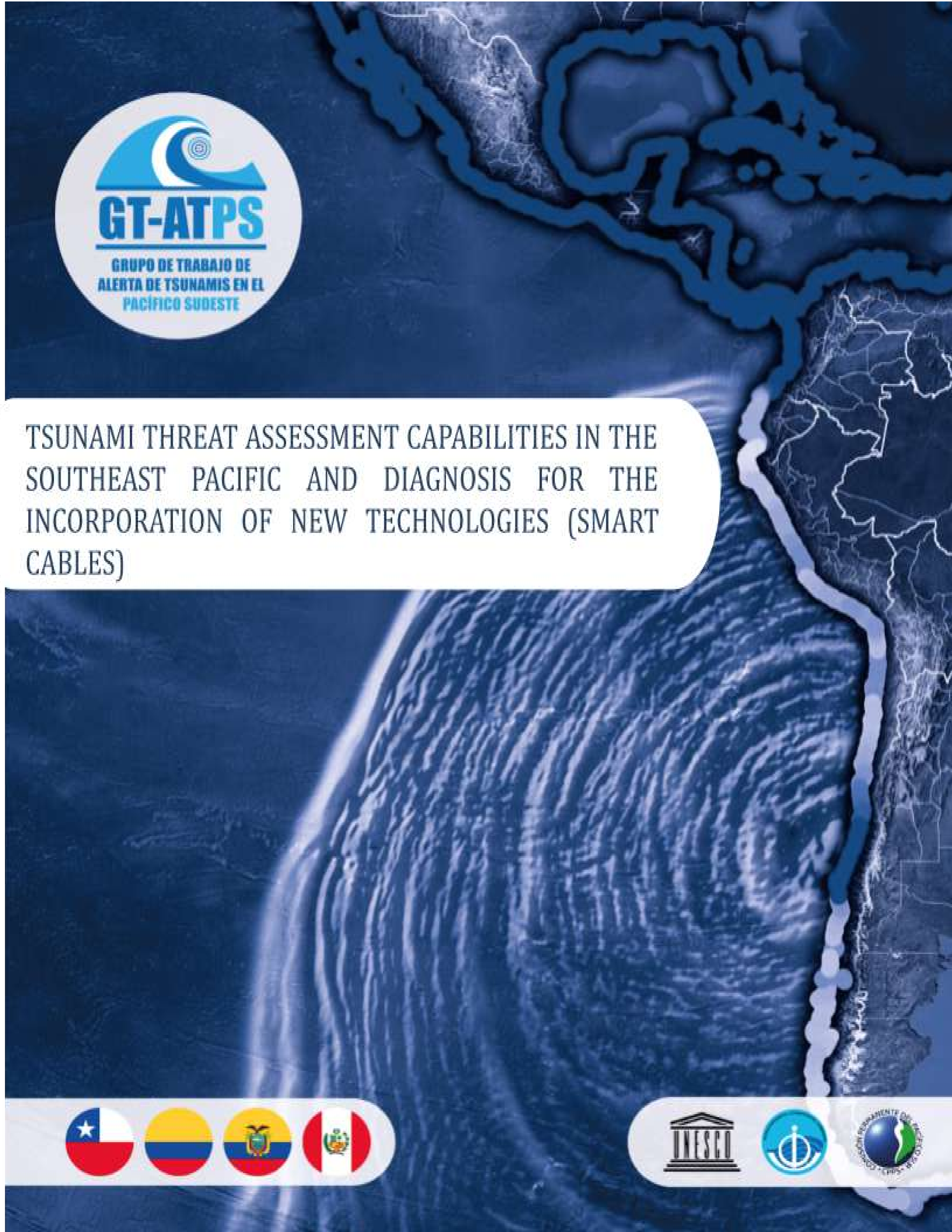

GT-ATPS

GRUPO DE TRABAJO DE
ALERTA DE TSUNAMIS EN EL
PACÍFICO SUDESTE

TSUNAMI THREAT ASSESSMENT CAPABILITIES IN THE SOUTHEAST PACIFIC AND DIAGNOSIS FOR THE INCORPORATION OF NEW TECHNOLOGIES (SMART CABLES)

UNESCO

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1. Seismic and sea level capabilities in the south-east pacific region for tsunami detection and warning

1.1. Chile

1.1.1. Seismological Network

The National Seismic Network (NSN) consist in a group of seismological multiparametric stations located in the national territory, a communication system capable of transmitting all the data to the datacenter for acquisition, archive, analyze and distribution of seismic information at the National Seismological Center (CSN). A station is called multiparametric because it's composed of sensors and systems for ground motion acquisition such as:

1. Speed (broadband seismograph)
2. Acceleration (accelerographs)
3. Position (GNSS, Global Navigation Satellite System)

The Seismological Network nowadays consists of 110 seismographs from north to south and east to west, including new GNSS stations in the Chilean Antarctic Territory. There are sensors at the coast and at inner territory, for example in cities at the foot of the Andes Mountains.

Additionally, the Accelerograph Network has instrument for measuring the acceleration of the ground. The main purpose is to study the behavior of the ground in order to improve the regulations for earthquake-resistant construction (in the medium and long term). Therefore, the stations installed in the main cities of the country and those places where infrastructure is appropriate for their location. Currently, the network has 94 accelerographs. The last component is the Geodesic Network which has 121 GNSS devices.

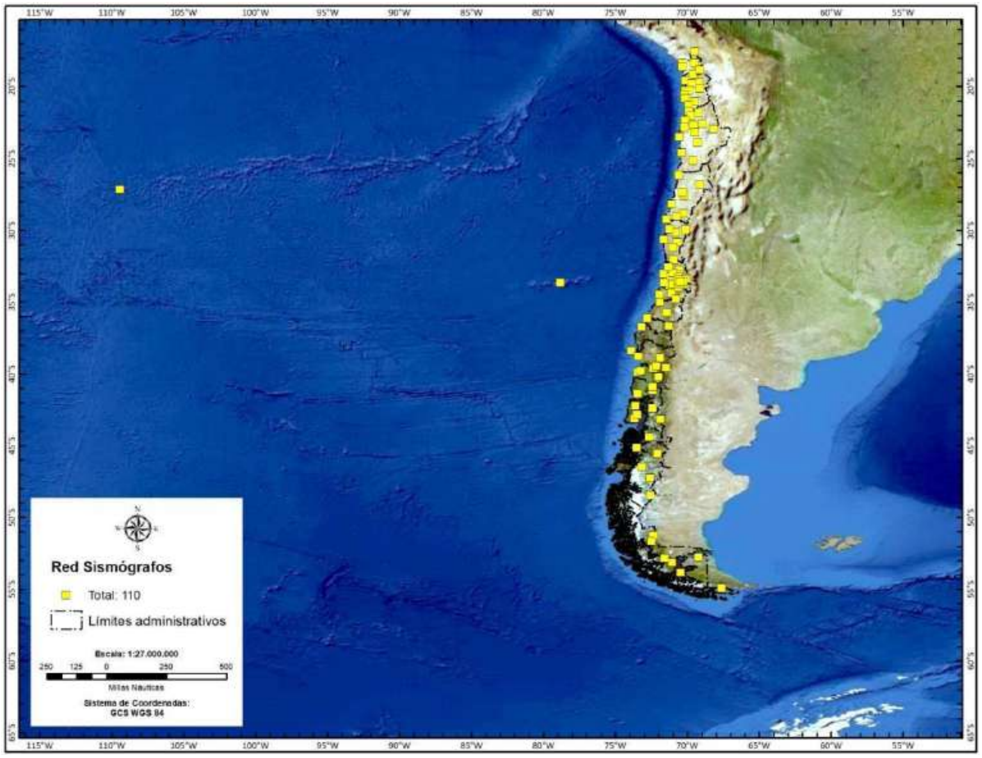


Figure 1. Geographical location of the 94 seismographs of CSN. Source: CSN.

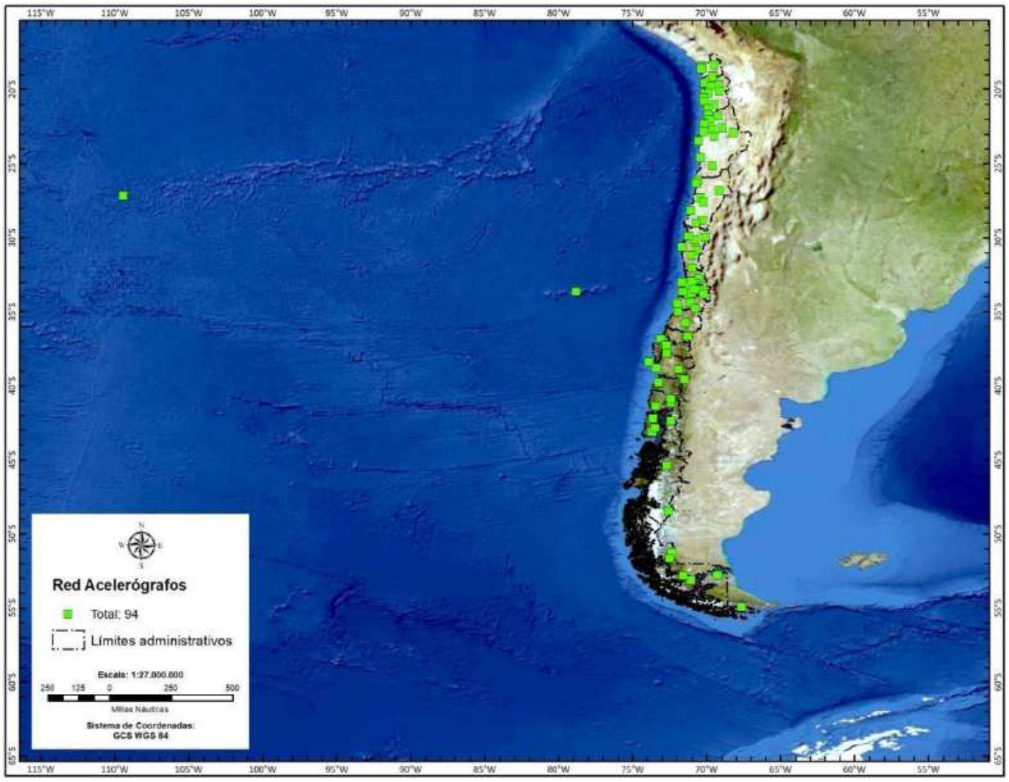


Figure 2. Geographical location for the 94 accelerographs of CSN. Source: CSN.

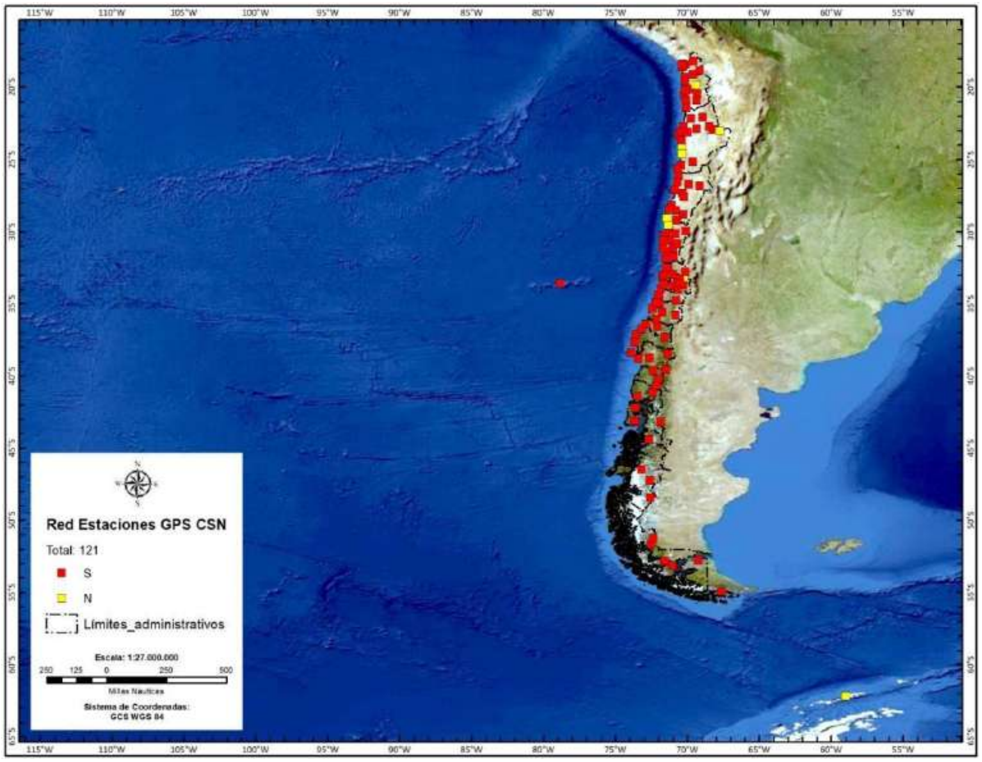


Figure 3. Geographical location for the 121 GNSS of CSN. Source: CSN.

The NSN includes stations of the former Seismological Service of the University of Chile, and new stations donated by the National Service for Prevention and Response to Disasters (SENAPRED) to which they're incorporating GNSS devices. The CSN also receives the data from networks installed and supported by foreign entities, with financial support from project-based research funding.

The data measured by the seismological stations are transmitted in real time, through different telecommunications systems, including a subset of stations with satellite connection, to the datacenter where they receive, analyze, store and distribute to different users.

The Process and Analyze Office (OPA) is responsible for the estimation of hypocenter parameters (latitude, longitude, source depth and origin time). This information is delivered by different means to the Hydrographic and Oceanographic Service of the Chilean Navy (SHOA), for the timely evaluation of the tsunami threat and to the SENAPRED the National Disaster Management Office (NDMO) in Chile. This information is delivered for a regular case scenario within 5 minutes of the occurrence of the event. For this purpose, there are national protocols, standard operating procedures (SOP) and a robust system composed by different means of communication with high levels of redundancy to transmit this information.

1.1.2. Sea Level Network for detection and monitoring of Tsunamis

1.1.2.1. DART System

Near the coast of Chile there are five Deep-ocean Assessment and Reporting of Tsunamis (DART) Systems deployed, which are managed by the National Oceanic and Atmospheric Administration (NOAA) and maintained by SHOA.

There are two second generation (DART II) installed 180 NM west of Iquique and 180 NM west of Caldera respectively and three fourth generation (DART 4G): 91 NM west of Antofagasta, 120 NM northwest of Valparaíso and 119 NM northwest of Concepción.

The main differences between both DART standards are data processing speed and ability to differentiate between a seismic and tsunami wave. The DART Systems in Chile are installed west of the Perú-Chile Trench with the DART 4G located closer to the subduction zone.

1.1.2.2. Sea Level Station Network:

Since 1944 sea level observations are managed in Chile, initially with analog instrumental. The technological development allowed the use of digital data collection platforms with the capacity to integrate different oceanographic and meteorological sensors. Since 1999 the transmission system improved through satellite communication equipment.

The Sea Level Station Network is composed by 48 digital platforms Vaisala MAWS 110 installed in the Coast of Chile, Lake Villarrica, insular territory and the Chilean Antarctic Territory, allowing the monitoring of the propagation and evolution of a Tsunami in an efficient and timely manner.

The whole network has redundancy for the sensors and transmission. The primary channel is always a satellite transmission through BGAN-Inmarsat or GOES with a frequency of 1 minute and the secondary channel can be GPRS (cellphone network) or another satellite channel with a frequency of 5 minutes for locations close to urbanized zones and 10 to 15 minutes in interior waters where the tsunami threat is minor, for example in the fiords.

STATION	POWER SOURCE		TELEMETRY		SENSOR	
	PRIMARY	SECONDARY	PRIMARY	SECONDARY	PRIMARY	SECONDARY

ARICA	BATTERY SOLAR PANEL	22OV	GOES	GPRS	DRUCK	RADAR
PISAGUA	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
IQUIQUE	BATTERY SOLAR PANEL	220V	GOES	GPRS	DRUCK	RADAR
PATACHE	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
TOCOPILLA	BATTERY SOLAR PANEL	220V	BGAN	GPRS	DRUCK	RADAR
MEJILLONES	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
ANTOFAGASTA	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
PAPOSO	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
TALTAL	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
CHAÑARAL	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
CALDERA	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
HUASCO	BATTERY SOLAR PANEL	BATTERY BGAN	BGAN	GPRS	DRUCK	RADAR
PUNTA DE CHOROS	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
COQUIMBO	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR

PUERTO ALDEA	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
PICHIDANGUI	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
QUINTERO	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
VALPARAÍSO	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
SAN ANTONIO	BATTERY SOLAR PANEL	220V	GOES	GPRS	DRUCK	RADAR
CONSTITUCIÓN	BATTERY SOLAR PANEL	-	GOES	GPRS	RADAR	RADAR
COLIUMO	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
ISLA QUIRIQUINA	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
TALCAHUANO	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
CORONEL	BATTERY SOLAR PANEL	220V	GOES	GPRS	DRUCK	RADAR
LEBU	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
NEHUENTUÉ	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	DRUCK
VILLARRICA	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
QUEULE	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR

CORRAL	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
BAHÍA MANSA	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
PUERTO MONTT	BATTERY SOLAR PANEL	-	GOES	GPRS	RADAR	RADAR
ANCUD	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
CASTRO	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
MELINKA	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
PUERTO AGUIRRE	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
PUERTO CHACABUCO	BATTERY SOLAR PANEL	220V	GOES	GPRS	DRUCK	RADAR
PUERTO EDÉN	BATTERY SOLAR PANEL	220V	GOES	GPRS	DRUCK	RADAR
CALETA METEORO	BATTERY SOLAR PANEL	220V	GOES	BGAN	DRUCK	DRUCK
PUNTA ARENAS	BATTERY SOLAR PANEL	220V	GOES	GPRS	DRUCK	RADAR
BAHÍA GREGORIO	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
PUERTO WILLIAMS	BATTERY SOLAR PANEL	220V	GOES	GPRS	DRUCK	RADAR
BASE PRAT	BATTERY SOLAR PANEL	220V	GOES	BGAN	DRUCK	DRUCK

BASE O'HIGGINS	BATTERY SOLAR PANEL	220V	GOES	BGAN	DRUCK	DRUCK
SAN FÉLIX	BATTERY SOLAR PANEL	BATTERY	GOES	BGAN	DRUCK	RADAR
JUAN FERNANDEZ	BATTERY SOLAR PANEL	-	GOES	GPRS	DRUCK	RADAR
ISLA DE PASCUA	BATTERY SOLAR PANEL	220V	GOES	GPRS	DRUCK	RADAR

Table 1. Configuration of Sea Level Station in Chile. Source: SHOA.

To ensure the operation of the SLS in the event of a major seismic event or the effects of a tsunami, the need to maintain their operability was developed to obtain the information required for decision-making, determining that it was essential to ensure their autonomy; installing robust and redundant platforms with power supply; sensors for measuring sea level and data transmission, considering the following criteria:

- **Telemetry:** All Maws 110 platforms have a dual transmission system, the main one being satellite and a secondary one that can be via GPRS cell phone messages and in some cases, there is a second satellite transmission system as there is no cellular signal available.

  In most of the stations, the main telemetry is a GOES satellite transmitter, which operates with a speed of 300 bps, compatible with the requirements of the NESDIS (National Environmental Satellite Data and Information Service) -, of the NOAA (for its acronym in English: National Oceanic and Atmospheric Administration). These stations use transmission via GPRS as a secondary system.

  A smaller group of stations uses the INMARSAT-BGAN satellite system, with antennas for HUGHES 9502 devices. Similarly, these stations have GPRS messaging as a secondary transmission system.

  Finally, there is a third group of stations that uses the two satellite systems: GOES and BGAN, in places where cellular network is not available.

- **Sea level sensors:** Given the importance of measuring the sea level, each station has two independent sensors for this. The first corresponds to a relative pressure transmitter gauge of the water column which is installed submerged at a depth around two meters under local sounding datum. The second sensor is positioned above the highest expected sea level including the wave contribution, and operates on radar waves emitting pulses which are reflected by the sea surface and received by the transducer of the radar sensor.

There are certain locations that doesn't allow a combination of radar and pressure sensor, so they have either two radars or two pressure gauges, for example Constitución where the local coastal dynamic produces siltation or Puerto Montt where the structure of the dock doesn't allow for pressure sensors because of the high tidal range.

- **Power source supply:** The platforms MAWS 110 have three power sources for their operation; solar panel of 55 W / 15 V with an AC/DC adapter; 220 V grid supply, and a power bank 12 V / 55 Ah.

  The stations with BGAN-Inmarsat, require a 220 V supply because of the high power consumption, for remote locations without power grid it is considered the installation of a second power bank only for BGAN devices.

- **Structure:** The stations uses an H-Type body structure fixed to the dock usually in concrete. In turn, for the installation of the submerged sensors they use hydraulic PVC and galvanized steel tubes, anchored to piles or the wall of the dock with anchors bolts, clamps and stainless steel belts according to the conditions of each location.

  The use of modern instrumental and suitable densification of stations, has enabled a multipurpose network for operational and scientific purposes, especially for the National Tsunami Warning System.

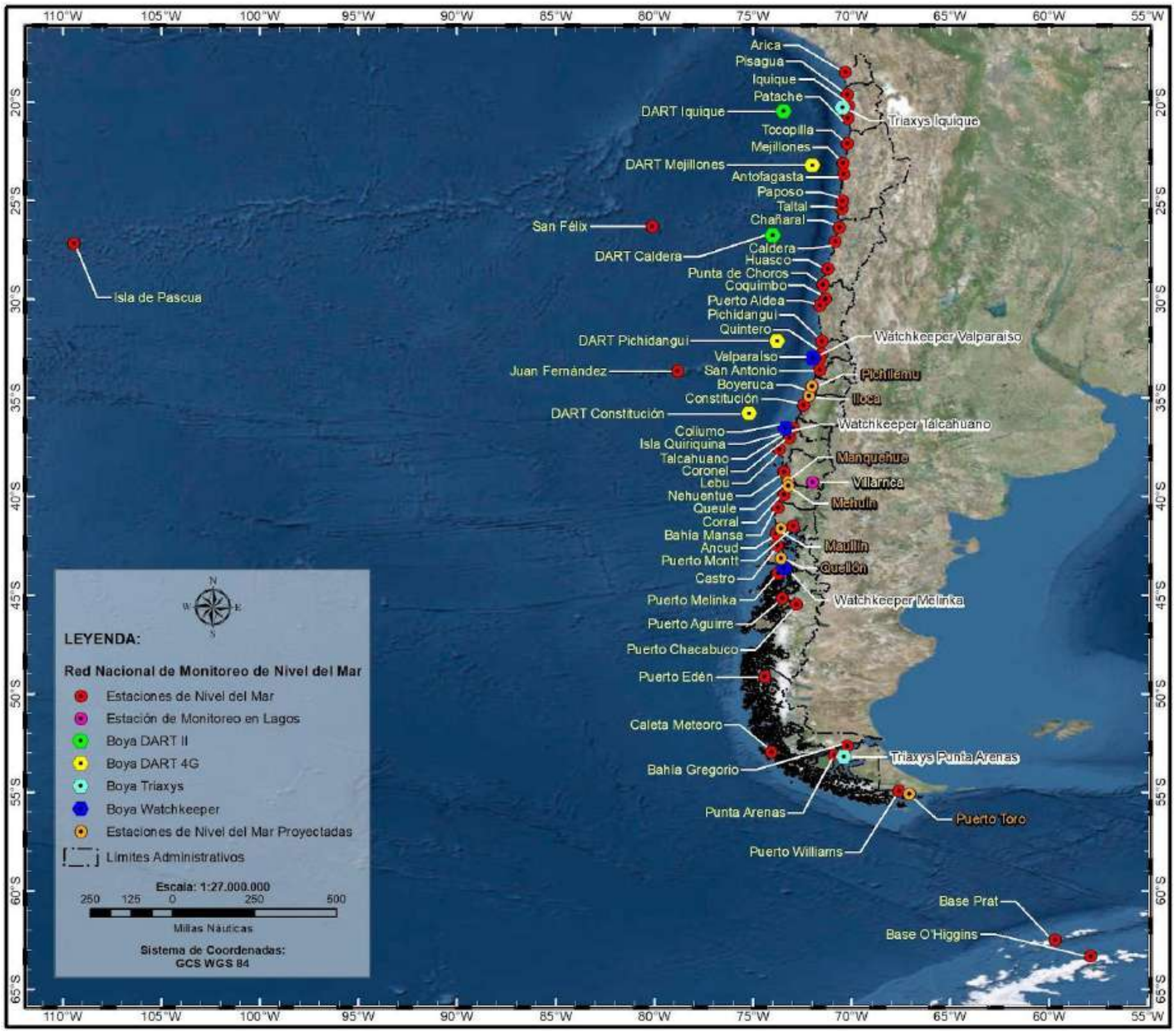


Figure 4. Chilean Sea Level Network for detection and monitoring of Tsunamis. Source: SHOA.

1.2. Colombia

1.2.1. Seismological Network

The National Seismological Network of Colombia - RSNC, belonging to the Colombian Geological Service - SGC, began its operation in 1993 as an official entity in charge of recording and instrumentally monitoring the seismicity of the Colombian territory, in addition to informing the National Risk Management System and the population.

Initially, the RSNC had 12 short-period (SP) seismological stations. By 2021, it has 59 seismological stations that transmit in real time to the monitoring room located in Bogotá. Within its stations it has: 50 broadband stations (BB) and 9 short period (SP).

The growth of the RSNC has resulted not only in greater reliability in the reported information, but also in a more complete seismicity database with better quality standards. That information is the input to increase knowledge about the country's seismic hazard and for high-impact research in the area of geohazards and geosciences in general.

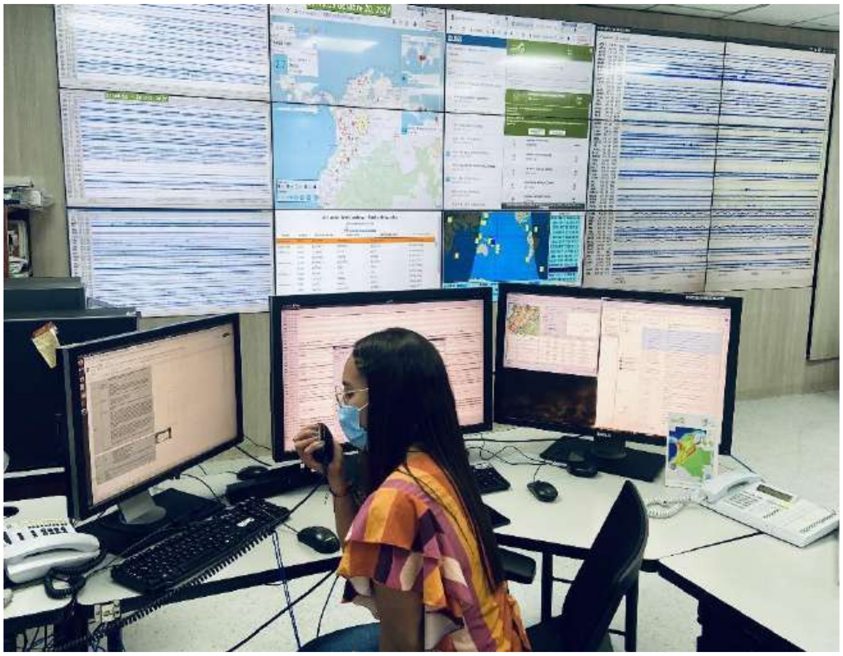


Figure 5. RSNC Monitoring Center in Bogotá. source: SGC.

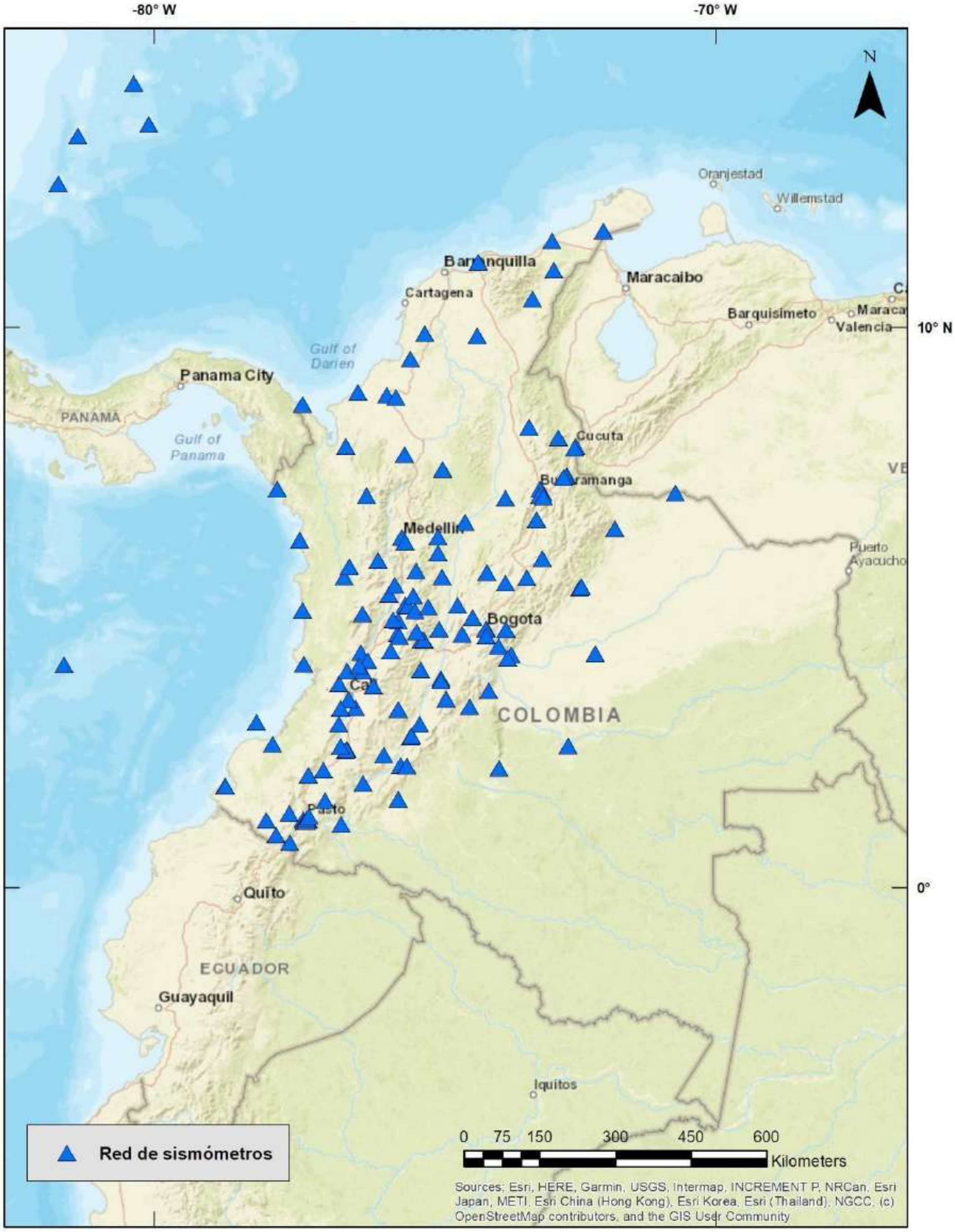


Figure 6. Location of 59 permanent seismological stations for RSNC. Source: SGC.

Figure 7. Satellital seismological station. Source: SGC.

Figure 8. Real time seismological equipment. Source: SGC.

- **Acelerographic network**

  The National Network of Accelerographs of Colombia - RNAC began operations in 1993, with 16 stations, by 2021 it has 127 accelerograph stations: 64 download stations and 63 remote connection stations.

  The main purpose of creating this network is to provide useful information for building construction and design standards, for example, for updating and improving the description of seismic wave attenuation effects in the national territory. These studies are prepared in order to reduce the risk of loss of life and affectation of the infrastructure.

On the other hand, the information recorded by the stations in real time helps to improve the locations of earthquakes that occur in the national territory and is also used for seismic source studies. On the other hand, portable stations are used to carry out seismic microzoning studies in densely populated regions.

Figure 9. Real time seismological monitoring equipment. Source: SGC.

Figure 10. Acelerographers equipment. Soutce: SGC.

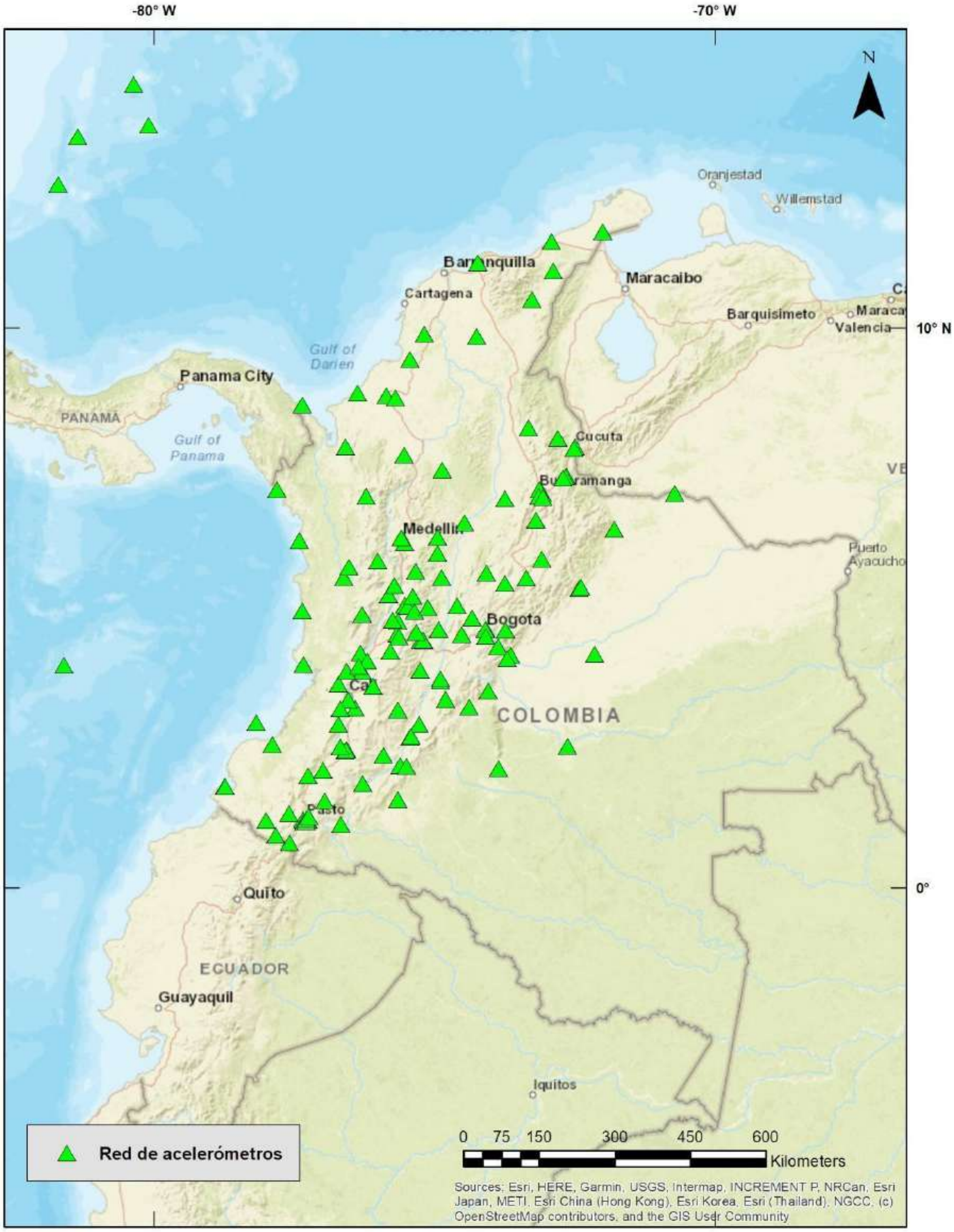


Figure 11. Location of 124 acelerographers of RSNC. Source: SGC.

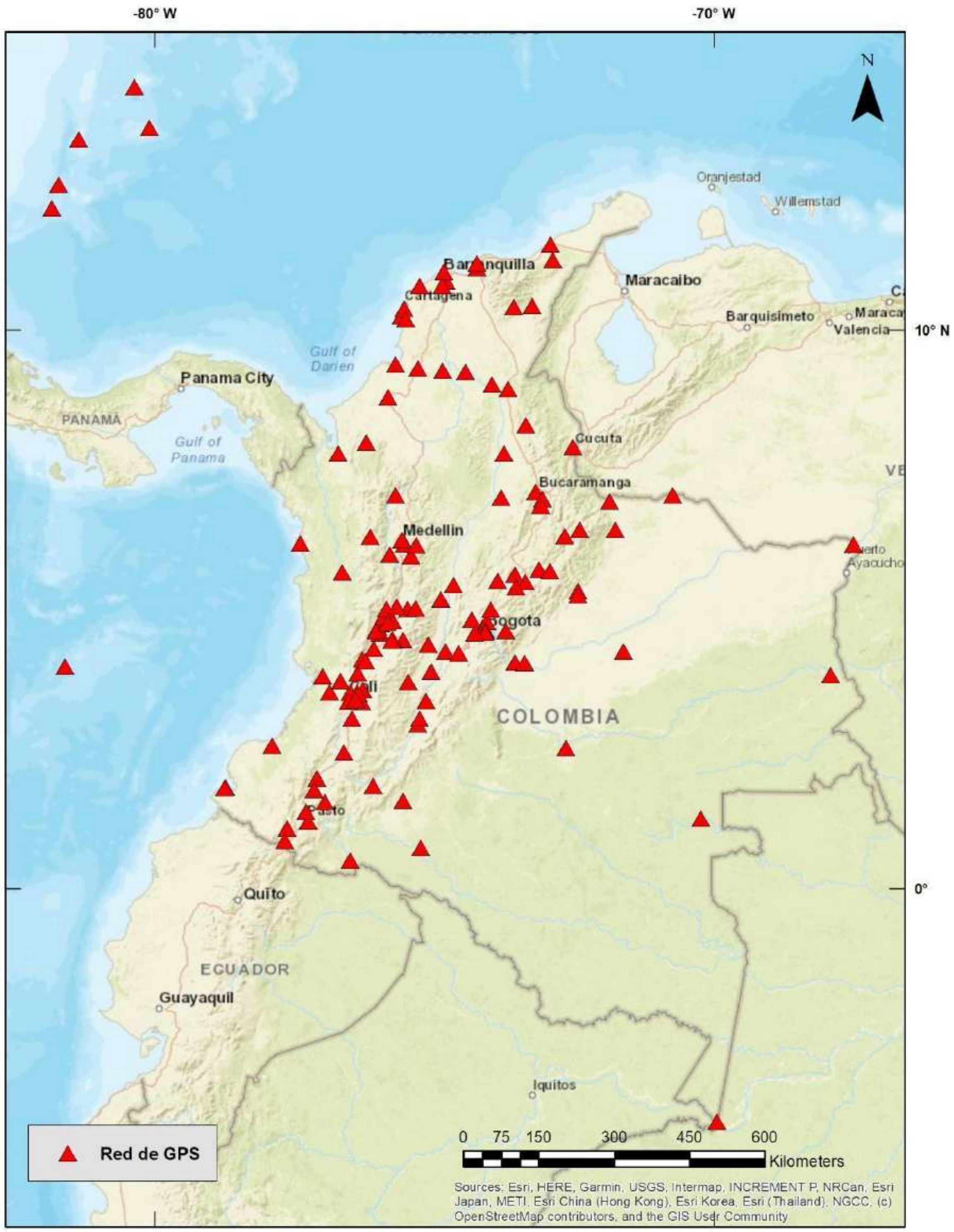
- **Geodetic Network and GeoRED deformation studies**

GeoRED is the name adopted for the project "Implementation of the National Network of GPS Satellite Geodetic Stations for geodynamic purposes", its name is also derived from the contraction of "Geodesy: network of deformation studies" which represents the specific application in the study and analysis of the deformation of the earth's crust in Colombia (Mora, 2006).

The instrumentation-based GeoRED research and development project began its operation at the Colombian Geological Service - SGC in 2007, under the framework of the Geothreats Technical Department, as a result of considerations of technical, scientific, social, economic and political relevance.

By 2021, the GeoRED project has 131 installed stations that make up the national high-precision geodetic infrastructure. The project is oriented towards geosciences, with geodynamic purposes, for the study of natural phenomena such as earthquakes, volcanic eruptions, mass movements, subsidence, and also for atmospheric and ionospheric studies. After more than 24 years, GeoRED continues to grow, and currently operates and supplies continuous data to the national and international geodetic community for the development of geodynamic investigations and reference frame definition.

Figure 12. GPS stations installed in Colombia. Source: SGC.



Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c) OpenStreetMap contributors, and the GIS User Community

Figure 13. Location of 131 GPS stations of GeoRED. Source:SGC.

1.2.2. Sea Level Network for detection and monitoring of Tsunamis

For tsunamis detection and monitoring, the General Maritime Directorate - DIMAR has six OTT brand sea level stations on the Pacific coast, which work with radar sensors, with transmission through Radio Package Service (GPRS for its acronym in English) and by satellite communication with a time window of 5 minutes through the NOAA GOES satellite.

Additionally, DIMAR deployed in 2014 a tsunami detection system located 73 NM off the coast of Tumaco, integrating a Sonardyne brand BPR depth sensor anchored at a depth of 2700 meters, which transmits acoustically the pressure data from the water column to the surface buoy and then the data is send via IRIDIUM satellite communication to a server at the National Tsunami Warning Center in the city of Bogotá.

Station Location	LATITUDE	LONGITUDE	SENSOR
Bahía Málaga	3°58' 21" N	77°19' 39" W	2 sensores OTT Radar
Bahía Solano	06°13'58,36"N	77°24'43,68"W	1 sensor OTT Radar
Buenaventura	3º53'31,2"N	77°4'44,4"W	1 sensor OTT Burbujero y 1 sensor OTT Radar
Juanchaco	03°54'54,36"N	77°21'32,7"W	2 sensores OTT Radar
Malpelo	04˚00'33“N	81°36’33“W	2 sensores OTT Radar
Tumaco	01˚49'12"N	78˚43'43,32"W	1 sensor OTT Radar
73 MN de la costa de Tumaco	2.986	-79.074	Sonardyne BPR

Table 2. Sea level monitoring network. Source: DIMAR

Figure 14. Sea level monitoring network location. Source: DIMAR.

1.3. Ecuador

1.3.1. Seismological Network

Ecuador has a seismic network that has been strengthened through inter-institutional projects improving monitoring capacity at the national level. The National Network of Seismographs - RENSIG began its installation at the end of the 1970s and has been densified through inter-institutional projects at the national and international level, allowing the increase in the number of these stations, as well as the implementation of new seismic technology and optimization of the network in the coastal margin from the province of Esmeraldas (northern sector of Ecuador) to El Oro (southern sector of Ecuador). At present, this network has sixty-five (65) seismographic stations distributed throughout the Ecuadorian territory as shown in Figure 15 and whose characteristics are shown in Table 3.

It is necessary to mention that in some points of the stations have been installed accelerograph sensors belonging to the National Network of Accelerographs - RENAC and also the Very Strong Motion - VSM sensors, which are seismic sensors that allow covering a wide range of frequencies (seismic waves).

Code	Latitude	Longitude	Network	Datalogger model	Sensor model

CABP	-0.39	-80.43	RENSIG - RENAC	Agecodagis KEPHREN	CMG-3ESP
HSPR	-0.35	-78.85	RENSIG - RENAC	Agecodagis KEPHREN	CMG-3ESP
LGCB	0.38	-79.58	RENSIG - RENAC	Agecodagis KEPHREN	CMG-3ESP
PDNS	0.11	-79.99	RENSIG - RENAC	Agecodagis KEPHREN	CMG-3ESP
LITA	0.79	-78.36	RENSIG	Reftek130-01	eentec
URCU	0.44	-78.26	RENSIG	Q330S	FBS-3A
YAHU	0.37	-78.07	RENSIG	Q330S	FBS-3A
IGUA	-1.49	-78.64	RENSIG	VCO analogic	L4C-1D
PAST	-0.70	-78.65	RENSIG	VCO analogic	L4C-1D
PITA	-0.56	-78.43	RENSIG-ROVIG	Reftek130-01	L4C-1D
MAG1	-0.07	-79.77	RENSIG	VCO analogic	L4C-1DC
CHIS	-1.05	-80.73	RENSIG	Reftek130-01	L4C-3D
JAMA	-0.27	-80.21	RENSIG	Reftek130-01	L4C-3D
PECV	-0.78	-80.38	RENSIG	VCO analogic	L4C-3D
OTAV	0.24	-78.45	IRIS	múltiple	múltiple
PAGY	-0.67	-90.29	IRIS	múltiple	múltiple
ELAR	-1.05	-80.83	RENSIG - RENAC	Reftek151_120	reftek151-120
ESM1	1.10	-79.16	RENSIG - RENAC	Reftek151_120	reftek151-120
MOMP	0.50	-80.02	RENSIG - RENAC	Reftek151_120	reftek151-120
SFCO	0.66	-80.06	RENSIG - RENAC	Reftek151_120	reftek151-120
ALAU	-2.16	-78.85	RENSIG	Q330S	trilliumcompac
ARDO	-0.99	-77.80	RENSIG	Q330S	trilliumcompac
ARNL	-3.55	-80.07	RENSIG - RENAC	Q330S	trilliumcompac
AUCA	-0.55	-76.90	RENSIG	Q330S	trilliumcompac
BALZ	-1.38	-79.91	RENSIG - RENAC	Q330S	trilliumcompac
BIBL	-2.76	-78.89	RENSIG	Q330S	trilliumcompac
CASC	0.14	-77.34	RENSIG	Q330S	trilliumcompac
GONZ	-4.24	-79.39	RENSIG	Q330S	trilliumcompac
ISPG	-2.97	-80.17	RENSIG - RENAC	Q330S	trilliumcompac
JSCH	-1.72	-78.98	RENSIG	Q330S	trilliumcompac
MILO	-2.28	-79.56	RENSIG	Q330S	trilliumcompac
MONB	-1.77	-79.20	RENSIG	Q330S	trilliumcompac
MORR	-2.64	-80.34	RENSIG	Q330S	trilliumcompac
PAC1	0.27	-78.79	RENSIG	Q330S	trilliumcompac
PIS1	-1.06	-78.39	RENSIG	Q330S	trilliumcompac
PKYU	-1.65	-77.60	RENSIG	Q330S	trilliumcompac
PUYO	-1.49	-78.02	RENSIG	Q330S	trilliumcompac

QUEV	-1.04	-79.30	RENSIG	Q330S	trilliumcompac
SAGO	-1.15	-78.67	RENSIG	Q330S	trilliumcompac
SALI	-2.19	-80.99	RENSIG - RENAC	Q330HRS	trilliumcompac
SEVS	-1.01	-80.05	RENSIG - RENAC	Reftek130-01	trilliumcompac
TAMH	-1.55	-78.78	RENSIG-ROVIG	Q330S	trilliumcompac
TAIS	-2.38	-77.50	RENSIG	Q330S	trilliumcompac
TULM	0.72	-77.79	RENSIG	Q330S	trilliumcompac
VCES	-0.80	-78.39	RENSIG	Q330S	trilliumcompac
YANT	-3.86	-78.76	RENSIG	Q330S	trilliumcompac
ANTC	-0.42	-78.02	RENSIG	Q330HRS	trillium120p
BONI	0.45	-77.53	RENSIG - RENAC	Q330HRS	trillium120p
BOSC	-3.15	-78.50	RENSIG - RENAC	Q330HRS	trillium120p
BV15	0.16	-79.22	RENSIG-RENAC-OCP	Reftek130-01	trillium120p
COHC	-2.47	-79.26	RENSIG	Q330HRS	trililum120p+VSM
CSOL	-1.66	-80.45	RENSIG	Q330HRS	trililum120p
FLF1	-0.36	-79.84	RENSIG	Q330HRS	trililum120p+VSM
GYEB	-2.14	-80.09	RENSIG - RENAC	Q330HRS	trililum120p
ISPT	-1.26	-81.07	RENSIG - RENAC	Reftek130	trillium120p
JIPI	-1.36	-80.56	RENSIG	Q330HRS	trillium120p
LAMO	-4.01	-80.02	RENSIG	Q330HRS	trillium120p
MCRA	-4.37	-79.95	RENSIG	Q330HRS	trillium120p+VSM
ONHA	-3.48	-79.16	RENSIG - RENAC	Q330HRS	trillium120p
PIAT	-0.98	-78.26	RENSIG	Q330HRS	trillium120p+VSM
PPLP	-1.55	-80.78	RENSIG	Q330HRS	trillium120p+VSM
PTGL	0.78	-80.03	RENSIG - RENAC	Q330HRS	trillium120p
RVRD	1.07	-79.39	RENSIG - RENAC	Q330HRS	trillium120p
SNLR	1.29		RENSIG	Q330HRS	trillium120p+VSM
ZUMB	-4.86		RENSIG - RENAC	Q330HRS	trillium120p

Table 3. Detail of the characteristics of the RENSIG.

Since 2006, the Instituto Geofísico de la Escuela Politécnica Nacional implemented the National Geodesy Network - RENGEO. Currently, RENGEO has 85 permanent stations of which 30 are in potentially active volcanoes, along the Ecuadorian territory as shown in Figure 16. The data generated are sent to the monitoring center through different means of transmission such as radio, internet, microwave, and satellite systems.

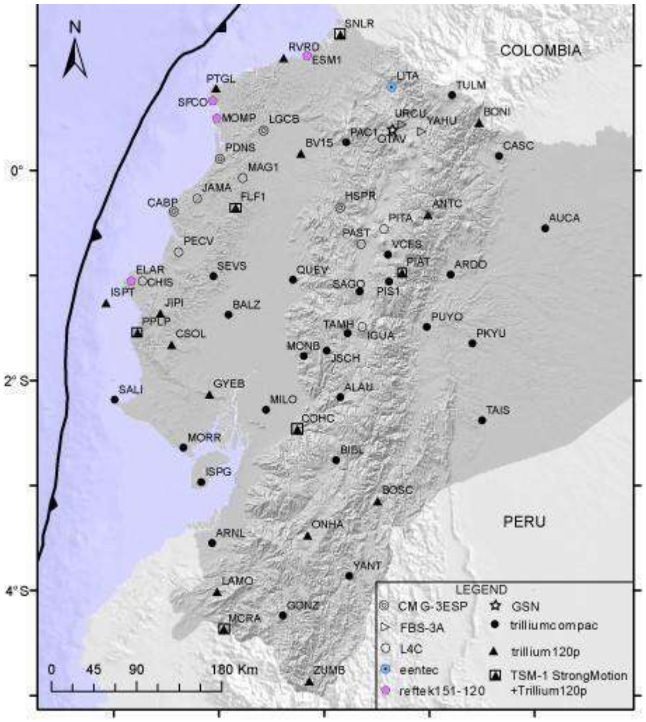


Figure 15. Distribution of the stations of the National Seismic Network Instituto Geofísico- Escuela Politécnica Nacional - RENSIG. Source: IGEPN, 2020

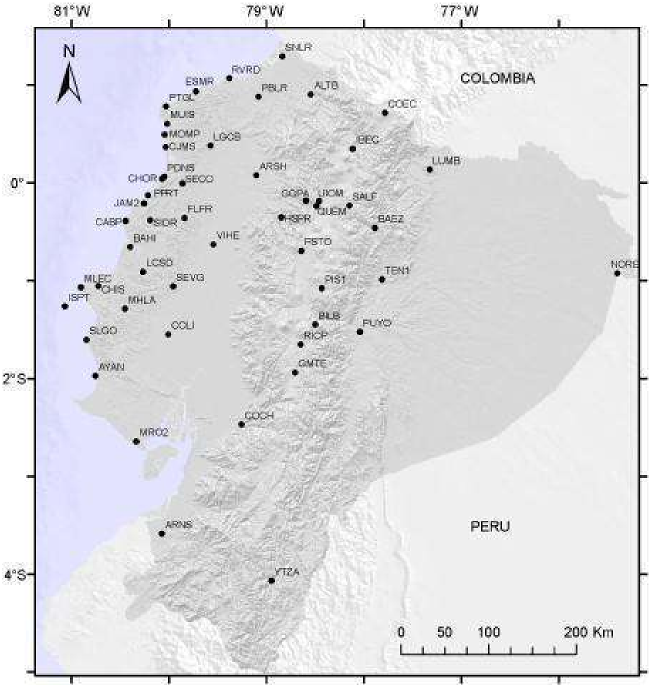


Figure 16. Distribution of geodesy network stations for tectonic deformation monitoring. Source: IGEPN, 2020.

The fundamental axis of data transmission from the various points of the national territory to the data interpretation center is the network of repeaters of the Geophysical Institute REPET. The network connects the remote stations with the data center using different types of technology, depending mainly on the location of the instruments and the type of stations to be connected. REPET includes satellite communication, microwave links, optic fiber, digital radio links, analog radio links and GSM communication. REPET is the real time support base for surveillance with the different monitoring networks. This network is made up of analog, digital, satellite, microwave, and communications networks (digital voice coverage network).

The seismic network has been strengthened along the Ecuadorian coast. These sensors, which are part of the national network and contribute to the investigations of the Ecuadorian coastal margin from the north in Esmeraldas to the south in the province of El Oro, correspond to short period, broadband, multi-parametric stations. Their distribution is shown in Figure 17, while their characteristics can be seen in Table 4.

Code	Latitude	Longitude	Network	Datalogger model	Sensor model	Period
CABP	-0.39	-80.43	RENSIG - RENAC	Agecodagis KEPHREN	CMG-3ESP	Triaxial, broadband, GPS and accelerographs. (0.003-50 Hz)
ELAR	-1.05	-80.83	RENSIG - RENAC	Reftek151_120	reftek151-120	Broadband, frequencies 0.0083Hz – 50 Hz
ESM1	1.10	-79.16	RENSIG - RENAC	Reftek151_120	reftek151-120	Broadband, frequencies 0.0083 Hz – 50 Hz.
ISPT	-1.26	-81.07	RENSIG - RENAC	Reftek130	trillium120p	Broadband, GPS and accelerographs
JAMA	-0.27	-80.21	RENSIG	Reftek130-01	L4C-3D	Short period and three-component
MOMP	0.50	-80.02	RENSIG - RENAC	Reftek151_120	reftek151-120	Broadband, frequencies 0.0083Hz – 50 Hz

MORR	-2.64	-80.34	RENSIG	Q330S	trilliumcompac	Broadband
PAYG	-0.67	-90.29	IRIS	multiple	multiple	Broadband
PDNS	0.11	-79.99	RENSIG - RENAC	Agecodagis KEPHREN	CMG-3ESP	Broadband, GPS and accelerographs
PECV	-0.78	-80.38	RENSIG	VCO analogic	L4C-3D	Short period and three-component
PTGL	0.78	-80.03	RENSIG - RENAC	Q330HRS	trillium120p	Broadband, GPS and accelerographs
RVRD	1.07	-79.39	RENSIG - RENAC	Q330HRS	trillium120p	Broadband, GPS and accelerographs
SALI	-2.19	-80.99	RENSIG - RENAC	Q330HRS	trilliumcompac	Short period
SFCO	0.66	-80.06	RENSIG - RENAC	Reftek151_120	reftek151-120	Broadband, frequencies 0.0083Hz – 50 Hz
SNLR	1.29	-78.85	RENSIG	Q330HRS	trillium120p+VSM	Broadband

Table 4. Characteristics of the sensors of the national network located along the Ecuadorian coast.

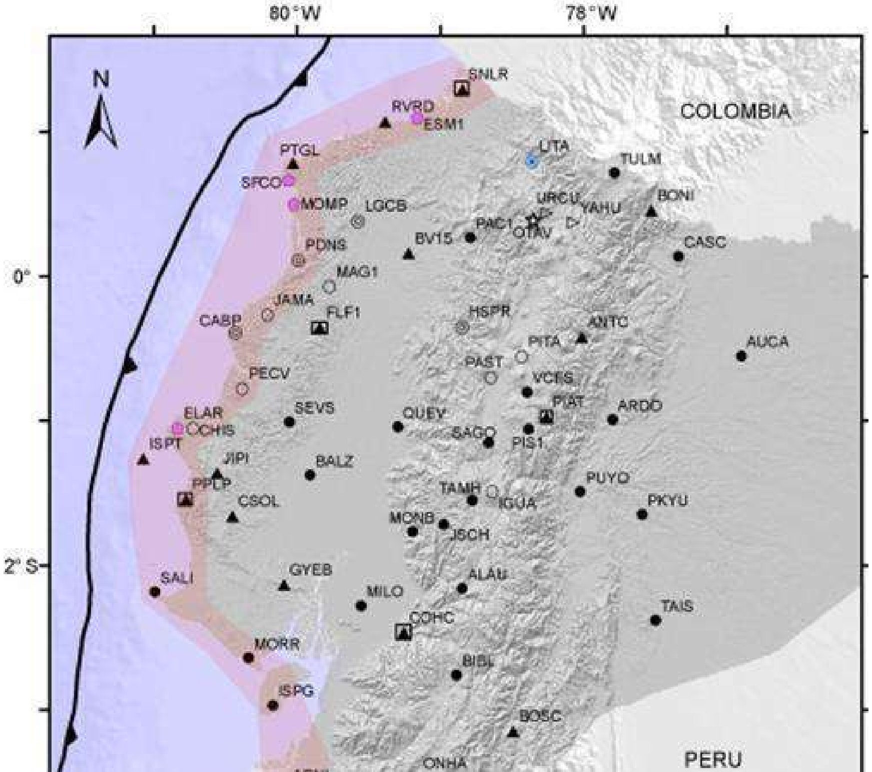


Figure 17. Distribution of the National Seismic Network stations of the Instituto Geofísico- Escuela Politécnica Nacional - RENSIG located along the Ecuadorian coast. Source: IGEPN, 2020.

1.3.2. Sea Level Network for detection and monitoring of Tsunamis

For sea level measurements and tsunami monitoring, Ecuador has a national network of tide gauges and tsunami detection buoys, which is managed by the Oceanographic and Antarctic Institute of the Ecuadorian Navy.

Since 1976, the Oceanographic and Antarctic Institute of the Navy - INOCAR, is part of the Pacific Tsunami Warning System - PTWS and has maintained the study of tsunamis as a permanent program within its activities.

INOCAR is in charge of the operation of the tide stations that make up the national sea level measurement system. The oldest station, with more than 70 years of measurements, is located in the city of La Libertad (Santa Elena province - southern sector), that was installed in 1948.

The national network of tide gauges is located along the Ecuadorian coast and consists of ten (10) stations for measuring sea level, of which seven (7) belong to Inocar and three (3) to the University of Hawaii.

The tide stations are installed in: San Lorenzo and Esmeraldas north coastal sector, both with pressure sensors and GPRS telemetry; Bahía de Caráquez and Manta, in the central sector of the Ecuadorian coast, equipped with a pressure sensor, GPRS telemetry; Río Guayas, Isla Puná and Puerto Bolívar in the southern sector, in the first two locations counter-pulley sensors are installed, while in Puerto Bolívar a pressure sensor has been installed; the three stations are equipped with GPRS telemetry.

The tide stations of the University of Hawaii are located in La Libertad, on the Ecuadorian continental coastal margin, while the other two are installed on the insular coastal margin, on Baltra and Santa Cruz islands. The purpose of these stations is to monitor sea level for tsunami warning, are equipped with three different types of sensors: pressure, radar, and counter-pulley. Added to the network of coastal tide gauges there are two tsunami detection buoys or ocean sensors located 80 NM from Pedernales, an Ecuadorian coastal city located in the northern sector of the country and 65 NM from Manta, one of the main fishing ports and commercials from Ecuador; Manta is located in the northern sector of the coastal margin. The location and characteristics of the entire network can be seen in table 5 and figures 18 and 19.

Station	Latitude	Longitude	Tipo sensor	Recording interval (minutes)	Transmission interval (minutes)	Remarks Operability
San Lorenzo	1.2956	78.8421	SDI-12 SHAFT ENCODER – PRESIÓN GE DRUCK	10	1	Station near the Ecuador - Colombia coastline
Esmeraldas	0.9909	79.6466	PRESIÓN GE DRUCK	10	1	Operative
Bahía de Caráquez	-0.6064	80.4229	SDI-12 SHAFT ENCODER – PRESIÓN GE DRUCK	10	1	Operative
Manta	-0.9396	80.7260	PRESIÓN GE DRUCK	10	N/A	Operative
Isla Puná	-2.7346	79.9119	SDI-12 SHAFT ENCODER	10	1	Operative
Puerto Bolívar	-3.2612	80.0860	SDI-12 SHAFT ENCODER – PRESIÓN GE DRUCK	10	1	Station near the Ecuador-Peru coastline
Guayaquil	-2.1953	79.8798	SDI-12 SHAFT ENCODER	10	1	Operative

La Libertad	-2.2177	-80.9064	Presión Radar Encoder	1 1 5	5	Operative Operative Operative
Baltra –Galápagos	-0.433	-90.283	Presión Radar Encoder	1 1 5	5	Operative Operative Operative
Santa Cruz –Galápagos	-0.752	-90.307	Presión Radar Encoder	1 1 5	5	Operative Operative Operative
Manta	-0.881	-81.664	EBM-24TS	15	180	Operative
Esmeraldas	0.256	-81.216	EBM-24TS	15	180	Operative

Table 5. Stations characteristics detail of the national tide gauge network.

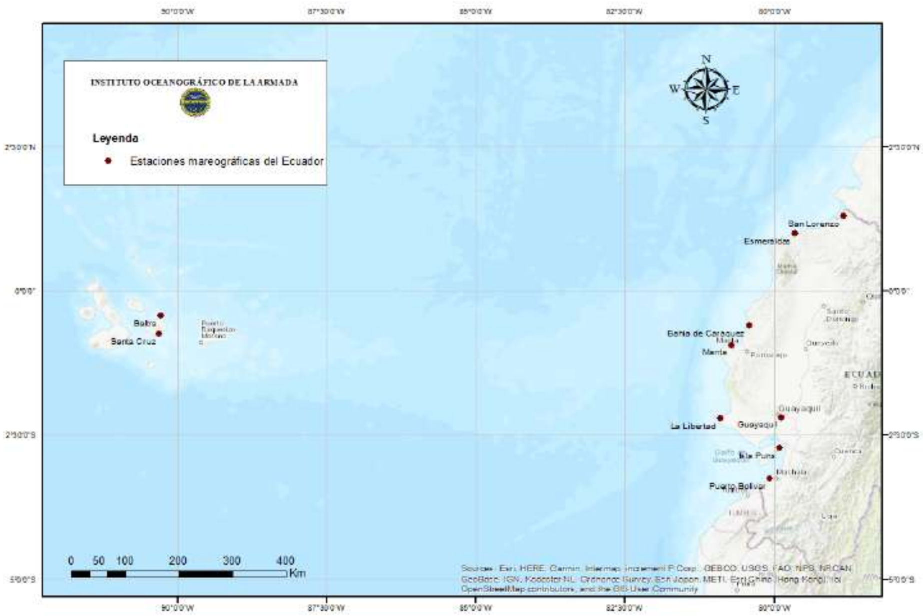


Figure 18. Stations distribution of the tide gauge network along the Ecuadorian continental and insular coasts. Source: INOCAR, 2020.

Figure 19. Distribution of the two tsunami detection buoys off the northern and central Ecuadorian coasts. Source: INOCAR, 2020.

1.4. Perú

1.4.1. Seismic monitoring network

Peru has a total of 62 broadband seismic stations (48 with satellite transmission and 14 with internet transmission), which are managed by the National Seismic Monitoring Center - CENSIS, of the Geophysical Institute of Peru - IGP. In addition, the IGP has implemented the Seismic Satellite Network for Tsunami Early Warning - REDSSAT, consisting of 7 seismic stations and 5 accelerometers that perform the recording, analysis and automatic processing prior to the issuance of the seismic report for tsunami early warning.

The REDSSAT stations are located in the cities of Chiclayo, Toquepala, Yauca, Huancayo, Pucallpa, Iquitos and Puerto Maldonado, as shown in Figure 20.

Figure 20. Distribution of seismic stations managed by the Geophysical Institute of Peru. Source: IGP, 2019.

The Geophysical Institute of Peru has a seismic sensor network covering a large part of the Peruvian territory. The location of these sensors is based on the distribution of the largest localities throughout the territory (Table 6).

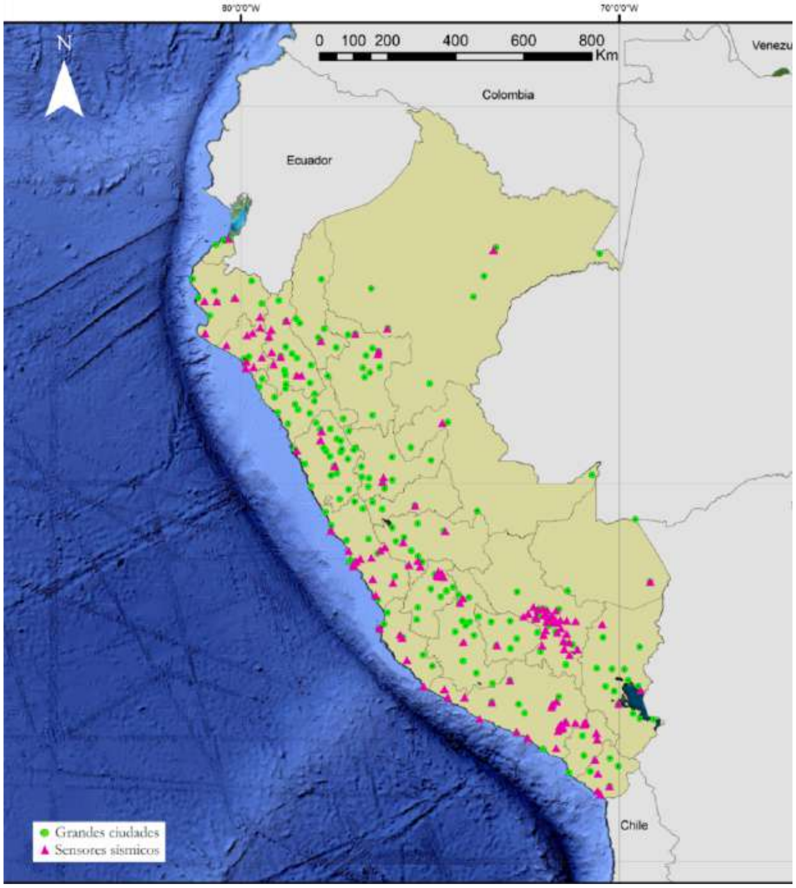


Figure 21. Seismic sensors and geographic location of Peru's great cities (provincial capitals). Source: IGP.

ID	ACRONYM	LATITUDE	LONGITUDE	DISTRICT	DEPARTMENT
1	ACA	-15.4	-74.6	ACARI	AREQUIPA
2	ANC	-11.7	-77.1	ANCON	LIMA
3	AND	-13.6	-71.6	ANDAHUAYLILLAS	CUSCO
4	ARE	-16.4	-71.4	AREQUIPA	AREQUIPA
5	ATH	-7.1	-78.3	ATAHUALPA	CAJAMARCA
6	ATI	-16.2	-73.6	ATICO	AREQUIPA
7	ATP	-12.4	-74.8	ATOCPUNTA	HUANCAYO
8	AUB	-16.3	-70.9	AUBINAS TEMP	
9	AYA	-13.1	-74.2	AYACUCHO	AYACUCHO
10	AYE	-17.0	-71.6	AYANQUERA	AREQUIPA
11	BUB	-16.3	-70.8	BUBINAS TEMP	
12	CAJ	-7.1	-78.5	CAJAMARCA	CAJAMARCA
13	CJM	-15.8	-71.7	CAJAMARCANA	AREQUIPA
14	CJNA	-15.8	-71.7	CAJAMARCANA	AREQUIPA
15	CAL	-12.6	-75.9	CALACHOTA	
16	CAM	-12.0	-76.9	CAMACHO	LIMA
17	CAR	-6.1	-79.2	CARHUAQUERO	LAMBAYEQUE
18	CAV	-15.7	-73.3	CARAVELI	AREQUIPA
19	CAY	-16.3	-71.5	CAYMA	AREQUIPA *
20	CBT	-9.1	-78.5	CHIMBOTE	ANCASH
21	CCH	-13.5	-72.2	CONCHACALLE	CUSCO Proy. Cusco 2K3
22	CCP	-14.0	-72.0	CAPACMARCA	CUSCO Proy. Cusco 2K3
23	CCY	-13.5	-71.6	CAICAY	CUSCO
24	CHA	-6.2	-77.8	CHACHAPOYAS	AMAZONAS
25	CHI	-6.7	-79.8	CHICLAYO	LAMBAYEQUE
26	CHL	-14.2	-73.2	CHALHUANCA	APURIMAC
27	CHU	-5.0	-80.1	CHULUCANAS	PIURA
28	CLG	-12.5	-76.5	CALANGO	MALA-LIMA, Temporal
29	CON	-15.4	-69.4	CONIMA	PUNO
30	COS	-12.1	-75.5	COSMOS	COSMOS

31	CPA	-12.3	-74.7	CARPAPATA Jun2002	HUANCAVELICA
32	CQM	-14.2	-72.0	COLQUEMARCA	CUSCO Proy. Cusco 2K3
33	CQP	-13.3	-71.6	COLQUEPATA	CUSCO Proy. Cusco 2K3
34	CSI	-16.4	-71.5	CERRO SAN IGNACIO	AREQUIPA
35	CTC	-13.6	-71.5	CATCA	CUSCO Proy. Cusco 2K3
36	CTH	-15.2	-72.8	COTAHUASI	AREQUIPA
37	CHO	-5.1	-80.9	CHOCAN	PIURA
38	CUB	-16.3	-70.9	CUBINAS TEMP	
39	CUS	-13.4	-71.9	TAMBOMACHAY	CUSCO
40	CUS1	-13.5	-71.8	CUSCO	CUSCO
41	CVE	-16.5	-71.6	CERRO VERDE	AREQUIPA
42	CYB	-13.8	-71.9	COYOBAMBA	CUSCO Proy. Cusco 2K3
43	DUB	-16.3	-70.8	DUBINAS TEMP	
44	ELD	-14.5	-71.3	EL DESCANSO	CUSCO Proy. Cusco 2K3
45	ETE	-6.9	-79.8	MORRO ETEN	CHICLAYO
46	GUA	-13.9	-75.7	GUADALUPE	ICA
47	HCA	-5.5	-79.4	HUARMACA	LAMBAYEQUE
48	HCO	-9.9	-76.2	HUANUCO	HUANUCO
49	HCO1	-9.8	-76.2	HUANUCO	HUANUCO
50	HLS	-8.8	-77.8	HUAYLAS	ANCASH
51	HRN	-13.3	-72.0	HUARAN	CUSCO Proy. Cusco 2K3
52	HRO	-13.6	-71.6	HUARO	CUSCO
53	HRZ	-9.5	-77.5	HUARAZ	ANCASH
54	HSA	-13.9	-71.3	HUASAPAMPA	CUSCO Proy. Cusco 2K3
55	HSAL	-16.3	-71.1	HSALAR	MOQUEGUA
56	HYO	-12.0	-75.3	HUANCAYO	JUNIN
57	HUA	-12.0	-75.3	HUANCAYO	JUNIN
58	HUB	-12.0	-76.9	MAYORAZGO	LIMA
59	ILL	-6.0	-80.9	ILLESCAS	CHICLAYO
60	IQT	-3.8	-73.3	IQUITOS	LORETO
61	JAN	-5.7	-78.8	JAEN	CAJAMARCA
62	JOL	-15.9	-71.8	JOLLO JELLO	AREQUIPA
63	JUN	-11.5	-75.7	JUNIN	JUNIN
64	LAM	-13.4	-71.9		CUSCO

65	LBA	-17.7	-70.6		TACNA
66	LCR	-13.6	-71.7	LUCRE	CUSCO
67	LLA	-12.2	-75.3	LLAMAHUAQUI	JUNIN
68	LM2	-12.1	-77.0	MIRAFLORES	LIMA
69	LYAR	-18.1	-70.6	YARADA	TACNA
70	MAY	-12.1	-76.9	MAYORAZGO	LIMA
71	MCH	-6.5	-79.2	MAYCHIL	LAMBAYEQUE-CARHUAQUERO
72	MIS	-16.3	-71.4	MISTI	AREQUIPA
73	AMIM	-16.3	-71.4	MISTI	AREQUIPA
74	EMIM	-16.3	-71.4	MISTI	AREQUIPA
75	MLL	-13.5	-72.5	MOLLEPATA	CUSCO Proy. Cusco 2K3
76	MOR	-12.2	-77.0	MORRO SOLAR	LIMA
77	MOY	-13.0	-74.1	MOYA	AYACUCHO
78	MPA	-6.7	-79.4	MAL PASO	LAMBAYEQUE-CARHUAQUERO
79	MRS	-13.3	-72.2	MARAS	CUSCO Proy. Cusco 2K3
80	MTA	-6.8	-79.1	MONTAITA	LAMBAYEQUE-CARHUAQUERO
81	MYB	-6.0	-77.0	MOYOBAMBA	SAN MARTIN
82	NNA	-12.0	-76.8	LIMA	LIMA
83	NNAP	-12.9	-76.8	LIMA	LIMA
84	OAS	-6.3	-80.4	OASIS	CHICLAYO
85	OCG	-13.6	-71.4	OCONGATE	CUSCO Proy. Cusco 2K3
86	OCR	-13.6	-72.2		CUSCO
87	OLL	-13.3	-72.3	OLLANTAY	CUSCO Proy. Cusco 2K3
88	OLM	-6.1	-79.8	OLMOS	LAMBAYEQUE
89	PAL	-16.6	-70.6	TICSANI	MOQUEGUA
90	PAR	-13.8	-76.3	PARACAS	ICA
91	PAT	-15.8	-71.7	PATAPAMPA	AREQUIPA
92	PTPA	-15.8	-71.7	PATAPAMPA	AREQUIPA
93	PCH	-6.0	-79.7	PORTACHUELO	LAMBAYEQUE
94	PCO	-13.4	-72.4	PAMPACONGA	CUSCO Proy. Cusco 2K3
95	PCU	-5.9	-79.5	PORCULLA	PIURA-LAN LAN
96	PMA	-5.9	-79.2	POMAHUACA	CAJAMARCA
97	POC	-11.3	-74.6	PUERTO OCOPA	JUNIN

98	PITU	-13.9	-71.6	PITUMARCA	CUSCO Proy. Cusco 2K3
99	PTM	-12.6	-69.2	PUERTO MALDONADO	MADRE DE DIOS
100	PTMA	-12.6	-69.2	PUERTO MALDONADO	MADRE DE DIOS
101	PUC	-8.4	-74.7	PUCALLPA	UCAYALI
102	PUCR	-11.8	-76.3	PUCRUCHACRA	LIMA
103	PUN	-15.8	-70.0	PUNO	PUNO
104	PUQ	-14.2	-74.1	PUQUIO	AYACUCHO *
105	PYC	-12.5	-74.6	POCLLAC	HUANCAVELICA
106	QCH	-12.4	-74.7	QUINSACHUMPI	HUANCAVELICA
107	QCO	-12.5	-74.6	QUELLOCOCHA	HUACAVELICA
108	QQJ	-13.8	-71.5	QUIQUIJANA	CUSCO Proy. Cusco 2K3
109	QSN	-14.4	-71.1	QUISINI	CUSCO Proy. Cusco 2K3
110	QUE	-14.4	-71.5	QUEHUE	CUSCO Proy. Cusco 2K3
111	QUI	-12.9	-76.4	QUILMANA	LIMA
112	QLK	-16.7	-72.4	QUILCA	AREQUIPA
113	RUN	-12.3	-74.8	RUNDOVILCA	HUANCAVELICA
114	SAL	-11.2	-77.6	SALINAS	LIMA
115	SCA	-16.4	-71.6	SACHACA	AREQUIPA
116	SCH	-12.0	-76.5	SUCHE	LIMA
117	SFE	-11.7	-76.2	SANTA FE	LIMA
118	SGB	-13.7	-70.5	SAN GABAN	PUNO
119	SGR	-16.6	-72.7	SAN GREGORIO	AREQUIPA
120	SJU	-15.4	-75.2	SAN JUAN DE MARCONA	ICA
121	SPB	-14.2	-71.3	SAN PABLO	CUSCO Proy. Cusco 2K3
122	SPU	-6.9	-79.7	SEÑAL PUNTERIA	LAMBAYEQUE

123	SSA	-13.5	-71.8	SAN SALVADOR	CUSCO Proy. Cusco 2K3
124	STC	-6.6	-78.9	SANTA CRUZ	CAJAMARCA
125	TAC	-18.0	-70.3	TACNA	TACNA
126	TA11	-13.5	-72.0	SALCANTAY	CUSCO
127	TAR	-6.5	-76.4	TARAPOTO	TARAPOTO
128	TBL	-12.5	-74.8	TABLACHACA Telem	HUANCAVELICA
129	TBL2	-12.5	-74.8	TABLACHACA Reg.Vis	HUANCAVELICA
130	TCP	-13.6	-71.2	TOCTOPATA	CUSCO Proy. Cusco 2K3
131	TGS	-14.2	-71.5	TUNGASUCA	CUSCO Proy. Cusco 2K3
132	TIC	-16.8	-70.6	TICSANI	MOQUEGUA
133	TOC	-15.7	-74.1	TOCOTA	AREQUIPA
134	TOQ	-17.3	-70.6	TOQUEPALA	MOQUEGUA
135	TTO	-6.6	-76.4	TARAPOTO	SAN MARTIN
136	TBM	-3.5	-80.3	TUMBES	TUMBES
137	UBI	-16.3	-70.9	UBINAS	MOQUEGUA
138	UBI1	-16.3	-70.9	UBINAS1	MOQUEGUA
139	UBI2	-16.3	-70.9	UBINAS2	MOQUEGUA
140	UBI3	-16.4	-70.9	UBINAS3	MOQUEGUA
141	UBI4	-16.3	-70.9	UBINAS4	MOQUEGUA
142	UDEP	-5.2	-80.6	ACELERACION	PIURA
143	UICA	-14.1	-75.7	ACELERACION	ICA
144	UNAP	-15.8	-70.0	UNIVERSIDAD	PUNO
145	WAL	-12.4	-74.7	WALLPARI	HUANCAVELICA
146	YCA	-15.7	-74.5	YAUCA	AREQUIPA
147	YAC	-8.6	-77.9	YANAC	ANCASH

148	YAR1	-18.2	-70.5	YARADA-Antiguo	TACNA
149	YAU	-13.7	-71.9	YAURISQUE	CUSCO Proy. Cusco 2K3
150	YLS	-8.8	-77.9	HUAYLAS	ANCASH
151	YRM	-5.9	-76.1	YURIMAGUAS	LORETO
152	ZAM	-14.7	-75.6	ZAMACA	ICA
153	OXA	-10.6	-75.4	OXAPAMPA	PASCO

Table 6: Seismic stations of the Geophysical Institute of Peru.

1.4.2. Sea Level Network for detection and monitoring of Tsunamis

The National Tide Gauge Network is currently composed of 19 automatic continuous sea level recording stations. Eleven of them are equipped with Geonica radar sensors, model Datamar 2000C, with sampling every second and recording averaged per minute with a double system of information transmission every ten minutes, via cellular network (GPRS) and satellite (INMARSAT), acquired at the end of 2009 by the Directorate of Hydrography and Navigation of the Peruvian Navy - DHN, in order to strengthen the tsunami early warning system and flood forecasting (rough seas). The other eight are ultrasonic stations, Sonic Corporation brand, with sampling every second and recording averaged per minute, with information transmission system every five minutes via cellular network (GPRS), acquired in 2015, under the Project for the Improvement of Equipment for Disaster Risk Management. These were donated by the Japanese Agency JICA.

The Geonic stations are mostly composed of two tide gauges (radar and pressure type), a tidal ruler, a surveillance camera and a reference point system (BMs) or marks for periodic geodetic leveling, allowing the proper processing of information by obtaining their monthly climatological standard values and their harmonic and non-harmonic characterization (harmonic constituents, tide reference level and amplitudes); necessary for their use in different research areas, such as El Niño and La Niña phenomena, seiches, climate change, post-tsunami studies, among others.

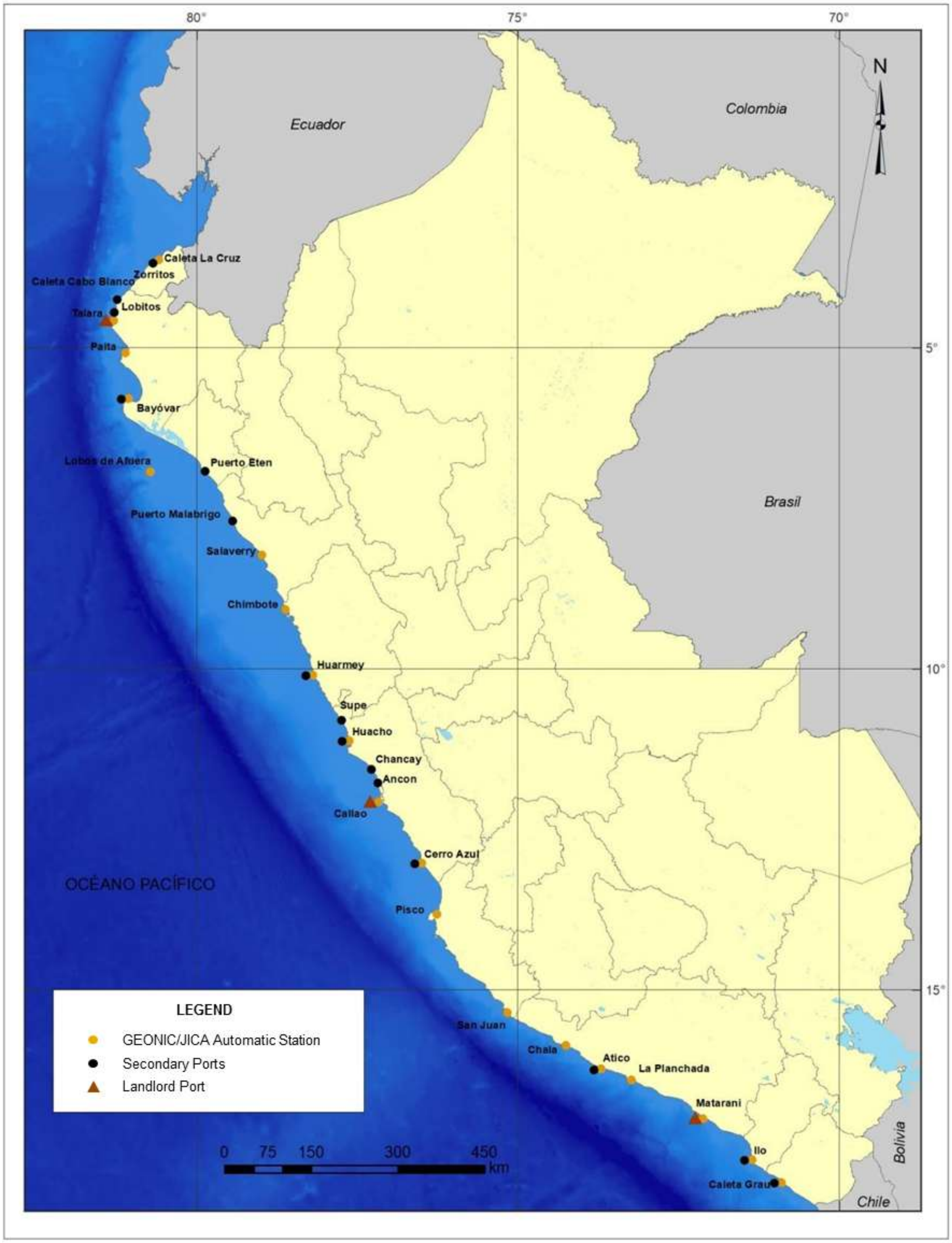


Figure 22: National Tide Gauge Network on the Peruvian coast. Source: IGP.

2. Geographical context and distance from large cities in the earthquake and tsunami generation area in the South-East Pacific region.

2.1. Chile

In Chile there is a long history of tsunamis of tectonic origin (Figure 23), among which recent events such as those generated by the Maule earthquakes in 2010, Iquique Earthquake in 2014 and Illapel Eartquake in 2015. These events have the capacity to spread throughout the ocean (Figure 24) and cause great damage to the coasts.

There is also evidence of great events, such as those of 1868 and 1877, in the northern zone; 1922, in the "Norte Chico" that corresponds to the area between Atacama and Valparaíso; 1730, in central Chile, and those of 1835 and 1960, in Central-South Chile.

On the other hand, there are local events such as those generated by mass movements or collapse of glaciers. An example of this occurred in April 2007, where a landslide tsunami in the Aysén fjord (Figure 25), which caused the death of 10 people (Sepúlveda & Serey, 2009).

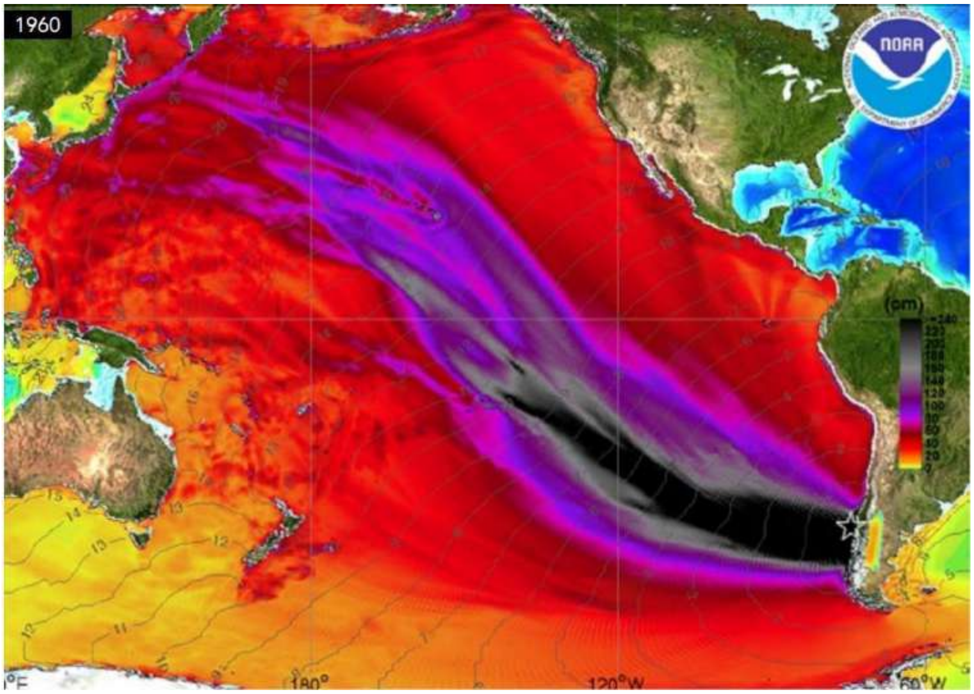


Figure 23. Numerical modeling of the Tsunami generated by the Valdivia Earthquake (1960, M9.5). This earthquake is considered the largest recorded instrumentally. Source: National Weather Service, NOAA.

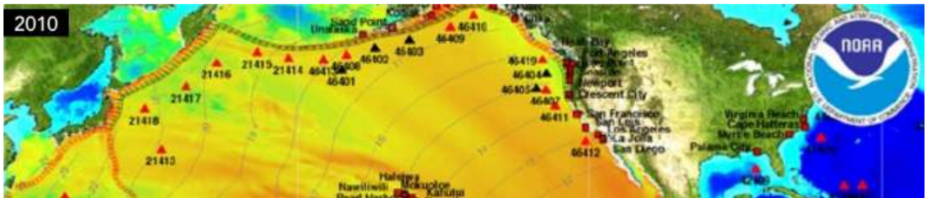


Figure 24. Numerical modeling generated by the 27F Earthquake (2010, M8.8). The scale represent the maximum heights reached by the tsunami in the deep ocean. The isochron lines show the tsunami propagation every hour since the earthquake occurred. Source: National Weather Service, NOAA.

Figure 25. Landslide that caused the Aysén fjord tsunami on April 21, 2007. Source: Sepúlveda & Serey, 2009.

The geology and geomorphology of Chile has originated in one of the most important subduction zones on the planet, product of the combination of seismic activity, volcanism and gravity anomalies.

According to what was described by Morales E., Winckler P. and Herrera M. (2019), subduction in the continental margin of Chile generates a powerful seismic zone that extends for more than 2600 km, between the northern limit with Peru and 45º S. A review of seismological research confirms that intermediate and deep earthquakes, located below Chile, occur as a result of accumulated stresses in the lithospheric zone of penetration. Seismic activity, however, is heterogeneous, with seismic gaps like the one located in the north of the country and more active zones. At present, there are seismicity maps in which the position of the epicenter of historical earthquakes is illustrated as a function of depth. This type of information allows the development of models of the descending lithospheric slab and estimates of the seismic hazard in the country.

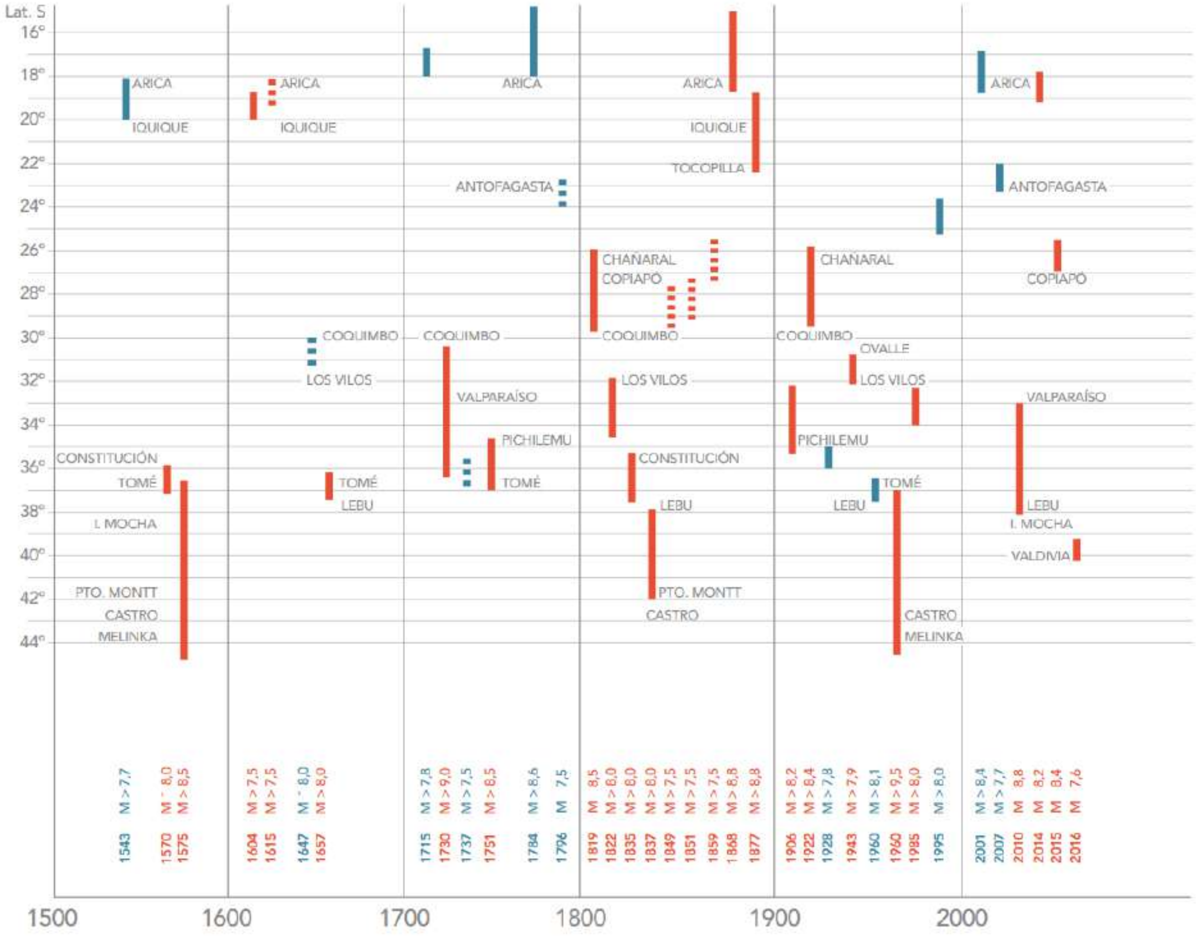


Figure 26. Space-time diagram of rupture lengths of big earthquakes off the coast of Chile. Events highlighted in red have associated tsunamis. Source: Coasts of Chile, Morales E., Winckler P. and Herrera M., 2019.

2.2. Colombia

The Colombian continental territory is part of the northwestern tip of South America, limited to the west by the Pacific Ocean and to the north by the Caribbean Sea. The insular territory in the Caribbean Sea is made up of the San Bernardo Archipelago, Rosario Islands, San Andrés Archipelago, Providencia and Santa Catalina and in the Pacific Ocean by the islands of Gorgona and Malpelo.

Northwestern South America experiences significant tectonic deformation from the late Cretaceous to the present, as a result of the interaction of the South American, Nazca, and Caribbean plates. The Nazca plate moves east with respect to that of South America at speeds of 53.6±2.1 mm/year and 58.2±1.4 mm/year according to measurements made on the islands of Malpelo and the Galapagos (Trenkamp et al., 2002) and subducts below it with a variable dip angle of 30° to 40° through the Pacific subduction zone. Recent measurements indicate that the islands of Malpelo and Galapagos on the Nazca plate are converging towards the east-northeast in relation to South America, at rates of 53.1±0.6 mm/year and 54.8±0.2 mm/year respectively (Mora-Páez H. et al., 2019).

Subduction is manifested through active seismicity throughout the region and volcanism in the Cordillera Central up to 5.5° north latitude. The Caribbean plate moves southeast with respect to South America, at a speed of 20 ± 2 mm/year (Trenkamp et al., 2002). The islands of San Andrés and Providencia on the Caribbean plate converge obliquely with South America at rates of 18.2±0.4 mm/year and 17.0±0.6 mm/year respectively (Mora-Páez H et al., 2019). Several authors have proposed that the Caribbean plate subducts under the South American plate, with a low dip angle, without subduction-related volcanism, and with very low seismicity.

The Colombian Pacific coast is made up of four departments, Chocó, Valle del Cauca, Cauca and Nariño, in these departments the following municipalities are located on the coastline. Table 7 and figure 27.

Departments	Municipality
CHOCÓ (5 municipalities)	Juradó, Bahía Solano, Nuquí, Bajo Baudó, San Juan coast
VALLE DEL CAUCA (1 municipality)	Buenaventura
CAUCA (3 municipalities)	López de Micay, Timbiquí, Guapi
NARIÑO (7 municipalities)	Santa Bárbara, El Charco, La Tola, Olaya Herrera, Mosquera, Tumaco, Francisco Pizarro

Table 7: Distribution of Pacific Colombian Coast

Figure 27. Pacific Colombian Coast. Source: https://pacificocolombia.org/pacifico-colombiano/

The most populated cities or municipalities are Buenaventura, considered the port city of the Colombian Pacific region where most of the country's imports and exports take place. It is located approximately 156.1 kilometers from the subduction zone.

Tumaco is another of the most populated cities in the region, it is made up of two islands and the mainland, according to historical records, Tumaco has been considerably affected by the tsunami events of 1906 and 1979. It is located at 124.5 kilometers from the subduction zone. Figure 28.

Figure 28. Municiality of Tumaco. Source: Google Earth.

2.3. Ecuador

In Ecuador, subduction of the Nazca plate and the Carnegie seismic ridge beneath the South American plate generates significant stress accumulation at the margin. This stress accumulation is evidenced by GPS measurements, marine terrace uplift and recurrent interplate zone seismicity. Four large magnitude earthquakes (Mw > 7.6) have occurred in the interplate zone of the northern Ecuadorian margin in the 20th century. Meanwhile, in the Manta region, between 0.5ºS and 2.5ºS, seismicity falls within the medium magnitude range (Mw < 7.1) and for certain periods there have been several seismic swarms (1998, 2002 and 2005) (Vaca, 2007; IG-EPN).

The northern Ecuadorian coast or Esmeraldas region (north of latitude 0, 5º S) has been affected by several large magnitude earthquakes (Figure 46) during the last century (Mw>7.6). On the contrary, between latitudes 0, 5º S and 2, 5º S, only seismic swarms with events of low and medium magnitude (Mw<7.1) have been recorded (Kelleher, 1972; Segovia, 2001). About this same area, (Nishenko, 1991) states that the absence of data (reported earthquakes of high magnitude) in historical time does not allow to evaluate the seismic potential of the region and that the Carnegie range would be responsible for the fact that the earthquake recurrence period is higher than the average of nearby areas. However, he emphasizes that it is a populated area with a high potential for the occurrence of a strong magnitude earthquake, with a possible epicenter around Jama town (latitude approximately 0.2°S), at the northern limit of the Carnegie subduction. In this sector are located cities such as Bahía de Caráquez and Manta, considered very important for their important population and their contribution to the economic development of the country.

Towards the southern coast of Ecuador, the subduction margin is active, where the Nazca oceanic plate collides and subducts the South American continental plate and the Norandino block. In this region, historical earthquakes records are since June 11, 1787. However, information (documents) about seismic-tsunami in this sector is poor; January 7, 1901 earthquake with magnitude approximately 7.2 (other catalogs and authors estimate it as 7.6 and 7.8) offshore of the Santa Elena Peninsula at a location around 2.0°S, 82.0°W has not sufficiently information about tsunami damage in this area. October 2, 1933 tsunami (Ms ~ 6.9) at ~ 3.5°S, 80.0°W, registered tsunami sea level oscillations since 2 m to 2.5 m, like inundation to Santa Elena coast, but not as turbulent waves(Chunga, 2013; Arreaga and Ortiz, 2002). December 12 1953 earthquake (Ms ~ 7.8) at ~ 3.4°S, 80.6°W, it was generated near the coast of Tumbes (the Ecuador - Peru border) and generated a tsunami with 20cm waves records in La Libertad city and rapid inundation in the Salinas coast (Chunga, 2013; Silgado, 1957). There is no information about the tsunami of February 07, 1959, generated by an earthquake of Ms ~ 7.5 at ~ 4.0°S, 81.5°W. Adding the condition of little earthquakes information in this sector where Salinas is located (one of the ecuadorian main resorts), Salinas and others bay are very close to the subduction zone between 20 to 50 km, and they are floodable areas and according to the local seismic analysis, since 1959 there is a seismic gap in this place. Figure 29.

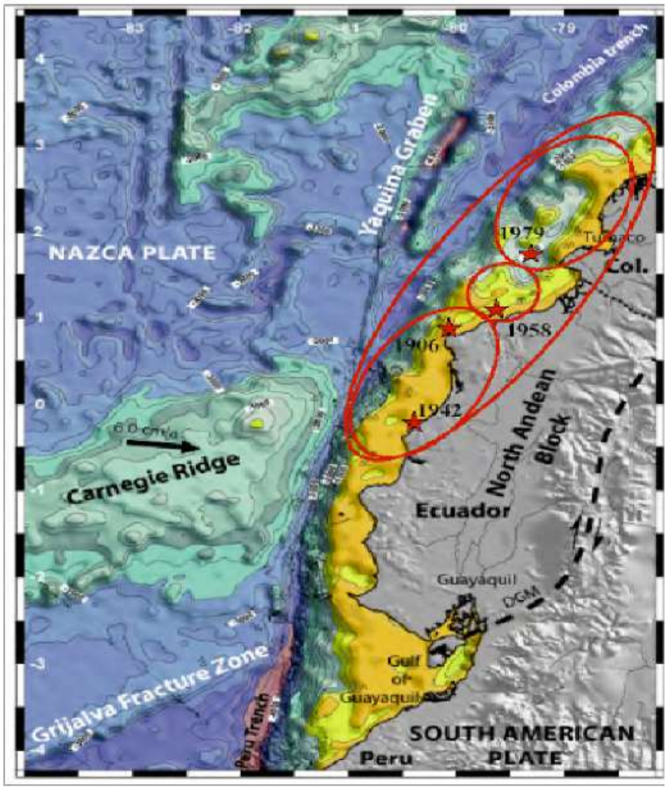


Figure 29. Main geodynamic structures of the Colombo-Ecuadorian subduction. The stars represent the epicenters and the ellipses the rupture zones of the great earthquakes since 20th century, M>7.6 Historical earthquakes in the northern sector. Source: Collot et al., 2002.

Along the continental margin there are several cities with important population. They could be vulnerable to tsunami impacts because they are in front of the large earthquakes and tsunamis have been generated. Esmeraldas city is located in the northern sector of the Ecuadorian coast and it was affected by four big earthquakes in the 20th century. Esmeraldas is approximately 80 km from the subduction zone and it is one of principal Ecuadorian port. Atacames is another coastal city, it is close to Esmeraldas and it is one of the most visited resorts in this region, it is a beautiful place. This popular beach is located 60 km from big earthquakes generation zone.

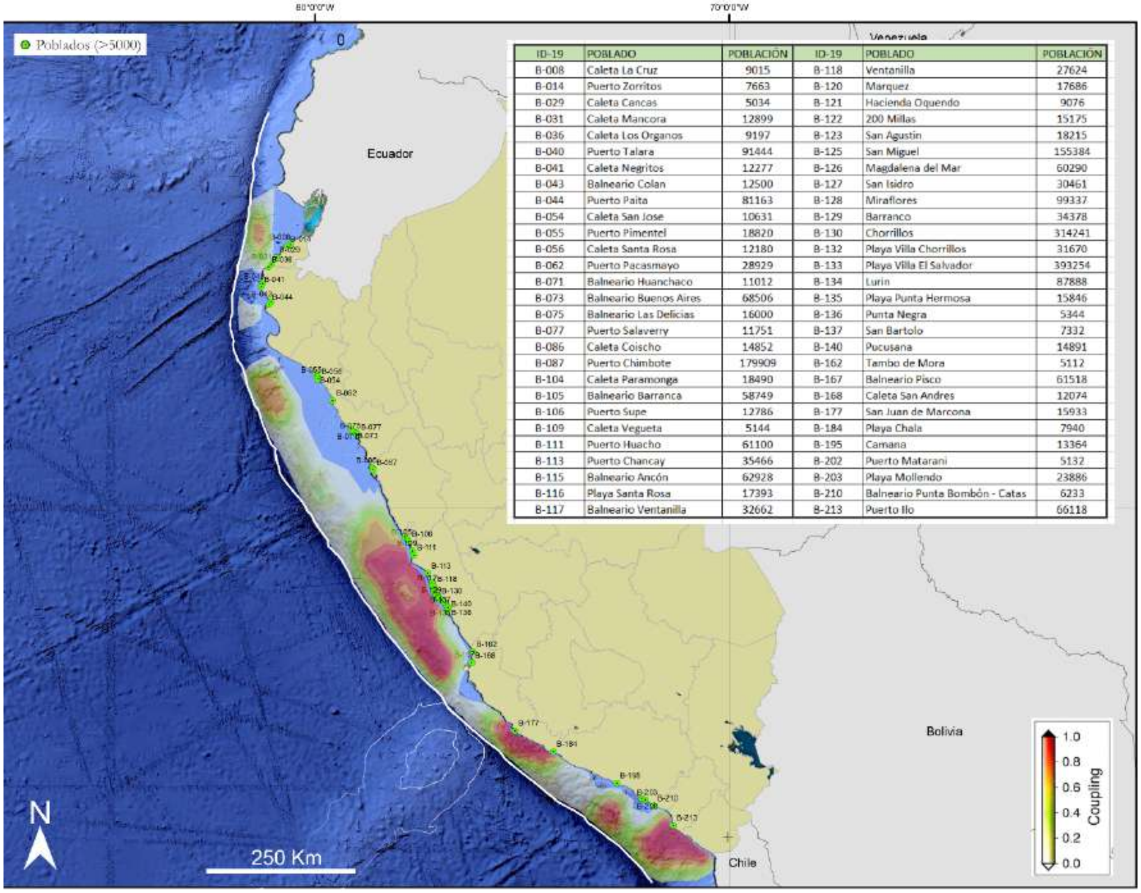
In the Ecuadorian central coastal we find other important cities for their great contribution to the country economic development, such as Manta city, one of the most important fishing ports of Ecuador and Bahía de Caráquez, both located 63 km and 85 km respectively from the large earthquakes area generation. Towards the southern sector, we find Salinas, known as an important beach with a high floating population during all months of the year because it offers a very nice weather for tourists from different regions of the country. In the past, Salinas was affected by a coastal earthquake in 1953 that resulted in a rapid coastal inundation. Salinas is located approximately 50 km from the subduction zone.

Machala and Puerto Bolivar are also important port cities located along the Gulf of Guayaquil, in the southern sector of the Ecuadorian coast, and are only a few kilometers from the subduction zone (195 km).

Figure 30. Cities established along the coastal margin whose economic activities and populations make them highly vulnerable to tsunami risk due to their proximity to the subduction zone. Source: INOCAR 2020.

2.4. Perú

There are 56 large towns (with population greater than 5,000 inhabitants) and 169 growing towns along the Peruvian coast, being 9 of the large towns geographically located far away from the earthquake and tsunami generation areas (Villegas-Lanza et al., 2016) mainly due to the relative distance between the trench and the coastline. They are shown in Figure 31 and correspond to ID B-055 to B-087.



ID-19	POBLADO	POBLACIÓN	ID-19	POBLADO	POBLACIÓN
B-008	Caleta La Cruz	9015	B-118	Ventanilla	27624
B-014	Puerto Zorritos	7663	B-120	Marquez	17686
B-029	Caleta Cancas	5034	B-121	Hacienda Oquendo	9076
B-031	Caleta Mancora	12899	B-122	200 Millas	15175
B-036	Caleta Los Organos	9197	B-123	San Agustin	18215
B-040	Puerto Talara	91444	B-125	San Miguel	155384
B-041	Caleta Negritos	12277	B-126	Magdalena del Mar	60290
B-043	Balneario Colan	12500	B-127	San Isidro	30461
B-044	Puerto Paita	81163	B-128	Miraflores	99337
B-054	Caleta San Jose	10631	B-129	Barranco	34378
B-055	Puerto Pimentel	18820	B-130	Chorrillos	314241
B-056	Caleta Santa Rosa	12180	B-132	Playa Villa Chorrillos	31670
B-062	Puerto Pacasmayo	28929	B-133	Playa Villa El Salvador	393254
B-071	Balneario Huanchaco	11012	B-134	Lurin	87888
B-073	Balneario Buenos Aires	68506	B-135	Playa Punta Hermosa	15846
B-075	Balneario Las Delicias	16000	B-136	Punta Negra	5344
B-077	Puerto Salaverry	11751	B-137	San Bartolo	7332
B-086	Caleta Coischo	14852	B-140	Pucusana	14891
B-087	Puerto Chimbote	179909	B-162	Tambo de Mora	5112
B-104	Caleta Paramonga	18490	B-167	Balneario Pisco	61518
B-105	Balneario Barranca	58749	B-168	Caleta San Andres	12074
B-106	Puerto Supe	12786	B-177	San Juan de Marcona	15933
B-109	Caleta Vegueta	5144	B-184	Playa Chala	7940
B-111	Puerto Huacho	61100	B-195	Camana	13364
B-113	Puerto Chancay	35466	B-202	Puerto Matarani	5132
B-115	Balneario Ancón	62928	B-203	Playa Mollendo	23886
B-116	Playa Santa Rosa	17393	B-210	Balneario Punta Bombón - Catas	6233
B-117	Balneario Ventanilla	32662	B-213	Puerto Ilo	66118

Figure 31. Location of large cities and growing towns with respect to the most probable areas of occurrence of large magnitude earthquakes in the sea with probability of tsunami occurrence. Source: DHN.

3. Capacity of Seismological Centers to disseminate early warning information.

3.1. Chile

- **Xancura, early warning of earthquakes and tsunamis.**

The Xancura system has a private monitoring network with more than 80 monitoring stations distributed in strategic points of the national territory. The service is designed for institutions and industries that want to mitigate the effects of an earthquake by receiving an automatic preventive alert (with seconds and even minutes in advance). Its usefulness is to inform visually and aurally the characteristics of the approaching earthquake (instrumental intensity and a countdown that shows how many seconds are left before the movement begins to be perceived. Figure 32.
Since November 2018 and as part of a collaboration agreement, the Hydrographic and Oceanographic Service of the Chilean Navy (SHOA) has this early warning device.

Figure 32: Xancura system.

- **Earthquake Underwater Observation Project (POST)**

A new project will use underwater fiber optic cable to detect earthquakes. This is the Underwater Earthquake Observation Project (POST), which seeks to use the submarine fiber optic “Prat” cable from the Telecommunications and Technology Services company "GTD" as if it were thousands of seismic sensors arranged on the seabed, using an innovative technique called Distributed Acoustic Detection (DAS) applied to seismology.

The importance of this research project is that it will help to face one of the main difficulties in Chile in terms of seismic detection, given that a large part of the earthquakes have their epicenter on the seabed, and up to now it is not possible to detect them except until the generated waves are detected by seismic sensors installed on the continent.

For this research project to be successful, in terms of the quantity and quality of the information that it manages to collect, it opens up the important possibility of having an earthquake early warning system for Chile in the medium or long term, which would allow warning to the public, with a few seconds in advance, about the arrival of the most violent shock resulting from a great earthquake. Until now, the geographical characteristics of the country have made this objective difficult, but the possibility of having a large number of sensors on the underwater floor would facilitate the detection of earthquakes before their waves reach the continent, giving valuable additional seconds to manage to alert not only the population, who can take measures to protect themselves, but also those productive processes that could benefit.

Chile continues to behave as a natural laboratory that, through international and public-private collaborations, this type of project will allow a better understanding of earthquakes and their characteristics, enabling the development of new techniques that help provide greater security to the population and that can be replicated in other locations.

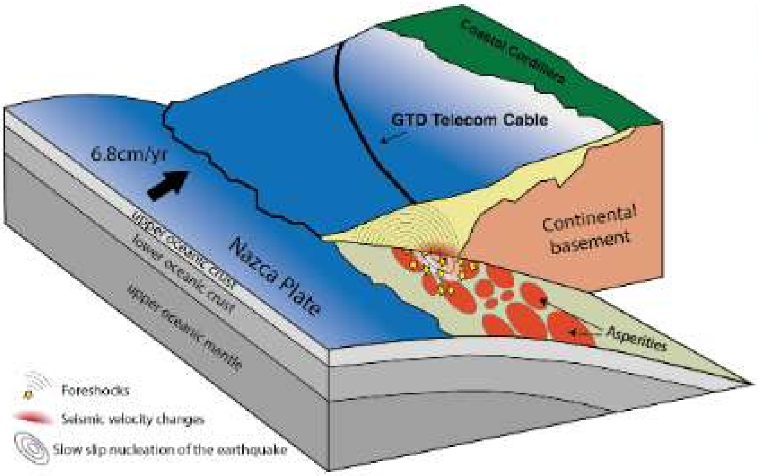


Figure 33: The left figure shows the location of the cable in relation to the contact of the tectonic plates. The right figure shows the interior detail of the cable. Source: National Seismological Center -CSN.

3.2. Colombia

Once the National Seismological Network of the Colombian Geological Service receives the information from the sensors through satellite communication, an auto-location of the epicenter of the earthquake is generated, which takes between 2 to 5; minutes, this is automatically disseminated to the National Tsunami Detection and Alert System - SNDAT, with this information the National Tsunami Warning Center -NTWC is activated, then the seismologist on duty performs a primary processing that takes between 6 to 8 minutes and confirm the seismological information to the National Tsunami Warning Center through email and calls by VHF radio or cell phone, the next step is to carry out a secondary processing to have more detailed information on the event, such as the calculation of the parameters of the seismic source and focal mechanism, a process that takes between 12 to 20 minutes and is sent automatically by the SWIFT system to the NTWC and used by the tsunami assessment tool to determine the tsunami threat level for the coastal municipalities.

3.3. Ecuador

The Instituto Geofísico de la Escuela Superior Politécnica Nacional-IGEPN is the main research center in Ecuador for the diagnosis and monitoring of seismic and volcanic hazards, which can have a great impact on the population, infrastructure, and the natural environment. The IGEPN is part of the National Tsunami Warning System in Ecuador.

The Institute, through the National Seismology and Volcanology Service, has a real-time instrumental monitoring and surveillance service, which ensures permanent scientific surveillance of tectonic faults and active volcanoes in the national territory. Data analysis is performed at the TERRAS center, with data collected by the National Network of Seismographs and operates 24/7. Additionally, there is a geodesy network that contributes substantially to the interpretation of these phenomena.

Within the technical protocol for the evaluation and definition of the tsunami warning (Version 3.0), the IGEPN shall comply with the following general responsibilities:

1. Evaluate the information of a tsunamigenic earthquake with an epicenter within the Ecuadorian territory.

2. To permanently communicate and issue information on earthquakes to INOCAR and the National Risk Management Service - SGR through channels established between the institutions that make up the National Tsunami Warning System.

The IGEPN is able to analyze and issue seismic reports (at least three) if the earthquake is located in domain one ECC-1 (the preliminary (automatic) bulletin, the confirmed bulletin and the SWIFT solution); two seismic reports if the earthquake is located in domain two ECG-1 and no report if the earthquake is located in domain three ECF-1, this information will be obtained through PTWC and USGS.

The bulletins or reports issued by the IGEPN will contain the seismic parameters of the source. The first report 3 minutes after the event occurs is generated automatically, will present the hipocentral location and the preliminary magnitude. Additionally, this first report automatically triggers the SWIFT system to calculate the moment magnitude, seismic moment and rupture time.

The second report issued 5 to 8 minutes contains the location, verification and the revised magnitude. This report will be used by INOCAR to analyze the information according to its internal protocols and to calculate the arrival time of the tsunami waves at different points along the coast.

Finally, between 13 and 15 minutes after the earthquake, the third report, which includes the parameters of moment magnitude, seismic moment, and rupture time, will be sent to INOCAR to improve the prediction of the possible tsunami. In order to achieve a good reception and dissemination of information, this Institute currently has a diversified transmission network consisting of fiber optic networks, microwave central network, satellite network, Spread Spectrum technology and long-range Wi-Fi.

3.4. Perú

As part of the Peruvian Seismic Alert System (SASPe) in Lima, the Julio Kuroiwa seismic station was put into operation in July 2020. This station allows to alert the population seconds before the arrival of the waves. This station is the precedent for starting the operation of accelerometers in Isla Hormigas and Isla San Lorenzo, located off the coast of Lima.

In order to respond to an earthquake, the Geophysical Institute of Peru issues the seismic parameters to the National Institute of Civil Defense for response actions. This entire process is carried out within 11 minutes after the earthquake.

4. Proposal of regional network for monitoring in the southeast pacific

The main submarine cables systems employed in telecommunications are composed of a cable that currently has 16 fibers, power supply equipment in continuous current, pressure housings with amplifiers spaced along the cable between 60 and 150 km and landing stations at the surface.

More specifically, the pressure housing contains repeaters use to amplify the signal to avoid loses in signal through the cable, taking advantage of this, the implementation of SMART focus in the integration of sensors in the structure of the repeaters. (Howe et al., 2018) address that a SMART setting would require adding to the repeaters: sensors, signal processors, data switch, fiber optic transceiver and power supply.

4.1. Details of sensors to use

The sensors for the implementation of SMART are for temperature, pressure in the water column and accelerometers. It is considered that the instruments are attached directly to the structure of the repeaters; nevertheless this will depend of the coordination and agreements between the manufacturers of each component. In this case the temperature and pressure sensors must be mounted on the exterior of the repeater and the accelerometers in the interior.

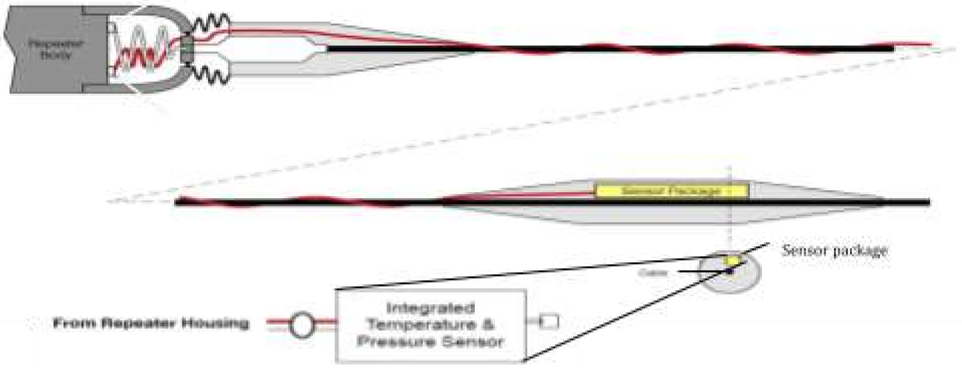


Figure. 34. Diagram of the proposed configuration for a SMART cable in the Southeast Pacific. Source: Modified from Tilmann, F. et al. 2016.

At this stage of the development of SMART Cables, there are still no fully functional prototypes of the proposed installation. However, Howe et al., 2018 suggest, as an alternative, to use a branch unit with the sensors, but this would reduce the synergy between the telecommunications and the scientific effort.

The alternatives are either go for the branch units or a previous coordination with the repeater manufacturers, to attach the sensors directly to the repeater in order to reduce changes to the external design.

4.2. Proposed route for the network

According to the current structure of submarine telecommunications cables in the Southeast Pacific region, the locations that already have terminal station equipment on the mainland are: Valparaíso (Chile), Lima (Peru), La Libertad (Ecuador) and Buenaventura (Colombia); there are also other locations with stations, but one per country is considered to centralize the information and to achieve better integration as national and regional alert systems. Figure 35.

Figure 35. Submarine cable infrastructures for telecommunications considered for SMART implementation. Source: Submarine Cable Map, TeleGeography.

According to the routes that the submarine cables follow along these stations on the continent, an approximate length of 5,900 km is recorded. Taking as a basis the PRAT, South America – 1 and South American Crossing cable infrastructures as indicated in figure 35. Favorable submarine cable structures have been addressed in the GT-ATPS report presented in Nicaragua, 2019.

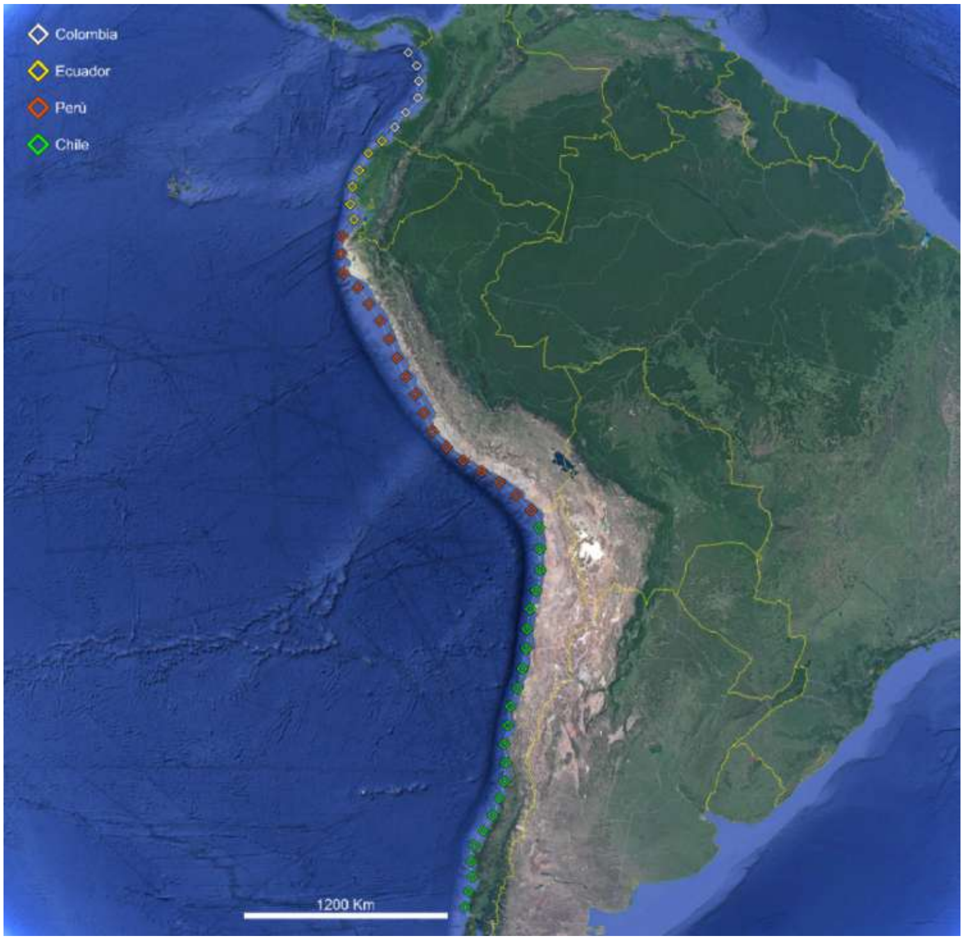


Figure 36. Schematic distribution of the sensors along the routes considered for the implementation of SMART in SEP. Source: Own elaboration in Google Earth.

Considering that the distance standard between the repeaters indicates that they must be spaced every 120 km and taking into account a sensor node in each repeater, the following distribution is proposed (Figure 36.):

To the south of Valparaíso:	8 installation points.

Between Valparaíso and Lima: 23 installation points.
Between Lima and La Libertad: 11 installation points.
Between La Libertad and Buenaventura: 7 installation points.
To the north of Buenaventura: 3 installation points.

Being a total of 52 sensor installation points that would integrate the regional alert system. For which, Chile would have 22 points, Peru with 18 points, Ecuador with 6 and Colombia with 6 sensor installation points on its coasts (for purposes of direct administration and implementation of national alert systems).

4.3. Costs

Due to this type of initiative has an initial phase like tested project, there are not exact numbers about its implementation. At a general level, as a SMART project, there are 3 steps considered according to Howe et al., 2019: development, implementation, and operation. Development involves the costing of a demonstration system, a reference system, and non-recurring costs to support these first tests. Implementation and operations are those that directly involve financing by the countries where the installation will take place.

	Item	**Unit cost (USD)**	**Total cost for 52 sensors (USD)**
Implementation	Repeater	207 000.00	10 764 000.00
	Additional	43 000.00	2 236 000.00
Operations	Data management, transmission, and processing	20 700.00 (/year	1 076 400.00
		Estimated total	14 076 400.00

Table 8. Implementation estimated cost and SMART project first year operation in the Southeast Pacific region, after the development step.

4.4. Operational use of the data in the NTWC and seismological Centers

The basic operational structure of the SMART cables implementation is shown in Figure 37. The information obtained by a sensor is received at the coastal station, where it is stored, processed and transmitted to databases, national agencies and subsequently provided to academic institutions for research when required.

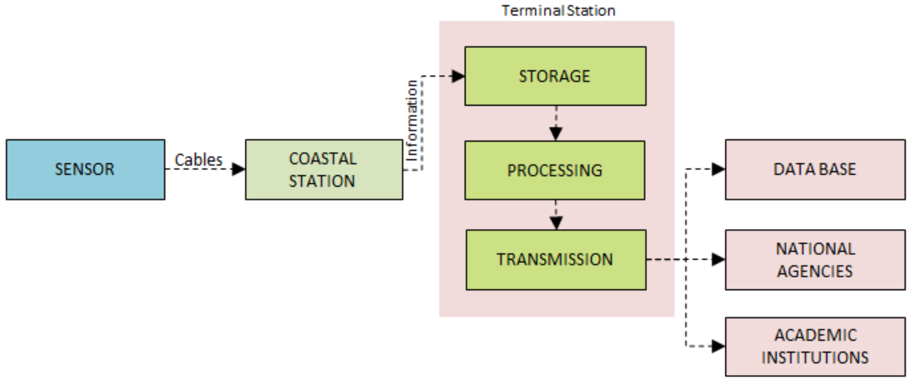


Figure 37. Standard data management scheme in a SMART system.

A tsunami warning system considers a seismic detection component, a tsunami assessment component, and a response component. It is important for the system the information provided by the SMART sensors, the information from the accelerometers and the pressure sensor. Information management is proposed from the perspective of tsunami warning according to the responsibilities and protocols established at the country level.

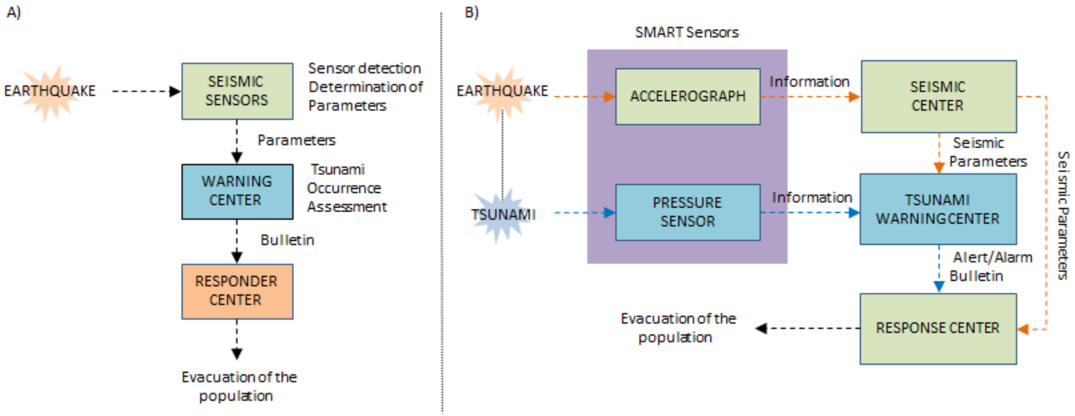


Figure 38. (A) Proposed general information management scheme for SMART implementation. (B) Operating scheme of a tsunami warning system.

5. Legal aspects and challenges

5.1. Benefits of the installation of submarine cables with SMART technology.

The ocean is key to understanding the various threats not only to humans, but also to all life on earth, such as climate change, sea level rise, ocean warming, tsunamis, and earthquakes. Because the ocean is difficult and expensive to monitor, especially in real time, we lack the data necessary to be able to adequately model, understand, and address these threats. Currently, the oceans are monitored through platforms or in situ instruments (ships, tide gauges, buoys, etc.) and remote sensing techniques (satellite), however, the depths of the ocean and the important processes that occur remain unsampled and unmonitored.

One of the solutions is the initiative of submarine cables SMART (Science Monitoring And Reliable Telecommunications), promoted by the joint international working group Joint Task Force - JTF made up of three United Nations agencies - NU (International Telecommunications Union - ITU , World Meteorological Organization - WMO and Intergovernmental Oceanographic Commission - UNESCO IOC), whose concept makes it possible to cover vast areas of the ocean and at the same time obtain a large amount of physical-oceanographic data in real time, integrating sensors along the cables of submarine telecommunications. Data from the SMART cables would fill critical gaps in our existing monitoring systems, complement existing observations, increase our current level of understanding of the ocean, and improve our ability to predict its future evolution.

SMART sensors would take advantage of the power and communications infrastructure of kilometers of submarine fiber optic cable and thousands of repeaters, constituting a tool with great potential for global ocean observation from the seabed at a modest cost compared to hundreds or thousands. of buoys or sensors that would have to be deployed in the ocean to get a fraction of that data.

Currently, the sensors have been designed to be able to measure temperature, pressure and seismic acceleration, later more capacities could be incorporated to measure other variables. Temperature and pressure measurements of the deep oceans would aim to improve estimates of ocean circulation and heat content (associated with global warming), and seismic acceleration and pressure sensors could improve tsunami warning times and the calculation of earthquake parameters.

In other words, the data captured from SMART technology would address two critical issues in the scientific and social context:

1.The long-term need for permanent ocean data, deep ocean temperature, sea level, and ocean circulation.
2. The short-term need to improve global seismic and tsunami warning networks.

- **Tsunami monitoring and warning**

One of the most urgent problems for coastal communities or for countries that have a high population density on their coasts has been developing and enhancing capacities to distinguish destructive tsunamis from those that do not represent a danger along the coasts. distant (Angove et al., 2019). In 1949, 75% of the evacuations from the coasts of Hawaii have been unnecessary, with direct and indirect costs of millions or tens of millions of dollars per event. This is also valid for other coasts of the Pacific basin and other places. To alleviate this problem, NOAA's Pacific Marine Environmental Laboratory (PMEL) developed the Deep-Ocean Assessment and Reporting of Tsunamis (DART) system (Paros et al, 2011; Bernard and Titov, 2015) consisting of a pressure sensor or BPR (Bottom Pressure Recorder) that communicates via an acoustic modem with a surface buoy that in turn transmits the pressure measurements through the IRIDIUM satellite constellation. Prior to the development of the DART system, warning systems had to rely on tide gauges and coastal observations when assessing the potential destructiveness of a tsunami to distant coastlines. As tsunami height can be strongly affected by near-shore bathymetry and harbor and harbor resonance, reliance on coastal observations together with worst-case scenario assumptions made unnecessary evacuations unavoidable. The main limitations of DART systems are that they require their own power source, require maintenance every 2-3 years, and their continuous availability is significantly reduced by adverse weather conditions and, in some regions, by acts of vandalism. Compared to DART systems, SMART pressure sensors installed along submarine cables offer much denser sampling and low or near zero maintenance costs after implementation.

Perhaps the greatest uncertainty facing tsunami warning systems is the determination of the source. Historically, about 72% of tsunamis have been generated by seafloor displacement associated with large submarine earthquakes (the rest from landslides, volcanoes, and others), so tsunami warning systems have focused on the seismology in real time to facilitate and accelerate the dissemination of early warnings of danger by tsunami. Until the last decade, the Pacific Tsunami Warning Center (PTWC) based these warnings solely on the location and magnitude of the earthquake, however, this data alone is not sufficient to accurately assess the effects of a Tsunami. As a result, excessive or unnecessary warnings have been a flaw in ocean-wide warning systems since their inception.

The destructive effects of a tsunami can be further enhanced by submarine landslides (for example, Tappin et al., 2014) because they are very difficult to detect using purely seismological parameters. Faced with this variable, SMART cables, equipped with a set of pressure sensors, would make it possible to generate an accurate assessment of the tsunami wave field as it propagates through the ocean. Currently, there are only about 70 deep ocean sensors (eg DARTs and DONET, S-net wired underwater observatories) in permanent operation and the vast majority of them are in the Pacific basin. Adding pressure sensors along SMART cables could increase that number to hundreds or thousands. This additional near real-time information can be used to validate and/or revise forecasts, making tsunami warnings for areas more than 1,000 km from the earthquake more accurate, greatly reducing the potential for unnecessary warnings and evacuations.

In addition to pressure sensors, the SMART cables are expected to include seismic instruments such as accelerometers or seismometers, which measure the movement of the seabed during an earthquake. With a few exceptions, currently all seismometers and accelerometers are installed on dry land, resulting in a one-sided view of earthquakes generated in the subduction zone. SMART wireline accelerometers would fill the gaps in the global seismic network (GSN) by acquiring data along their paths, even in some cases, as they cross subduction zones. Having a SMART cable with accelerometers close to an underwater earthquake (ie having at least one sensor package within 100 km) would allow for faster hypocenter locations, magnitude estimates, and seismic moment tensor calculations. This additional information would reduce the processing times of the information to be included in the tsunami propagation and forecast models.

Reducing detection time together with a better description of the seismic wave field would help to better characterize the source and improve forecasts in both the near and far fields, reducing unnecessary evacuations, which have long been the subject of criticism to tsunami warning systems and centers.

Many destructive earthquakes occur in nearshore settings, where the oceanic and continental lithosphere converge. Such plate interactions often occur offshore, therefore onshore seismic networks are some distance from the source and provide a one-sided distribution of receivers, limiting the capacity of tsunami warning centers and/or seismological centers for the rapid and correct location of the earthquake. Having a nearby SMART cable, compared to the previously proposed scenario, would significantly improve the estimates of the location of the earthquake by reducing the azimuthal gap of the sensors near the epicenter. Sensors embedded along SMART cables can improve earthquake early warning for offshore events by faster detection of the first seismic waves on closer sensors. This can provide a few seconds of additional seismic warning time for earthquakes that occur near a deployed SMART wire, and also improved detection capability could be applied to the analysis of moderate and small earthquakes that frequently occur in these margins.

The inclusion of highly sensitive accelerometers and pressure sensors along SMART cables has great potential in the field of seismology, improving capabilities to detect and locate small earthquakes below the ocean floor.

5.2. Financing alternatives

The financing alternatives for the incorporation of sensors associated with SMART technology, about the submarine cables, considering that the data obtained from these submarine sensors will be of great interest in both the private and public sectors.

Currently, the SMART cables have been endorsed by major ocean science organizations, and the Joint Task Force - JTF has been working with cable suppliers and sponsors, development banks and end users of the data to incorporate SMART capabilities into future submarine cable projects in various regions of the world, with the idea that by investing now, we can build a global ocean network of long-lived SMART cable sensors that will strengthen the Global Ocean Observing System.

As described in the article "SMART Cables for Observing the Global Ocean: Science and Implementation." Howe et al., 2019, today's submarine cable projects are divided into three main categories: consortium, private, and government. In Projects developed in the consortium mode, a group of established operators join to share costs, however, one of the difficulties in implementing SMART technology is the requirement to obtain approval from a majority of the consortium members.

The private cable projects are undertaken by a single developer using seed funding followed by full project financing with equity and debt. Implementing SMART technology in this category is a reasonable option because the system developer is usually a small group of investors that can be worked directly. However, the priority for these projects is rapid return on investment, so SMART technology implementation should not cause delay or additional costs to the owners.

The projects developed by government entities, or government-backed cables, seek to improve a country's link to the global network. These projects have longer timelines and a wider range of objectives and therefore represent a good opportunity for SMART technology, as they can involve stakeholders from different areas.

Early engagement with potential projects is important to influence the configuration, ensure that SMART requirements are included and obtain funding. Because there is not always prior information on the implementation of these projects, efforts to include SMART technology must have the ability to react quickly and introduce the concept of these sensors into the technical requirements of the project.

An International Telecommunication Union (ITU) study summarized several funding options for SMART cables (IOC Group, 2015), highlighting potential funding sources in the following categories:

- International development agencies.

- Philanthropic foundations.

- Government agencies.

- Private companies.

International development agencies: Regional multilateral development banks have indicated their support for SMART capabilities in the submarine cable projects in which they are involved. The study conducted by ITU mentions that the Asian Development Bank - ADB supports the inclusion of SMART capabilities in the Manatua cable, in part because the locations where these cables are installed are highly exposed to tsunami and climate change risks. The Inter-American Development Bank - IDB is also interested and is supported by the committee of the IOC Intergovernmental Coordination Group / Pacific Tsunami Warning and Mitigation System - ICG / PTWS.

Philanthropic Foundations: Only large foundations can support grants of the size envisioned for SMART technology incorporation (OCI Group, 2015). Foundations contacted by the JTF Working Group include the Schmidt Ocean Institute, Schmidt Marine Technology Partners, Simons Foundation, Paul G. Allen Philanthropies, Moore Foundation, Packard Foundation, and Keck Foundation.

Government agencies: UIT believes that all government agencies manage complex processes associated with bureaucracy and as a result require a great deal of effort to develop financial support, relationships, and consensus. In addition, all government agency funding will depend on the appropriations and budget cycle of the government(s) involved.

Additionally*, Howe*, 2019 mentions that there are several candidates government organizations that should be further investigated for funding, including in Canada "Environment and Climate Change Canada" and "Natural Resources Canada"; in Europe, the Directorate for Research and Innovation - Research Infrastructure Unit of the European Commission, with the participation of the Institute for Environment and Sustainability and the European Multidisciplinary Seafloor and Water Column Observatory - EMSO; in Japan, the Japan Agency for Marine and Earth Science and Technology - JAMSTEC; and in the United States several agencies, including the Department of the Interior, the United States Geological Survey - USGS, the Environmental Protection Agency, the Department of Defense, the Office of Naval Research and the Department of Commerce, Economic Development Administration and National Oceanic and Atmospheric Administration - NOAA. In NOAA's case, funding may be facilitated by the Tsunami Warning, Education, and Research Act 2017 (TWERA; Public Law 115-25) which gives NOAA the responsibility to consider "... integrating tsunami sensors into Federal and commercial undersea telecommunications cables."

The JTF Working Group mentions that funding may be more readily available from governments that are interested in promoting new submarine cable projects associated with telecommunications, and in turn appreciate the value to their country of having SMART technologies as part of strengthening their detection and monitoring systems. In addition, developing countries may be able to obtain funding from the Ministry of Foreign Affairs, or other developed country partners, for community/international connectivity and climate and disaster monitoring purposes.

Private companies: As suggested by the JTF Working Group, their study (OCI Group, 2015) concluded that commercial entities are unlikely to allocate funds to SMART technology because funds for internal research and development are a scarce resource and because such developments may indirectly assist a competitor's development efforts. However, JTF does provide an avenue for commercial entities to support this initiative, through engineering assistance, technical review or standard setting. However, JFT also mentions that as leading digital technology companies (e.g., Alibaba, Alphabet, Amazon, Apple, Facebook, Microsoft) become more involved with cable systems and more socially conscious, they may become more receptive to the development of dual-purpose cables.

In conclusion, it could be suggested that the multiple existing sources of financing should not be approached individually, taking into account the great potential of the private, academic, philanthropic and public sectors to obtain data through the use of submarine cables incorporating SMART technology, highlighting the importance of promoting a strong link between the telecommunications sector, Ministries of Telecommunications of each country, research centers, among others, through incentives or requirements prior to their conceptualization and subsequent use.

6. CONCLUSIONS

The scientific community is now taking advantage of the global network of research vessels, offshore tide gauges, satellites, platforms and buoys, both anchored and drifting to strengthen the Global Ocean Observing System. But while the data collected are critical to better understanding climate change and natural events, they remain very weak with most sensors deployed on the surface and in shallow water, which means that important environmental data are not collected from the deep ocean. In addition, meteorological or tsunami detector buoys, equipped with a number of expensive instruments, are subject to theft and/or vandalism.

The monitoring of accelerations, pressure and temperature of the seabed will help in the early detection of natural events, such as submarine earthquakes and tsunamis that cause damage to human life, coasts, property, security and telecommunications, from a safety perspective. Therefore, the implementation of oceanographic sensors on new submarine telecommunication cables, under the SMART (Scientific Monitoring and Reliable Telecommunications) concept, is a promising solution for obtaining a greater amount of real-time data that are critical to understand and manage urgent environmental problems such as climate change and tsunami impacts. Such sensors can provide important environmental data from deep ocean sites that would otherwise be difficult and expensive to obtain in real time and on large time scales.

Some challenges related to legal, regulatory, financial, security and data exchange aspects still need to be discussed and overcome before SMART technology is adopted and implemented on a large scale. In addition, considering that submarine cables cross different maritime zones and territorial waters, the provisions set forth in the United Nations Convention on the Law of the Sea (UNCLOS) must be taken into account from a national security perspective.

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