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Literature review on the land subsidence of Quetta, Pakistan

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Abstract – Land subsidence in Quetta, Pakistan, is primarily driven by excessive groundwater extraction, resulting in significant environmental, infrastructural, and social challenges. This phenomenon has led to the sinking of land by approximately 10 cm annually, contributing to severe degradation of infrastructure, increased flood risks, and water supply disruption. This paper explores literature to summarise the up-to-date research on land subsidence in Quetta city. The existing literature and research highlight various causes that include seismic activity, urbanization, and mining, and highlights the urgent need for sustainable water management and urban planning strategies. By examining the geographical and geological context of Quetta, this study emphasizes the critical need for mitigation measures to protect the region's infrastructure and inhabitants. The integration of engineering solutions and community awareness is crucial in addressing the ongoing land subsidence and its far-reaching impacts.

Keywords – Land Subsidence, Quetta, Subsidence Mitigation, Groundwater Extraction, Urbanization.

I. INTRODUCTION

Quetta's history indicates that the city has long struggled with issues including ground subsidence and a lack of water [1]. Since its founding in 1878, Quetta has seen rapid population expansion, with 260,000 residents in 1975 and 3.1 million in 2024 because of the inflow of Afghan refugees and rural migrants looking for better possibilities [2]. The region's water resources have been stretched by the region's fast urbanization and historical reliance on wells and springs for water supply, which has led to the current problems with land subsidence. The physical environment of Quetta is affected by land subsidence, as seen by the deep fissures in the ground that deteriorates homes and roadways [3].

Sustainable water management techniques are desperately needed, as seen by the startling rate of subsidence as well as efficient urban planning. Both natural and man-made forces can cause land subsidence, which is the slow settling or abrupt sinking of the Earth's surface. Sediment compaction occurring naturally, volcanic activity, and earthquakes are examples of natural causes. But often, the main forces are human activities, especially in cities. One important factor is over- extraction of groundwater, which weakens the soil's ability to maintain itself and eventually causes it to collapse [4]. Additional contributing elements are the weight of construction and infrastructure developments, which compresses the earth, and mining operations, which produce subterranean spaces [5]. Furthermore, taking thorough action to remediate ground subsidence can help stop additional land degradation and safeguard important infrastructure [6].

II. MATERIALS AND METHOD

Geography & geology of Quetta

With a strategic location in a valley encircled by the Takatu, Murdar, Chiltan, and Zarghoon mountain ranges, Quetta, the capital of Baluchistan province in Pakistan, is roughly 1,680 meters (5,510 feet) above sea level [7]. Due to its location, Quetta enjoys a high altitude, semi-arid environment with hot summers, chilly winters, and little too sporadic rainfall. Because of its location on the tectonically active Chaman Fault, the city is vulnerable to earthquakes. Quetta's geological makeup consists of a variety of rock formations, including the Shirinab Formation, Bostan Formation, Chiltan Limestone, and Alluvium [8]. It also has large aquifers that have historically been used as a source of water [9].

Historically, the Kasi Pashtun tribe possessed a tiny hamlet that has since grown into Quetta, an urban area that is expanding quickly. Influenced by a range of political forces, including the British, the Mughals, and the Ghaznavids, the area experienced notable urbanization and population expansion, especially after 1878 [10]. The issues of land subsidence and environmental degradation have been exacerbated by this growth, which has led to greater groundwater extraction and urban expansion [11]. It is imperative to comprehend the distinct geographical and geological backdrop of Quetta to effectively tackle these concerns and guarantee sustainable development [12]. The geographical layout of Quetta is illustrated in Fig. 1 , highlighting its diverse topography, including valleys and mountainous regions that influence land subsidence patterns.

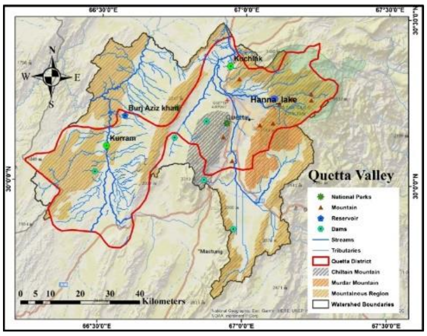

Fig. 1. Geography of Quetta [13]

Topographical map of Quetta is shown in **Hata! Başvuru kaynağı bulunamadı.** which is taken from google m aps, The Quetta is a part of collision zones between Indian and Eurasian plates. This collision zone is known as Kirthar and Sulaiman Fold-Thrust belts. The region is surrounded by broad and tight folds, and reverse, thrust, and strike-slip faults.

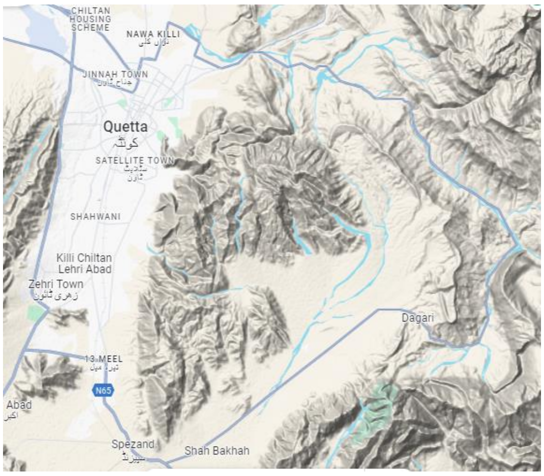

Fig. 2 Terrain of Quetta [14]

The interaction of these geographical and geological factors plays a crucial role in the region's vulnerability to subsidence.

Causes of land subsidence

Quetta is particularly vulnerable to land subsidence because of its location on the Chaman Fault. In essence, geological faults are rifts in the crust of the Earth where major tectonic processes take place [15]. The Indian Plate and the Eurasian Plate are separated by the Chaman Fault, a significant transform fault. Land subsidence may result from the deformation and shifting of the Earth's crust brought on by movement along this fault line [16].

The earth above may sink because of the cavities created by shifting the crust or a reduction in its supporting structure. These shifts can occur suddenly, particularly during major seismic events, or gradually over time, resulting in creeping sinking [17].

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Moreover, mining activities may disturb the natural flow of groundwater, exacerbating subsidence. The interaction between material extraction and changes in groundwater patterns creates a complex situation that increases the likelihood of subsidence [21]. In areas with extensive mining operations, the combined effects of these activities significantly contribute to the observed land subsidence.

This additional load can cause soil compaction and collapse. In addition, urban development is often associated with large-scale excavations and diversions that affect waterways and crop production [22]. Covering the ground with stones and asphalt reduces the permeability of the soil, prevents the natural nutrition of the soil and increases subsidence.

Large scale changes to land to meet growing population and infrastructure needs are beneficial to sustainable land use [23]. The challenge for urban planners and architects is to develop strategies to reduce these impacts while adapting to urban growth and making housing safe and sustainable when problems persist [24].

The primary causes of land subsidence in Quetta are shown in Fig 03. It appears that the groundwater extraction is the leading cause, accounting for 50% of the issue, followed by seismic activity and mining activities, each contributing 20%. Urbanization, responsible for 10%, also plays a role in exacerbating the problem. The graph highlights the major contributors to subsidence, emphasizing the critical impact of human and natural factors.

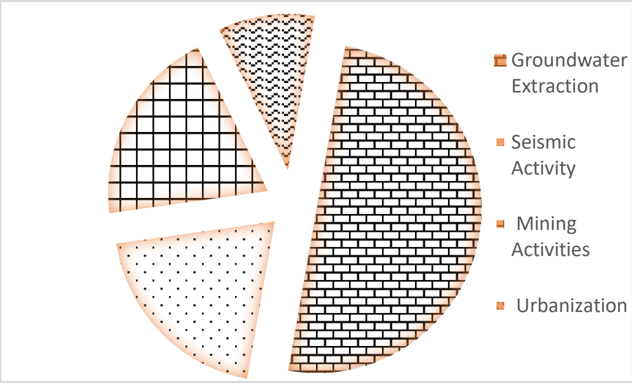

Fig. 3 Causes of land subsidence in Quetta [25]

Impacts of Land Subsidence

The deterioration in Quetta has resulted in significant land degradation, which has adversely impacted agriculture and natural vegetation. As soil sinks, the soil becomes compacted, reducing porosity and the soil's ability to retain water and nutrients. This planting makes it difficult for the plant to remove the necessary material and water, causing the crop to decrease [26]. In addition, deterioration of soil structure increases the surface of the soil, causing erosion and loss of fertile topsoil [27]. These changes destroy local ecosystems and biodiversity, making the land unsuitable for agricultural and ecological purposes in the long term. As water levels drop, wells and boreholes may dry up, reducing water availability for human consumption and agriculture [28]. Lowering water levels can also affect the natural and groundwater balance, affecting rivers and streams. Water scarcity can lead to water scarcity in Quetta, affecting communities and the environment. Changes in groundwater levels can also cause seawater to intrude into coastal areas, contaminating water resources and affecting water management [29]. House lines have been damaged, broken, and moved. The destruction of these structures can lead to poor living conditions and disruption of essential ser vices such as water, gas, and sewage. Unstable foundations and weak power lines require constant maintenance and repair, placing a financial burden on the city. The disaster also disrupts business, reduces assets, hinders investments, and increases Quetta's available resources. Mitigating and restoring dam age caused by groundwater has significant economic implications [30]. Efforts to maintain and strengthen infrastructure, rebuild, and improve water management are costly. These costs can impact local government budgets and divert money from other important areas such as health, education, and social services [31]. Access to basic services such as clean water, sanitation and transportation will be disrupted, negatively impacting low- income families and deepening inequality [32]. The financial burden of repairing damaged property can strain a family's finances, further impacting residents' health [33]. In addition, feelings of insecurity and instability can lead to social cohesion and dysfunction, making it difficult for residents to cope with other problems and harm. Damaged sewer lines can contaminate water supplies and spread infectious diseases. Mental stress in a disaster- prone area can affect mental health, causing anxiety [34].

Fig. 4 illustrates the increasing rates of land subsidence in Quetta over time, showing a sharp rise, particularly after 2016.

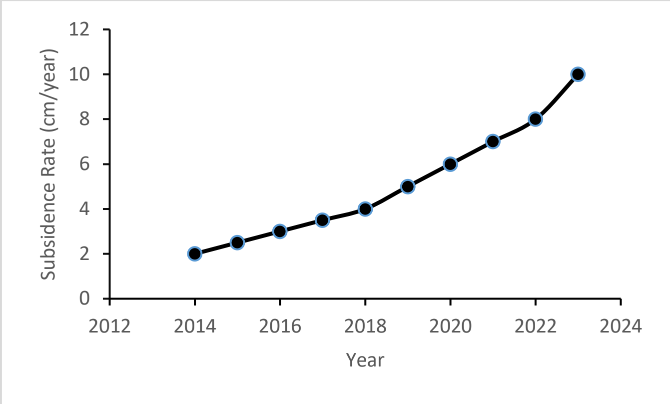

Fig. 4 Subsidence rates over time [35]

Over the same period the decline in groundwater level is shown in Fig. 5, correlating the drop in water tables with the increasing subsidence.

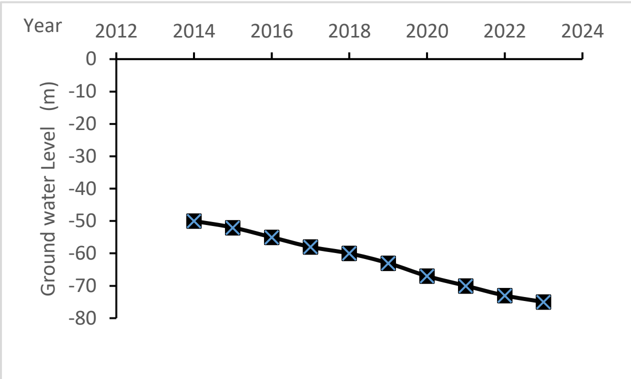

Fig. 4 Decline in groundwater levels [36]

Fig. 6 shows the impact of subsidence on infrastructure, with roads and buildings being the most affected, followed by utilities and low-rise structures, indicating the widespread consequences of land subsidence on critical infrastructure.

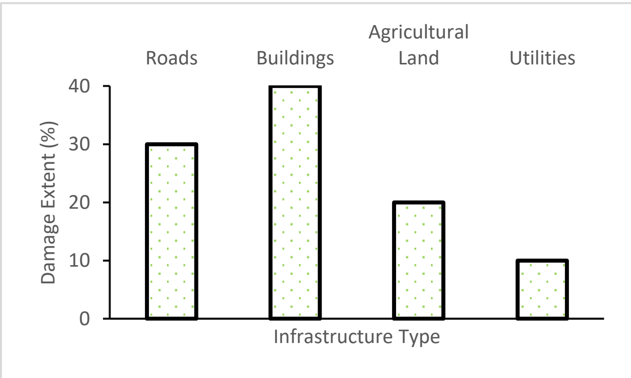

Fig. 5 Extent of damage as per infrastructure type [37]

Case studies

One of the most significant incidents of land subsidence in Quetta occurred during the devastating earthquake of 1935 [38]. This earthquake, with a magnitude estimated at 7.7 to 8.1, struck the region on May 31, 1935, resulting in widespread destruction and loss of life. The earthquake caused significant ground shaking, resulting in the collapse of buildings and infrastructure. Subsequent studies revealed substantial land subsidence in various parts of Quetta, with ground sinking observed at alarming rates [39]. The deep cracks formed in the ground following the earthquake highlighted the extent of the subsidence, with some areas experiencing sinking of several feet. The seismic activity not only led to immediate damage but also triggered long-term subsidence trends in Quetta, underscoring the enduring impact of natural disasters on the region's landscape [40].

A more recent case study of land subsidence in Quetta involves the intersection of groundwater depletion and rapid urban expansion. As the city's population has grown, so has the demand for water, leading to extensive groundwater extraction [41]. This overexploitation of groundwater resources has resulted in the sinking of the ground in various urban areas. Studies have identified significant subsidence rates in neighbourhoods where groundwater extraction is most intense [42]. The sinking ground has caused damage to buildings, roads, and infrastructure, posing risks to public safety and economic stability. The expansion of urban areas exacerbates the problem, as the increasing weight of buildings and infrastructure further compresses the underlying soil. This case study highlights the complex interplay between human activities, such as urbanization and groundwater extraction, and their consequences for land stability in Quetta [43].

Comparative studies have been conducted to assess land subsidence in Quetta in relation to other regions facing similar challenges [44]. These comparisons highlight both the unique characteristics of land subsidence in Quetta and the common underlying factors shared with other areas [45]. For example, comparisons with cities in other tectonically active regions have revealed similarities in the impact of seismic activity on land subsidence. Additionally, studies comparing Quetta with cities experiencing rapid urbanization and groundwater depletion have provided valuable insights into the shared vulnerabilities and potential solutions for addressing land subsidence globally [46].

Methods of detection & warning:

Various methods such as remote sensing techniques, land cover analysis and field information (GIS) are used to determine changes in elevations and ground water content in Quetta [47]. Satellite sings tools like satellite images and aerial surveys give us the big picture of the landscape so that we can watch out for signs over large areas [48]. For instance, millimetre-scale ground subsidence patterns and their temporal variations can be recognized using SAR satellites [49]. These electronic gadgets are preferred because they have a wide range of services and easily repeatable monitoring which is vital for long-term monitoring [50]. Global Navigation Satellite Systems (GNSS) including GPS receivers measure vertical and horizontal displacements of the ground with centimetre level accuracy [51]. Another radar-based system called InSAR uses radar signals to detect surface elevation change revealing detailed information about very large-scale ground conditions. This enables localized measurements that supplement far-field data, making it possible to accurately monitor sinking spots within zones [52].

III. RESULTS

A multi-faceted approach that includes engineering and technological solutions, policy, and regulation, as well as community awareness and education initiatives, is required to mitigate land subsidence in Quetta [53].

Engineering solutions such as retrofitting and strengthening existing buildings and structures are needed to mitigate the impact of land subsidence. Structural modifications are needed to enhance their resilience to ground movement [54]. Reinforcement techniques can include the use of bracing, underpinning, or innovative materials [55]. Flexible infrastructure designs that can accommodate ground movement without compromising safety should be considered in new construction projects [56]. Reducing water consumption, promoting water recycling and reuse, and investing in alternative water sources are some of the sustainable water management practices [57]. When excess surface water is intentionally directed to replenish underground aquifers, it can help maintain groundwater levels and mitigate subsidence.

Land subsidence can be prevented if land- use regulations are enforced. It is possible to restrict development in areas prone to subsidence or limit construction to low impact structures [58]. It is possible to promote sustainable land-use practices, such as compact urban development and the preservation of natural drainage systems, to minimize the risk of subsidence [59].

Comprehensive groundwater management policies are essential for sustainable water resource management. These policies may include measures such as establishing limits on the amount of water that can be taken out of the ground. Regulatory frameworks can encourage the use of alternative water sources [60].

Raising awareness about the causes and consequences of land subsidence is crucial for fostering community engagement [61]. Public outreach programs can inform residents about the risks associated with the ground [62]. These initiatives can help people adopt water-saving practices, report subsidence-related issues, and participate in community resilience-building activities.

Future generations can be educated about the importance of sustainable land management practices by incorporating lessons on land subsidence and urban resilience into school curriculum [63]. Students can develop an understanding of the environmental, social, and economic impacts of subsidence by incorporating these topics into science, geography, and civics courses. A culture of environmental stewardship and community resilience can be fostered by educating youth [64].

Incorporating these strategies and solutions into policy frameworks, engineering practices, and community engagement initiatives can help address the challenges of land subsidence [65]. Quetta can work towards sustainable land management and resilience in the face of subsidence-related risks if it adopts a holistic approach that integrates technical expertise, regulatory measures, and public participation [66].

IV. DISCUSSION

Understanding underlying causes, assessing the extent of subsidence, and evaluating its impact on the environment are some of the things land subsidence in Quetta has focused on [67]. Satellite imagery and InSAR are used to detect subsidence patterns over time in these studies [68]. To understand the interplay between geological factors and subsidence in Quetta, interdisciplinary research efforts have been conducted [69]. The alarming rates of subsidence in urban areas, the vulnerability of infrastructure to ground movement, and the need for proactive measures to address the issue effectively are all findings from these studies [70].

There are several key knowledge gaps despite recent advances in understanding land subsidence. Further research is needed to understand the complex interactions between natural and anthropogenic factors that are driving subsidence [71]. Long-term monitoring studies are needed to assess the temporal variability of subsidence rates [72]. To inform policy and planning efforts, research needs to be done on the socio-economic implications of subsidence, such as its impact on livelihoods, public health, and community resilience [73]. Integrating expertise from geology, hydrology, engineering, and social sciences is essential for developing holistic solutions to mitigate subsidence risks effectively [74].

Our understanding of land subsidence in Quetta requires interdisciplinary approaches [75]. Collaborative research efforts that bridge disciplines such as geology, hydrogeology, urban planning, and sociology can give insights into the complex drivers and impacts of subsidence [76].

For example, integrating geological studies with hydrological models can improve understanding of groundwater-land subsidence interactions [77]. Similarly, engaging government agencies, academia, civil society, and community stakeholders in a participatory research process can increase the relevance and effectiveness of mitigation efforts [78]. Applying a multidisciplinary approach can enable researchers to address the complex nature of Quetta's land subsidence and develop sustainable solutions that consider both environmental and socio-economic factors [79].

In summary, current research on Quetta's land subsidence has made significant progress in understanding the phenomenon, but several knowledge gaps remain [80]. Addressing these gaps requires further multidisciplinary research, especially in areas such as understanding the causes of land subsidence, assessing socio-economic impacts, and developing integrated mitigation strategies [81]. By fostering collaboration and innovation across disciplines, researchers can contribute to more effective management of land subsidence and promote sustainable development in and around Quetta [82]. Although many multi-hazard disaster risk assessment studies for Pakistan are available prior to 2024, However this year National Disaster Risk Management Fund (NDMRF) introduced its first official national level studies. Natural catastrophe modelling was performed by SUPARCO which is available on the website of NDMRF. The Risk Calculator calculates the risks like earthquake, Tsunamis, and landslide for selected region against.

However, subsidence related information is still to be added.

V. CONCLUSION

In conclusion, the study on land subsidence in Quetta has underscored the critical and multifaceted nature of this issue, linking it primarily to over-extraction of groundwater and rapid urbanization. Based on the recommendations of the researchers the conclusions can be described as under: -

I. The research has contributed to a deeper understanding of how these factors, in conjunction with the region's geological vulnerabilities, exacerbate land degradation and pose significant threats to infrastructure, agriculture, and public safety.

II. A notable deduction from this study is the urgency to integrate advanced technologies such as InSAR (Interferometric Synthetic Aperture Radar) and GIS-based monitoring systems, not only for the detection of subsidence patterns but for developing early warning systems that can mitigate future risks.

III. Furthermore, there is a need for stricter regulatory frameworks and sustainable water management practices, as traditional solutions appear insufficient against the accelerating rates of land subsidence.

IV. The interdisciplinary approach having a more robust collaboration between civil engineers, urban planners, and environmental policymakers can improve the subsidence risk management.

V. There is need to establish solutions such as groundwater recharge zones and reinforced urban planning techniques to limit structural vulnerability in subsidence-prone areas.

VI. Both local and international agencies should be urged to invest in not only technological but also educational solutions that raise community awareness about the impacts of over-extraction and irresponsible urbanization.

VII. The collaboration between science-based policies and local engagement should be encouraged.

VIII. National level organisations like NDRMF involved in risk management and calculations should include land subsidence in their risk calculator like (NATCAT).

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