (2005)	The Asian tsunami: A protective role for coastal vegetation	2005	Science	477	408
Masson et al. (2006)	Submarine landslides: processes, triggers and hazard prediction	2006	Philosophical transactions of the royal society	462	408
Saraceno et al. (2007)	Barriers to improvement of mental health services in low-income and middle-income countries	2007	Lancet	465	–
Morton et al. (2007)	Physical criteria for distinguishing sandy tsunami and storm deposits using modern examples	2007	Sedimentary geology	444	407
Freed (2005)	Earthquake triggering by static, dynamic, and post-seismic stress transfer	2005	Annual review of earth and planetary sciences	432	–
Gedan et al. (2011)	The present and future role of coastal wetland vegetation in protecting shorelines: Answering recent challenges to the paradigm	2011	Climatic change	419	158
Ide et al. (2011)	Shallow dynamic overshoot and energetic deep rupture in the 2011 M w 9.0 Tohoku-Oki earthquake	2011	Science	407	378

In 2010, among the most cited documents Paris et al. (2010), Nouri et al. (2010) were the magnitude estimate of the 2004 Indonesian tsunami by analyzing the relationship between boulder impact and hydraulic forces using computational models as well as discrimination between boulder impacts to estimate tsunami run-ups. The Tohoku tsunami incident in 2011 also influenced the coming years, lessons learned, and processes of recovery. One of the initial articles related to this event, by Zijlema et al. (2011), published an open-source code[1] for the numerical tool to estimate source characteristics using shallow water equations. The incident resulted in a nuclear accident. Many socialists captured the after-effects on the community where through surveys (Yabe et al. 2014). In 2015, Chile experienced a tsunami initiated by an earthquake. The majority of highly-cited documents in 2016 and 2017 discussed and studied the Chile tsunami source estimation and after-effects. Two of the critically cited papers were from Melgar et al. (2016) and Aránguiz et al. (2016), where the kinetic model was used to estimate co-seismic slip and run-up heights with arrival time calculations using field data, respectively. However, recovery process coverage of the Tohoku disaster continued, as emphasized by Kuriyama et al. (2016). They discussed the Tohoku Medical Bank Project (TMM), highlighting the post-disaster recovery process's challenges and solutions.

Much of the last 2 years have been about the tsunami in the Palu region, Indonesia, in 2018. Initially, Takagi et al. (2019) have concluded that landslides were the primary source of this tsunami. They calculated a possible arrival time based on surveyed bathymetry data for the mentioned non-seismic tsunami. Some of the other major contributions were impact assessment using machine learning and deep learning discussed in Sect. 4.8.2.

Several datasets have been used in the contributions mentioned above and in the upcoming sections. With a newly launched website,[2] NOAA has contributed about fifty-nine tsunami datasets.[3]

4.2 The Indian Ocean tsunami: December 2004

One of the initial articles that also covered the physical context of the Indian Ocean tsunami was given by Lay et al. (2005), further supplemented by Ammon et al. (2005), explaining the process through seismic equations and assumptions. The papers concluded that the rupture took about 515 s and extended from Sumatra to Andaman with a trench length of about 1500 km. The studies merely relied on land surveys, also known as geodetic measurements in the seismic corpus. In 2006, Subarya et al. (2006) attempted to model displacement characteristics using Global positioning System (GPS) measurements. Meltzner et al. (2006) used Synthetic Aperture Radar (SAR) images for the displacement characteristic study. Rabinovich et al. (2006) explained the frequencies, wave, and amplitude structures of this Indian Sumatra tsunami. Despite such active contributions, no model adequately integrated the tsunami source, the seismological data, and the geodetic data. The reason was mainly due to a certain clock error rate in sensing instruments at the time of the event, as commented by Neetu et al. (2005). Some complementary research continued until one of the pioneering researches was published by Chlieh et al. (2007) in the Bulletin of the Seismological Society of America in 2007.

[1] http://swash.sourceforge.net/.

[2] https://catalog.data.gov/dataset?tags=tsunami.

[3] https://www.ngdc.noaa.gov/hazard/tsu_db.shtml.

The authors used the post-seismic deformation data from GPS surveys, campaign measurement data from neighboring countries like Thailand and Malaysia, and remotely sensed geodetic data from coral reefs. The data helped predict and model a similar tsunami, which matched the altimetry measurements reported by satellites such as JASON. The estimates omitted the impact of any smaller incidents in the past to the 2004 December tsunami incident. Major contributions continued in the following years, studying post-tsunami assessments based on tide gauges, GPS systems, and digital recordings (Fujii and Satake 2007). Another study by Grilli et al. (2007) used the fully nonlinear and dispersive Boussinesq model (FUNWAVE). The authors estimated dispersive effects to be more than 20% in several nearby areas. A similar physical model explaining the dynamics behind tsunami generation was given by Grue et al. (2008) using a fully non-dispersive method and Korteweg-deVries (KdV) equations. Levin and Nosov (2009) later compiled other articles and summarized the physics behind the December 2004 Tsunami.

The next few years typically contributed to modeling and understanding another devastating and similar event in its impact – the 2011 Tohoku Tsunami. The subsequent section reviews the most cited and pioneer articles concerning this event.

4.3 The great Indian Japan Tsunami: march 2011

2011 marked another devastating year for humankind. A series of events where an earthquake followed by a tsunami wash and a nuclear accident took place in Japan. Preliminary coverage of the event was given by Simons et al. (2011) in December 2011. The authors used the GPS time series and bottom pressure sensor records (BPR) from the NOAA website for simulations. Mofjeld et al. (2001) evaluated slip depth and rupture process using Cornell Multi-Grid Coupled Tsunami Model code already given by Smith and Sandwell (1997). Later, Ide et al. (2011) analyzed fifty seismogram data to conclude that an earthquake rupture is a precursor to a tsunami. Image sensors are a must when a similar rupture happens in the future to produce timely alerts. This event opened many research directions, as addressed by Goto et al. (2012a–d). Later, scientists claimed that the geology of the tsunami had not developed globally before this event occurred. Also, the focus should be more on multidisciplinary research in predicting tsunamis rather than forecasting earthquakes. A series of articles came from author Kazuhisa Goto affiliated to the International Research Institute of Disaster Science, Tohoku University, Japan, in 2012. He used field measurements and run-up heights (Goto et al. 2012a–d), the role of liquefaction in sediment deposit movement offshore (Goto et al. 2012a–d), the role of palaeotsunami in determining the impact of the Tohoku event (Goto et al. 2012a–d). The author defined palaeotsunami as a tsunami occurring before a given record for which there is not much-written evidence. Also, author Prof. James Goff, affiliated to the University of New South Wales, Australia, an eminent contributor in palaeotsunami, concluded in 2012 (Goff et al. 2012) that palaeotsunami needs a multidisciplinary approach attracting contributions from archaeology, sociology, and stratigraphy. Providing new insights to palaeotsunami research, the author has developed a tsunami database for Australia (Goff and Chague-Goff 2014) and New Zealand (Goff 2008). An interesting observation that was also given by authors (Goto et al. 2011) was that a predecessor existed in the literature in the name of the AD869 Jogan earthquake based on geological evidence. Underestimating the after-effects of the incident resulted in inadequate defense measures. The authors have highlighted those similarities between the two cases needed manifestation in developing tsunami risk assessment and mitigation programs in the future.

The Jogan earthquake was later re-analyzed by authors Namegaya and Satake (2014). They reiterated the proposition that both the AD869 event and 2011 event emitted similar characteristics in terms of sediment deposits. Both cases were compared on slip fault models and resulted in striking similarities. Since then, different models have been operating on various types of data obtained from available sensors. For example, Romano et al. (2014) presented a joint analysis using 3D images and geodetic data. Similar to the 2004 tsunami simulation, Baba et al. (2017) modeled the Japan event using Boussinesq dispersion and shallow water equations. During this disaster, a nuclear accident also happened that released radionuclides from Fukushima Daiichi nuclear power plants (FDNPP). A complete review of its after-effects has been presented by Buesseler et al. (2017), stating that not much direct casualties have happened due to exposure. However, in terms of disorder and tension among children and the elderly population, social consequences have been prominent. With developments in the 5 years following this event, substantial changes have influenced this event's effects. The one given by Bai et al. (2018) was a contribution that was different from the previously described physical modeling techniques. Here, a U-net deep learning model was used to classify building damage from the pre- and post-disaster image dataset[4](Worldview2) of the 2011 event.

One of the recent articles by Fauzi and Mizutani (2019) presented a convolutional neural network applied to tsunami fault scenario data,[5] further trained using a multi-layer perceptron to generate a forecast. Similar work presented by Mulia et al. (2018) also used principal component analysis (PCA) to select the best fit scenario rather than generate a forecast.

Other aspects of these two events, including disaster management, survival studies, preparedness, and impact analysis, are summarized in the coming sections.

4.4 Other countries affected

Apart from India and Japan, various other countries have also experienced this life-threatening hazardous event. Just after the 2004 December Sumatra event, Solomons Island that lies to the east of Paua New Guinea, experienced a tsunami in April 2007. Fritz and Kalligeris (2008) presented the complete numerical details like local flow depth, run-up heights, and tectonic modeling of the 2007 event. McAdoo et al. (2008) later reported the post-survey analysis carried out by seismologists and socialists visiting the local population survey action site. Their results showed that much of the sediment deposits had started disappearing at the event's time, and the area was much under-recovery. Instead of the subsequent tsunami from it, the major damage was due to the earthquake that occurred. Also, Bouchard et al. (2007) showed that how the newly planted Deep-Ocean Assessment and Reporting of Tsunami (DART) were able to successfully provide data and timely information to the Tsunami Warning Center (TWC). The real-time testing-based success of the newly installed Australian TWC, as reported by Dominey-Howes et al. (2007), achieved good results where it could issue warnings in time. However, as outlined, the local community's indigenous knowledge and their preparedness over past experiences saved many lives from this event (McAdoo et al. 2009).

[4] https://earth.esa.int/web/guest/data-access/browse-data-products/-/article/worldview-2-full-archive-and-tasking.

[5] https://github.com/jagurs-admin/jagurs.

Later, a similar event also happened simultaneously in the Kuril Islands in November 2006 and January 2007. Lobkovsky et al. (2009) briefly presented the numerical analysis and simulations describing the nature of tsunami waves generated initially due to an earthquake. The events were recorded by the NOAA DART's newly installed after the 2004 Sumatra tsunami, with high accuracy. The formation and propagation modeling for the Kuril Islands event had already begun in advance, derived from lessons learned after the 2004 tsunami incident. Laverov et al. (2006) examined and presented the pre- investigations. Fortunately, this 2007 tsunami did not cause any causality. However, as the alerts provided by the West Coast Alaska Tsunami Warning Center (WCA TWC), aka National Tsunami Warning Center (NTWC), were canceled three and a half hours later after it reached the Kuril Islands, the Crescent city residents experienced significant tremors. Numerical analysis by Dengler et al. (2009) clearly showed why and how the warnings got delayed for about 5 hours, and yet another wave struck the Crescent city in California. As a result, the WCATWC's advisory board updated the warning guidelines and claimed that a possible tsunami could occur within 6 h of its source generation and impact nearby locations.

Chile, located in South America, also witnessed an earthquake-generated tsunami in the year 2010. Fritz et al. (2011) were among the few early ones who surveyed the post-tsunami impact in this country. Pacific tsunami warning center (PTWC) issued a warning 5 min after the earthquake had arrived, but the tsunami arrived within 30 minutes. Education and awareness among the locals helped early evacuation and saved many lives, as Synolakis and Bernard (2006) reported. Chile also observed another earthquake that initiated a tsunami in 2014. At an interval of 15 and 21 min, NOAA's PTWC again released two periodic warning signals, which occurred within the 30-min interval of the tsunami incident. Aranguiz et al. (2019) performed one of the first computational simulations for the same, concluding that the bathymetry, coastal morphology, and the slip distribution of the causative earthquake greatly affected tsunami arrival time and spatial variation of the tsunami amplitudes.

Several reports mentioned the DART's wave run-up height for various far-field locations along with the factors mentioned above. The observations were re-evaluated by authors Heidarzadeh et al. (2015) using Fourier transform analysis of the DART measurements. The authors concluded no relation between the wave height and the direction from the source. Lately, Indonesia had, unfortunately, witnessed a tsunami in September 2018. The initial field survey data given by authors Muhari et al. (2018) suggested an underwater landslide and not an earthquake-generated the mentioned tsunami. Omira et al. (2018) showed the post-event field survey with seventy-eight run-up measurements, among the recent papers here, which helped them infer that behind this unfortunate event, there were undoubtedly some secondary non-seismic indicators. Heidarzadeh et al. (2019) recently contributed an article in December to analyze the marine recordings and measurements of two source locations: Palu Bay and Indonesia's Mamuju. Once again, the findings highlighted the difference in characteristics between a seismic and a non-seismic tsunami, concluding that a non-seismic tsunami is the Palu bay 2018 case. Three months later, Indonesia witnessed another volcanic tsunami. With 130 volcanoes, Indonesia has been among the most vulnerable countries to volcanic tsunamis. Paris et al. (2014) review some ancient volcanic tsunamis' generation mechanisms. For many geologists and seismologists, modeling and understanding of non-seismic tsunamis remain an unexplored area. Using the numerical simulation model already proposed by Fritz et al. (2004), Heidarzadeh et al. (2020) have proposed a static source model. The model legally replicated the recording of the tide gauge data at the arrival time and thus studied volcanic tsunamis' effects and source.

4.5 Early warning systems: evolution and products

Lesson learned from various tsunami occurrences led to the evolution of the existing and invention of a new tsunami warning system (TWS). For the two most major tsunami events in India (2004) and Japan (2011), Arcas and Titov (2006) and JMA (Japan Meteorological Association) documented specific lessons. Both articles indicated a need for technological improvements in wave height estimation, timely estimation of real earthquake severity, and valid forecasting models. Various forecasting models were then proposed by the scientific community, as discussed in the previous section, which resulted in the efficient evolution of TWS. One of the initial contributions that modeled the tsunami reach was given by Titov et al. (2005), which used seafloor displacement, ariel extent magnitude, and refined their own MOST (method of splitting tsunami model) already given in 1998 (Titov and Synolakis 1998). This model identified two main factors affecting tsunami wave, viz. focusing origin and waveguide structure of the ocean ridges. The authors' findings and results were consistent with the data obtained from the tide gauge published in a book by Hebenstreit et al. (2013). The three worldwide TWS(s) are currently operational for the Pacific Ocean, the Indian Ocean, and the Mediterranean and Connected Seas countries. NOAA has two warning centers named PTWC located in Hawaii and NTWC (National Tsunami Warning Center) located in Alaska. Initially, they operated on the MOST model for Tsunami warnings.

Further refined using deep ocean measurements after the 2007 Kuril Islands tsunami, Uslu et al. (2010) proposed a SIFT model in their article. Later the enhanced model was published by authors in the dissertation (Titov et al. 2016). After the 2004 tsunami, a conference held in the United Nations in 2006, Kobe introduced the Indian Ocean Tsunami Warning System (IOTWS). There were 25 seismographic stations in this system combined with 6 DART buoys. Apart from prediction, these stations also helped relay information to local other national tsunami information centers. Till 2012, it worked as per PTWC guidelines.

Later in 2012, researchers from the Indian National Centre for Ocean Information Services (INCOIS) documented and presented a local Indian Early TWS (IETWS) in a contribution, Nayak and Kumar (2008a, b). The system primarily worked on bottom pressure recorders (BPR) and tide gauges to predict probable seismic surges. The numerical model behind the framework was one given by Imamura et al. (2006). Another set of observations also given again by Nayak and Kumar (2008a, b) evaluated the Indian TWS on September 12, 2007 earthquake, where it performed well and could issue timed warnings wherever required. In 2012, the authors Kumar et al. (2012) also presented Indian TWS's performance on 73 global earthquakes reported well in time. They also showed a comparison with similar other deployed warning systems, viz. PTWC and JMA. Japan, after the 2011 Tohoku Tsunami event, did bring considerable changes to its warning system. Supassari et al. (2013a; b) gave complete coverage to all the plans, policies, and warning system inconsistencies that made 2011 another devastating event for Japan's inhabitants. Gupta and Gahalaut (2013) have briefly described all major TWS operating across the world.

The failure of warning systems to measure the tsunami height was one of the prime disadvantages. The need for structural countermeasures to protect buildings and houses from heavy ocean flow, awareness, and good evacuation routes was addressed just after the event, indicating the hour's need. Concluding that the impact analysis was flawed, one reason was the misunderstood wave height. Hence later, in 2012, Tang et al. (2012) came up with a novel method to compute total energy transmission via tsunami waves. This method calculated the impact based on source and propagated energy using seafloor topography. Later, the three newly installed DART's were again checked for recurrent earthquake events in December 2012 by some of the latest methods. The enhanced device worked well and released the alert about 11 min before the incident, making it the shortest time for any DART to predict. Bernard et al. (2014) presented some of these results. The seismic technology has evolved and still is, to predict and forecast tsunami much before time. Satake (2014) has captured these advancements, where the author discusses progress in tsunami science concerning the new DART deployments, improvements in propagation models, and the technical progress in GPS buoys. Similarly, Bernard and Titov (2015) also covered the breakthrough in tsunami science and technology. They mentioned that Canada, Japan, Oman, and the USA have also deployed cabled observatories for timely predictions apart from buoys and DARTs.

The Mediterranean Sea tsunami warning system uses an earthquake-centric approach, as there are no current DART stations in the Mediterranean Sea. Schindelé et al. (2015) document the implementation and challenges. Inundation defines the last stage of tsunami evolution. Here, the oceanic wave intentionally wets the dry land. Scientists have recognized the need for forecasting and impact analysis methods using bathymetry and topographical data. Authors Synolakis and Bernard (2006) explained the science behind the 2004 tsunami and the need for adequate flood maps production to warn the coastline population. They have also laid some guidelines for community awareness. Scientists have been proposing various prediction models and tools, where later, Titov et al. (2011) presented a pioneer tool: ComMIT. It is a web-based model implemented in Java language that generates inundation maps, thus assisting the coastline community. The tool helps community individuals who are not developers to further assist in local community preparedness effectively. This tool separated the complexities behind the source and propagation of tsunami waves from the regional flooding estimates, which will help the future for community preparedness. The United States-coordinated NOAA continues to work and use this tool to train several scientists who can assist as much as possible in future local training. Despite the ongoing progress in tsunami science concerning warning systems, there have been recent instances where the event did go un-predicted. For example, Palu and Sunda tsunami events in 2018 documented by Mai (2019), where all the warning systems developed post-2004 failed to generate warnings. Therefore, in a recent contribution by Imamura et al. (2019), it was concluded that: (i) predicting cascading disasters like the 2011 Tohoku and the Indonesian 2018 non-seismic tsunami event remains a considerable issue (ii) there is a dire need for globally functional warning items that can assist local communities in assessing risks (iii) tsunami experiences and past observations need to be shared and disseminated through a popular forum to inform consumers further, developers, and the coastal community, complementing the current alert systems. The Indonesian Early Tsunami Warning System (IndEWTS), launched in 2008, was based on the finite element numerical model given by Hanert et al. (2005) with certain modifications including boundary conditions, bottom friction, and corrected momentum terms. Harig et al. (2019) have also provided recent coverage of related early warning systems. The data maintained by the

Metrology, Climatology, Geophysical Agency, Indonesia (BMKG) as individual datasets[6], [7] are available for visualization maps that have also been used by Harig et al. (2019).

4.6 Role of sediments, vegetation, and mangroves

Various other factors play a vital role in determining tsunami mitigation and protection. Mangrove vegetation along the coast of Sumatra was one of the factors initially reported in 2005. One of the initial contributions came from Kathiresan and Rajendran (2005). They provided the complete data for 18 fishing villages on mangrove vegetation with distance from the sea, elevation from the sea, vegetation cover area, and many deaths. The study was conducted using multiple regressions stepwise and concluded that regions with thick mangrove vegetation suffered fewer tsunami deaths. However, the proposition was criticized by Kerr et al. (2006), stating that one cannot ignore the co-variation among dependent variables such as distance and elevation level. Further, Vermaat and Thampanya (2006) contributed a response discussion contributed supporting the claims made by Kathiresan and Rajendran 2005, re-verifying their results using the ANNOVA model, also considering the concerns raised by Kerr et al. (2006). One of the pioneer contributions came in 2008 by Alongi (2008)—a review which revisited the previous tsunami records of the 2004 event claimed absolute results: (i) there are observable patterns of mangrove recovery from specific hazards, (ii) some model exhibits showed a 90% decrease in tsunami flow due to a 100-m wide belt. (iii) Mangroves have an inherent ability to absorb shock tremors from tsunami flow based on particular density and size parameters. Also, Gedan et al. (2011) provided some exciting insights from previous case studies: (i) mangroves could provide case-dependent protection against tsunami damage; in terms of magnitude and wave characteristics (ii), there is a nonlinear relationship between the vegetation size and wave properties. Many other studies and approaches were produced, including successful ecological engineering (Borsje 2011) and mangrove expansion (Saintilan 2014), which have proven to be an effective defense mechanism against this fatal event. Later, several affected countries by tsunami started mangrove restoration and re-plantation. However, it was concluded by Kodikara et al. (2017) that an effective post-care and ground property needs revision to aid the easy restoration.

Studying vegetation and its role in protecting coastal hazards such as tsunami has become another research area for scientists. Xie et al. (2017) have recently analyzed another vegetation type: the halophyte population adapted to absorb different tidal rushes. A similar study by Satyanarayana et al. (2017) also indicated that mangroves are resistant to tsunami hits. Here, scholars have identified coastal areas close to Sri Lanka as vulnerable and less vulnerable using ASTER satellite data[8] and simulations from 2004 tsunami source wave models. Another recent laboratory experiment by Chen et al. (2018) showed an inherent relation between vegetation density and tsunami wave height using developed empirical equations. Later, Yao et al. (2018) reverified the hypothesis using Boussinesq equations. Zhang et al. (2019) recently conducted a study on another different plant species: Pandanus odoratissimus. The results concluded a probable resistance (of the mentioned species) towards tsunami wave run-ups demonstrated by applying a two numerical

[6] https://www.gebco.net/.

[7] https://www2.jpl.nasa.gov/srtm/.

[8] https://terra.nasa.gov/data/aster-data.

model ensemble. Several countermeasures attempted concerning increased implantation of vegetation, which, as highlighted by Suppasri et al. (2016), conclusively demonstrated immunity towards tsunami waves in the past five years since the tsunami in 2011. Therefore, it is essential to note that various ecologists are working to explore and discover the variety of vegetation forms that have features to withstand ocean surges such as a tsunami and contribute to the protection and mitigation of tsunamis.

Pre- and post-tsunami analytics have also gathered a lot of interest from sedimentologists and geologists from the sediment records and their subsequent effects. Sediment deposits resulting from tsunami need to be separated or identified from storm deposits. An initial textural analysis by Morton et al. (2007) gave physical parameters like thickness, layers, and rip-up clasts to differentiate tsunami deposits. Jankaew et al. (2008) initially showed via post- and pre-sediment analysis that the 2004 Sumatra tsunami was not new to the Indian Ocean; there were significant predecessors around 600 years ago. A similar study by Monecke et al. (2008) presented the results deduced from Aceh (a province in the northernmost portion of Sumatra) having a similar characteristic of sediment deposits. These deposits were from some ancient tsunami and added that such events like the Sumatra 2004 tsunami could recur infrequently. For the 2011 Japan tsunami, the contributions for estimating tsunami source and similarity characteristics are covered in Sect. 4.3. In a study, authors Sugawara et al. (2014) report that forward and inverse models can simultaneously simulate tsunami run-up time improvement, estimate flow velocity, and depth.

Some of the latest articles in this field analyzing past tsunamis simulation from sediment deposits are Sugawara et al. (2019), Inoue et al. (2017), Basavaiah et al. (2019). These contributions point to the scope in palaeotsunami studies, as already discussed in Sect. 4.3, to aid in predicting recurring tsunami arrival time and thus enhanced coastal risk assessment as well as its preparedness. These results opened up different possibilities for scientists to work on coastal defense against tsunami hazards.

4.7 People as warning systems: resilience and community preparedness

Warning systems have evolved and are still maturing. Despite the existence of TWS, giving an early warning is always a challenge that exists. Interpreting and reacting effectively within time to this warning is also imperative for humanity to protect themselves from tsunami-like hazards. Such observation is supported by survey results presented in a study by Gaillard et al. (2008) conducted using interviews and questionnaires. The research here was motivated by the mere fact that from the affected areas, Simeulue, which is an island in Indonesia, suffered from less death toll as compared to the count reported for Aceh, a province in Indonesia. The results concluded the difference in the preparedness and education between the people from these places. Fritz et al. (2011) also highlighted the explanation that the 2010 Chile tsunami may have spared the inhabitants due to the knowledge and education among them that prevailed from previous experiences. Suppasri et al. (2013a, b) also reported some of the initial lessons from the Japan tsunami in 2011, highlighting the need for soft steps, i.e., knowledge of how to construct infrastructure, homes, houses, and bridges.

The authors also concluded that awareness on how to comprehend warning messages and act accordingly is equally imperative. However, as Esteban et al. (2013), in their work, analyzed that some population communities in various areas of Chile, Japan, and the USA have shown an inclination towards disaster preparedness. A recent study conducted by Sun and Sun (2019) highlighted that, due to high reaction time to alert messages, the elderly population needs more evacuation time than adolescents. Despite a revised framework proposed by UNISDR[9] (United Nations Office for Disaster Risk Reduction) named Sendai Framework for Disaster Risk Reduction (SFDRR), researchers continue to emphasize the persistent issues of disaster risk preparedness among individuals. Recently in an article, Harnantyari et al. (2020) have concluded that almost 83% of the people evacuated Palu city areas after seeing younger people evacuate. Rasyif et al. (2020) have also identified five affected areas in Indonesia 2018 tsunami that have inefficient evacuation infrastructure. These studies drive the need for better mitigation, resilient plans, and mechanisms to be proposed to improve the community's non-seismic tsunami preparedness, such as in Indonesia, in 2018, where an official alert went missing.

However, in the past, humans have served as explicit sensors to help assess such modifications in existing warning products that contribute to early warning and efficient evacuation outcomes. Gregg et al. (2006) reported some facts from 663 interviewees, where 69% saw something unusual, and 55% heard something unique. Acar and Muraki (2011) indicated how Twitter became a useful tool for people in alarming each other about the unusual happenings they had witnessed just before and during the 2011 Tohoku event. Eventually, authors Carley et al. (2016) proposed a Tsunami Warning and Response Social Media System (TWRsms) that can help in early warning and rapid evacuation.

Apart from generating early warnings, mankind can also act as a source of information to help researchers, practitioners, and scientists in other inventions and findings. Hicks (2019) commented that a non-seismic signal discussed by a section of people in the Comoros Islands on Twitter did provide particular insights to scientists then and helped in specific findings. Also, videos and locally collected data shared by people on social media sites have enabled scientists to understand this undetected non-seismic tsunami's mechanism.

4.8 Impact assessment: mitigation, response and recovery

4.8.1 Impact on humans

The ecosystem that contains both living and non-living components has always been affected by hazards. Tsunami, specifically, has affected humans, animals, buildings, and bridges. This section explores the impact of the tsunami on humans over the last 15 years. Initially, in 2006 Thienkrua et al. (2006) conducted a post-tsunami health survey in southern parts of Thailand showing the prevailing post-traumatic disorder (PSD) and depression in children even after 9 months of occurrence of the 2004 December tsunami. In the past, the government has made attempts to come up with sponsored policies to tackle after-effects. Polices and funds manifested in Sri Lankans post-2004 tsunami's health have been on no small scale, as Saraceno et al. (2007) quoted in their study. Hollifield et al. (2008) presented a similar analysis of adults where PSD was significantly observed. However, the local population recovered during the next 21 months reported in the form of percentage facts. To mitigate the impact and effectively strengthen resilience, Lyons (2009) proposed a Building Back Better (BBB) framework. It addressed the strategies, priorities, and coordination processes of the government that should be followed to ensure recovery. Raju

[9] Sendai framework for disaster risk reduction: hybrid machine model consistinghttps://www.unisdr.org/files/43291_sendaiframeworkfordrren.pdf.

Table 9 Contributions to building impact assessment

S. No	Author	Tsunami	NOB
1	Suppasri et al. (2012a, b)	2004, Indian Tsunami, Thailand	4596
2	Koshimura et al. (2009)	1993, Okushiri Island tsunami	769
3	Gokon et al. (2014)	2009, Samoa tsunami	6239
4	Foytong and Ruangrassamee (2007)	2004, Indian Tsunami in Thailand	120
5	Murao and Nakazato (2010)	Sri Lanka	1535
6	Valencia et al. (2011)	Banda Aceh, Indonesia	2576
7	Reese et al. (2011)	2009, Samoa tsunami	201
8	Suppasri et al. (2012a, b)	Japan	150
9	Mas et al. (2012)	2010, Chile tsunami	915

and Becker (2013) also identified specific parameters that affected the post-2004 tsunami recovery process in Tamil Nadu. The Tohoku tsunami in 2011 also harmed the environment. One of the initial studies where Aoki et al. (2012) surveyed central Tohoku residents concluded that cardiovascular disorders, heart failure, and pneumonia had increased after this disaster. Therefore, the findings emphasized the need for improved medical management to cope with such incidents' after-effects.

4.8.2 Impact on buildings

For non-living elements, satellites have played an essential role in identifying the damaged or impacted areas and buildings. Voigt et al. (2007) described how to analyze multisource image data from different satellites that could generate adequate maps in collaboration with geological data. The process of disaster management and mitigation is improved and eased by such established maps.

One of the critical contributions came from Koshimura et al. (2009), in which the authors suggested and evaluated fragility functions using numerical models and GIS (Global Information Satellite) data from one of the commercial satellites: IKONOS[10] (Satellite Imagery) post-2004 tsunami incident. Here, the analysis is limited to one of the affected areas from the Indian Ocean tsunami, Aceh, in Indonesia. However, other affected areas have also been researched, such as Miura et al. (2006), providing a review of the impact assessment on Sri Lanka building structures. Fragility functions expressed in mathematical probabilities define physical tsunami parameters such as inundation depth, depth, and velocity. Therefore, Lyons (2009) 's framework BBB, as discussed in the previous Subsect. (4.8.1), was revisited and re-defined by UNISDR, presenting some updated policies and highlighting the guidelines for new designing procedures that can assist in a significant recovery for effective disaster preparedness. Analysis and countermeasures based on SFDRR are discussed in Sect. 4.8. As summed up by Maly and Suppasri (2020), the challenges of assessing recovery procedures, with the need for new hazard risk assessment and mitigation using a multidisciplinary method, remain an open field.

A qualitative study of the event's damage persisted even after the 2011 Japan earthquake, where different contributions came in. Another one was given by Suppasri et al.

[10] https://www.satimagingcorp.com/satellite-sensors/ikonos/.

(2013a, b), which used a dataset provided by the Ministry of Japan to identify 250,000 buildings based on an analysis of the likelihood of damage.

The contribution provided impressive results like higher steel building resistance towards tsunami flow, tall story building being more resistant than small ones. The other contributions in this field are summarized in Table 9, showing the number of buildings (NOB) assessed in each contribution, respectively. The previous papers' analysis concludes that there is a need to significantly strengthen those countermeasures required in the coming years to mitigate and increase tsunami resilience. Suppasri et al. (2016) have also highlighted these initiatives in the form of steps taken over the last 5 years towards buildings: for example, proposing new building design standards, building high-story buildings, building resistant coastal structures to withstand potential turbulence.

In addition to the numerical analysis conducted as fragility functions, Chen and Sato (2012) presented another method to determine buildings' effects by analyzing changes in buildings' polarimetric characteristics. The authors proposed a damage index using a polarization-based decomposition model. The model's input was PolSAR and ALOS satellite images taken from open source repositories,[11] provided by Japan Aerospace Exploration Agency (JAXA).

Later and recently, using deep learning and machine learning methods, several contributions have been made to automate the damage assessment process. Split-based image analysis, coupled with the deep neural network, was performed by Bai et al. (2017) on a dataset[12] (Terra) for damage recognition. The framework proposed took only 2 h for training and few minutes to predict the damage. Machine learning classifiers such as SVM (support vector machines) applied by Ji et al. (2018) on PolSAR and ALOS image dataset have outperformed the decomposition models given above. Authors Gupta et al. (2019), Fujita et al. (2017) contribute open-source datasets.[13,14] The authors have analyzed the building impact assessment using deep learning techniques. After the occurrence of a non-seismic tsunami (discussed in Sect. 4.4), a hybrid machine model consisting of random forests, rotation forests, and canonical correlation forests is used by Adriano et al. (2019) on various open satellite image datasets[15] (DisasterData) using the toolbox ESA.[16] These datasets have captured pre- and post-images of Indonesia Tsunami 2018 achieving an assessment accuracy of over 90%.

The most cited articles, along-with areas spanning the top keywords, were covered in the systematic overview presented after the bibliometric study. The subsections concerning the top keywords discuss several major cited and pioneer contributions extensively. The work presented will provide readers with a brief and substantial summary relevant to the topic, recognizing new directions and gaps that can be explored and analyzed.

[11] https://www.eorc.jaxa.jp/ALOS/en/dataset/dataset_index.htm.

[12] http://en.alos-pasco.com/.

[13] https://xview2.org/dataset.

[14] https://github.com/gistairc/ABCDdataset.

[15] https://www.planet.com/disasterdata.

[16] http://step.esa.int/main/.

5 Conclusions and inferences

Natural hazards have always garnered attention among various categories of scientists. Among the people and the government, its unpredictability has raised many questions. This paper discusses several scientific fields or subject areas where the tsunami had an indirect or direct impact. Such a contribution is unique. These impacted areas are focused in the form of a storyline concerning how things have progressed in the last fifteen years through top-cited papers and most talked keywords extracted from the two bibliographic databases. The main contributions and conclusions reached by this article are as follows:

5.1 What is new in this article?

While there have been previous documents on bibliometric tsunami analysis, this is a first attempt to demonstrate a one-stop simultaneous coverage of 15 years in this field with all and most of the subjects researched and related. This article can be an archive to understand the story of the tsunami of the last 15 years.

5.2 Directions to multidisciplinary research

As recently indicated, there is a dire need for interdisciplinary research to combine sources and results between various subject areas. For common welfare and goals, ecologists, sedimentologists, communists, physicists, seismologists, and geologists aspire to work symbiotically.

5.3 Bibliometric inferences

This paper summarizes the essential publications that have published tsunami-related documents for researchers. A list of the most active authors, top-cited documents, and most indexed keywords is also available. These contributions offer an index-key pair from any of the essential tools to understand any domain.

5.4 Public and latest research

Through this analysis, concerning different related topics, we have captured the inherent storyline followed by specific definitive open research problems.

5.5 Available Datasets

This paper lists twelve available data sources datasets being used by the scientific community in social science, geology, and seismic records that can be used by the academic community for more insights.

5.6 2018–2020 what is the trend?

Much of the last 2-year documents have focused on finding the source and simulating the presence of Indonesia's Palu tsunami in 2018. There has been a shift in the convergence of machine learning and deep learning with geophysics and sedimentology. The Palu tsunami has been identified as a non-seismic one and needs greater and enhanced community preparedness with much-evolved alert systems.

This study's limitations are that 15-year data also includes documents of an earthquake, landslides, and volcanic eruptions. Those, as mentioned above, are also sources of a tsunami. Nevertheless, effect and source simulations are identical, although there are differences in some variables. Therefore, by adding more databases like Google Scholar and discovering ways to segregate effectively, well-deep research can be analyzed and discussed.

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