Journal of Geography, Environment and Earth Science International

Volume 27, Issue 12, Page 45-63, 2023; Article no.JGEESI.110343
ISSN: 2454-7352

The Geohazard as Land Subsidence in Anthropocene, India

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

Article Information

DOI: 10.9734/JGEESI/2023/v27i12736

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/110343

Original Research Article

Received: 08/10/2023
Accepted: 15/12/2023
Published: 19/12/2023

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 compel land 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 Bhuban data, Arc GIS software and Microsoft Excel, India's hazard, organic and inorganic maps 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.

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1. INTRODUCTION

The earth has a geodetical surface area of (land: 148326000 km^2), 70-71% is undersea, and the rest is the crustal zone with the land, https://www.nations online. org/oneworld/ earth. html. India, the largest populous country, has a geological area of 3.287 mi. km^2, inclusive of all ghats areas of 1.23 mi. Km^2 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, disasters 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).

The land shows 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).

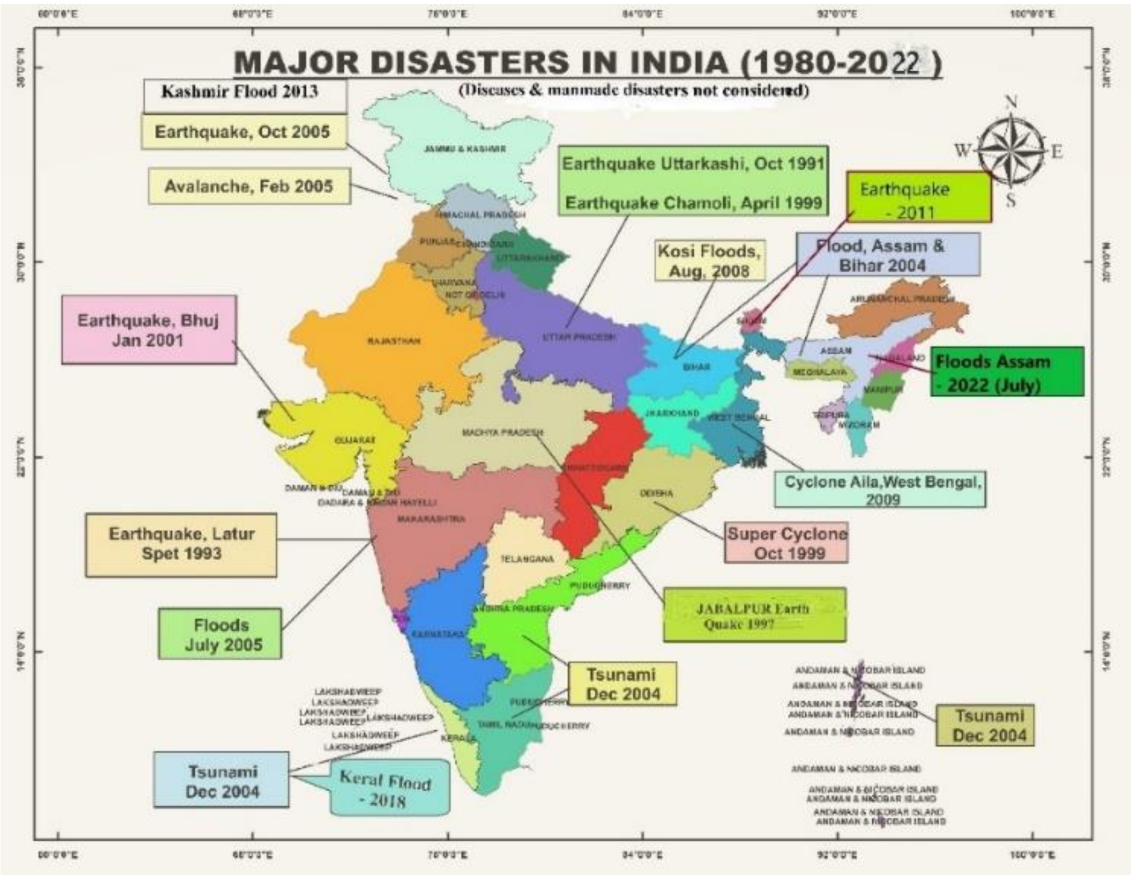


Fig. 1. The major disasters in India except bio-hazards (pandemics) F.Y- 1980-2023

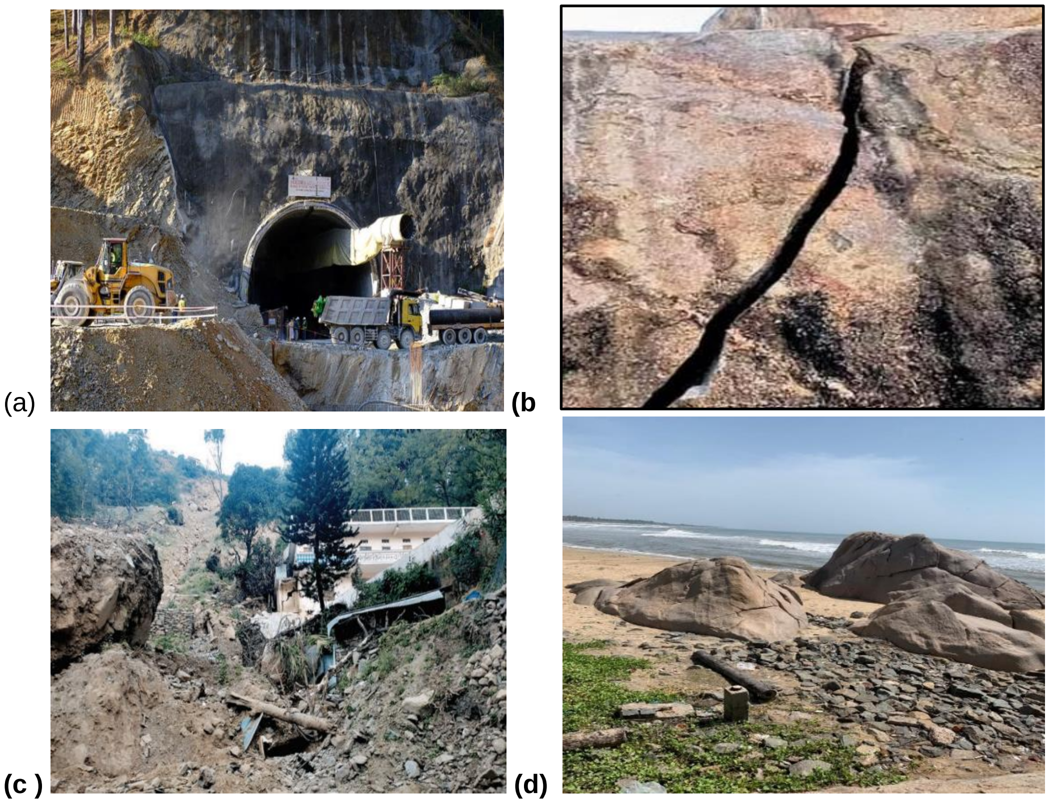


Fig. 2(a). Tunnel subsidence UttarKasi Fig. 2(b) Crack in Narasappa Konda hills, Kurnool (Fault induced) Fig. 2(c): LS in Gaharwar Hills on 7th Jan 2023, *National herald; Chaturvedi, P.,* Fig. 2(d): Subsidence near shore temple Mahabalipuram (24.08.2023)

2. REVIEW OF LITERATURE

Land subsidence due to sinking has become a national crisis to many countries in the world such as Jakarta, Beijing, and Bangkok of Thailand, [2,3]). 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 [4,5,6,7,8]). 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, [7,8,9].

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, Newyork (1.6mm/year), Tokyo, and Venice are the observed LS zones having major shrinking, sinking, and subsiding zones, [10,11]. Coastal towns like (Kolkata, & Khulna) within the Ganga Brahmaputra Delta (GBMD), the Nile Delta, the Mekong River Delta (Hanoi), the California Bay coasts (Mexico City), and the cities underneath oil and carbon basins in Iran, and Northeast China are undergoing substantial LS [12,13,14,15,16,17].

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, In SAR, Interferometric synthetic aperture radar, continuous Global Positioning System (CGPS), if not by global positioning system (GPS) surveying, and DGPS by using GNSS method, [18,19]. The LS can be estimated by downloading Sentinel-1A (ascending and descending) SLC (S1 Single Look Complex) images analyzed by In SAR (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, [20,21,22,23].

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 [24,8]. Land Subsidence is triggered by groundwater (GW) withdrawal in emerging and expanding urban areas with rising populations [25,26].

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 subsidence caused catastrophe in India
2. Discussing the sinking, shrinking and subsiding of deltas along the coast of India
3. Preparing a zonal map other than biological and man-made disasters in India,
4. The search stresses/ actors for various types of land subsidence occurring presently their ferocity, finding, causes, and ameliorating measures in India.

3. METHODOLOGY

Subsidence is loss of inland 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.

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 [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 [26,27,28,29,30].

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, [31,32, 33,34].

4. RESULTS

4.1 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, [35,36,37,38,39].

Geo-related, celestial, biological and meteorological disasters and Coastal along with deltaic subsidence impacts are becoming more apocalyptic. The COVID-19 pandemic a Biological Disasters left its signature after 100 years. . The decadal geo-related disasters and Bio-related disasters from 1900 to 2020 are in Table- 1.

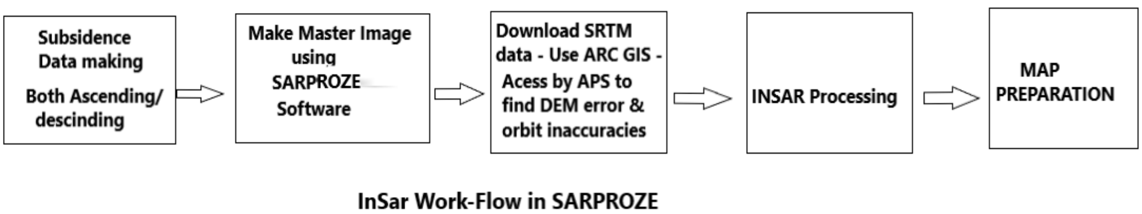


Fig. 3. In Sar Workflow diagram (Sarproze) to measure land subsidence

Table 1. Geo-based 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**	**No Out-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 storms; 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, Land Slides, Flood,	43	1515843	Outbreaks	1	3029
1971-1980	Drought; E,, HW, Flood, LS; WS	93	38708	Outbreaks	9	3461
1981-1990	Drought; EQ, HW, Flood, LS, WS	107	23730	Outbreaks	18	16413
1990-2000	Famine; EQ, HW, Flood, LS Slide; WS	93	46778	Outbreaks	20	1676
2001 -2010	Geo-related disasters	13	≈852	Outbreaks	5	2165
2011-2020	All-natural disaster	Na	20047	Cholera+Covid death India 2020	2 (considered)	148738 +263= 149001

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

4.2 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.

4.3 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 Kapa Shera (10-17cm/year), Raj Nahar at Faridabad (5-7cm/year), Landan at Mohali (4-7.5cm/year), Kolkata University (0.65cm/year), and Raysan Gandhinagar (0.52cm/year).

4.4 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 [40,41]. 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.

4.5 Factors 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, [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 [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, Jharna, Bailadila, Talcher, Sukinda mines, and Rajgamar coal mines of Korba [44,45].

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, [46,47,48], Fig 4 (a, b).

4.6 Over Extraction of Underground / Surface Water

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

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 WestBengal contribute largely to LS [49,50,16]. Urban areas like Calcutta, Mohali [51] North India [52], and NCR New Delhi [37] are extracting huge quantities from aquifers for drinking [53].

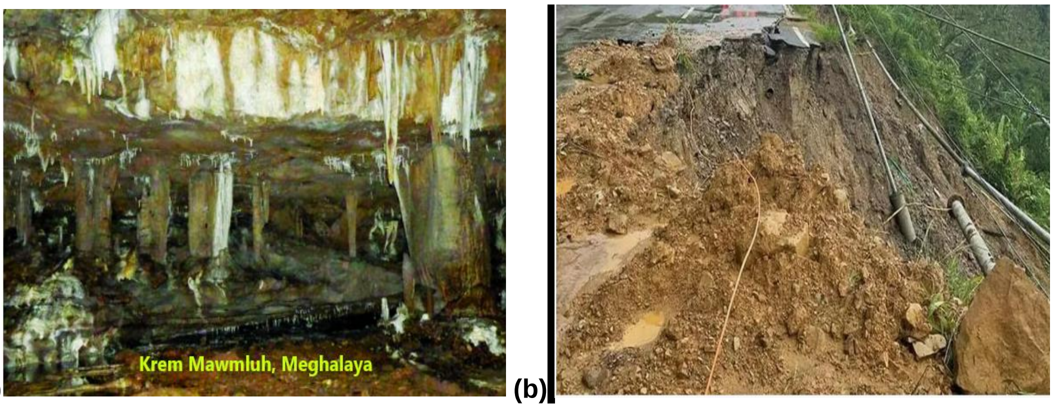
(a)


Fig 4 (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

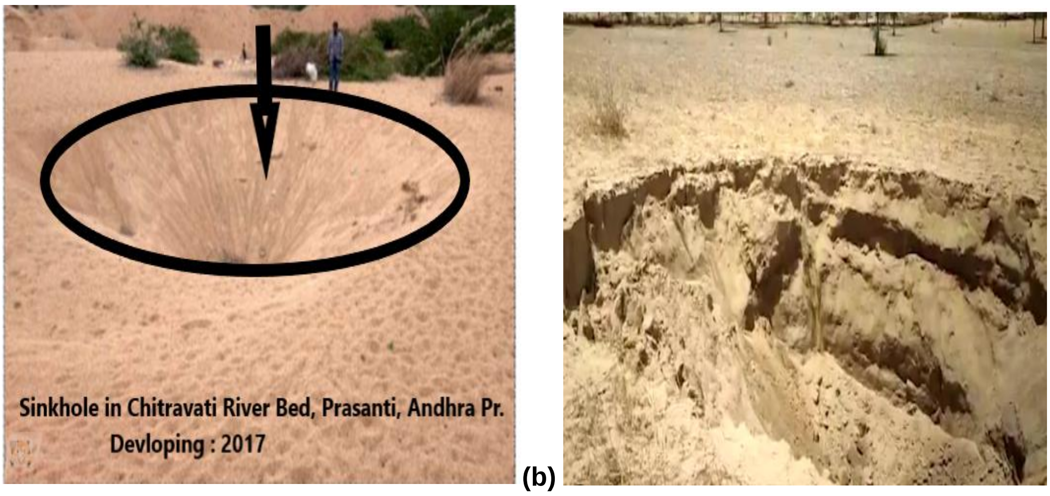
(a)


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

4.7 Excess Drawl of Natural Gas or Crudeoil

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 NER states India. Other coastal areas where extraction is yet to start are the Coromandel coast (Andhra and Tamil Nādu), Kuchha coast (Saurashtra and Gujarat) DGH, [54,07,55].

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).

4.8 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) [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 [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 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 [58,59,60,61, 62,63].

The GBMD is the largest delta subsiding due to changes in sun-earth geometry, climate, and global temperature, [64,65,66,67]. Some deltas 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 [68,69]. The details are in Table 2.

4.9 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 38867Km^2 in the state 6365.12 km^2 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 [75].

(a)

(b)

(c)

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

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 km2	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. [66]
Brahmani-Baitarani	Jenapur	799	≈2989	75%	depositional	Dandekar P. [70]
Mahanadi delta	Naraj	851	9500	67%	Developing; depositional	Mishra et al [71]
Godavari delta	Raj-Mahendri	1464	5200	74%	1-2mm/year	RaoKakani etal. [72]
Krishna	Vijayawada	1400	4800	87%	4mm/yr depositional	Narayayan [73]
Cauvery	Tiruchirappa lli	805	17386	80%	2.3mm/yr	Gupta et. Al. [74]
Narmada	No delta	1312	Join the Gulf of Khambhat	95%	Estuaries	Dandekar et al., [70]
Sabarmati	No deltas	371	Join the Gulf of Khambhat	96%	Estuaries	Dandekar et al., [70]

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

a) (b)

Fig. 7 (a). Karna Prayag 80km below Joshimath (Source modified: BBC news, The Print); Fig 7(b): Aljazeera (Anushree Fadnavis/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;	surged buildings, Dam structures; population; erosion; balding; hydro -power activities. geo-graphs of the area	Start 1976; peak 2023; 5.4cm in 12 days (Dec 27th to Jan 8th) (ISRO)	Ban new house; balding; close hydro-projects; drainage plan; divert snowmelts correct weather forecast
Calcutta City (Raja, & Machhua, Bazar, CU, Sci. Col., (Banerjee [76])	1992–98 with an @ ≈ 5 to 6.5 mm/y, subsidence due to overburden silt & clay	D-InSAR (GPS tech), DIAP ASON 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 vat landslide (2003) & flash flood Asi Ganga (2012)	RS technique; Cloud burst; Seism tectonics	Building slope defense to roads, and agriculture near steep sloping areas & drains
Jharia coal field belt, India (Sunil Ku. et al., [77]	Coal mining activities without refilling, deformation 29mm/yr. Cumulative 90mm	Multi-temporal C-band ENV-ISAT ASAR data by modified PS-(InSAR tech)	detect, monitor, and mapping of slow deformation, plan for vegetation, and refill
Subsidence Kapa Shera & Farida-bad in New Delhi, Uplift at Dwarika, Delhi (Dasgupta A., [16], Garg et al., [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 image of European Space Agency-014; by RS technique by differential interferometry,	Rainwater harvest, aquifer recharge, pond revitalization, curbing GW thefts, rural plantation, & GW conservation.
Sinkhole Cuddapah Basin, YSR Dist., AP. India (Prasad M., [78])	Sinkholes form after heavy rains & sudden recharge, Buggavanka, Chitravati River beds	Prolonged drought and over-drawl of groundwater	Parnapalli Chitravati Balancing Reservoir and Buggavanka Dam (2000)
Ganga Brahmaputra delta (GBT)	Installed new GNSS co-located with Rod Surface Elevation Tables (RSET)	GPS stations give LS rate estimates of 3-7 mm/yr (2003-12	Krien et al., [66] also found the LS valued at 0-3mm/yr., Steckler, et al., [60]
Chennai city	GW exploitation Madras City (Kodambakkam); shift seaward ≈ -30.66 to 25 mm/yr	Persistent Scatterers Interferometry (PSI) method.	Steady & Constant g -65 mm/yr. in 2019; Av 1.2 mm/yr. Seshanath, et al, [79]

Abbreviations: OIL: Oil India Limited, India 2019; Synthetic Aperture Radar (SAR); Global Positioning System (GPS)

4.10 Land Subsidence in Joshimath

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

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

4.11 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 4.

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.

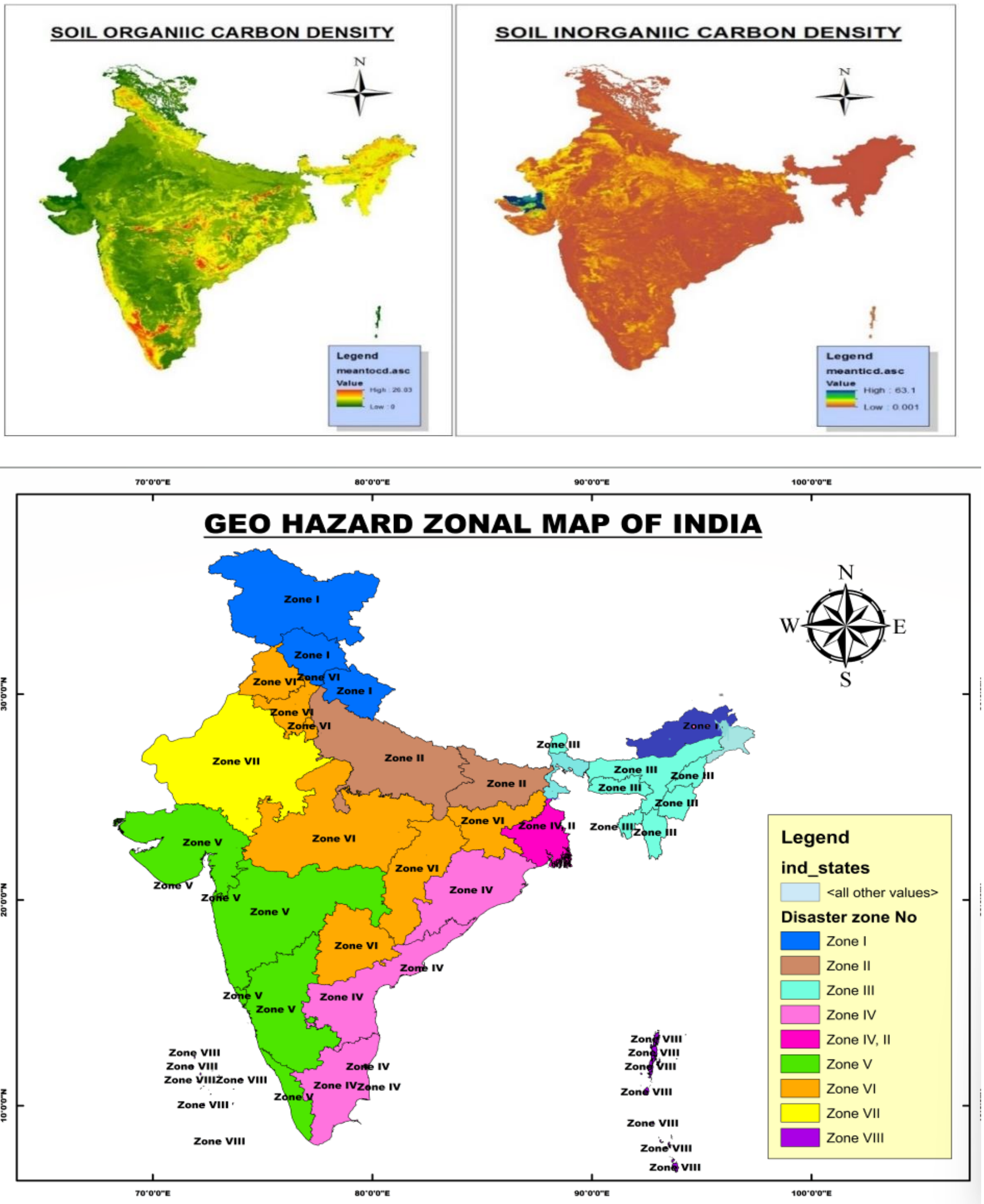


Fig. 8(a). The organic carbon density soil map of India Fig 8(b). The inorganic soil density map of India. Fig 8(c) The dominating geo-hazard map of India

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 & 1979-267deaths; 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 15th Jan 1934; 25th 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; 4000dead, seismicity:8.6R	Mishra et al., 2022
Zone IV (2500km EC India)	WB, Odisha Andhra Pr, TN, Pudu cherry	Storms, Coastal erosion, Floods, Tsunami droughts	31st Oct 1999 Supper Cyclone Paradip: >10000 dead; Deltaic subsidence	Sahoo et al., 2019
Zone V (West Coast India)	Kerala; Goa Karnataka; Maharashtra; Gujarat, Damn, Diu	Storms; RSLR; cyclonic storms; land subsidence; Soil piping in WGB Hills	Mumbai coast is subsiding 2mm /year; Munroe Island shrinking after Tsunami 2004	TOI News 6th July 2022
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;3rd 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;3rd 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;3rd 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.

4.12 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.

4.12.1 Resolutions to diminish land subsidence

LS is a natural process that comes without notice but measures can be taken to reduce it.

5. 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-meteoric 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 Garhwal 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, [80]. Warming places the region at high risk for storm disasters, land subsidence and

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 in equilibrium	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 Active and live mines	(It can be active mines, and mines abandoned 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 fly ash or fly ash slurry or grout Injection or pumping; Gravel Column; Fabric Formed Concrete Areal Backfilling,		

ABB: UGW: Underground water; GWT: groundwater table

flooding [81]. Places like Mexico City even have annual land subsidence of 38mm/yr [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.

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.

6. 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. Major deltas are sinking shrinking and subsiding due to anthropogenic interventions either in the river dynamics or deltas sediment processes. 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 or land Subsidence disasters in mountains which a manmade disaster, can be ameliorated, by field surveys, sinking estimation, and standard monitoring methods. The land use and the Land cover should be well-planned before developmental works. 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, coastal protection, over-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

ACKNOWLEDGEMENT

The author is obligated to Triyasa Chakravarti in helping the GIS works in the article.

COMPETING INTERESTS

The author has declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/110343