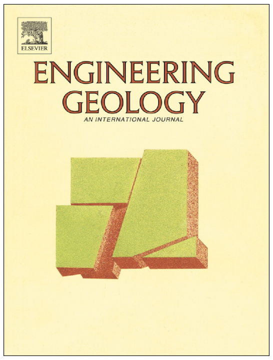

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Land Subsidence by Groundwater Over-exploitation from Aquifers in Tectonic Valleys of Central Mexico: a review

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Abstract

Structurally-Controlled Differential Subsidence (SCDS) is the gradual sinking of the ground, characterized by the development of a damage band, terrain discontinuities and collapses, aligned according to the strike of a controlling geological structure. SCDS has been reported since the 1980s in several cities settled on tectonic valleys in central Mexico. Although groundwater abstraction is the main trigger, recent research efforts also point-out a tectonic component as a driving force. The monitoring and quantification of SCDS has been done through a variety of techniques, such as extensometry, GPS and InSAR. Furthermore, the associated hazards endangering the population are floods, aquifer pollution, cracking and housing collapse. This paper presents a comprehensive review of the current state of SCDS, allowing, for the first time, the standardization of its definition, mechanisms and triggering factors. Additionally, this helps to avoid misinterpretation in the cases of sinking produced by the Mexico City Subsidence Type (MCST) and thus, provides the elements for proper methodological study of SCDS. Finally, the review includes future research directions that need to be improved in order to reduce the impact of the phenomenon.

Keywords:

Land subsidence

Structurally-controlled

Groundwater abstraction

Tectonic valley

Geohazard

1. INTRODUCTION

Land subsidence is defined as the gradual settling or sudden sinking of the earth's surface due to subsurface movement of earth materials (Galloway et al., 1999). In addition, land subsidence is usually associated with horizontal deformation and the occurrence of ground failures that cause significant damages. It is believed that land subsidence began to develop from the era of World War II because of the accelerated extraction of water, oil and gas from the subsoil. Currently, the main cause of land subsidence in the world is attributed to groundwater withdrawal, first introduced by Poland and Davis (1969). The *Guidebook to Studies of Land Subsidence Due to Ground-water Withdrawal* (Poland, 1984) collects several cases studies throughout the world that constitute a rich source of research on the topic.

The regions affected by land subsidence are usually extensive, for example, one of the most emblematic cases occurs in the San Joaquín Valley, where the sinking has exceeded 9 m and the affected area is 13,500 km^2 (Galloway et al., 1999). By the 1990s, more than 150 cities with subsidence-related problems (Barends et al., 1995) generated economic losses that exceeded US$125 million per year (Nuhfer et al., 1993). Nowadays some of the cities most affected by land subsidence due to groundwater withdrawal are Beijing (Zhu et al., 2015), Shanghai (Shi et al., 2008), Murcia (Tomás et al., 2010), Bologna (Modoni et al., 2013), Tokyo (Sato et al., 2006), Las Vegas (Galloway et al., 1999) and Mexico City (Ortiz-Zamora and Ortega-Guerrero, 2010; Sowter et al., 2016).

The comprehensive reviews of the occurrence, mechanisms, monitoring techniques, and approaches to assessment and mitigation of land subsidence due to groundwater withdrawal have gained relevance (Galloway et al., 2008; Galloway and Burbey, 2011; Gambolati et al., 2005; Hu et al., 2004; Wang et al., 2018; Xu et al., 2008). On the one hand, many of these cases of subsidence are related to the compaction of soft materials from multi-aquifer-aquitard systems (Mahmoudpour et al., 2016; Phien-wej et al., 2006; Xu et al., 2013) but not associated with controlling geological structures (or not taken into account). On the other hand, two types of land subsidence have been identified in Mexico: (a) the Mexico City Subsidence Type (MCST), reported by Gayol (1925), similar to the previous cases. The formation of a concentric circular spatial pattern at the regional level is its main feature caused by the consolidation of the highly compressible clays that constitute the aquifer-aquitard system of the Mexico Basin (Cabral-Cano et al., 2008; Osmanoğlu et al., 2011; Solano-Rojas et al., 2015) (Fig. 1); and (b) Structurally-Controlled Differential Subsidence (SCDS) reported in the early 1980s in several cities in central Mexico settled on grabens and semi-grabens filled with lacustrine and fluvio-lacustrine sediments (Aranda-Gómez and Aranda-Gómez, 1985; La Voz de Michoacán, 1988; Trujillo-Candelaria, 1985).

SCDS has specific characteristics that differentiate it from the MCST (Figs. 1 and 2). Therefore, documenting SCDS will reduce the discrepancies between those involved in the search for solutions to the problems generated by this geohazard. Furthermore, standardization of the concepts related to SCDS will allow differentiation from the MCST, thus providing the elements for adequate methodological planning to confront this phenomenon. This, in turn, will give way to the implementation of accurate prevention, mitigation and remediation actions as well as the development of technologies that will reduce the impact of affectation in the field of civil and geological engineering.

Hence, this paper presents a comprehensive review of the current status of SCDS. The topics of its definition, spatial distribution, main causes, mechanisms, monitoring strategies, associated hazards and economic impact are presented. Finally, future research directions are proposed.

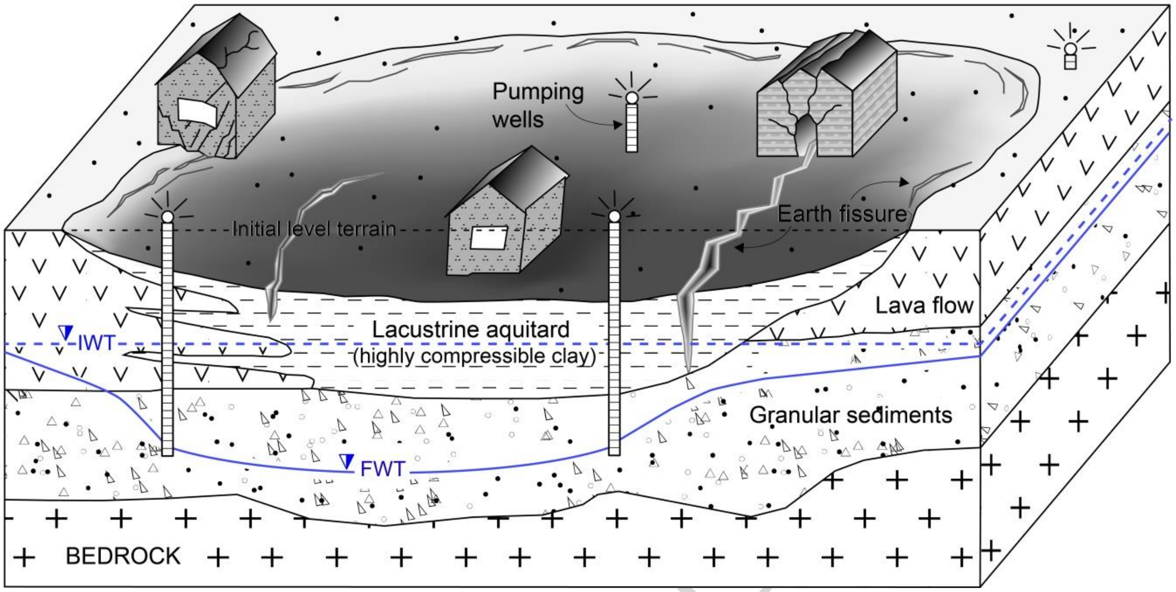

Figure 1. Mexico City Subsidence Type. The excessive demand for groundwater has caused the depressurization and consolidation of the highly compressible aquitard of Mexico Basin. This has induced a circular regional sinking pattern according to the shape of the ancient lake, where the largest subsidence occurs in the depocenter. The abbreviations refer to: IWT: Initial Water Table, FWT: Final Water Table.

2. STRUCTURALLY-CONTROLLED DIFFERENTIAL SUBSIDENCE

2.1 Definition

The term *land subsidence* is used indistinctly to refer to two types of ground sinking that occur in Mexico: MCST and SCDS. This has led to strong discrepancies between researchers, technicians and decision-makers. For this reason, it is necessary to make the distinction and define SCDS. Based on pioneering investigations of differential land subsidence (Bell, 1981; Carpenter, 1993; Holzer, 1984; Maxey and Jameson, 1948; Poland, 1984) and field observations in Mexico cases, the definition for SCDS is proposed.

SCDS refers to ground subsidence, generally gradual (on a regional scale), triggered by groundwater abstraction and characterized by the appearance of discontinuities and ground collapses, aligned according to the direction of a controlling tectonic structure. This aligned pattern has been recognized in field surveys and Interferometric Synthetic Aperture Radar (InSAR) analysis results. SCDS is typified by the formation of a damage band (being the most severely affected area) ranging from a few meters to tens of meters wide (Avila-Olivera and Garduño-Monroy, 2008; Cigna et al., 2012a) and corresponding to the surface projection of the pre-existing fault or geological structure (Fig 2). Additionally, subsidence rates are variable, controlled by the thickness and geomechanical characteristics of the sediments, the intensity of groundwater extraction rates and aquifer recharge (due to infiltration of surface water through the ground discontinuities).

In some cases, the regional aligned sinking caused by SCDS has been better identified when the controlling structures are tilted fault blocks (Fig. 2), as occurs in Morelia (Cigna et al., 2012a).

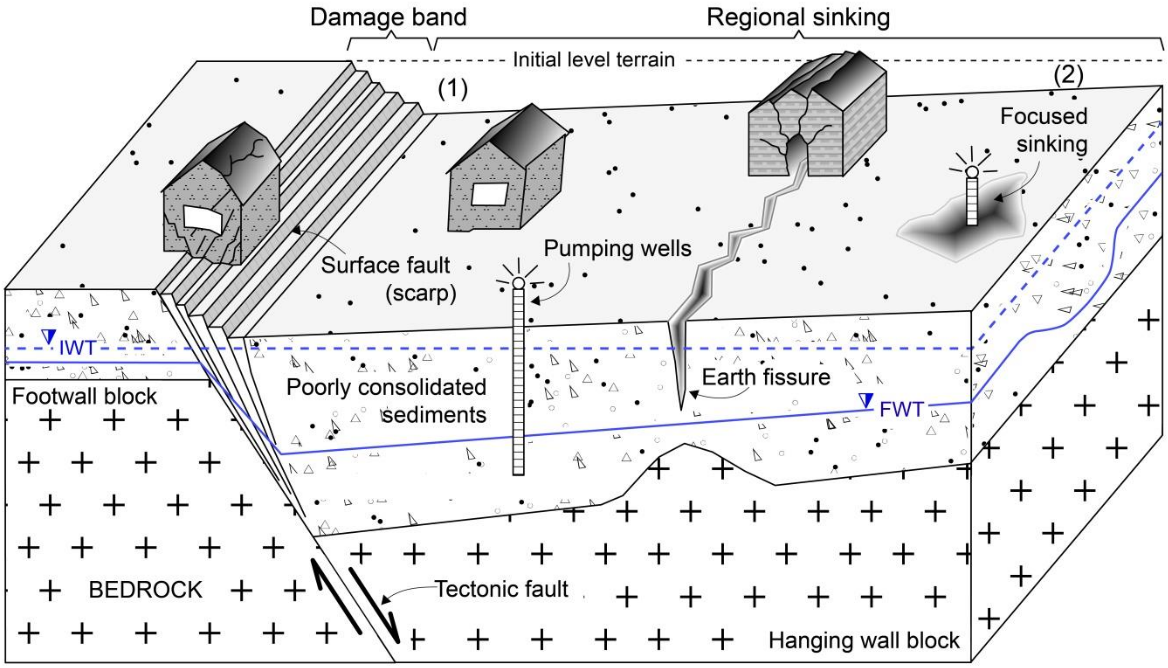

Fig. 2. Structurally-Controlled Differential Subsidence. (1) The greater sinking can be observed in the vicinity of the tectonic fault due to tilting, conversely (2) the sinking is minor in areas far away from it. The formation of surface faults and earth fissures is controlled by the configuration of the bedrock. In the regional sinking zone, damage to structure and infrastructure is less severe than in the damage band area. The abbreviations refer to: IWT: Initial Water Table, FWT: Final Water Table. Modified from Hernández-Madrigal et al. (2014).

Different terms have been used to refer to ground discontinuities that accompanies SCDS in Mexico, such as cracking, or faulting (Arzate et al., 2006; Martínez-Reyes and Nieto-Samaniego, 1990), ground fissuring (Rojas et al., 2002), fracturing (Carreón-Freyre et al., 2005), or ground failure (Pacheco-Martinez et al., 2013). This has caused uncertainty and confusion in both population and research community because each of the terms refers to different aspects depending on the context in which they are involved. Therefore, this paper uses the definition established by Holzer (1984) and adopted by Ávila-Olivera (2004) and Pacheco-Martínez et al. (2013) as the correct ones to cite these terrain discontinuities.

The term *ground failure* should be used to refer to any terrain discontinuity related to subsidence due to groundwater abstraction in alluvial or lacustrine valleys. Two subtypes are derived from this term: (a) *surface fault* refers to ground failures that develop a scarp between the blocks that generate the rupture, which generally correlates with the pre-existing tectonic fault (Fig. 2), and (b) *earth fissure* is the term that should be assigned to ground failures that do not develop scarp and is generally associated with tensile stress due to changes in the bedrock topography (Fig. 2). The terms *pre-existing fault*, *tectonic fault* and simply *fault* are the appropriate terms for the previous or ancient geological discontinuities and are also used in this paper.

2.2 Background and spatial distribution

Land subsidence is a geohazard that has been affecting Mexico for decades. However, a proper quantification of the localities and types of subsidence is nonexistent. Thus, based on the bibliographical review, which also includes governmental digital platforms (i.e. CENAPRED, 2017; INEGI, 2017a; SGM, 2017), it has been found that 99 cities and 12 mayoralties in Mexico City are affected by land subsidence. Nevertheless, these data do not consider limestone-dissolution subsidence occurring in several localities of Yucatán Peninsula (SGM, 2017). According to the previous data, the state of Mexico has the highest number of affected cities with 17, followed by the states of Jalisco and Chihuahua with 16 and 11, respectively.

From the cases of land subsidence mentioned above, only 25 are reported as SCDS in journals, theses and technical reports. The first case of SCDS in Mexico was reported by inhabitants in Celaya in the 1950s (Trujillo-Candelaria, 1985). Subsequently, other cases were identified in Irapuato (Rodríguez et al., 2012) and the state of Aguascalientes (Pacheco-Martínez et al., 2013) in the 1970s. Although the reports were early (1950s), research and publications appeared three decades later, including reports in local newspapers (La Voz de Michoacán, 1988). The most relevant cases identified in the 1980s were in Morelia (Garduño-Monroy et al., 1998) and San Luis Potosí (Arzate et al., 2006); in the 1990s, land subsidence and ground failures occurred in Querétaro (Trejo-Moedano and Martinez-Baini, 1991) and Jocotepec (Hernandez-Marin et al., 2014). Additionally, some localities with ground failures were previously identified but not linked to land subsidence. For instance, Suárez-Plascencia et al. (2005) highlight the reports of local inhabitants about the existence of cracking and fissuring in the Tesistán Valley since 1912.

Furthermore, through the bibliographical review, another 14 localities likely correspond to SCDS but lack formal studies to confirm it. Nevertheless, they have features in common with the verified SCDS cases, like geographical location (tectonic valleys), structural-regional geology, and aquifer condition. For this reason, and in order to encourage their study at the local level, they are annexed as “not defined” cases (ND, in Fig. 3 and Table 1) in this paper.

Some of the most outstanding localities (Fig. 3 and Table 1) affected by SCDS are Morelia and Querétaro, designated cultural world heritage cities; others are high-density population cities like Zapopan, Aguascalientes, Irapuato, and San Luis Potosí; finally Celaya and Salamanca are major agricultural areas. On the other hand, relevant cities (Fig. 3 and Table 1) with undefined land subsidence type include Guadalajara, and León with population density above 1,000 inhabitants/km^2, Puebla (cultural heritage city) as well as Tepic and Zamora.

Although 18 more cities are reported in this paper, other than those previously listed by Chaussard et al. (2014), this quantity is still underestimated because of the difficult access to local and national newspaper reports, government risk assessment documents, and unpublished research.

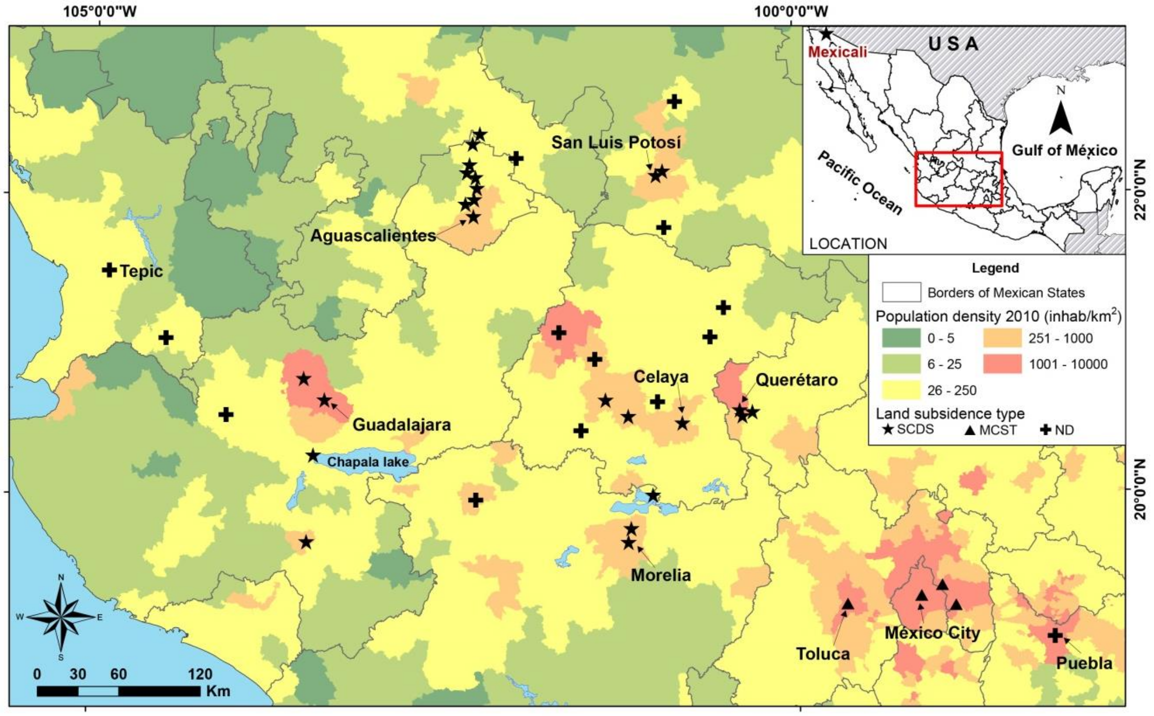

Fig 3. Spatial distribution of land subsidence cases reported in the literature. From the 39 cities reported in this paper, 64% are confirmed SCDS cases, and 36% are not defined (ND) cases. Also, the relationship between the occurrence of land subsidence and densely populated areas can be observed.

2.3 Main causes

2.3.1 Groundwater abstraction

The first research efforts on SCDS considered the phenomenon as a consequence of tectonic processes or the presence of unconsolidated soils (Aranda-Gómez and Aranda-Gómez, 1985; Trujillo-Candelaria, 1985). Whilst the tectonic aspect plays a significant role as a conditional factor, groundwater abstraction is considered the main trigger of SCDS.

The intense groundwater pumping is directly related to population growth (quadrupled from 1950 to 2010) in the country, which moved from rural areas to urban centers. As a result of the disorganized growing cities, the exploitation of aquifers increased to the point where it almost supplied 75% of the volume of water consumption in these urban centers (CONAGUA, 2013). For instance, by 1975, the number of over-exploited aquifers was 32 of the 653 aquifers recognized at the national level. More recently, the number of these has increased to a range between 100 and 106 which provided 50% of the water demand for all uses (CONAGUA, 2013).

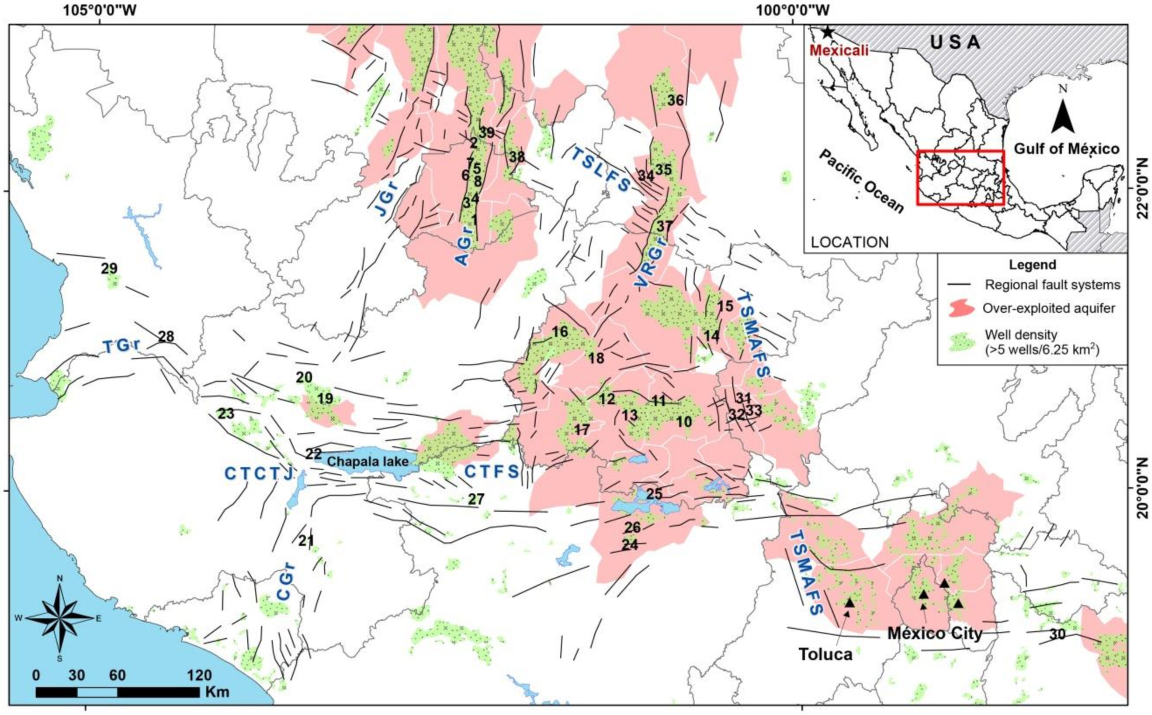

Fig. 4. Relationship between groundwater abstraction and SCDS cases. Twenty-two percent of the over-exploited aquifers in México are associated with SCDS. Regional fault systems constrain the occurrence of SCDS. The density of pumping wells mostly correlates with urban and agricultural centers, where in some cases, they produce focalized subsidence. Numbers refer to the reported localities in Table 1. The abbreviations refer to: AGr: Aguascalientes Graben, CGr: Colima Graben, TGr: Tepic Graben, JGr: Juchipila Graben, VRGr: Villa de Reyes Graben, CTFS: Chapala-Tula Fault System, TSLPFS: Tepehuanes-San Luis Potosí Fault System, TSMAFS: Taxco-San Miguel de Allende Fault System, CTCTJ: Colima-Tepic-Chapala triple junction.

Seventy-six percent of cities with SCDS are located on both over-exploited aquifers and areas with a high density of wells, that is, more than 5 per 6.25 km^2 (Fig. 4). Furthermore, more than 50% of the water extracted from aquifers in these cities is used for agricultural activities (Table 1). In this sense, Rodríguez-Castillo and Rodríguez-Velázquez (2006) mention that agricultural wells in Bajío Guanajuatense (where cities like Celaya, Irapuato and Salamanca are located) can exceed urban wells by up to two orders of magnitude, thus, promoting severe subsidence and deficiency of groundwater. Moreover, Carranco-Lozada et al. (2013) indicate that changes in agricultural practices (from seasonal to irrigated agriculture) accelerate the drop in the water table and, consequently, the increase in land subsidence. On the other hand, some authors mention that exploitation techniques or inadequate construction of pumping wells also influence the acceleration of the sinking (Garduño-Monroy et al., 2001).

The intense pumping has had a negative impact on static levels of aquifers in several cities with SCDS. Although static levels have fluctuated throughout the pumping history, the most recent reports indicate the formation of large depletion cones with depths of up to 180 m in Aguascalientes (COTAS, 2006), 170 m in Morelia (Ávila-Olivera, 2008), 100 m in Celaya (Huizar-Álvarez et al., 2011), 70 m in Salamanca (CONAGUA, 2015) and 50 m in San Luis Potosí (Arzate et al., 2006), to name a few. Likewise, the depletion rates fluctuate between 3 and 4 m/year on average, in the cities mentioned above. In addition, the poor management of groundwater abstractions induces: (a) the surpassing of the groundwater concessions (Table 1) and (b) the generation of focused sinking areas (Fig. 1).

Table 1. Condition of aquifers in cities with land subsidence. Seventy-six percent of cities affected by SCDS are related to over-exploited aquifers, which use water mostly to satisfy agricultural activities. The abbreviations refer to: CC: Capital City, SCDS: Structurally-Controlled Differential Subsidence, ND: Not Defined, OE: Over-Exploited, NOE: Not Over-Exploited.

State	ID	City	Population (inhabitants)[a]	Land subsidence type	Official aquifer unit[b]	Aquifer type[b]	Main groundwater use[b] (%)	Average recharge[b] (Mm^3/año)	Concession volume[b] (Mm^3/año)	Pumping for all purposes[b] (Mm^3/año)	Groundwater deficit[b] (Mm^3/año)	Aquifer condition[b]
Aguascalientes	1	Aguascalientes (CC)	722 250	SCDS	Valle de Aguascalientes	Unconfined and semi-confined	Agricultural (68)	235.0	339.3	430.0	-114.31	OE
	2	Cosío	15 577									
	3	Jesús María	120 405									
	4	Jesús Gómez Portugal	11,589									
	5	Pabellón de Arteaga	46 473									
	6	Pabellón de Hidalgo	4,316									
	7	Rincón de Romos	53 866									
	8	San Francisco de los Romo	46 454									
Baja California	9	Mexicali	689 775	SCDS	Valle de Mexicali	Unconfined and semi-confined	Agricultural (97)	520.5	974.0	602.0	-456.04	OE
Guanajuato	10	Celaya	468 469	SCDS	Valle de Celaya	Unconfined and semi-confined	Agricultural (84)	286.6	423.4	593.0	-136.9	OE
	11	Juventino Rosas	79,214	ND								
	12	Irapuato	574 344	SCDS	Irapuato-Valle	-	Agricultur	522.2	553.1	563.2	-163.	

	13	Salamanca	491 646				al (80)				3	
	14	El Paredón	136	ND	Laguna-Seca	Unconfined	Agricultural (96)	128.5	153.8	263.1	-25.3	
	15	San Luis de la Paz	49 914									
	16	León	1 578 626	ND	Valle de León	Unconfined	Agricultural (50)	156.1	333.7	48.3	-177.7	
	17	Abasolo	79 093	ND	Pénjamo-Abasolo	-	Agricultural (93)	225.0	350.5	440.2	-125.5	
	18	Silao	173 024	ND	Silao-Romita	Unconfined and semi-confined	Agricultural (84)	243.5	363.7	363.7	-120.2	
Jalisco	19	Guadalajara (CC)	1 495 182	SCDS	Atemajac	-	Urban (65)	147.3	132.7	159.5	-11.1	NOE
	20	Zapopan (Valle de Tesistán)	1 243 538									
	21	Ciudad Guzmán	97 750	SCDS	Ciudad Guzmán	Unconfined and semi-confined	Agricultural (69)	266.1	271.0	105.6	-20.9	
	22	Jocotepec	42 164	SCDS	Chapala	Unconfined and semi-confined	Urbano (51)	65.6	36.3	18.4	0.0	
	23	Ameca	60 000	ND	Ameca	-	Agricultural (85)	277.3	278.4	200.2	-22.0	
Michoacán	24	Morelia (CC)	597 511	SCDS	Morelia-Queréndaro	Unconfined and semi-confined	Agricultural (54)	286.7	193.3	162.2	-34.4	OE
	25	Santa Ana Amaya	12 466									
	26	Tarímbaro	105 400									

	27	Zamora	186 102	ND	Zamora	Unconfined	Agricultural (52)	308.5	137.1	107.1	-8.7	NOE
Nayarit	28	Ahuacatlán	6 754	ND	Valle Ixtlán-Ahuacatlán	-	-	68.8	16.1	-	0.0	NOE
	29	Tepic (CC)	590 863	ND	Valle de Matatipac	Unconfined	Urban (77)	123.9	75.7	100.2	0.0	
Puebla	30	Puebla (CC)	1 434 062	ND	Valle de Puebla	Unconfined	Urban (39)	360.7	254.9	-	0.0	NOE
Querétaro	31	Querétaro (CC)	626 495	SCDS	Valle de Querétaro	-	Urban (65)	70.0	133.0	103.0	-67.0	OE
	32	Corregidora	143 073									
	33	El Marqués	116 458									
San Luis Potosí	34	San Luis Potosí (CC)	722 772	SCDS	San Luis Potosí	Unconfined and semi-confined	Urban (67)	78.1	153.4	125.6	-75.3	OE
	35	Soledad de Graciano	255 015									
	36	Villa de Arista	15 528	ND	Villa de Arista	Unconfined and semi-confined	Agricultural (71)	48.2	102.7	74.8	-54.5	OE
	37	Villa de Reyes	42 010	ND	Jaral de Berrios-Villa de Reyes	Unconfined	Agricultural (81)	132.1	130.8	213.4	0.0	NOE
Zacatecas	38	Loreto	43 411	ND	Loreto	Unconfined	Agricultural (91)	52.5	81.4	81.4	-29.0	OE
	39	Luis Moya	10 982	SCDS	Ojocaliente	Unconfined	Agricultural (97)	56.6	67.0	80.0	-11.7	

[a] INEGI, 2017b. Intercensal survey, 2015.

[b] CONAGUA, 2015. Availability by aquifers.

2.3.2 Tectonic fault and seismicity

Groundwater abstraction is recognized as the main trigger of SCDS; however, several authors consider that a tectonic component must be annexed as the driving force of ground sinking (Cabral-Cano et al., 2010; Cigna et al., 2012b; Garduño-Monroy et al., 2009). For example, they mention that some pre-existing faults in Morelia could have an influence on the sinking without yet having it clear. On the other hand, one of the cities where moderate tectonic seismicity has caused ground failures was Ciudad Guzmán in the 1980s (Padilla-Corona, 2004). However, the sudden and recent appearance of subsidence and ground failures in this locality are not related to seismic movements (Brunori et al., 2015). Further, Pacheco-Martínez and Arzate-Flores (2007) mention that active faults can generate maximum stress areas capable of triggering low-intensity earthquakes, which is consistent with the detection of smaller-scale seismic movements located at shallow depths in Aguascalientes (Garduño-Monroy et al., 2001) and Celaya (Huizar-Álvarez et al., 2011). Hence, seismic instrumentation is necessary to characterize low-magnitude seismic movements and to dissipate doubts about the influence of active tectonic faults in these tectonic valleys.

Especially, a region of interest is the Colima-Tepic-Chapala triple junction, recognized as a highly seismic area (Ferrari et al., 1994), where some cities begin to present problems of land subsidence (Fig. 4).

2.3.3 Geothermal heat pumping

A special case of SCDS occurs at Cerro Prieto Geothermal Field in Mexicali Valley (Fig. 3), located in a complex tectonic environment and exploited since 1970. In this place the main driving force of SCDS is related to the recharge and extraction of geothermal fluids, which has been generating circular patterns of maximum sinking around of the geothermal wells (Glowacka et al., 2010; Sarychikhina et al., 2011). Furthermore, the seismic events from the active faults in the valley are increasing the subsidence rates and ground failures manifestation (Glowacka et al., 1999). Hence, even when this is a particular case, the major role of the active faults in the occurrence of SCDS is reinforced. Finally, the adverse effects of groundwater withdrawal (more than 100 pumping wells; CONAGUA, 2015) destined to satisfy the necessities of the geothermal field, need to be considered in further research.

2.4 Mechanism

2.4.1 Geological setting

The majority of the cities with SCDS are located in tectonic valleys in two regional physiographic provinces (Fig. 5): Trans-Mexican Volcanic Belt (TMVB) and Mesa Central. The first one is distributed in the central part of the country and form a strip of 20 to 200 km wide and nearly 1000 km long, characterized by the presence of volcanic structures and normal faults due to the extensive stress regime. These tectonic processes promoted the formation of basins and grabens in which the favorable conditions allowed the accumulation of compressible deposits (García-Palomo et al., 2000). Furthermore, temperate and semi-warm climates predominate in this area (INEGI, 2017a). The second one is located in the north-central part of Mexico and has a predominance of dry and semi-dry climates (INEGI, 2017a). The Mesa Central is characterized by large plains surrounded by mountains, where normal faults were formed by extensive stress in the Cenozoic and also favored the development of grabens and basins (Nieto-Samaniego et al., 2005).

The large accumulations of lacustrine and fluvio-lacustrine sediments in these tectonic valleys play an essential role in the ground sinking capacity. For example, the maximum sediment thicknesses reported in some cities settled on these valleys are: 600 m in Aguascalientes (Romero-Navarro et al., 2010), between 250 and 300 m in Bajío Guanajuatense (Carranco-Lozada et al., 2013), up to 230 m in Morelia (Ávila-Olivera, 2008), 300 m in Querétaro (Chávez-Alegría, 2008) and around 500 m in San Luis Potosí (Arzate et al., 2006).

Finally, both physiographic provinces meet the criteria proposed by Burbey (2002) for the development of pumping-induced ground deformation: (a) an arid to semiarid climate (condition only met in the Mesa Central), (b) long-term pumping of groundwater resulting in large water table declines, (c) a considerable thickness of compressible sediments, (d) variable distribution of compressible sediments, (e) variability in the values of the compression index of the granular material, and (f) the existence of geological structures, such as tectonic faults or irregularities in the bedrock.

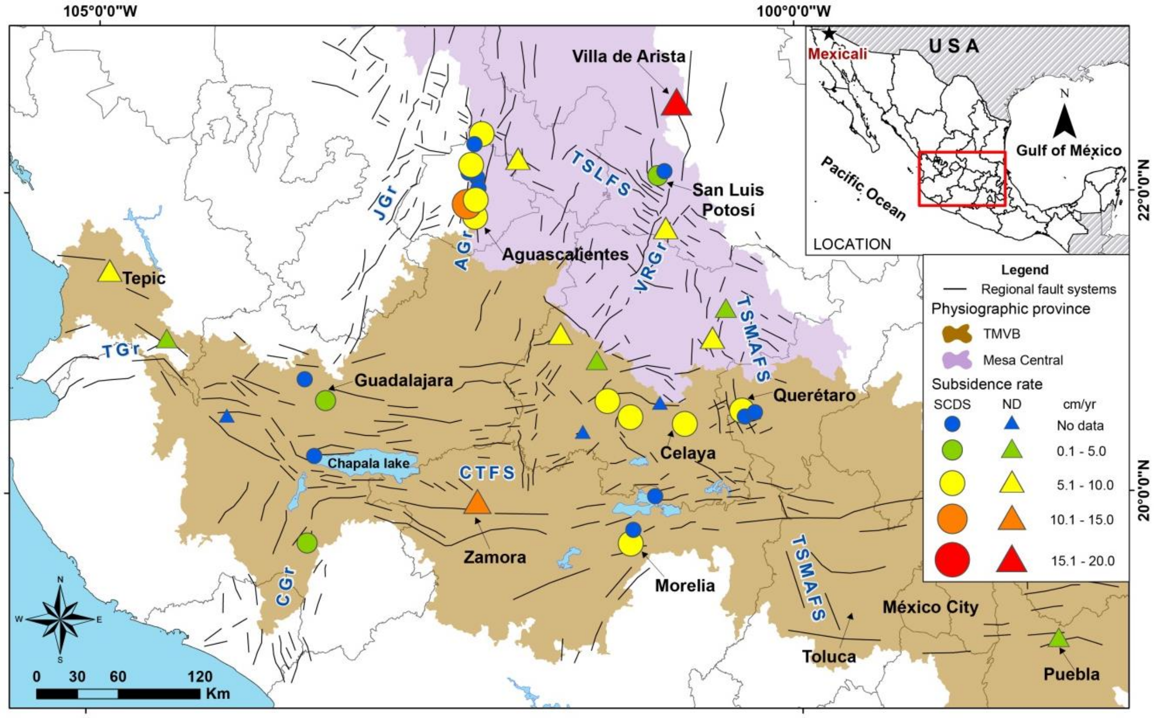

Fig. 5. Regional physiographic provinces where SCDS takes place, and maximum values of subsidence rates obtained only with InSAR techniques. Villa de Arista and Zamora, which have rates above 10 cm/year, are cases with accelerated subsidence lacking in local studies. Subsidence rate is reported in Line Of Sight (LOS). For the abbreviations, refer to Fig. 4

2.4.2 Subsidence and development ground failures

The principal features of SCDS are ground discontinuities and a spatial sinking pattern, both aligned along the direction of the controlling geological structure. The development of these features is related to three bedrock configurations (Carpenter, 1999; Jachens and Holzer, 1982; Pacheco-Martínez et al., 2013):

a) Shallow bedrock with moderate slope. In this configuration, as water level decreases and sinking increases, a parallel system of surface faults is generated in the lowest sediment-thickness zone. As time progresses, other faults are generated toward the depocenter where the sediments are much thicker (Fig. 6a),

b) Bedrock with pronounced protuberance. The bedrock protrusion (or if applicable, horst) generates a much greater sediment thickness on both sides of the protuberance and less at the top. When the water table depletion is intensified, the sediment consolidation generate extensive stress that eventually form patchy-parallel earth fissures at the top of the protuberance, and small scarps on the sides (Fig. 6b), and

c) Bedrock with buried tectonic faults. In this configuration, the differential sinking occurs owing to the contrast in sediment thickness on both sides of the fault trace; earth fissures are then generated at the surface, mimicking the fault plane and evolving to surface faults over time (Fig. 6c).

This last configuration has been used to develop a conceptual model known as *Subsidence-Creep-Fault Processes (SCFP;* Ávila-Olivera and Garduño-Monroy, 2008; Garduño-Monroy et al., 1998), to explain the differential land subsidence in Morelia and Celaya. More recently, this model was taken by Brunori et al. (2015) to describe the Ciudad Guzmán case.

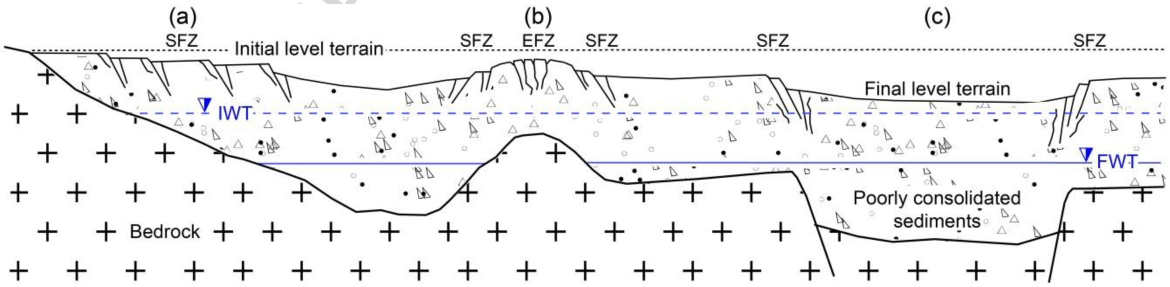

Fig 6. Bedrock configurations that induce ground discontinuities and aligned sinking patterns in SCDS. In some cases, as in that of Aguascalientes, all configurations can be present. The abbreviations refer to: SFZ: Surface Fault Zone, EFZ: Earth Fissure Zone, IWT: Initial Water Table, FWT: Final Water Table.

2.4.3 Origin and characteristics of ground failures

Ground failures generated by SCDS have a systematic orientation that is related to pre-existing buried faults. These faults correspond to different regional-structural systems of Mexico (Fig. 5). For instance, ground failures in Aguascalientes (and neighboring cities) have a N-S and NE-SW orientation associated with the Aguascalientes Graben (Loza-Aguirre et al., 2008; Nieto-Samaniego et al., 2007, 2005). In Celaya, they are related to the Taxco-San Miguel de Allende fault system with a NW-SE orientation (Alaniz-Álvarez et al., 2001; Suter et al., 1995). Ground failures in Querétaro are restricted and aligned with two regional fault systems, Taxco-San Miguel de Allende and Chapala-Tula (Aguirre-Díaz et al., 2005). In San Luis Potosí, ground failures with N-S and E-W directions can be identified; however, only the first ones are associated with the Villa de Reyes Graben (Arzate et al., 2006; Pacheco-Martínez et al., 2010). The surface faults in Morelia have a NE-SW orientation related to the Chapala-Tula fault system, which has generated large historical earthquakes (Garduño-Monroy et al., 1998; Suter et al., 1995). The preferential direction in Jocotepec is E-W, related to the Chapala Graben (Rosas-Elguera and Urrutia-Fucugauchi, 1998). The ground failures in Ciudad Guzmán have a NE-SW orientation and are linked to the Northern Colima Graben (Suárez et al., 1994). On the other hand, it is worth mentioning that some of the ground failures registered in these regions are not related to the regional fault systems or the SCDS process but to a piping effect and/or the dragging of fine sediments in buried paleo-channels (Arzate et al., 2006; Pacheco-Martínez et al., 2013; Suárez-Plascencia et al., 2005).

The continuous temporo-spatial nature of SCDS encourages the geometrical and numerical growth of ground failures observed in most of the studied regions. For instance, Aranda-Gómez and Aranda-Gómez (1985) and Lermo et al. (1996) observed a widening of a few centimeters in the first ground failures reported in the Aguascalientes Graben. Currently, some of these ground failures had reached 4 m width (Table 2) due the groundwater abstraction and erosion agents, such as precipitation (Pacheco-Martínez et al., 2013).

Furthermore, the complete characterization and quantification of ground failures have not yet been covered in several of the affected localities. In this respect, the state of Aguascalientes has the best inventory of ground failures (legally recognized and constantly updated) that are used to manage the concessions for new civil constructions (e.g. SIFAGG, 2017). On the contrary, in other cities, like San Luis Potosí, mapping of the features of the ground failures is very limited (Table 2).

Table 2. Geometric characteristics of ground discontinuities in some cities related to SCDS. The first and last columns include features of tectonic faults since they have not been differentiated from ground failures in the research studies.

City	Number of ground discontinuities	Maximum ground failure width (m)	Maximum ground failure drop (scarp) (m)	Total cumulative length of ground discontinuities (km)	Reference
Celaya	6	1	3.2	30	Carranco-Lozada et al., 2013; Huizar-Álvarez et al., 2011
Ciudad Guzmán	19	-	0.35	-	Brunori et al., 2015

Irapuato	18	-	2.1	27	Rodríguez et al., 2012; Rodríguez-Castillo and Schroeder-Aguirre, 2010
Jocotepec	3	0.6	-	6	Hernandez-Marin et al., 2014
Morelia	13	-	1	38.2	Ávila-Olivera, 2004
Querétaro	74	-	1	318	Pacheco et al., 2006
Salamanca	2	-	2	4.2	Borja-Ortiz and Rodriguez, 2004; Rodríguez-Castillo and Schroeder-Aguirre, 2010
San Luis Potosí	22	-	-	-	Arzate et al., 2006
Aguascalientes Graben	208	4	2	322	Pacheco-Martínez et al., 2013

3. MONITORING AND QUANTIFICATION STRATEGIES

3.1 Measuring and monitoring techniques

3.1.1 Geotechnical instrumentation

Geotechnical instrumentation (principally extensometry) has been used to quantify land subsidence in several confined aquifer systems around the world (Buckley, 2003; Liu and Helm, 2008). These techniques allow accurate measurements with millimeter resolutions at a local level (Gambolati et al., 2005). Moreover, the deformation history resulting from these instruments can be used in compaction (subsidence) modeling of the aquifer system (Galloway and Burbey, 2011). Lastly, they allow measuring horizontal deformation in faulting zones (Carpenter, 1993).

Extensometry has been used to evaluate the MCST in aquitard-aquifers systems of Mexico City and Toluca Valley (Calderhead et al., 2011; Ortega-Guerrero et al., 1999). As for the cases of SCDS, only the Mexicali Valley has been instrumented and monitored since 1996 with extensometers, piezometers and inclinometers (Glowacka et al., 2015; Sarychikhina et al., 2011). The use of these instruments has allowed continuous recording of sinking and identification of other deformation events in the valley. In addition, the combination of these data with other measurement techniques enabled the development of land subsidence models.

Unfortunately, in other case studies the installation of extensometers or other geotechnical devices is lacking. For this reason, instrumentation in all the affected regions is recommended. On the other hand, although most of the country's aquifers have piezometers installed, they are not used to complement the study and monitoring of SCDS.

3.1.2 Precise leveling

Leveling is particularly used to cover small lengths of about 10 km or less. Under these conditions it is usually economical and precise. The installation of benchmarks embedded in pavement or rock and the use of high-precision geodesic equipment are a requirement (Gambolatti et al., 2005).

Leveling has been used since the 1960s in Mexicali Valley, with variability of coverage and frequency in monitoring of SCDS (Glowacka et al., 1999; Sarychikhina et al., 2011). In the state of Aguascalientes, Aranda-Gómez and Aranda-Gómez (1985) pioneered in applying this methodology to quantify sinking near the first reported ground discontinuities. Later, the technique was applied by Llamas-Hernández (2004) and Zermeño de León et al. (2004) using theodolite, Total Station and high-precision leveling instruments. In Querétaro (Pacheco et al., 2006), San Luis Potosí (Arzate et al., 2006) and, more recently, Jocotepec (Hernandez-Marin et al., 2014), leveling works have been carried out with high-precision topographic instruments.

According to the above authors, the application of this technique depends on equipment, work personnel availability, and specially, on the fact that monitoring is applied to small areas or specific ground failures. Furthermore, Hernández-Marín et al. (2014) mention that errors associated with these methodologies are related to human manipulation in data acquisition or bad geopositioning. Nevertheless, methods can be applied to minimize these errors. For example, using GPS to corroborate level measurements is an alternative. In some case studies, leveling was carried out in short periods of time (one year or less), limiting satisfactory results because the subsidence rate is only a few centimeters per year (Table 3). For this reason, monitoring is recommended for at least 2 years, meaning that the availability of time should be considered prior to survey. On the other hand, leveling is not adequate for large land subsidence areas (regional scale) because implementation of extensive benchmarks arrangements is often complicated to measure, and the technique becomes slow, costly and time-consuming.

3.1.3 Differential GPS

GPS uses earth-orbiting satellites to obtain accurate positions, based on the time required by radio signals transmitted from the satellites to reach a receiving antenna (Gambolati et al., 2005). Absolute positioning by GPS is not precise enough to perform a suitable survey owing to satellite ephemerides, clock errors and delays in signal paths through the atmosphere. For this reason, Differential GPS (DGPS) technique is used in land subsidence surveys, as it improves vertical coordinate accuracy (or elevation) and practically eliminates Selective Availability (S/A) errors. DGPS has been widely used worldwide for land subsidence monitoring (Carruth et al., 2007; Mousavi et al., 2011; Sato et al., 2003). Among the different methods (static, dynamic, and real time) used to carry out a DGPS measurement, static-fast subtype has been mostly used in SCDS surveying because it reduces working times without losing precision.

DGPS was implemented in Aguascalientes (Esquivel et al., 2006; Zermeño-de León et al., 2004). There, several permanent benchmarks have been installed and monitored in different stages since 2000. In Morelia (Ávila-Olivera, 2008; Hernández-Madrigal et al., 2011) more than 50 control points have been installed and continuously monitored since 2005. In Celaya, more than 30 benchmarks were installed and monitored in areas affected by ground failures over an 8-month period (Díaz-Salmerón, 2010). DGPS has also been used as a complementary method in some works where SAR images have been utilized (Ávila-Olivera, 2008; Cigna et al., 2012a; INEGI, 2015), allowing spatial-temporal analysis with guaranteed precision at the regional and local levels.

Authors report that GPS methodologies used to quantify SCDS are reliable and accurate. Nevertheless, they require the installation of a large number of control points, time investment, deployment of specialized brigades and, if the surveyed area is large, operating costs increase. Although the static-fast subtype is considered adequate, the low subsidence rates that occur in SCDS should be measured applying the static method as it has been implemented by Mousavi et al., 2011 and Sato et al., 2003.

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3.1.4 InSAR

In recent years, InSAR has been the most widely used technique for measuring and monitoring SCDS in Mexico (Brunori et al., 2015; Farina et al., 2008; INEGI, 2015; Pacheco-Martínez et al., 2015; Sarychikhina et al., 2011). This technique makes use of synthetic aperture radar images from diverse satellites and temporalities to calculate vertical and horizontal ground displacements (Massonnet et al., 1993; Massonnet and Feigl, 1998). There are different InSAR techniques (DInSAR, PS-InSAR, SBAS-InSAR and Squee-SAR^{TM}) that allow land subsidence monitoring and each one is best matched to a particular set of conditions. Some examples with a detailed description about the techniques are given by Bernardino et al. (2002), Ferretti et al. (2011, 2001, 2000) and Strozzi et al. (2001).

In Mexico, these techniques have been applied to different scales and study periods. Significant InSAR analysis has been carried out on a regional scale making possible the detection of new land subsidence areas that had been previously ignored, such as Loreto, Luis Moya, San Luis de la Paz, Villa de Reyes, Villa de Arista, and Zamora (Fig. 4 and Table 1) (Chaussard et al., 2014; Pacheco-Martínez et al., 2015). Also, regional studies have the advantage of obtaining spatio-temporal evolution on a decennial scale of land subsidence, achieved by comparing results with previous InSAR studies (Castellazzi et al., 2016). On the other hand, Cigna et al. (2011) mention that SCDS is best characterized by combining both, vertical displacement and horizontal gradient as this defines better the areas that are vulnerable to ground failures and sinking. On the local or regional scale, InSAR analyses are supplemented with data on pumping wells, geological information, land use maps, rainfall data, gravimetric surveys and GPS measurements for explaining and allowing an understanding of spatial-temporal variations in SCDS. In some cases this data reduces deficiencies that may be encountered in the application of InSAR.

Finally, InSAR techniques also have allowed a more synoptic perspective of the phenomenon and identification of new terrain discontinuities, thus, making it a viable and highly effective tool for generating hazard maps of SCDS and MCST (Cabral-Cano et al., 2015; Hernández-Madrigal et al., 2011; Pacheco-Martínez et al., 2015).

3.2 Subsidence rates

The subsidence rates of SCDS are low (see Fig. 5 and Table 3). However, they are not related to natural processes, such as isostatic sediment loading or consolidation of recent deposits, which are even lower (Dixon et al., 2006; Teatini et al., 2011).

In the case of SCDS, the factors conditioning the velocity and widespread sinking are the thickness of compressible sediments, the decline of the water table and the hydraulic-mechanical characteristics of sediments (Chaussard et al., 2014; Cigna et al., 2012a). This last factor is the most complicated to evaluate and less considered in SCDS study because of the complexity in obtaining samples and parameters. The role of sediment thickness can be observed in normal faults where the subsidence rates are higher in hanging wall blocks than in the footwall block (Fig. 2). Also, the groundwater pumping of the hanging wall block (shallow aquifer) increases the subsidence rates (Ávila-Olivera, 2008).

On the other hand, some authors have found a connection between the reactivation of pumping wells and the acceleration of subsidence, which has generated local circular sinking patterns (Cigna et al., 2012b; Hernandez-Marin et al., 2014). However, this relationship is not clear in other case studies. Likewise, the relationship between high abstraction rates and accelerated sinking is not clear locally.

Ávila-Olivera (2008) also mentions that interdigitated lava flows in the sediment layers induce more intense depletion rates due to the geostatic weight of these materials, and therefore, faster subsidence rates. As a final point, Garduño-Monroy et al. (2001) pointed out that extreme hydro-meteorological events (i.e. *La Niña* and *El Niño*) promote crises of higher subsidence.

Table 3. Maximum subsidence rates in Méxican cities. Reports of high subsidence rates in El Paredón, Luis Moya, Loreto, Villa de Arista, Tepic, and Zamora should be considered in future research as detailed studies are lacking.

State	**City**	**Maximum subsidence rate (cm/yr)**	**Monitoring method**	**Study time-span**	**Reference**
Aguascalientes	Aguascalientes (CC)	11.18	DGPS	1993-2003	Esquivel et al., 2006
		7.2	Leveling	1985-2003	Zermeño De León, 2004
		7	PSI (InSAR)*	2003-2008	Cigna et al., 2011
		5.5	SBAS (InSAR)*	2007-2011	Chaussard et al., 2014
	Cities of Aguascalientes Graben**	12.0	PSI (InSAR)*	2003-2008	Cigna et al., 2011
		10.0	DI (InSAR)*	2007-2011	Pacheco-Martínez et al., 2015
		10.0	DI-PS-SBAS (InSAR)	2003-2012	INEGI, 2015
		12.0	SBAS (InSAR)*	2012-2014	Castellazi et al., 2016
Baja California	Mexicali	11.0	Geotechnical instrumentation	1977-1997	Glowacka et al., 1999
		12.0	Geotechnical instrumentation	1994-1997	Sarychikhina et al., 2011
		18.0	DI (InSAR)*	1993-2010	Sarychikhina and Glowacka, 2015
Guanajuato	Celaya	3.0	DI (InSAR)*	2003-2006	Farina et al., 2008; Avila-Olivera, 2008
		8.5	SBAS (InSAR)	2007-2011	Chaussard et al., 2014
		6.0	SBAS (InSAR)*	2012-2014	Castellazi et al., 2016
		15.0	Non-specified	?	Huízar-Álvarez et al., 2011
		14.0	DGPS	2008-2009	Díaz-Salmerón, 2010
	El Paredón	8.8	SBAS (InSAR)	2007-2011	Chaussard et al., 2014
	Irapuato	7.2	SBAS (InSAR)	2007-2011	Chaussard et al., 2014
		7.0	Non-specified	?	Rodriguez-Castillo and Rodriguez-

					Velázquez, 2011
		2.5	DGPS and Leveling	?	Rodríguez-Castillo and Schroeder-Aguirre, 2010.
	León	5.2	SBAS (InSAR)	2007-2011	Chaussard et al., 2014
	Salamanca	6.0	Non-specified	?	Borja-Ortiz and Rodriguez, 2004
	San Luis de la Paz	4.0	SBAS (InSAR)	2007-2011	Chaussard et al., 2014
	Silao	5.0	SBAS (InSAR)	2007-2011	Chaussard et al., 2014
Jalisco	Ciudad Guzmán	2.5	DI (InSAR)	2003-2012	Brunori et al., 2015
	Guadalajara (CC)	3.3	SBAS (InSAR)	2007-2011	Chaussard et al., 2014
	Jocotepec	0.89 (cm/mes)	Leveling	2012 (8 months)	Hernández-Marin et al., 2014
Michoacán	Morelia (CC)	3.5	DI (InSAR)*	2003-2006	Farina et al., 2008; Avila-Olivera, 2008
		6.7	SBAS (InSAR)	2007-2011	Chaussard et al., 2014
		5.0	PSI (InSAR)*	2003-2008	Cigna et al., 2011
		8.0	PSI (InSAR)*	2003-2010	Cigna et al., 2012a
		6.0	DGPS	2005-2007	Avila-Olivera, 2008
		4.0	SBAS (InSAR)	2012-2014	Castellazi et al., 2016
		4.0	DGPS	2005-2010	Hernández-Madrigal et al., 2011
	Zamora	12.8	SBAS (InSAR)	2007-2011	Chaussard et al., 2014
Nayarit	Ahuacatlán	5.0	SBAS (InSAR)	2007-2011	Chaussard et al., 2014
	Tepic (CC)	6.8	SBAS (InSAR)	2007-2011	Chaussard et al., 2014
Puebla	Puebla (CC)	4.4	SBAS (InSAR)	2007-2011	Chaussard et al., 2014
Querétaro	Querétaro (CC)	7.5 (cm/mes)	Leveling	2001 (9 months)	Pacheco-Martínez, 2007
		7	Leveling	1999-2008	Pacheco-Martínez, 2010
		5.0	SBAS (InSAR)	2007-2011	Chaussard et al., 2014
		0.6	SBAS (InSAR)	2012-2014	Castellazi et al., 2016
		6.8	DI (InSAR)	2003-2006	Farina et al., 2008
San Luis Potosi	San Luis Potosí (CC)-Soledad de	2.0	Leveling (only in CC)	2006 (4 months)	Arzate et al., 2006
		3.9	SBAS (InSAR)	2007-2011	Chaussard et al., 2014

	Graciano				
	Villa de Arista	18.4	SBAS (InSAR)	2007-2011	Chaussard et al., 2014
	Villa de Reyes	5.2	SBAS (InSAR)	2007-2011	Chaussard et al., 2014
Zacatecas	Loreto	6.0	DI (InSAR)*	2007-2011	Pacheco-Martínez et al., 2015
	Luis Moya	8.3	SBAS (InSAR)	2007-2011	Chaussard et al., 2014

*The subsidence rates are reported in *Line Of Sight* (LOS).

**Subsidence rates reported for the Aguascalientes Graben cities are not attributed to a specific locality. However, based on observation of maps, they likely correspond to Jesús María and/or Jesús Gómez Portugal.

SCDS subsidence rates have mostly been calculated through InSAR and to a lesser extent with DGPS, leveling, and geotechnical instrumentation. The analysis of subsidence rates reported in Table 3 indicate high variability for the same city or locality, which is mainly due to: a) use of different monitoring methods (in the case of InSAR, this depends on the chosen technique, satellite or acquisition geometry mode), b) temporality of monitoring (historical time of study, season of the year, and duration of measurements), and c) instrument precision and survey scale (local or regional).

Furthermore, Castellazzi et al (2016) mention that the variability is associated with elastic behavior of aquifers, capable of reducing or increasing its subsidence rates through seasonal or extraction rate changes. For example, in recent years, the subsidence rate in the Aguascalientes Graben (mainly Jesús María and Jesús Gómez Portugal localities) has increased because of the alarming drawdown rates in pumping wells. In Celaya they are constant in time but have minor seasonal variations. Querétaro has undergone a strong subsidence rate decrease attributed to implementation of hydraulic systems for bringing drinking water from other areas and, thus, reduce over-exploitation of the aquifer local system. Subsidence rates show temporary fluctuation in Morelia, which is mainly attributed to changes in the groundwater abstraction regime. Finally, in Mexicali Valley, the increase in rates compared to previous years is related to changes in the geothermal field production regime and occurrence of seismic events.

4. ASSOCIATED HAZARDS AND ECONOMIC IMPACT

4.1 Associated hazards

4.1.1 Cracking and fissuring in civil structures

As explained above, differential sinking triggers the appearance of ground failures. When these effects are combined with civil structures, direct danger to population begins (Fig. 7). Precisely, SCDS was detected initially by manifestation of fractures in housing, roads, hydraulic pipelines, public buildings and other infrastructures (Aranda-Gómez and Aranda-Gómez, 1985; Ávila-Olivera, 2004; Garduño-Monroy et al., 2001; Hernández-Madrigal et al., 2011; Lermo et al., 1996; Pacheco-Martínez et al., 2013; Trejo-Moedano and Martinez-Baini, 1991; Trujillo-Candelaria, 1985).

The most characteristic damage to housing and buildings is usually the following: (1) detachment of concrete and paint in reinforced concrete elements (Fig. 7a), (2) diagonal cracks in load-bearing walls (Fig. 7b and d), (3) cracking, tilting and unevenness in floors and ceilings (Fig. 7a), (4) distortion in window and door frames (Fig. 7b and d), (5) differential settlement in load-bearing walls (Fig. 7c), and (6) separation between structural elements (Fig. 7c and d). The damage to civil structures can reach significant levels that, ultimately, cause the demolition and abandonment of the properties (Fig. 7d).

Fig. 7. Effects of SCDS on civil structures: a) Aguascalientes: damage in load bearing walls and ceilings, and resurgence and rupture of casing of wells; b) Morelia: abandonment of properties; c) Querétaro: separation of structural elements and ground failure in road; and d) San Luis Potosí: diagonal cracks and distortion in window frames. Photos in a) and c) are taken from Pacheco-Martínez et al., 2013 and Pacheco-Martínez (2010), respectively.

For example, a total of 1,865 affected properties have been estimated in Aguascalientes Graben, of which 1,432 are located in Aguascalientes city, and the rest in surrounding municipalities and localities (SIFAGG, 2017). Jocotepec have 126 damaged buildings, mostly houses (Hernandez-Marin et al., 2014). In San Luis Potosí, the affected properties involve more than 39,000 m^2 built and almost 50,000 m^2 unconstructed land (Julio-Miranda et al., 2012). Hernández-Madrigal et al. (2015, 2014) determine a total of 643 properties damaged by 5 of the 13 surface faults that they report in Morelia. The Natural Hazards Report of the municipality of Ameca indicates more than 600 affected properties (SAP, 2011). Finally, the number of damaged homes in Irapuato is 200, where the economic losses are over $2 million US dollars according to Rodríguez et al. (2012).

The SCDS damage is also present in public buildings of historical or heritage value, such as temples, museums and government buildings. Some examples include the *Iglesia de San Felipe de Jesús*, the *Museo de la Insurgencia*, and the *Basílica Catedral de Nuestra Señora de Asunción* in the state of Aguascalientes (Arroyo-Contreras, 2003; Hernández-Marín et al., 2016; INEGI, 2015); the *Museo de la Máscara*, the *Museo Regional,* and the *Iglesia del Espíritu Santo* in historical downtown of San Luis Potosí (López-Doncel et al., 2006); the *Antiguo Convento de San Agustín* in Salamanca (Rodríguez-Castillo and Rodríguez-Velázquez, 2006), and the *Instituto Mexicano del Seguro Social* in Morelia (Ávila-Olivera, 2004).

As a final point, two novel research topics for damage mitigation in civil structures have been proposed:

(1) The instrumentation of housings. This allows the continuous recording of deformations in structural elements; therefore, the probability of collapse can be predicted (Ramírez-Cortés, 2015).

(2) The use of a cold formed steel structural skeleton with polystyrene coating. This prototype is recommended for the construction of buildings on differential sinking areas (or on the trace of surface faults). The researchers demonstrate that its application reduces the structural damage and prevents collapse (Ortiz et al., 2015).

4.1.2 Aquifer pollution

Aquifer contamination is another hazard related to SCDS. The ground failures can become kilometers long and a few meters wide. This geometry favors the rapid infiltration of polluting substances into deep zones.

Some examples of aquifer pollution occur in Salamanca and Irapuato cities. Rodríguez et al. (2000) report that one of the discontinuities produced an oil pipeline rupture in Salamanca, leading to the leak of hydrocarbons and affecting the shallow aquifer. In addition, Mejia et al. (2007) indicate that the ground failure has facilitated the migration of arsenic and vanadium from fuel oil burning, which is affecting the intermediate aquifer quality as well. On the other hand, toluene and chlorine were detected in Irapuato wells near both gas stations and ground discontinuities (Rodriguez-Castillo and Schroeder-Aguirre, 2010). In both cities, traces of arsenic have been found in groundwater; the highest concentrations were detected in wells of northwestern Irapuato, while in Salamanca the traces were identified in several wells inside the city (Rodríguez-Castillo and Rodríguez-Velázquez, 2011).

Finally, Borja-Ortiz and Rodríguez (2004) underline the importance of attaching detailed mapping of ground failures to aquifer vulnerability assessment because these can increase the hydraulic conductivity in the system by three magnitude degrees and drastically change the susceptibility to contamination.

4.1.3 Other hazards

According to investigations, the regional ground sinking will continue in several SCDS cities until (a) water table depletion has completely exceeded the thickness of deformable sediments and/or (b) total consolidation of sediment thickness occurs in the over-exploited aquifers.

On the other hand, the predictions of SCDS indicate several meter of sinking remaining in some localities (Ávila-Olivera, 2008; Pacheco-Martínez, 2007; Pacheco-Martínez and Arzate-Flores, 2007). This condition will eventually lead to more catastrophic flooding events in near and distant future; in fact, some researchers warn that SCDS is becoming a conditioning factor for more severe flooding. For example, Pacheco et al. (2006) mention that the modification of the natural drainage system in Querétaro has caused unexpected flooding. In Morelia, the water level reached by rains near surface faults is higher, and water takes longer to drain, which causes more durable floods

Moreover, a combination of factors, such as water table variation, tectonic faults and irregular topography of bedrock influence in seismic response of soil, which puts historic civil structures in danger of collapsing, has also recently been reported (Botero et al., 2012).

4.2 Economic impact assessment

On a global scale, several methods have been proposed to estimate economic losses triggered by regional land subsidence (Hu et al., 2013; Liu et al., 2012; Yi et al., 2010).

However, works to assess the economic impact by SCDS is limited. In this sense, two methodologies have been implemented in Mexico to estimate the degree of economic loss of land properties and buildings. On the one hand, Julio-Miranda et al. (2012) propose an adaptation of Blong (2003) methodology; in this proposal, the economic loss is calculated as the result of the degree of the severity of affectation, evaluated *in situ*, multiplied by a cost ratio, estimated with reference to a property of average characteristics. This methodology was applied in San Luis Potosí/Soledad de Graciano metropolitan area, where a monetary cost of more than 2.5 million US dollars was estimated owing to the impact of SCDS on 282 properties.

On the other hand, Hernández-Madrigal et al. (2014) propose a depreciation factor equation to evaluate the economic losses by SCDS. By this method, the economic impact results from the cadastral value of the affected property multiplied by a depreciation factor, which is based on the spatial relationship between the affected property, ground failure trajectory and damage band (Fig. 2). By this methodology, authors estimate an economic loss of almost US$400,000 for damage to properties affected by 5 ground failures in Morelia.

Both authors suggest that the availability of detailed geological cartography plays an important role in the application of the methods. Furthermore, a significant consideration in the economic impact assessments is the fact that they are extremely sensitive to the commercial value of the affected property because it varies according to its appreciation.

5. TOPICS AND SUGGESTIONS FOR FUTURE RESEARCH

Some suggestions and directions for research that should be considered in future SCDS studies are as follows:

One of the main issues that should be solved is the uniformity or conceptual standardization of the phenomenon. This will allow us to understand the origin of the geohazard and avoid the application of incorrect research methodologies and, consequently, deficient solutions. Once conceptual standardization has been achieved, these concepts should permeate into society, especially affected populations in order to raise awareness and improve their living conditions.

On the other hand, although research on SCDS have been more recurrent, some of them are not public knowledge, and those that are, do not allow the drawing up of a complete and adequate inventory of the phenomenon. Therefore, one recommendation is to expand the prospecting to marginalized and rural areas, and to encourage researchers to publish their case studies. In this sense, it is also essential that governmental institutions, such as INEGI, SGM and CENAPRED: 1) standardize subsidence reports on their digital platforms and hazard maps, and 2) distinguish or categorize the type of land subsidence. This will improve the national mapping inventory and facilitate action plans in the study of land subsidence.

The lack of detailed stratigraphic and geological information on a local scale is a common problem in Mexico. For this reason, studies of subsoil geology, hydrogeology and hydro-mechanical properties of sediments should be increased, in order to improve studies about SCDS. For example, in case studies of subsidence by compaction of aquifer-aquitard systems (similar to the MCST), the availability of these data has allowed the obtainment of more accurate subsidence prediction models (Shen and Xu, 2011). In addition, Geophysical surveys, remote sensing and fieldwork are options to improve the geological context.

Aquifer pumping and deformation measurement data play a key role in the analysis of land subsidence. Therefore, is suggested to increase piezometric instrumentation of aquifers, and to maintain a historical and updated database (static levels and abstraction rates) of the wells in operation. These measurements will allow clarifying the doubts about the correlation groundwater abstraction rates and subsidence rates, particularly in SCDS cases. Moreover, the water regulatory institutions should offer free access to this data in order for it to be used in future research.

The regional fault systems control the mechanism of SCDS. However, the role of the seismicity produced by some active faults in these systems is still unclear. For this reason, not only a detailed structural cartography is suggested but also the seismic instrumentation in these tectonic valleys. On the other hand, the Servicio Sismológico Nacional (SSN — Mexican National Seismological Service) should include low magnitude earthquakes (less than 4, in moment magnitude, M_W) in its reports because it is more likely that they are related to active faults. Furthermore, some of these regional fault systems have a noteworthy historical seismic activity (Suter et al., 1995). Finally, the earthquakes that occurred in Chiapas (September 7) and Morelos (September 19) in the last year, with magnitudes of 8.1 and 7.1, respectively (SSN, 2017), highlight the importance of seismic events in SCDS areas since they can cause the collapse of already damaged homes and/or reactivation of tectonic faults.

Some prediction models of SCDS have been done (Chávez-Alegría, 2008; Pacheco-Martínez et al, 2006). Nevertheless, complex deformation models (Shi et al., 2008; Wang et al., 2015), coupled with MODFLOW (Galloway and Sneed, 2013; Leake and Galloway, 2010), with InSAR (Calderhead et al., 2011; Solano-Rojas et al., 2015), and analytical or extrapolation models (Zhu et al., 2013), have been applied in other parts of the world, which can be revised and adapted for its implementation in SCDS cases.

Owing to continuous spatial and temporal nature of SCDS, development of hazard and vulnerability maps should be constant and continuous since this will allow the implementation of effective groundwater management schemes and sustainable use of resources at the regional level. To facilitate the monitoring and modeling of the geohazard, the application of geophysical methods (Ground Penetrating Radar, Electrical Resistivity Tomography, among others) is recommended. Yet another recommendation is the use of SAR images from recent satellites, such as Sentinel 1, Terra SAR X, TanDEM-X, COSMO Sky-Med, ALOS 2, and JERS1. The first four are capable of obtaining high resolutions in ground deformation; the last two, using shorter wavelengths, are capable of penetrating vegetation foliage.

Future researches efforts should pay special attention to precise determination of the damage band; methodologies implemented for this purpose are non-existent. For instance, the use of Terrestrial Laser Scanner (ScanStation) has started in some regions (Hernández-Madrigal, 2017, personal communication). This tool is useful for monitoring cracking in constructions, identifying deformation patterns and tectonic components as well as for achieving centimeter resolutions.

The studies about the performance of settled constructions on ground failures (Hernández-Castillo et al., 2015; Ortiz et al., 2015) should continue aiming to identifying and preventing the collapse of affected structures, as well as achieving the permanence of historic buildings with cultural, social or economic value. On the other hand, research on the impact on infrastructure (for example, underground tunnels) in areas with land subsidence has been carried out in other parts of the world (Shen et al., 2014; Xu et al., 2014, 2012), which may be adapted and considered for SCDS.

The accumulated sinking in SCDS areas is a poorly calculated aspect. It is generally reported as the height of scarp or jump that surface faults have. However, this is only representative of the faulting zone but not for the farther areas. Hence, a correct calculation of the regional accumulated sinking will allow the implementation of strategies to reduce the adverse effects of the increasingly severe floods. Some strategies need to be focused on the reduction of ground sinking (i.e, the Querétaro case; Castellazzi et al., 2016), on the implementation of more efficient rainwater drainage systems, and the prevention of irregular settlements.

Other topics of special interest in SCDS include: a) hydro-anthropic isostasy: isostatic effects in land surface owing to depletion of aquifers is an aspect that has not yet been studied and may be developed; b) influence of climate change: water demand has increased in recent years. Consequently, correlation between the effects of climate change, demand for water, and SCDS, are an issue that must be resolved by future studies; and c) economic impact assessment: the development and implementation of methodologies should be increased and improved while taking into consideration important variables, such as construction type, civil structure degree deformation and geotechnical characteristics of the real property. In addition, studies about the collateral impact in the economy and environment of surrounding cities should be initiated.

Finally, one topic that was not addressed in this paper owing to its complexity is the legislative aspect. In general, land subsidence in Mexico is not considered a severe hazard or natural disaster. Because of this, government laws and regulations do not protect the affected citizens. Therefore, economic losses are to the detriment of property owners. Many researchers have brought this observation to the attention of decision-makers. Nevertheless, progress has been limited. The aforementioned reiterates that SCDS must be included in Mexican legislation and even in construction regulations and development plans in order to avoid future settlements in risk areas.

6. CONCLUSIONS

Land subsidence in México is classified into two main types: Mexico City Subsidence Type (MCST) and Structurally-Controlled Differential Subsidence (SCDS).

SCDS is the most frequent type of land subsidence in the country and affects millions of people in nearly 40 cities. Despite this, reports in literature are still scarce and considered underestimated.

SCDS develops in tectonic valleys of central Mexico (mainly in the physiographic provinces of the Mesa Central and Trans-Mexican Volcanic Belt) and is triggered by intense groundwater abstraction although a tectonic component have been considered in recent years. Eighty percent of localities affected by SCDS are located on over-exploited aquifers, which have a density of wells greater than 5 per 6.25 km^2.

SCDS mechanisms are controlled by three different configurations of bedrock (shallow bedrock with moderate slope, bedrock with pronounced protuberance, and bedrock with buried tectonic faults), which explain the formation and alignment of surface faults and earth fissures. Moreover, high subsidence rates are associated to larger compressible sediment thickness.

Various quantification and monitoring techniques, such as extensometry, leveling, Differential GPS, and InSAR, have been applied, where the combination of two or more have shown better results. In addition, they have contributed to the development and better understanding of the spatio-temporal relationship of SCDS.

The main hazards associated with SCDS are the cracking and collapsing of civil structures, contamination of aquifers, and susceptibility to flooding, this last being the least studied and most dangerous in future scenarios.

The studies of economic impact are still scarce even though SCDS is causing millions of US dollars in material losses. Among the affected structures are public buildings of historical or heritage value.

In conclusion, progress in research on SCDS has been relevant at all levels but not enough. For this reason, the topics and suggestions for future research proposed in this paper should be attended.

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Highlights

- Land subsidence in México is classified into two main types: Mexico City Subsidence Type (MCST) and Structurally-Controlled Differential Subsidence (SCDS).
- The monitoring and quantification of SCDS has been done through a variety of techniques, such as extensometry, GPS and InSAR.
- The associated hazards to SCDS endangering the population are floods, aquifer pollution, cracking and housing collapse.
- Standardization of the concepts related to SCDS will allow differentiation from the MCST, thus providing the elements for adequate methodological planning to confront this phenomenon.
- The implementation of accurate prevention, mitigation and remediation actions as well as the development of technologies that will reduce the impact of affectation in the field of civil and geological engineering.