

The Geohazard as Land Subsidence; in Anthropocene, India

Abstract

Land subsidence events, natural or anthropogenic, will be future national challenges for India. The positioning of the Indian plate in the globe, and human activities on the frustum compelland subsidence everywhere, on mountains, in deltas, riverbeds and in settlements. Many mega deltas of the globe including India are sinking, shrinking, and subsiding which shall invite catastrophes.

The present search uses the available datasets in print media, books, information technology and electronic media. The survey responses sourced from websites were physically ground verified, etc. Considering Bhuvan data, Arc GIS software and Microsoft Excel, the hazard, organic and inorganic maps of India are prepared to alert our forthcoming ancestors. Using those maps the zonal map of geo-hazards in various states of India can be prepared and future action plans can be shorted out.

Studies reveal that geo-hazards in various zones of India are different. Hazards on mountains are land slide, torrential rain, and land subsidence, whereas the calamities along the coasts, and deltas are cyclones, coastal erosions, floods, and deltaic subsidence. With surging human activities, the frequency and intensity of geo-hazards are swelling presently. It is high time to plan to appease the vulnerability of the rising devastation to attain sustainability of SDG Targets 11.5, and 13 which will moderate the adverse effects of such disasters.

Keywords: Disaster, Land subsidence, InSAR, Sinkhole, Soil piping, SDG 11

Introduction:

The earth has a geodetical surface area of (land: 148326000 km²), 70-71% is undersea, and the rest is the crustal zone with the land, <https://www.nationsonline.org/oneworld/earth.htm>. India, the largest populous country, has a geological area of 3.287 mi. km², inclusive of all ghats areas of 1.23 mi. Km² is most susceptible to land subsidence (LS) as per the Geological Survey of India studies (Upadhyay 2023, The Hindu^[1]). Land subsidence can be natural or Anthropogenic. Generally, natural LS occurs at a sluggish rate but at times turns violent mostly when anthropogenic. Subsidence impacts were scarcely reported during the Holocene (12.80K years before the present, YBP). With the onset of the Anthropocene epoch (from 1950), when humans overruled nature, the subsidence became wild, expeditious, and apocalyptic. It has been amalgamated with other types of geological, meteorological, and climatologic, disaster triggered by anthropogenic activities. At times the LS process is so slow that, it is difficult to detect, measure, and manage losses.

Distractions like excess mining, dams across rivers and underground (UG) oil/water extractions impose penalties that humans made. round subsidence has surged with huge mining activities, underground (UG) water overexploitation, Petrographic wells, dams, industrialization, and urbanization. The common causes of LS are stability of slopes, clay or shell beds between two rock strata, in-situ stresses, mining without filling, weak planes, weak planes, weathering, and seismicity. The major causes are faults, sinkholes, basin sediment and human activities (Fig 1).

Comment [JGEESI1]: This abstract effectively presents the challenges of land subsidence in India and research efforts using various data sources and technologies. The results involve hazard maps in different zones of India, from mountainous to coastal, showing the different geo-hazards and impacts of human activities. For improvement, more details of the methodology and specific findings could be added, as well as some concrete numbers or statistics to reinforce the message. Simpler wording could also improve readability.

Comment [JGEESI2]: for improved clarity, it is suggested to simplify the information. For instance, briefly mentioning the Earth's surface area, India's susceptibility to LS as indicated by Geological Survey studies, and distinguishing between natural and anthropogenic causes would enhance the introduction. Furthermore, providing the historical context of subsidence, particularly the transition from Holocene to Anthropocene, would underscore the intensified impact of human activities on subsidence. The section outlining the causes of LS could be more concise, concentrating on significant factors such as mining, water extraction, and industrialization. Additionally, streamlining the discussion of major disasters in India is recommended, ensuring a clear link to LS. Lastly, the description of subsidence effects could be condensed, potentially consolidating details on structural failures and briefly mentioning the referenced figures to enhance clarity.

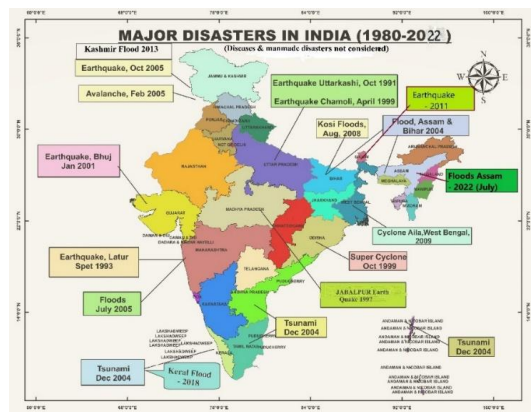


Fig 1: The Major disasters in India except bio-hazards (pandemics) F.Y- 1980-2023

The landshows buckling, sliding, sinking, shrinking, and subsidence by distorting the earth's surface directly by earthquakes, Floods, delta subsidence, tsunamis, avalanches, etc. Resulting structural failures are the formation of fractures in large stones, bridges, foundation settlements or cracks, continuous flood upshots, landslides, sinkholes, and changes in topography, *Fig 2(a, b,c,d)*. (<http://suvratk.blogspot.com/2019/01/cracks-in-rock-and-western-ghat.html>).



Fig 2(a):

Tunnel subsidence UttarKasi Fig 2(b) Crack in Narasappa Konda hills, Kurnool (Fault induced) Fig 2(c): LS in Gaharwar Hills on 7th Jan 2023, *National herald; Chaturvedi, P*, Fig 2(d): Subsidence near shore temple Mahabalipuram (24.08.2023)

Review of Literature:

Comment [JGEES13]: 1. References and Recency of Information: Ensure that the references used are current and relevant to the current research context. Some references are quite dated, and including recent research may provide a more up-to-date understanding of the issue.

2. Separation of Information: Separate information on land subsidence caused by oil and gas extraction activities from information on other causes of subsidence. This will make the literature review more structured and easier to understand.

Land subsidence due to sinking has become a national crisis to many countries in the world such as Jakarta, Beijing, and Bangkok of Thailand, (Schmidt et al., 2015^[2], Mishra et al., 2017^[3]). Land subsidence at a faster rate has been globally observed at @0.75m/yr in petroleum and high-carbon gas extraction oil fields, Mayuga et al., 1970^[4], Van Hasselt, 1992^[5], Pahari et al., 2008^[6], OILproject report 2019^[7], Buffardi et al., 2023^[8]. In SAR (Synthetic Aperture Radar) is employed to guess the relative prompt distortion due to geological disasters like earthquakes, Landslides, glacier shifts, slow subsidence, and uplift over the earth's crust, (OIL, India, 2019^[7], Buffardi et al., 2023^[8], Wang et al., 2023^[9]).

Over-exploitation of groundwater (GW) from shallow/perched aquifers, crude oil, and natural gas extraction are the places of LS. In such aquifers, the overburden (OB) sediment is compressible, unconsolidated, and semi-confined. Globally cities like Jakarta, Middle East, Bangkok, Cochin, Delhi, Osaka, Houston, San Jose, Shanghai, New York (1.6mm/year), Tokyo, and Venice are the observed LS zones having major shrinking, sinking, and subsiding zones, (Gambolati et al., 1996^[10], Arabameri et al., 2021^[11]). Coastal towns like (Kolkata, & Khulna) within the Ganga Brahmaputra Delta (GBMD), the Nile Delta, the Mekong River Delta (Hanoi), the California Baycoasts (Mexico City), and the cities underneath oil and carbon basins in Iran, and Northeast China are undergoing substantial LS (Minderhoud et al., 2017^[12], Bagheri et al., 2021^[13], Mohamed et al., 2020^[14], Garg et al., 2022^[15], Dasgupta 2022^[16], Bramanto et al., 2023^[17]).

The identification, mapping, and management of the LS is a herculean task comprising of in-situ observations, documentation, and mapping of the destruction from time to time by using modern surveying instruments like total station, spirit-levels, InSAR, Interferometric synthetic aperture radar, continuous Global Positioning System (CGPS), if not by global positioning system (GPS) surveying, and DGPS by using GNSS method, (Bilich et al., 2008^[18], Anjasmara et al., 2019^[19]). The LS can be estimated by downloading Sentinel-1A (ascending and descending) SLC (S1 Single Look Complex) images analyzed by InSAR (Interferometric Synthetic Aperture Radar) using SARPROZ, or Multi-Temporal InSAR methods. Advanced technology like PS-InSAR, SBAS-InSAR (small baseline subset of InSAR), or GIS-based ANN model, created by using ArcGIS 10.8 and later mapping for management is made, (Chu et al., 2021^[20], Zhang et al., 2023^[21], Ku CY et al., 2023^[22], Susilo et al., 2023^[23])

Report of land subsidence (LS) is of recent origin (60YBP) in Shanghai City in China with an average land subsidence rate (ASLR) of 7cm/year and increasing with the rise in RSLR (Zhu et al., 2020^[24], Bufardi et al., 2023^[8]). Land Subsidence is triggered by groundwater (GW) withdrawal in emerging and expanding urban areas with rising populations (Abd Elaty et al., 2023^[25], Babtubara et al., 2023^[26]).

The literature available depicting LS identification, estimation, and management is scanty and sporadic as not covering all subsidence types. The present investigation is to search electronic media, past literature, newspapers, and library sources and make an assessment of the gravity, trend, and future catastrophe.

Objective: The objectives are:

1. Type of disasters pertain to the land disaster that is causing catastrophe in India
2. To find the sinking, shrinking and subsiding deltas on the East coast of India

3. Preparing a zonal map other than biological and man-made disasters in India,
4. These research stresses various types of land subsidence that are occurring presently in India, their ferocity, finding their causes, and ameliorating measures in India.

Methodology:

Subsidence is loss of land and endangering people in millions more vulnerable. Various profile has been associated with subsidence. They are (a) Continuous subsidence (b-1) Stepped deep subsidence profiles with strong and rigid overburden, and (b-2) Incessant stepped subsidence profiles with weak and flexible overburden. The subsidence is an outcrop of aquifer differential compaction or aquitard drainage, huge extraction of UG organic soils, mass wasting of sodic soil, and failure of vulnerable UG materials and overburden.

Comment [JGEESI4]: providing further explanation of the type of Remote Sensing (RS) data used, its characteristics, and the selection of the SENTINEL-1A platform can provide richer context and understanding of the fit with the research needs.

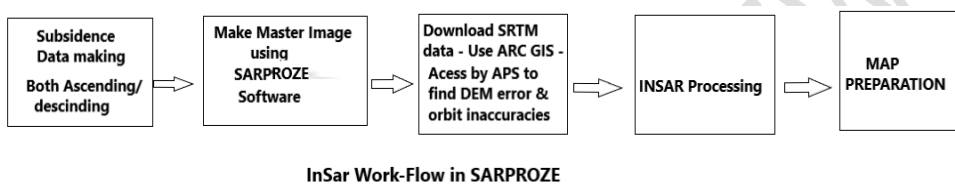


Fig 3: In Sar Workflow diagram (Sarproze) to measure land subsidence

Fig 3: The In-SAR workflow diagram to prepare the subsidence hazard map diagram. As per NOAA's geodetic survey network, the high precision GPS receivers called CORS, Continuous Operating Reference Stations (CORS), detect and track differential heights by using satellites or use of InSAR (Interferometric Synthetic Aperture Radar), or SBAS-InSAR, regular geodetic installations of ground/water sensors (Orhan et al., 2021^[25]). For ascertaining the amount rate and degree of subsidence, initially, RS data is acquired by using the SENTINEL-1A platform for both ascending and descending SLC images. Later analyzed by applying the InSAR and PS-InSAR, with SARPROZ software (Fig 3). The estimation of subsidence depends upon the knowledge availability and the sincerity of the government (Wang et al., 2019^[26], Shirzaei, et al., 2021^[27], Sekkaravani et al., 2022^[28], Ku et al., 2023^[29], Liu et al., 2023^[30]).

Other methodologies that can be used are stochastic methodology, GIS-based Artificial neural network (ANN), and preparation of maps can lead to planning efficiently GW management, lift Irrigation, and management for forthcoming agriculture, particularly in Arid regions of India using evapotranspiration (ET) method, (Nazari et al, 2020^[31], Garg et al., 2022^[32], Tzampoglou et. Al., 2023^[33], Cigna et al., 2023^[34]).

Result

Types of Subsidence:

Subsidence can be natural or Anthropogenic. Natural land subsidence comprises tectonics, coastal subsidence caused by extreme geo-meteorological events, Climate changes, regional sea level rise (RSLR), global warming, natural sediment compaction, glacial isostatic modification, and changes in sun earth geometry are sluggish and slow, (Mishra et al., 2020^[35], White J., 2018^[36], Mishra 2018^[37], Siriwardane et al, 2021^[38], Britannica 2022^[39]).

Comment [JGEESI5]: 1. Improving Topic Structure and Unity:

Break up long paragraphs into smaller paragraphs by focusing on one main topic. Make sure each paragraph has a clear topic sentence. Refinement of Sources and References:

2. Add more information for each reference mentioned. Choose more recent and relevant references to increase credibility. Additional Explanations on Tables and Graphs:

3. Include a detailed caption for each table and graph so that the reader can understand its context and relevance.

Georelated and Biological Disasters: Georelated and Biological Disasters: Coastal subsidence impacts are becoming more apocalyptic than Biological Disasters gradually. The decadal geo-related disasters and Bio-related disasters from 1900 to 2020 are in **Table- 1**
 Table 1: Geobased disaster and biological disasters, fatalities with outbreaks (1901-2010).

Decade	Geo-related hazard deaths			Bio- Hazards deaths		
	Geological disaster	No of spells	No of deaths	Disease	NoOut-breaks	No of deaths
1901-1910	Landslide(LS)	1	20000	Outbreaks	1	1300000
1911-1920	Wind storm;	1	30000	Outbreaks	2	2500000
1921-1930	Wind storm;floods	6	2043	Outbreaks	2	72300
1931-1940	Wind storm; Eq	6	122342	Outbreaks	0	0
1941-1950	WS; EQ;Floods, LS;	13	1548939	Outbreaks	0	0
1951-1960	EQ, HW, Flood Landslide; WS	30	5423	Outbreaks	0	0
1961-1970	Drought;EQ,HW,Lan dSlide;WS,Flood,	43	1515843	Outbreaks	1	3029
1971-1980	Drought;EQ,HW,Flo od,LS;WS	93	38708	Outbreaks	9	3461
1981-1990	Drought;EQ,HW,Flo od,LS, WS	107	23730	Outbreaks	18	16413
1990-2000	Famine; EQ,HW, Flood, LS Slide;WS	93	46778	Outbreaks	20	1676
2001 -2010	Georelated disasters	13	≈852	Outbreaks	5	2165
2011-2020	All natural disaster	Na	20047	Cholera+C ovid deathIndia 2020	2 (consid ered)	148738 +263= 149001

Source:https://www.adrc.asia/publications/databook/ORG/databook_20th/IND.pdf: Synchronims : EQ: earthquake; LS: Landslide; WS: wind storm; HW: Heat waves;
<https://www.statista.com/statistics/1007056/india-number-of-deaths-due-to-natural-disasters/>

Types of Natural Subsidence.

They are (i) Eruption of UG materials: (ii) Drainage of organic soils: and (iii). Natural consolidation: (iv). Sinkholes: (v). Thermokrasts or Thawing permafrost: (vi). Hydro compaction: (vii). Landslide; (viii). Tunnel erosion: Present soil pipes or tunnel erosion occurring in Western Ghats Belts, LS in Uttarkashi tunnel have become national issues.

The rate of various Land Subsidence:

The observed Land subsidence in various places in India as per Down to Earth (Sah, VK., July 19th 2023) are New Delhi at Kapashera (10-17cm/year), Raj Nahar at Faridabad (5-7cm/year), Landran at Mohali (4-7.5cm/year), Kolkata University (0.65cm/year), and Raysan Gandhinagar (0.52cm/year).

Geological formation India

The Great Himalayas are geologically of recent origin (130 to 140 MYBP) covering the northern Indian border. It is structurally steep, and folded mountains stretch over India's

northern borders. The two ridges are the Western Ghats Belt (WGB) Hills and the Eastern Ghats Belt (ECB) Hills. (Subramanya 1996^[40], Nayak et al, 2020^[41]). The Mean Sea Level (MSL) rise of 170 mm globally, has surged the flood risk and land subsidence, and the melting of glaciers in the Himalayas, and a series of manmade dams has added to the land subsidence.

Factor affecting Land subsidence

Anthropogenic coastal: The growth of the population from about 361 million in 1951 to about 1428.6 million in India has almost emptied the coastal aquifers and has increased salinity intrusion. Deforestation, agriculture, drinking water, urbanization, and socio-economic growth have augmented land subsidence, (Jade et al., 2017^[42]). The salinity intrusion, sea level changes, high waves, and storm surges trigger coastal LS. In the future, the problem shall grow and become worse in many coastal reaches, (Marker 2013^[43]).

Subsidence in Mining areas: Mining activity in India in 3527 mining lease (3159 km²) areas to extract 40 major minerals. The mining (coal, stone, or Karstic) causes UG voids (man-made or natural), relatively adjacent to the earth's crust surface. The areas in Raniganj, Jharia, Bailadila, Talcher, Sukinda mines, and Rajgarh coal mines of Korba (Harichandan et al., 2022^[44], Govil et al., 2023^[45]).

Karst environment: In the Karst environment, cavern formations with subterranean drainage systems are created by the subsurface. It is due to the presence of limestone/dolomite and develops speleothems. Krem Mawmluh or Lait Prah Cavern, near Cherapunji in Khasi Hills of Meghalaya. The limestone rocks are physically barren and rocky with caverns, sinkholes, UG streams, and lakes formed seasonally. The Cuddapah basin in central India is suffering from subsurface dissolution (solution sinkholes, or subsurface karstification) are subsidence sinkholes. The mechanisms are collapse, sagging, and suffusion occur as one or conjointly, (Bhaskar et al., 2011^[46], Mishra SP, 2022^[47], Saikia et al., 2021^[48]),

Fig 4 (a, b).

Over extraction of UG water: Over-exploitation of GW in India:

The population burst in Indian cities has overdrawal of GW is the main cause of man-made subsidence. The depletion of groundwater as per Down to earth between 2000-2020 is Punjab ranks highest with 150.678m, Meghalaya (13.511m), followed by Uttar Pradesh with 10.629m and Haryana with 6.592m (source: National Water Informatics Center, Groundwater report for India).

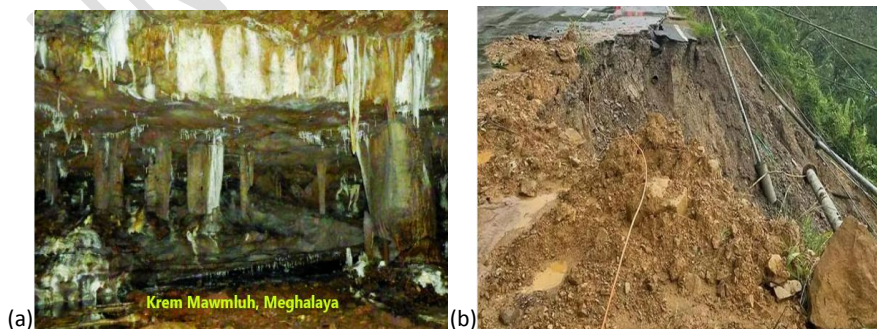


Fig4 (a): The Krem Mawmluh (Cavern), Natural Karst subsidence Meghalaya; Fig 4(b): Land subsidence Assam 21st May 2022. Source: The Sentinel, 30th Aug 2023, Mr. Gunin Borah

The intrusion of saline water has made the aquifers brackish. The problem of coastal subsidence is well felt along the coasts. Lift irrigation borewells in number in Kerala, AP, Tamil Nādu, Odisha, Gujarat, and West Bengal contribute largely to LS (Huang et al., 2014^[49]; Mitra et al., 2016^[50], Dasgupta A., 2022^[16]). Urban areas like Calcutta, Mohali (Kadian et al., 2021^[51]), North India (Raju et al., 2022^[52]), and NCR New Delhi (Kumar et al., 2022^[37]) are extracting huge quantities from aquifers for drinking.

Excess drawl of natural gas or crude oil:

The differential interferometric technique reveals that there shall be subsidence in and around the oil or natural gas extraction areas Chabua, Tinsukia, Duliajan, and Digboi of Arunachal Pradesh/ Assam in NE states India. Other coastal areas where extraction is yet to start are the Coromandel coast (Andhra and Tamil Nādu), Kachha coast (Saurashtra and Gujarat) (DGH, 2019^[54], OIL report, 2019^[07], Ellis et al., 2023^[55])

Sinkholes: Local collapse of the upper layer triggered by underlain materials causes cavities in comparatively soluble deposits like limestone salts like carbonate and gypsum rocks, Karst Terrain. (Fig 5 (a) & (b))

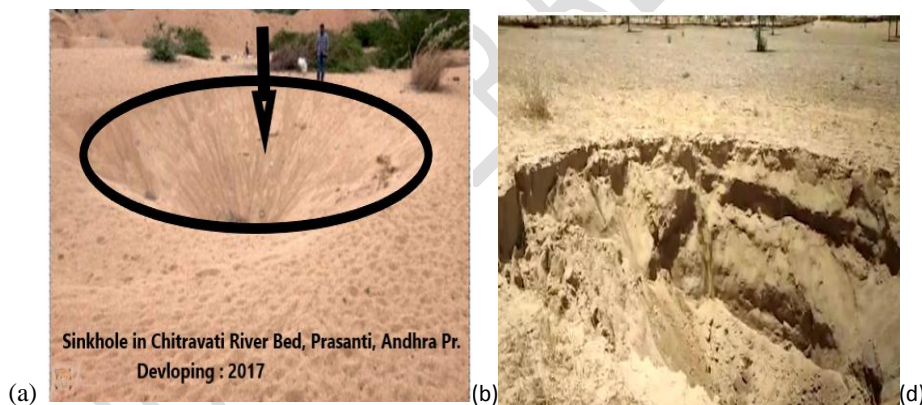


Fig5(a): The sinkhole found on Chitravati R. (Anantapur dist. AP) Prasad; et al., 2020 Fig 5(b): Odisha coast, a day in dry summer

Deltaic subsidence:

Major deltas are formed along the East Coast of India. They are granary to millions of people but some of them are in states of sinking, shrinking, and subsiding (SSS). (Syvitski, et al., 2009^[56]). The subsidence of the Ciliwung Delta (like The Irrawaddy Delta, and Parana deltas) confronted 9m of subsidence in menacing Jakarta north, due to overexploited groundwater, (Loukes, 2019^[57]).

The huge deltas are formed along the east coast in large rivers, but small rivers do not. The east-flowing small and west-flowing rivers do not form deltas but have estuaries as they travel through rocks, and elevated WGB Hills. Huge numbers of Dams, hydraulic structures, and anastomosed canal systems are the reasons for the paucity of sediment entry to their respective

delta. The climate change and MSLR (av. 1.29mm/yr) add to the subsidence of the deltas. Assessed sediment deficits to the major deltas along the east coast are @40%, 50%, 74%, and 94% in the Godavari, the Brahmani, the Mahanadi, and the Krishna deltas respectively. (Unikrishnan et al, 2007^[58], Mishra et al, 2017^[59], Steckler et al., 2021^[60], Rahman et al, 2022^[61], Syvitski et al., 2007^[66], & 2022^[63]).

The GBMD, is the largest delta subsiding due to changes in sun-earth geometry, climate, and global temperature, (Farooqui et al., 2016^[68], Grall et al., 2018^[65], Krien et al., 2019^[66], Mishra et al. ^[67]). Some delta on the east coast and west coast of India are under SSS due to the construction of dams that sink, shrink, and subside. The effects are loss of coastal vegetation, wildlife, ecosystem, and storm defence, (Mishra et al., 2015^[68], Zhao et al., 2022^[69]). The details are in Table 2.

Table 2: Land subsidence in Various deltas along East Coast India.

Delta of river	Apex of Delta	Length of river (Km)	Area of delta in km ²	Silt retained	Subsidence in mm/yr	Source
GBMD: Ganga B-putra Delta sub-aqueous	Farka	Ganges-2525km B-putra 2900Km	105000 Km ² (40% India)	50%	2-3mm/year	Krien et al. 2019 ^[66]
Brahmani-Baitarani	Jenapur	799	≈2989	75%	depositional	Dandekar P. 2014 ^[70]
Mahanadi delta	Naraj	851	9500	67%	Developing; depositional	Mishra et al 2017 ^[71]
Godavari delta	Raj-Mahendri	1464	5200	74%	1-2mm/year	Rao Kakanie tal. 2010 ^[72]
Krishna	Vijayawada	1400	4800	87%	4mm/yr depositional	Narayayan 2014 ^[73]
Cauvery	Tiruchirappalli	805	17386	80%	2.3mm/yr	Gupta et. Al. 2012 ^[74]
Narmada	No delta	1312	Join the Gulf of Khambhat	95%	Estuaries	Dandekar et al., 2014 ^[70]
Sabarmati	No deltas	371	Join the Gulf of Khambhat	96%	Estuaries	Dandekar et al., 2014 ^[70]

GBMD: Ganga Brahmaputra Meghana delta Source: -Parineeta Dandekar, SANDRP parineeta.dandekar@gmail.com

Soil Piping (Kerala):

The major land subsidence has been affecting most of the districts of Kerala along the Western Ghats have sodic soils (with > 6% exchangeable sodium) that are susceptible to dispersion. The severely affected are 12 out of 14 districts. Out of a total area of 38867 Km² in the state 6365.12 km² of land is pretentious by soil piping or tunnel erosion. They are enumerated as 139 in number between 2018 and 2019 by the State Emergency Operations Centre SEOC-KSDMA (Kerala State Disaster Management Authority), (Fig 6 & Table 2). The districts, Kasaragod, Kannur, and Malappuram have oversized severe soil piping. The mature piping is in Wayanad, Idukki Kozhikode, and Thrissur districts with larger land subsidence sites. The small and juvenile pipes are sporadically seen in southern districts

of Kerala like Thiruvananthapuram, Pathanamthitta, Ernakulam, and Palakkad. The districts Kollam, Kottayam, and Alappuzha have the least soil piping areas (KSDMA PR by Jain 2020¹⁷⁵)

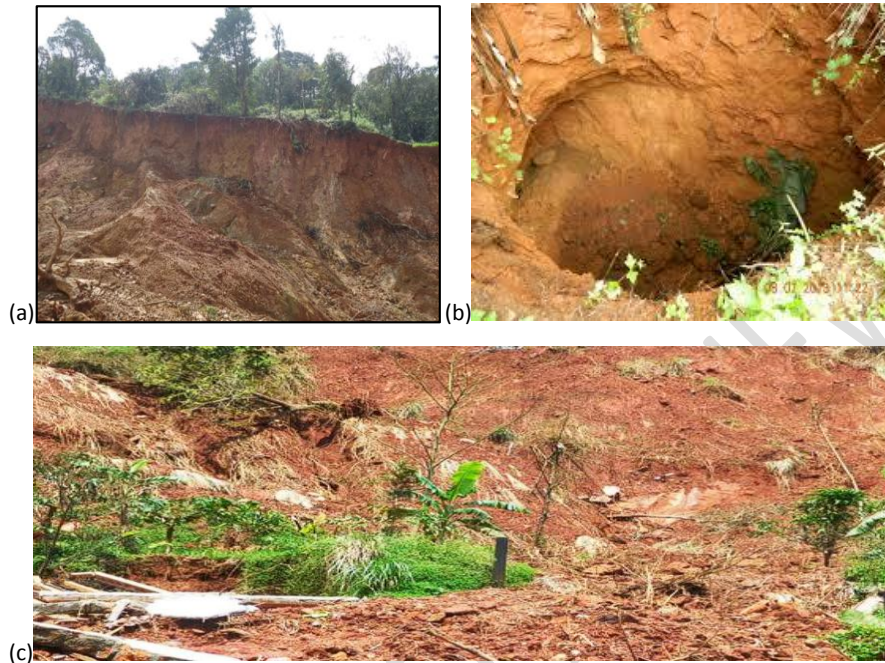


Fig 6 (a), (b), (c): The soil piping disaster in various states of Kerala (Source: KSDMA project reports)

Land subsidence in Joshimath:

Recent LS Occurrences in the western, central and eastern Himalayas are the focused crisis for India. Joshimath's incidence is recent. The LS causes, measuring and planning are in Table 3; Fig 7(a & b)

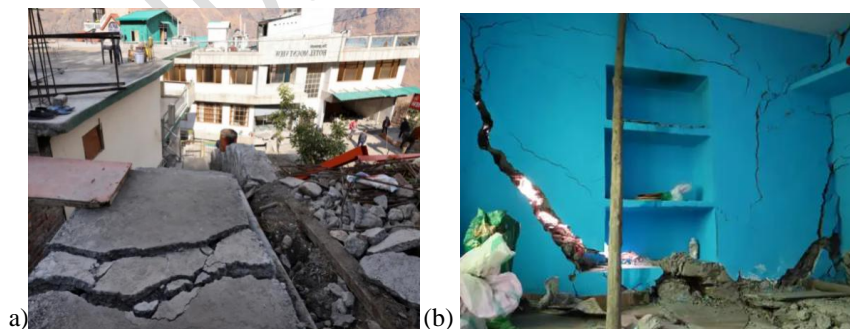


Fig 7 (a): Karna Prayag 80km below Joshimath (Source modified: BBC news, The Print); Fig 7(b): Aljazeera (AnushreeFadnavis/Reuters) LS at Joshimath 23-01-2023;

Table 3: Land subsidence detected, causes, and action plan at various places in India

Place or location	Cause of Subsidence	Measured	Action proposed
Joshimath, U- khand; 1403 from 2152homes unsafe declared; 472 need rebuilding; No access;	surgedbuildings, Dam structures; population; erosion; balding;hydro - power activities. geo- graphy of the area	Start 1976; peak 2023; 5.4cm in 12 days (Dec 27 th to Jan 8 th) (ISRO)	Ban new house; balding; close hydro- projects; drainage plan; divert snowmelts correct weather forecast
Calcutta City (Raja, &Machhua, Bazar, CU, Sci. Col., (Banerjee 2020 ^[76])	1992–98 with an @ \approx 5 to 6.5 mm/y, subsidence due to overburden silt&clay	D-InSAR (GPS tech), DIAPASON software, French makes	developed by the French space agency (CNES)
Raniganj Coalfield, Damodar Valley, Asansol, West Bengal	Subsidence is related to overburden	Freq. ratio (Fr),statistic index (SI), Mamdani fuzzy models	Visco-elastic model Indian coalmines; env. Awareness, retrieve subsided land
OIL, Chabua, Duliajan, Tinsukia, &Digboi, Assam, Diyan(Arunachal Pr.)	Envisat, ALOS PALSAR, I & II (GPS)	DIn-SAR application, Using GPS technology	DInSAR- finding &monitoring land sinking Brahma Putra Valley
Lat Tamala, Bhawari, Bhagirathi Valley, Garhwal Himalaya	Uttarkashi EQ,1991, Varuna vatlandslide (2003) & flash flood AsiGanga (2012)	RS technique; Cloud burst;Seismtectonics	Buildingslope defence to roads, and agriculture near steep sloping areas &drains
Jharia coal field belt, India (Sunil Ku. et al., 2020 ^[77])	Coal mining activities without refilling, deformation29mm/yr Cumulative 90mm	Multi-temporal C-band ENV- ISAT ASARdata by modifiedPS- (InSAR tech)	detect, monitor, and mapping of slow deformation, plan for vegetation, and refill
Subsidence KapaShera& Faridabad in New Delhi, Uplift at Dwarika, Delhi (Dasgupta A., 2022 ^[16] , Garg et al., 2022 ^[15])	Unregulated GW lift; 11 cm/year in Kapa- Shera& 3 cm/year in Faridabad. worsening subsidence 2014-2020; Tilt &cracks in UG pipes shall come up	Sentinel-1 imageof EuropeanSpace Agency-014; by RS technique using differential interferometry,	Rainwater harvest, aquifer recharge, pond revitalization, curbing GW thefts,rural plantation,&GW conservation.
Sinkhole Cuddapah Basin, YSRDist, AP. India (Prasad M., 2019 ^[78])	Sinkholes form after heavy rains & sudden recharge, Buggavanka,Chitravati River beds	Prolonged drought and over-drawl of groundwater	ParnapalliChitravati Balancing Reservoir and BuggavankaDam (2000)
Ganga Brahmaputra delta(GBT)	Installed new GNSS co- located with Rod Surface Elevation Tables (RSET)	GPS stations giveLS rate estimates of 3-7 mm/yr (2003-12	Krien et al., 2019 ^[66] also found the LS valuedat 0-3mm/yr,Steckler, et al., 2021 ^[60]
Chennai city	GWexploitation Madras City(Kodamb- akkam);	Persistent Scatterers	Steady & Constant g - 65 mm/yr in 2019; Av

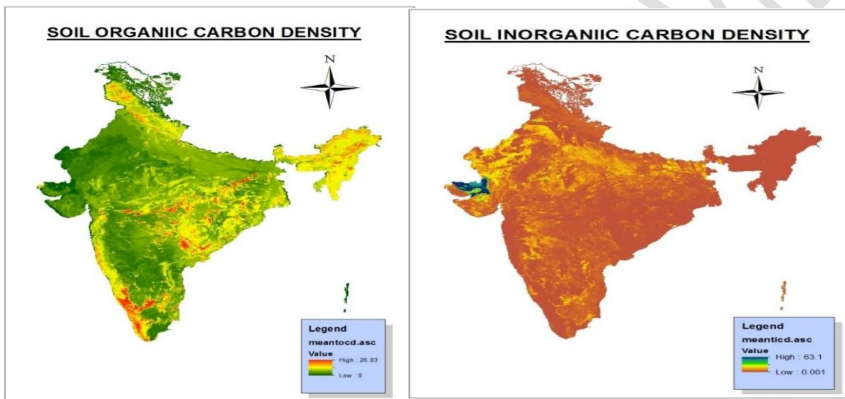
	shift seaward \approx -30.66 to 25 mm/yr	Interferometry (PSI) method.	1.2mm/yr Seshanath, et al. 2023 ⁷⁹ ⁵¹
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Abbreviations: OIL: Oil India Limited, India 2019; Synthetic Aperture Radar (SAR); Global Positioning System (GPS),

Radars of high resolution are used that recognize the expanses under rapid subsidence or structures under deformation. Radar interferometry (InSAR) has detected large numbers of buildings are at risk of subsidence. The core affected areas subside wild but the peripheral buildings deform slowly. This subsidence gradually ceases with time and normal sinking. https://nisar.jpl.nasa.gov/system/documents/files/23_NISAR_Applications_Subsidence.pdf

Zoning of Land Subsidence

The recent (2022) available soil data from the Indian satellite (Bhuban) has been captured and processed in Arc GIS to prepare the organic and inorganic maps of India. The zoning of the maps was based on the type of soil, its erosion or accretion capabilities, and meteorological and extreme events taken from print media and websites (Fig 8(a, b,c) and Table .



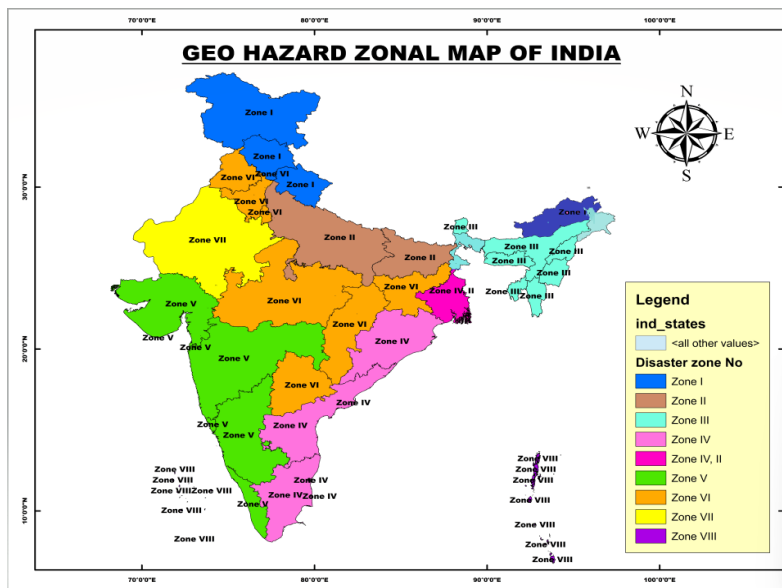


Fig 8(a): The organic carbon density soil map of India Fig 8(b): The inorganic soil density map of India. Fig 8(c)The dominating geo-hazard map of India

The major causes of LS in various zones in India are different. The causes that dominate along various zones except the biological disaster **SARS Covid-19** are given in Table 4

Table 4: Zoning land subsidence consequential of various Geo-climatic disasters in India

Zoning/zone name	States	Major geo-climatic disasters	Examples of recent large Geo-climatic disaster	Sources
Zone I (Western Himalayas)	J&K; H.P.; Arunachal Pr. Ladakh; Uttarakhand	Avalanches, landslides, cloud bursts, floods, Seismicity	Lahul valley-1978 & 1979- 267 deaths; J&K-2005 deaths 540	Acharya et al., 2022
Zone II (Central Himalayas)	UP, Bihar; North-Part of West Bengal	Seismicity; Landslide; Floods	Bihar; EQ of 15 th Jan 1934; 25 th Aug 1988, 166 dead/1209 injured.	OCHA- 22 Aug 1988
Zone III (North Eastern Himalayas)	Assam and its seven states and Tripura,	Seismicity, Karst subsidence, Floods, Landslide,	Assam: August 15, 1950; 4000 dead, seismicity: 8.6R	Mishra et al., 2022
Zone IV (2500km EC India)	WB, Odisha Andhra Pr, TN, Puducherry	Storms, Coastal erosion, Floods, Tsunami droughts	31 st Oct 1999 Super Cyclone Paradip: >10000 dead; Deltaic subsidence	Sahoo et al., 2019
Zone V (West Coast)	Kerala; Goa Karnataka; Maharashtra;	Storms; RSLR; cyclonic storms; land subsidence;	Mumbai coast is subsiding 2mm/year; Munroe Island	TOI News 6 th July 2022

India)	Gujarat, Damn, Diu	Soil piping in WGB Hills	shrinking after Tsunami 2004	
Zone VI (Peninsular India)	MP, Haryana, Chhattisgarh, Jharkhand, Telangana, Delhi	Drought, Landslides, Heavy Rainfall, landslides, mostly by man-made hazards	Mostly safe from major disasters but marginally affected by droughts, landslides & cloud bursts	GOI, MoHA, Lok Sabha unstarred AQ 1238; 3 rd Mar 2015
Zone VII (India in deserts)	Rajasthan, Gujarat	Heatwaves, Westerlies, Sand storm, LOO	Sand storm; Heatwaves; pestilence; westerly winds; desertification	GOI, MoHA, LS unstarred AQ 1238; 3 rd Mar 2015
Zone VIII (India in Ocean)	Andaman & Nicobar, Lakshadweep	Tsunami, Cyclone, High waves, Land subsidence,	Cyclones, sinkholes, Subsidence of islands	GOI, MoHA, LS unstarred AQ 1238; 3 rd Mar 2015

Source: Landslide Atlas of India-2023; MoHA: Ministry of Home Affairs; AQ: Assembly Question; **EQ:** Earthquake; **OCHA:** The United Nations Office for the Coordination of Humanitarian Affairs;

Along the coasts, the players are sediment trapping by dams, and Climate Change (CC). Presently the yield from farming is dwindling in the deltas as they are sinking, shrinking, and subsiding. The freshwater paucity in coastal aquifers, dwindling sediment influx to the lower delta, and increase in saltwater intrusion pledge land elevation to decline. The land subsidence in the deltas is prompted by anthropogenic activities of the highly populous deltas.

Quantifying Subsidence:

After identification of the LS site, type, and intensity, it is pertinent to quantify the rate of subsidence. The instruments and gadgets needed for measuring the amount and rate are time-to-time field surveys, geodimeters (an electronic distance measuring device, or EDM), LiDAR (Light Detection and Ranging) as extensometers, continuous GPS (CGPS) measurements, vertical sink for short elevations georeferenced with data, interferometric synthetic aperture radar (InSAR), and spirit-leveling.

Resolutions To Diminish Land Subsidence

Discussion:

The Variables that cause land subsidence and susceptible factors in India are Hydrometeorological, Geological Petrology, Geomorphological, climatological and Anthropogenic. Land subsidence (LS), which occur due to flood, Storms, droughts, landslides, and EQ are the major disaster associated with tectonic movement and climate change (CC).

Sinking and subsidence of the land or underneath materials occur due to UG material movement. The subsidence generally occurs in areas with high organic matter content associated with compaction and oxidation like swamps and recently deposited alluvium, faults, or sinkholes in coastal areas. The collective penalties of recent Anthropocene climate changes are induced by changes in sun-earth geometry, MSLR, Global warming, regional sea

level rise (RSLR), geo-meteoritic insurgences, deformations, storm intensification, and surges triggered by human activities are the causes of land subsidence, directly or indirectly.

Poor and unplanned water flow management associated with over-exploitation can alter the topography of drainage patterns and can cause land subsidence. Land subsidence occurs in rivers, drains, and canals, and increased underground (UG) water extraction is exhibited by landslides, embankment breaches, sinkholes, or depressions.

India is a land of mines, and minerals and mining are datable to the Chalcolithic (copper-stone) age (4000YBP to 3800YBP). Mining activities are intense in the Anthropocene epoch. The old mines and active mines can have subsidence. It is attributable to a few subsurface mining (both UG or opencast) techniques, like backfilling, pillar extraction, longwall mining, and caving," like "block" or "sub-level" caving". Mining subsidence has been detected after notice and intensity varies on its degree, time of mining, or surficial pothole appearance in the vicinity of structures or land.

The worst damage to the natural environment, structures, and infrastructure is typically caused by the associated surface compressive and tensile strains, curvature, tilts, and horizontal displacement rather than the vertical magnitude of the subsidence itself, except for drainage (including natural drainage).

Many parts of the Himalayas have unstable and dynamic geology, which may lead to land subsidence and landslides. The latest landslide and, subsidence hazard bump into the structures at Joshi Math, Uttarakhand, and Phagli in HP. The Geological Survey of India (GSI) has been equipped with landslide maps in those zones, whereas the subsidence map of India is yet not structured. In the western Himalayan range, the rise in land subsidence has surged due to global warming, deglaciation, erratic monsoon, mountainous slope intrusion along with human interventions, like the construction of dams, Roads, mining, deforestation, industrialization, and urbanization.

Chameli district is the 2nd ranked district after Tehri Gharwal district in Uttarakhand, has been designated by the MoEF&CC and has diverted 586.84Km² of forest land for other human uses such as the development of Hydropower, seepage, erosion, heavy rainfall, water supply, roads, urbanization, and power transmission during the period 1991 to 2021 (<https://qz.com/warnings-on-indias-sinking-town-have-been-ignored-1850010171>). Commencing from 1976, the Mishra Committee report and many studies to date. Joshimath LS tragedy can be ameliorated only by stabilizing the Himalayan mountainous slope, planning by zoning, an old water collection system, its forests, an efficient drainage network, and a tremor-resistant structure.

The cessation of ground sinking can sometimes result in unexpected environmental issues. Various natural players like, isostatic adjustment, tectonics, and the spatial/ temporal changes in sediment. Along the coastline, LS occurs onshore and lee side of dunes that may gradually affect the coastal zone areas, or/and distort the estuarian configuration. In the case of lagoons, natural phenomena like bay disturbances, high waves, tides, etc. The ground reflections are the closing/opening of tidal inlets, the lagoon's salinity, and spit width changes.

Sediment paucity reaching deltas due to the construction of dams and effective management of hydraulic structures blocks sediment reaching deltas through its single entry point the apex of the delta. The GBMD is the largest and most densely populated delta in the world,

covering ~100,000 km² with a population of over 130,000,000 people. The GBMD is susceptible to inundation, flash flooding, and cyclonic impulses, (Chiu et al., 2016[80]). Warming places the region at high risk for storm disasters, land subsidence and flooding (Mishra et al., 2020[81]). Places like Mexico City even have annual land subsidence of 38mm/yr (Mishra et al, 2023^[82])

Some LS is so sluggish that the damages caused remain unnoticed but apocalyptic. Subsidence generally occurs in places where there is plenty of space or more organic matter. So, subsidence is prominent in swampy areas or cracks, faults, floods, landslides, etc. So, the planners, economists, politicians, and the engineers should be blind to it.

SDG 11.5 stipulates by 2030 there shall be a considerable fatality reduction and the number of disaster victims. There shall be a substantial decline in the direct economic losses compared to global gross domestic product (GGDP) instigated by disasters, inclusive water-related disasters, focussing on the protection of the financially underprivileged and people in vulnerable circumstances. Methods in practice to reduce LS, are in *Table 5*

Table 5. Various methods and processes to prevent land subsidence

Methods to reduce LS	Process	Structures to be constructed	Protect type of subsidence
Slope Stabilization	Slope to be inequilibrium	Terracing/ erecting retaining walls	Landslide and erosion
Soil stabilization	Planting trees on slopes holding soil	Creating deep-rooted trees	Landslide and protect erosion
Firming up foundation	Foundation strengthening or underpinning	Constructing RCC terraces	Protecting sliding and collapsing
Planning and zoning	Finding vulnerable landslide/erosion zones	Isolating risk belts as green zones & erection zones adopt new methods	Separating safety from unsafe zones protecting LS
Coastal structures from erosion	Protect vulnerable areas from coastal inundation	slope protection, Spurs, geosynthetic walling, Iowa vane construction, mangrove or mangrove associate plantation	To save coastal flooding, LS & inundation
UGW recharging	Monitor GWT depletion zone due to over-exploitation	Protect Water harvesting structures, more surface flow, restrict GW, house recharge ponds artificially	To protect LS in Cosmopolis protect water bodies
Salinity intrusion or substitute water resources	Monitor coastal aquifer salinity; avoid over-use of water fresh GW. Water metering	Stop pumping GW for water supply & irrigation. Reduce use, pump depth, and vast construction along the coast	Coastal erosion, and yield from coastal farms, affect the food industry.
Control LS in Mines	(It can be active mines, and mines abandoned		

Active and live mines	Plane Fitting; Trench Around buildings; Tension cable; Hydraulic Sand Stowing, Goaf Pillar, Harmonic mining, Partial Extraction Method, Splitting of Pillar with Stowing or with side bolting, chess Board, wide and stall method of protection, Noneffective width
Abandoned Mines	Point Support Method, Pneumatic flyash or fly ash slurry or grout Injection or pumping; Gravel Column; Fabric Formed Concrete Areal Backfilling,
ABB: UGW: Underground water; GWT: groundwater table	

However, water resources managers need to control UG water drawl, identify potential substitute Water Resources for future use, mandatory artificial GW recharge in urban, and strengthen scientific research to monitor and plan for ameliorating land subsidence in places where there is water and oil wells, and UG mining activities.

Conclusion:

Globally deltas institute 5% of the inland area and accommodates more than 500 million stakeholders. The subsidence impacts are multifaceted, and both short-term and long-term consequences. The climate-induced subsidence has primarily ecological impacts, loss of vegetation cover, habitat fragmentation, and commotion in wildlife corridors. The overall result is a decline in biodiversity that has a negative move on the local ecosystem's resilience.

Mine Subsidence which is a manmade disaster, can be ameliorated, by field surveys, sinking estimation, and monitoring methods. The appropriate methodologies used to measure are 3-D models under geo-mining conditions in India. Innovative techniques like Global Navigation Satellite System (GNSS), Total Stations, 3D Laser Scanner (LiDAR), GPS methodology, etc., can be used and planned accordingly to assess causes and mechanisms, suggesting remedial measures to reduce impacts of Land subsidence in mines areas.

LS shall pose a major cataclysm in the future developing economy of rising cosmopolis for overexploitation of groundwater, extraction of mining materials, and erratic ENSO, and Coastal cities shall have problems of salinity intrusion, inundation, and submergence, due to global warming and RSLR. The sinking, shrinking, and LS of deltas due to anthropogenic activities like damming, climate change, and change in sun-earth geometry

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Comment [JGEESI6]: Ensure that the conclusion includes a summary of the main findings, is clearly linked to the introduction, and is consistent with previous results. Review the global implications of the issues discussed, include mitigation suggestions or recommendations, and describe the importance of your findings in the context of sustainability. Link to the role of stakeholders, and end with a strong statement summarising the significant impact of your findings in the relevant area. By doing so, the conclusion will be more coherent, informative, and effective in conveying the message to the reader.

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