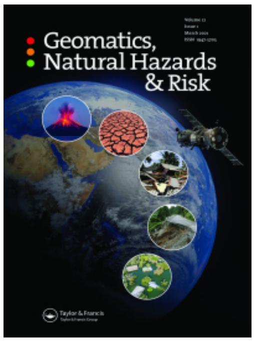

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Geomatics, Natural Hazards and Risk

ISSN: 1947-5705 (Print) 1947-5713 (Online) Journal homepage: www.tandfonline.com/journals/tgnh20

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To cite this article: Majid Nazeer, Gomal Amin & Man Sing Wong (2025) **Emerging from the depth: preliminary clues on groundwater upsurge in the coastal city of Zliten, Libya**, Geomatics, Natural Hazards and Risk, 16:1, 2475889, DOI: 10.1080/19475705.2025.2475889

To link to this article: https://doi.org/10.1080/19475705.2025.2475889

Published online: 10 Mar 2025.

GEOMATICS, NATURAL HAZARDS AND RISK
2025, VOL. 16, NO. 1, 2475889
https://doi.org/10.1080/19475705.2025.2475889

Emerging from the depth: preliminary clues on groundwater upsurge in the coastal city of Zliten, Libya

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ABSTRACT

This study focuses on localized groundwater flooding (GWF) in Zliten, Libya. The GWF caused significant damage to approximately 200 houses, leading to the relocation of 80 families. The lack of scientifically identified reasons for this groundwater upsurge poses challenges for effective remedial actions. To investigate the flooding causes, remote sensing techniques were employed. Preliminary results showed fluctuations in groundwater storage (GWS) over the past two decades in Zliten. Notably, a sustained decrease in groundwater levels occurred from 2008 to 2012. Sea Level Rise (SLR) patterns varied across Libya's coastline, with Zliten experiencing an estimated mean SLR of 2.8 mm/yr. Satellite-based findings suggested a consistent decline in Zliten's water storage capacity. It is possible that (i) overuse of the aquifers has disrupted the confined aquifer, leading to a groundwater upsurge, and/or (ii) recent extensive groundwater pumping activities have placed the confined aquifer under pressure exceeding atmospheric pressure. As a result, water has surged in the wells and even the land to relieve the pressure and reached its potentiometric level. An End-Member Mixing Analysis (EMMA) of water samples from the affected areas could further validate this hypothesis by determining the contributions of surface water, groundwater, or groundwater from the confined aquifer.

ARTICLE HISTORY
Received 5 June 2024
Accepted 1 March 2025

KEYWORDS
Aquifer; coastal flooding; environmental disaster; groundwater flooding; water upsurge

1. Introduction

Usually groundwater flooding (GWF) occurs as a temporary process when the water table rises, resulting in the emergence of groundwater where the potentiometric surface intersects or surpasses the land surface due to changing conditions (Bosserelle et al. 2022). It was observed that, approximately 60% of the recorded cases of rising groundwater levels in literature are associated with groundwater rebound (GWR) (Allocca et al. 2021; 2022). GWR occurs when there is a strong reduction in groundwater abstraction from large aquifers underlying urban centres due to a decrease in industrial activities

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(Jerome Morrissey et al. 2020; Stellato et al. 2020; Allocca et al. 2021). GWR frequently leads to the emergence of groundwater at the ground surface away from perennial river channels or the rising of groundwater into man-made structures such as basements and other subsurface infrastructures (MacDonald et al. 2012; Reiss et al. 2019). The impacts of GWF can be severe on rural and urban environments, as well as on cultural heritage, utility activities, human health, and can have significant socio-economic damages and costs associated with it (Allocca et al. 2018; Stellato et al. 2020). Over the past few decades, GWF has been observed in various regions, including the United States (Gotkowitz et al. 2014), northern and central Europe (Korkmaz et al. 2009; Kreibich and Thieken 2009), United Kingdom, and Ireland (MacDonald et al. 2014; Reiss et al. 2019), with different geological and land use settings, and triggered by various mechanisms and processes. Macdonald et al. (2008) has identified three possible scenarios which can triggered GWF i.e. (i) flooding related to the water table rising above the land surface in response to prolonged extreme rainfalls in unconfined and fractured aquifers, (ii) flooding related to the rapid response of groundwater levels to precipitation and limited storage capacity in shallow and porous sedimentary aquifers with a good hydraulic connection with river networks, and (iii) flooding induced by GWR.

Libya has an area of approximately 1.7 million km^2, with a population of around 6.5 million people. Notably, a mere 5% of its land accommodates a significant majority of 90% of the total population which is concentrated along the coast of Mediterranean Sea (Brika 2018). This high population density in coastal areas leads to heavy reliance on Libyan coastal aquifers for water needs, contributing to groundwater quality deterioration, Seawater Intrusion (SWI) and dropdown in piezometric levels (Wheida and Verhoeven 2007; Hamad 2012; Ekhmaj et al. 2014; Agoubi 2021).

There are two types of groundwater resources in Libya i.e. shallow aquifers (which are renewable as they receive water from rainfall and surface runoff) and deep aquifers (not renewable). Shallow aquifers are mainly found in the northern underground basins such as the Jiffarah Plain System, Al Jabal Al Akhdar System, and Al Hamada Basin, while the deep aquifers (fossil water) are found in most of the southern half of Libya such as the Murzuq Basin, Kufra Basin, and Sarir Basin (Wheida and Verhoeven 2007; Brika 2018; Mohamed 2019). For coastal aquifers, however, contamination is associated with salinization due to SWI arising from (i) gradual landward encroachment of the freshwater/saltwater interface, (ii) inundation, or (iii) excess pumping (Klassen and Allen 2017).

In connection to the pressure on coastal aquifers, the coastal town Zliten (160 km east of the capital, Tripoli) is suffering from mysterious GWF since October 2023. According to the international media reports (Al Jazeera 2024) and initial findings by United Nations Institute for Training and Research (UNITAR) reveal the presence of stagnant water and soft mud, that have inundated houses, streets, and many orchards/plantation sites (UNITAR 2024). This series of unfortunate GWF has resulted in the relocation of approximately 80 families to safer areas and approximately 200 homes are damaged due to this disaster (The Libya Observer 2024a). In consultation with an international team of experts, the government of Zliten has taken temporary measures such as water pumping and pit-refilling. According to media reports it has revealed that the implementation of a horizontal drainage system during mid-February has contributed to the reduction in water levels. Until now, no scientific reason has been identified for this upsurge of groundwater, making it very difficult for the local administration to take sustainable remedial actions.

Based on the available media reports and literature review on such water upsurge events around the world, it is perceived that such water upsurge events can be related to one or several of the scenarios mainly including the (i) interaction between surface water and groundwater, (ii) rising sea levels and SWI, (iii) increased rainfall, (iv) damaged pipelines (including those associated with the Great Man-Made River project (Brika 2018), and (v) inadequate or damaged drainage system. Therefore, this study aims at (1) investigating the causes of the mysterious upsurge of groundwater in the town of Zliten and its unprecedented scale; (2) identifying the potential sources and pathways of the groundwater influx, considering factors such as poor drainage infrastructure, damaged pipelines, heavy winter rains, and rising sea levels; (3) investigating the relationship between the stagnant water and other environmental factors such as rainfall patterns, and vegetation health using the latest and retrospective satellite datasets. Through this technical investigation, we aim to gain valuable insights into the GWF dynamics in Zliten and its implications.

2. Lithology of the study area

Zliten town is located in Ghadamis Basin (northwestern Libya) which has two lithological groups of deposits of Paleocene and Upper Cretaceous rocks (Rashrash and Farag 2016). The upper section, extending from the base of the Upper Cretaceous, consists of limestones, dolomites, and argillaceous sediments of various ages, accompanied by sandy, silty, and shaly layers (Al Farrah et al. 2011). Below the Lower Cretaceous, the layers primarily comprise thick sediments of Mesozoic and Paleozoic sandstones interbedded with shale, clay, and silt. Additionally, gypsiferous limestone strata from the Triassic and Jurassic periods are present. The Upper Cretaceous carbonate rocks and Kiklah sandstone serve as the aquifers in this region due to their notable porosity and permeability. These formations offer ample storage capacity for groundwater within the spaces between sand grains, while interconnected pore spaces facilitate the movement of water through the formation (Mohamed 2019). Moreover, the permeability of the Kiklah sandstone determines how easily water can flow through the formation. If the sandstone has high permeability and is well-connected, it can act as a relatively efficient conduit for groundwater movement. In areas where the Kiklah sandstone is near the surface and has limited overlying impermeable layers, groundwater can potentially rise to the surface and cause flooding (Saadi et al. 2023).

3. Materials and methods

3.1. Study area delineation

In this study, we used the area of interest/study area boundary as defined by the United Nations Satellite Centre (UNOSAT) to establish the spatial extent for analyses. Additionally, we also delineated the potentially flooded areas identified by UNOSAT as part of their emergency mapping service initiative, which were determined through very high-resolution satellite imagery analysis and expert assessments (as of February 8, 2024). To further refine our analysis, we incorporated data from the HydroATLAS, a secondary product of the Shuttle Elevation Derivatives at multiple Scales (HydroSHEDS) (Linke et al. 2019), which provided level 5 sub-basin boundaries and water stream information (Figure 1). By integrating these boundaries and affected areas into our methodology, we conducted geospatial analysis and interpretation within the defined study region of Zliten, ensuring a more precise and contextually relevant assessment.

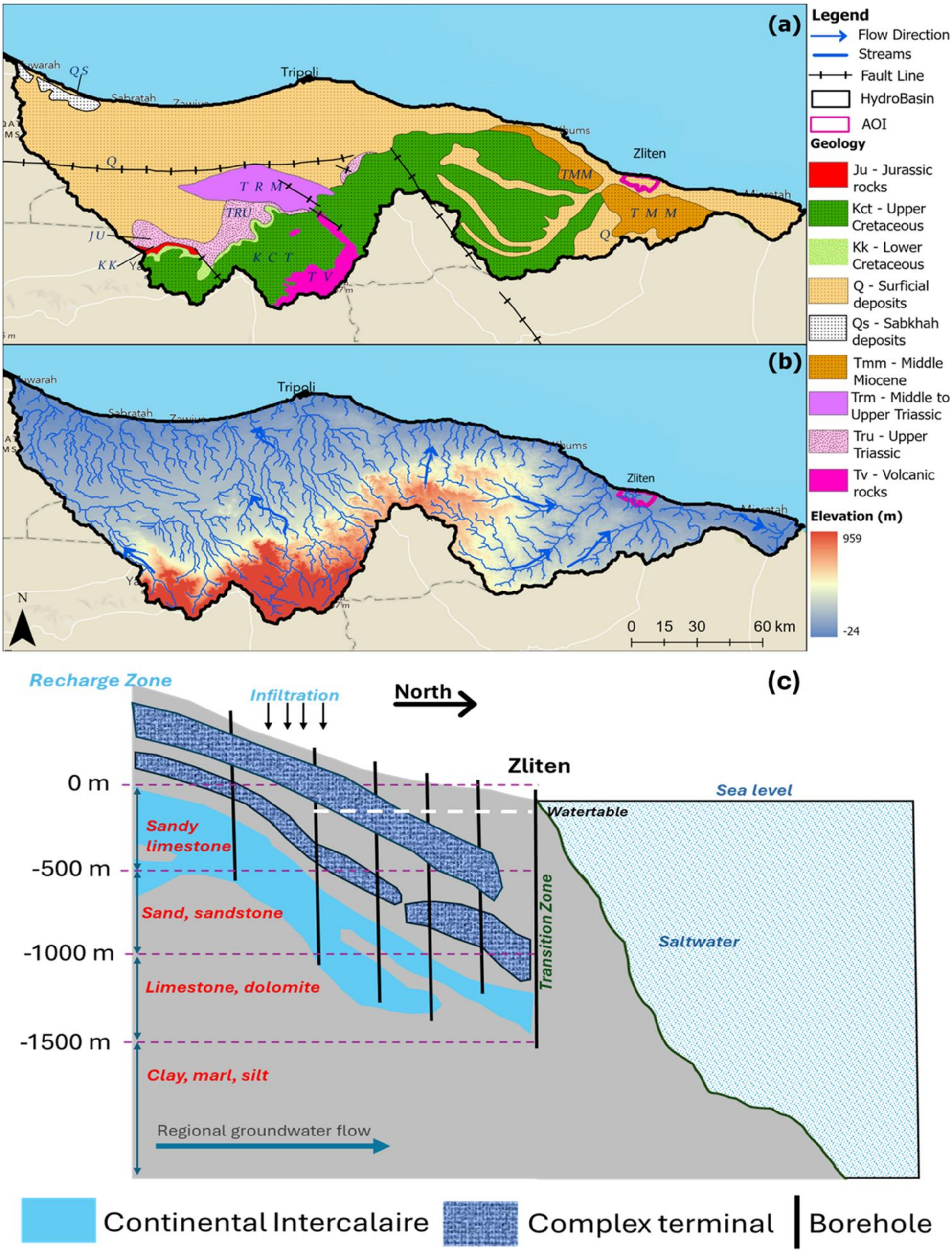

Figure 1. (a) Geological Map of the HydroBasin level 5 (ID: 1050032180) containing study area (b) Elevation model showing streams and water direction (c) schematic cross section of study area showing regional aquifers, and hydrogeological features.

3.2. Groundwater storage and sea level data

Gravity Recovery and Climate Experiment (GRACE) satellite gravity mission, launched as a cooperative work between NASA and the German Aerospace Center (DLR) in March 2002 to measure spatial and temporal changes in the earth gravity field (https://grace.jpl.nasa.gov/applications/overview/). Its data has been employed in various studies to (i) estimate regional-scale water mass variations (Ramillien et al. 2014), (ii) calculate water balance at the basin scale (Krichman 2023), (iii) analyse GWS changes, determine groundwater depletion and recharge rates (Alghafli et al. 2023), and (iv) enhance understanding of hydrologic settings within aquifers in response to climatic variations (Frappart and Ramillien 2018). In this study, we have utilized NASA's Global Land Data Assimilation System Version 2.2 (GLDAS-2.2) model which incorporates a state-of-the-art terrestrial water storage product derived from GRACE satellite observations (Li et al. 2019). This product was assimilated into NASA's Catchment Land Surface Model (CLSM) to derive 24 land surface fields including the time averaged GWS product since 2003. The method involves incorporating GRACE terrestrial water storage (TWS) observations into the model driven by meteorological data using a Kalman smoother approach to update and enhance the accuracy of forecasted model states. To analyse the historical GWS dynamics and behaviour of water resources in the disaster-hit area (Zliten), this study has used the analysis ready GWS product (Li et al. 2019) within the Google Earth Engine (GEE) from February, 2003 to March, 2024 (Table 1).

Moreover, in this study we have used pre-processed MSL trend product (based on satellite altimetry) from Radar Altimeter Database System (RADS) (Scharroo et al. 2012). This data will help us understand the long-term trends in sea level rise in the region and to evaluate the hypothesis of 'rising sea levels and SWI' which may have caused upsurge of groundwater in Zliten. Satellite altimeter radar measurements can be combined with precisely known spacecraft orbits to measure sea level on a global scale (Veng and Andersen 2021). A reference series of satellite missions, including TOPEX/Poseidon (T/P) (1992), Jason-1 (2001–2013), Jason-2 (2008–2019), Jason-3 (2016–present), and Sentinel-6 (2020–present), estimate global Mean Sea Level (MSL) and local trends with an uncertainty of 3–4 mm.

3.3. High resolution optical satellite data

Operated by Planet Labs, PlanetScope (PS) is a constellation of approximately 130 satellites which images the entire land surface of the Earth every day at high spatial resolution (3.5 m). To assess the impact of stagnant water on vegetation health, orthorectified, eight-band surface reflectance products were acquired from October

Table 1. Descriptive statistics of datasets used in the study.

Variable	Mean	StDev	Min	Max
GWS (mm)	301	22	258	377
SLR Trend (mm/yr)	2.31	0.95	0.67	3.49
Well Depth (m)	161.6	89.9	20.0	346.0
Elevation (m) Zliten	13.95	6.70	−8	33
Elevation (m) HydroBasin	182.85	178.17	−24	954
Daily Precipitation (mm) (Oct 2023-Mar 2024)	1.01	3.47	0	20.95

2023 (when water upsurge was first reported) to February 2024. Images were selected which had cloud cover of less than 10% over the study area. Five PS surface reflectance images corresponding to each month (October 21, 2023; November 25, 2023; December 27, 2023; January 27, 2024 and February 9, 2024) were then processed to calculate the Normalized Difference Vegetation Index (NDVI) using the red and near infrared bands (Houborg and McCabe 2018).

3.4. Precipitation data

To investigate and validate rainfall anomalies in Zliten and its surrounding areas, we employed the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) rainfall dataset (Funk et al. 2015). CHIRPS combines high-resolution satellite imagery with in-situ station data at a spatial resolution of 0.05° to generate gridded rainfall time series suitable for trend analysis and seasonal drought monitoring. Specifically, we extracted the daily rainfall (mm/day) from the CHIRPS Daily product from October 2023 to January 2024 (Table 1). Additionally, to analyse long-term rainfall trends, we utilized the CHIRPS dataset to obtain yearly average rainfall from January 2014 to January 2024.

4. Results

4.1. Impact of groundwater storage on water upsurge

The temporal analysis of the GWS over a span of two decades (2003–2023) revealed intriguing patterns and trends (Figure 2). The GWS value exhibited fluctuations over the years, ranging from a minimum of 258 mm in 2017 to a maximum of 377 mm in 2008. Interestingly, a general increase in the mean GWS value was observed from 2003 to 2008, reaching its peak, followed by a period of relative stability with intermittent fluctuations. Between 2008 and 2012, there is a significant downward trend in the mean groundwater values, indicating a sustained decrease in groundwater levels. Notably, a significant decrease in the GWS was observed between 2016 and 2023. The standard deviation of approximately 22 indicated moderate variability in the GWS, suggesting the presence of diverse influencing factors. Quartile analysis revealed that 25% of the data fell below 291 mm, while 25% fell above 330 mm, signifying a wide range of GWS values. Although there are some fluctuations and minor variations in subsequent years, the general trend suggests continued strain on groundwater availability. These findings suggest that the potential cause of water upsurge in Zliten is not due to GWS which is already continuously decreasing.

4.2. Impact of sea level rise on water upsurge

The coastal areas of Libya are experiencing the effects of long-term sea-level rise (SLR), raising the concerns on potential saltwater intrusion into coastal aquifers. In this study, we performed a spatial analysis of SLR trends (Figure 2) along the Libyan coastline to assess the implications for freshwater resources. Results revealed distinct patterns of SLR in different regions of Libya. Specifically, the city of Zliten exhibited an estimated

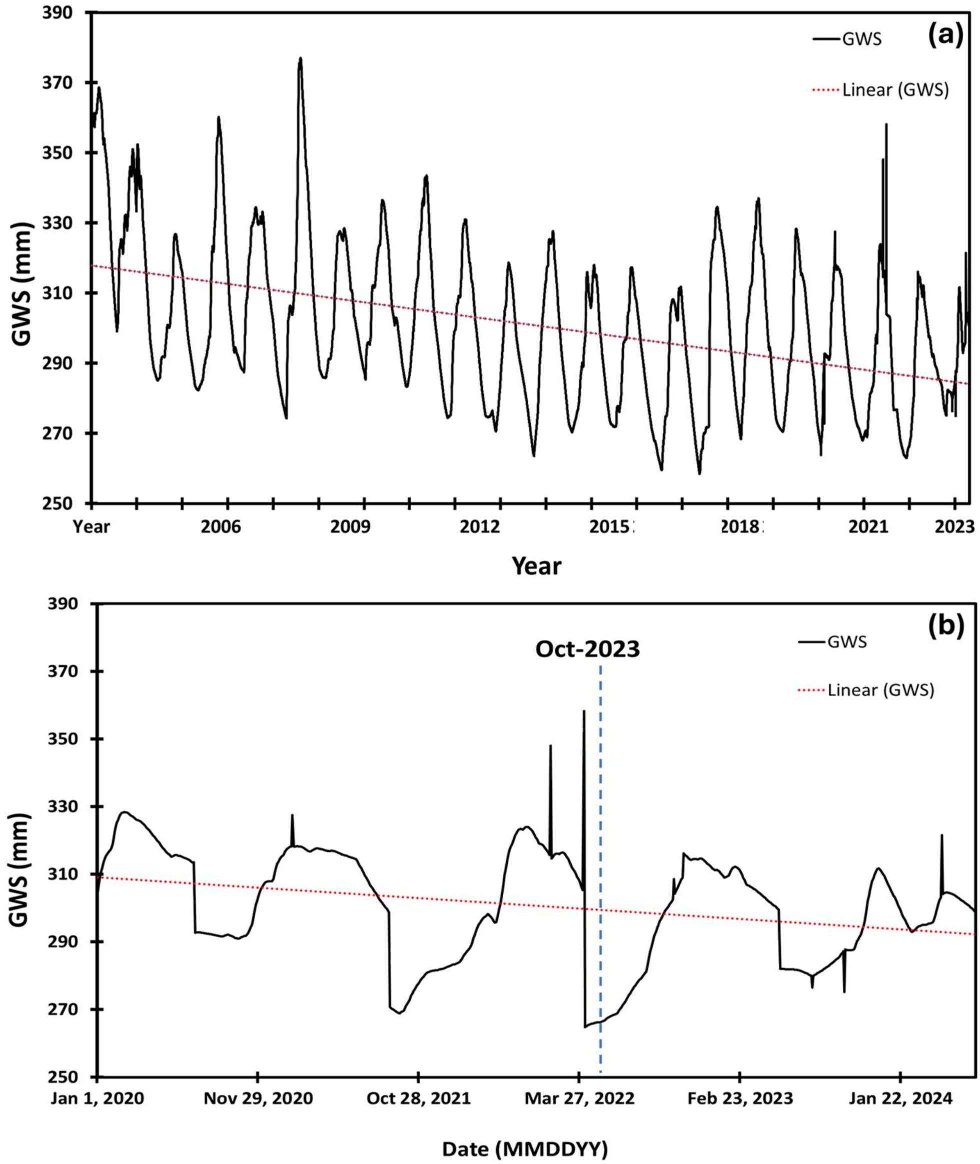

Figure 2. Time-series of daily ground water storage (GWS) over zliten from (a) february 2003 to March 2024 (b) GWS during the months of october, november, december, january, february, and March, from 2020 to 2024.

average SLR of 2.8 mm/yr, indicating a significant upward trend. Conversely, the coastal areas near Egypt experienced relatively lower SLR rates of 0.6 to 0.9 mm/yr. Moving eastward, the SLR increased to 3.4 mm/yr in the city of Sirte. Westwards from the capital city of Tripoli towards the Tunisian border, SLR ranged from 2.5 to 2.8. These findings highlight the spatial variability of SLR along the Libyan coast and provide crucial insights into the potential risks of saltwater intrusion. As there is well established relationship between SLR and climate change, it is widely assumed that this raise will have a severe adverse impact on SWI processes in coastal aquifers (Chang et al. 2011). The observed higher SLR rates in study region suggests an increased vulnerability to SWI, which might be linked to the recent water upsurge episodes. These findings also emphasize the need for proactive management strategies to protect freshwater resources from degradation and ensure sustainable coastal development in Libya.

Analysis of the digital elevation model suggests that water intrusion may have originated from the northeastern side of Zlitan, where the terrain exhibits a lower slope gradient (1.4 slope percent) and decreasing elevation values towards the northwest. Notably, the locations of water surge events are situated at distances ranging from 600 m to 2800 m from the coastline. Furthermore, these sites are in close proximity to the Al-Baqar Street drainage line, as illustrated in Figure 3(a). Due to limited resources and availability of data, a piezometric analysis along with groundwater quality cannot be performed at the moment, which are very important to understand the situation of GWF in Zlitan (Iqbal et al. 2024). Moreover, with precipitation and NDVI data suggests that groundwater recharge from atmospheric source is negligible. A detailed discussion of these findings is presented in subsequent sections.

4.3. NDVI trend for the latest water upsurge areas

As there was a peak of water upsurge and flooding locations during February 2024, the PS image acquired on February 9, 2024 was used to identify the water-logged

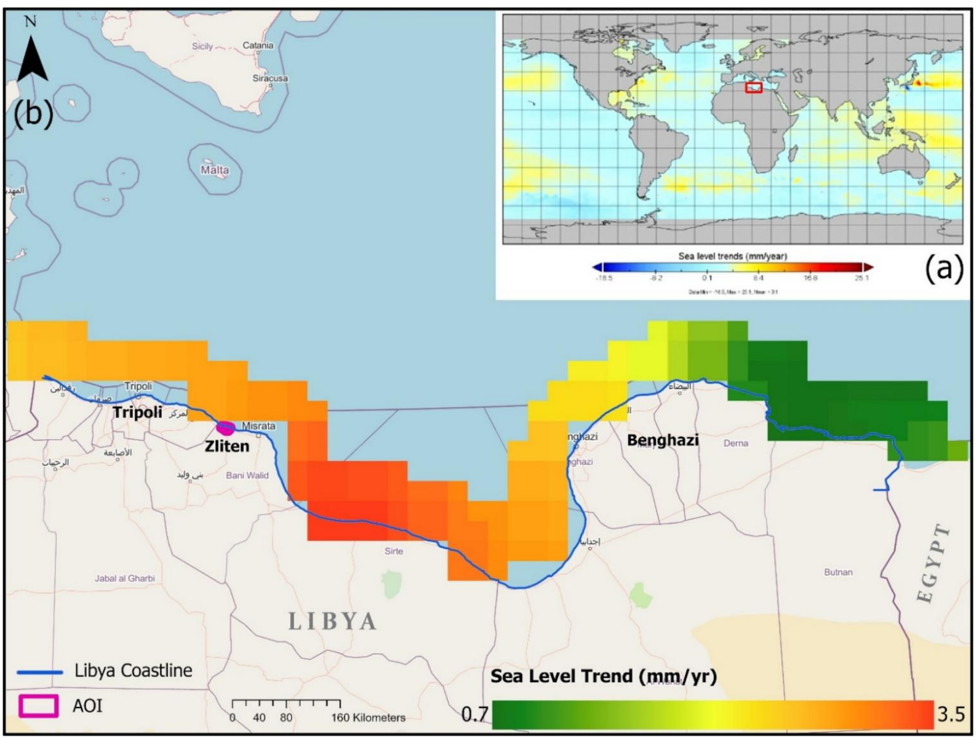

Figure 3. Global and regional mean sea level rise trends around the Coast of libya from 1992-present, provided by NOAA laboratory for satellite altimetry. (a) The inset map shows the location of study area on global sea level trend map. (b) a buffer of 10 km from the shoreline (blue colour) was used to extract the data for Libyan coast.

areas (Figure 4(a)). The locations of flooded areas were validated with United Nations Institute for Training and Research (UNITAR) delineated areas. These water-logged areas were used to analyse the trend of NDVI, which can be used as proxy for surface water availability. Interpreting the trend of NDVI within the water-logged areas helped us assessing the damage to the palm trees/orchards and their current health. It should be noted that, a decreasing trend in NDVI could indicate a negative impact on vegetation due to reduced surface water availability while an increasing trend may suggest improved vegetation health as a result of the presence of surface water. From NDVI (Figure 5(a,b)) it is evident that water pixels were not present in months of October and November 2023, but in the following months (December 2023, January and February 2024) water features can be observed with NDVI ranges (NASA 2000) of −0.4 to −0.10, in small frequencies. Moreover, the values of NDVI in the range of 0.2 to 0.5 have high frequency suggesting the availability of crop, grass, and agroforestry features. The results of the NDVI box plot analysis indicate that January had the highest median NDVI value, suggesting the healthiest vegetation among the studied months. While the presence of outliers in the months of Dec to Feb box plot suggests the existence of areas with significantly lower NDVI values (Figure 5), possibly indicating the presence of water content and confirming the media reports of stagnant water patches (The Libya Observer 2024b).

The vegetation type in Zliten is mostly date palm trees and crop fields (Figure 4(b-d)). This is a reason that the range of NDVI for the months of October and November 2023

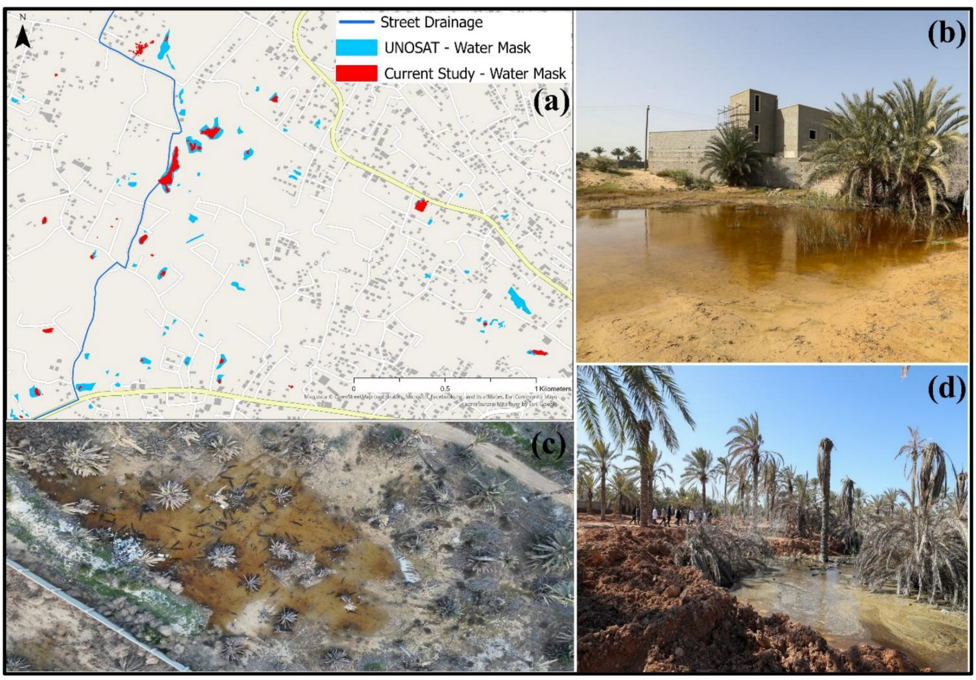

Figure 4. (a) Map of localised flooding areas identified using planetscope image in (red color) and UNOSAT identified areas (blue color), the street drainage was also extracted from UNOSAT/UNITAR (b) image showing the stagnant water (credits: Mahmud Turkia-AFP), (c-d) damaged vegetation and palm trees due to GWF (source: UNOSAT/UNITAR).

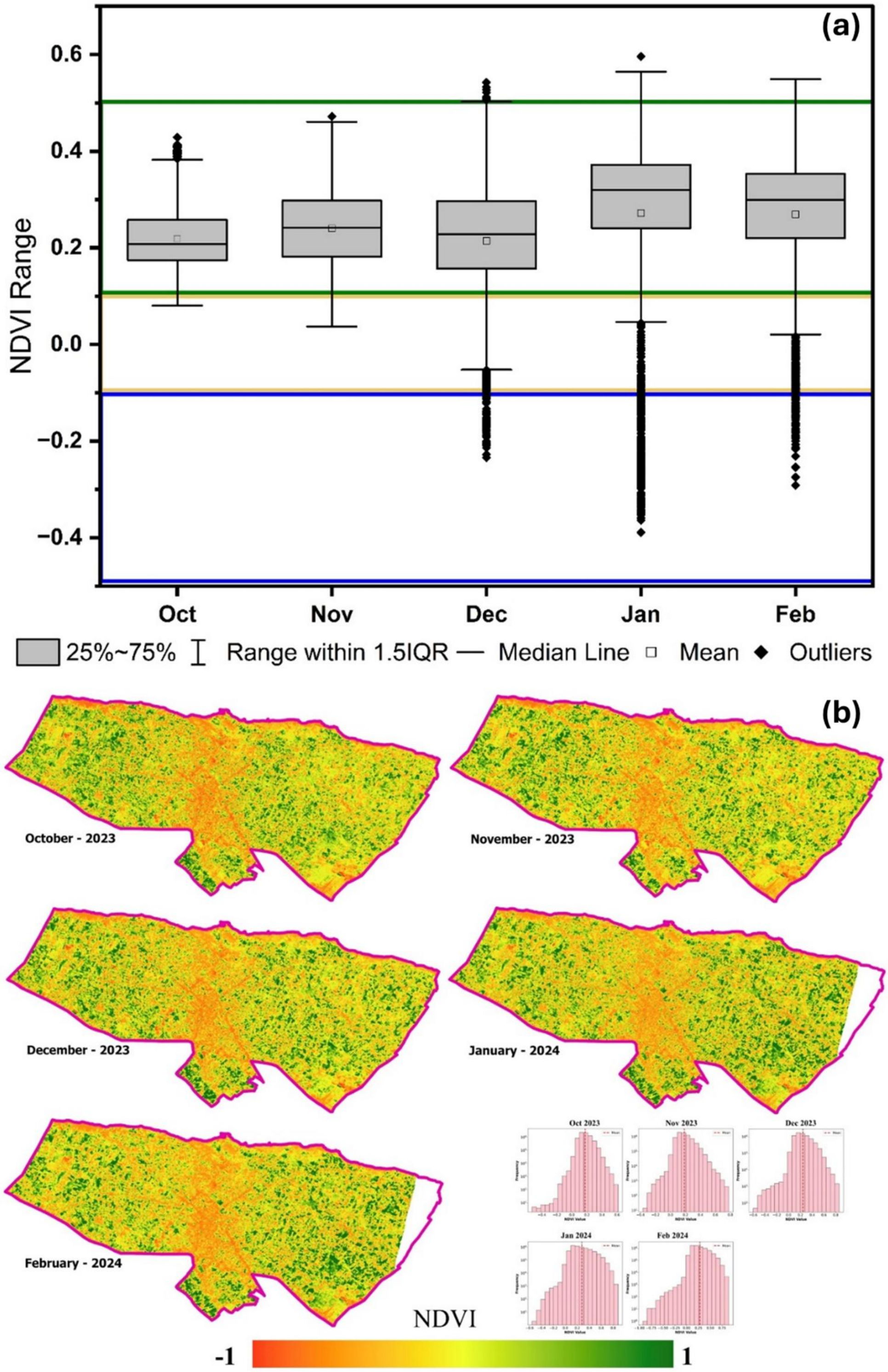

Figure 5. (a) Box plot showing the trend of NDVI for the groundwater flooded areas of Zliten. The green, yellow, and blue rectangles represent the community known NDVI ranges for sparse vegetation, barren areas and water, respectively (b) Monthly NDVI maps for each month along with corresponding histograms. The red colour in legend shows lowest values, while green colour shows the highest value of NDVI.

(over the flooded areas) is mostly between 0.15 to 0.3 (Figure 5). Starting from December, some of the areas improved in vegetation health while majority of the areas noted decrease in vegetation health due to water upsurge and stagnation. It should be noted that during the months of December and January, significant cover of vegetation has been converted to barren land (i.e. NDVI values of −0.1 to 0.1) with even more (previously vegetated) area being converted to dead plants during February (shift of outliers in the NDVI range of −0.1 to 0.1). Further, almost same values of mean and median during October and November show stable vegetation health while the decrease in mean NDVI value than the median indicates the degrading vegetation health during December to February (Figure 4(b-d)).

4.4. Link between rainfall and water upsurge events

The daily rainfall data for the study area from October 1, 2023 to January 31, 2024, was analysed to understand the rainfall patterns during this period. The analysis revealed mostly dry conditions with minimal rainfall from October to early December 2023. However, there were a few isolated days with low precipitation. Starting from early December 2023, the precipitation became more variable, with occasional rainfall events. Notable days with higher precipitation were observed in early December, with few days exceeding 20 mm/day of rainfall, which is normal. The total precipitation in the study area from the same span of time was about 149 mm. The precipitation data reveals a total of 167 dry days and 19 wet days from Oct 2023 to Mar 2024 (Figure 6(a)). Dry days are defined as those with rainfall below 1 mm/day, while wet days are characterized by rainfall equal to or exceeding 1 mm/day. Also, the occurrence of dry periods and sporadic rainfall events is not unusual for the region. It is characteristic of the arid and semi-arid climates found in this part of Libya, where extended dry periods are followed by intermittent rainfall.

To get the synoptic view of yearly rainfall pattern from 2014 to 2024 (till January), we have used the CHIRPS data (Figure 6(b)). The observed year-to-year variations in rainfall amounts indicate a non-stationary nature of the rainfall pattern, suggesting the presence of interannual variability. The highest recorded rainfall in 2019, with an average of 270.088 mm/year indicates a period of anomalously high precipitation. There was a distinct decline in rainfall from 2015 to 2016, with values dropping from 237.154 mm/year to 170.679 mm/year, indicating a shift towards drier conditions. Conversely, an increase in rainfall was observed from 2021 to 2022, with values rising from 196.702 mm/year to 235.988 mm/year, suggesting a transition towards wetter conditions. These interannual fluctuations highlight the dynamic nature of rainfall patterns, emphasizing the need for comprehensive monitoring and analysis.

5. Discussion and recommendations

This study has used multifaceted data sets to explore the relationship of groundwater upsurge with different environmental parameters. To our knowledge, this is the first study providing preliminary scientific insights on the water upsurge events of Zliten. The assessment of mean SLR reference data indicated varying rates of SLR along the Libyan

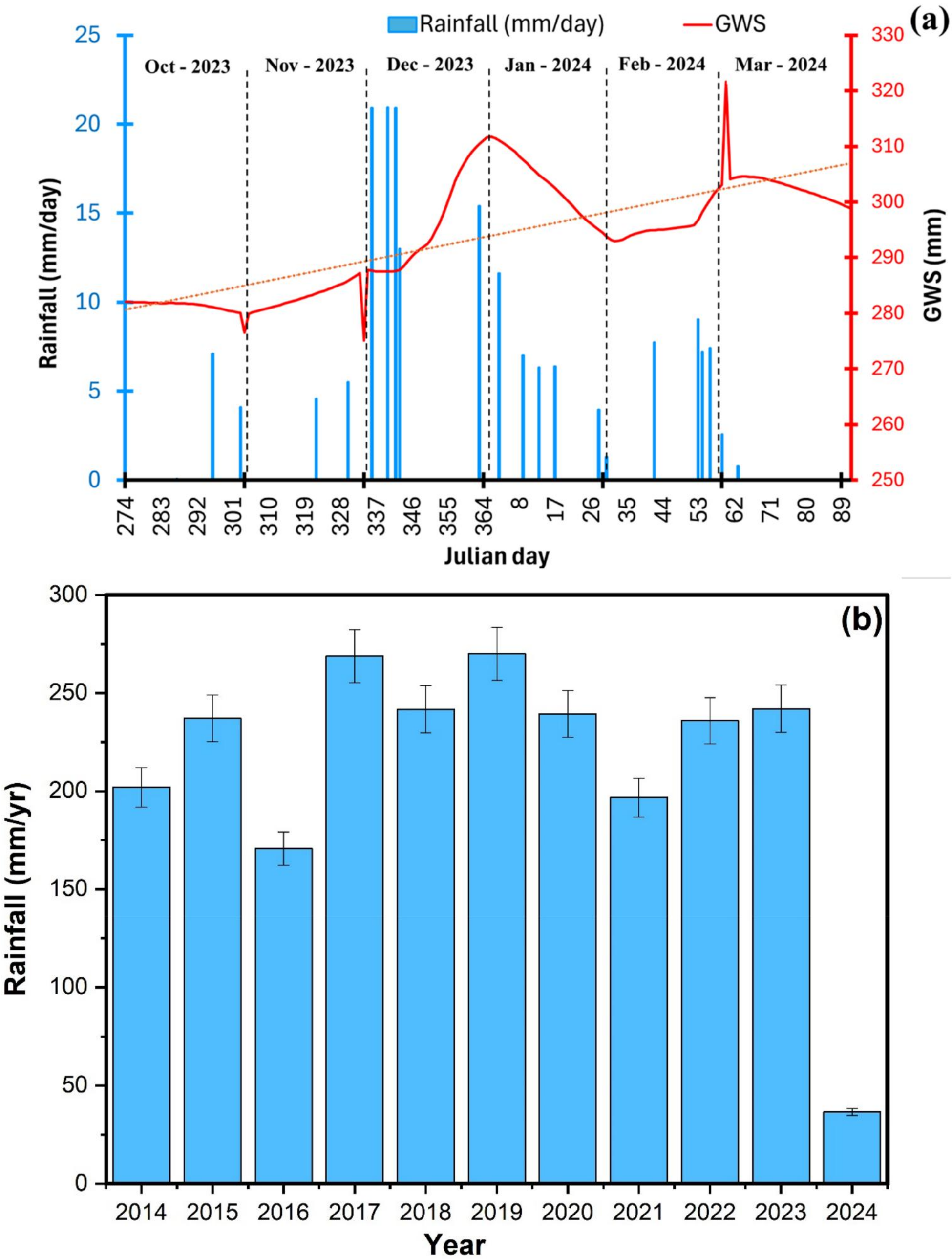

Figure 6. (a) Daily rainfall (mm) and GWS (mm) fluctuation between oct 2023 to mar 2024 and (b) annual rainfall from jan 2014 to jan 2024. The whiskers represent the standard deviation.

coastline. Different areas had different average SLR values, ranging from 0.6 to 0.9 mm/yr to 3.4 mm/yr. While these values provide insights into historical and current SLR, they do not prove a direct connection with the water upsurge, as no significant increase in SLR is observed, thus negating our hypothesis. But it is important to note that SLR is a complex phenomenon influenced by multiple factors, including global climate patterns, ocean currents, and localized geological processes (Klassen and Allen 2017). The lack of a significant increase in SLR observed in the data does not necessarily rule out the possibility of groundwater flooding events occurring in the area. Other factors such as storm surges, tidal fluctuations, or localized coastal erosion can lead to temporary variations in water levels, even if the average SLR remains relatively stable. Further investigation and analysis are required to assess the specific drivers behind the water upsurge events. Additionally, establishment of advance SLR monitoring station and comprehensive data collection framework will help improve our understanding of these phenomena and their long-term implications for coastal regions such as Zliten in Libya.

While natural factors such as rainfall patterns and SLR are considered in our study, it is crucial to recognize the potential impact of human activities on groundwater upsurge and its severity. Several man-made factors could play a role in exacerbating groundwater upsurge, such as poor land management practices, including improper drainage or land use changes, which alter the natural hydrological pathways, geologic and geomorphic features leading to the release of groundwater into surface (Mancini et al. 2020). These processes can result in water accumulation and subsequent groundwater flooding in the affected areas. A similar case was observed in Wisconsin River valley where high-permeability outwash aquifer was subject to water table rise at rates exceeding 1 m/day, causing low-lying areas inundated for 6 months (Gotkowitz et al. 2014).

Another factor that should be considered is the potential role saltwater intrusion. Coastal regions are particularly vulnerable to groundwater upsurge due to the intrusion of saline water into freshwater aquifers (Hereher 2015). Human activities such as excessive groundwater extraction, coastal development, and inadequate wastewater disposal practices can further aggravate saltwater intrusion, displacing freshwater resources and contributing to groundwater upsurge events. For instance, excessive groundwater extraction in coastal areas disrupts the natural pressure gradient between freshwater and saltwater, leading to saltwater intrusion. This occurs as pumping lowers the freshwater head, creating a pressure difference that draws saltwater from the sea into the aquifer (Figure 7). The intrusion forms a wedge-shaped body, pushing back the freshwater and contaminating the available supply (Jasechko et al. 2020). Excessive groundwater pumping poses a significant threat to freshwater resources by facilitating saltwater intrusion. This intrusion occurs through various mechanisms. Pumping can lower the hydraulic head, reducing the natural gradient that pushes freshwater towards the sea, allowing saltwater to move inland. Intense pumping can also cause the freshwater/saltwater interface to rise, forming a cone-shaped saltwater up-coning beneath the well, drawing saltwater into the well (Reilly and Goodman 1985; Alley et al. 1999; Agoubi 2021). Additionally, pumping can locally reverse the hydraulic gradient near the well, creating a pathway for saltwater to flow into the aquifer (Okasha 2011; Badaruddin et al. 2017). In fractured rock formations, saltwater can infiltrate wells through discrete fractures, bypassing the natural barrier between freshwater and saltwater (Klassen and Allen 2017).

Additionally, man-made factors such as damaged pipelines, and inadequate or damaged drainage systems can impede the efficient removal of excess water, resulting in increased vulnerability to groundwater upsurge. Further investigations, including detailed field studies and modelling, should be conducted to better understand the

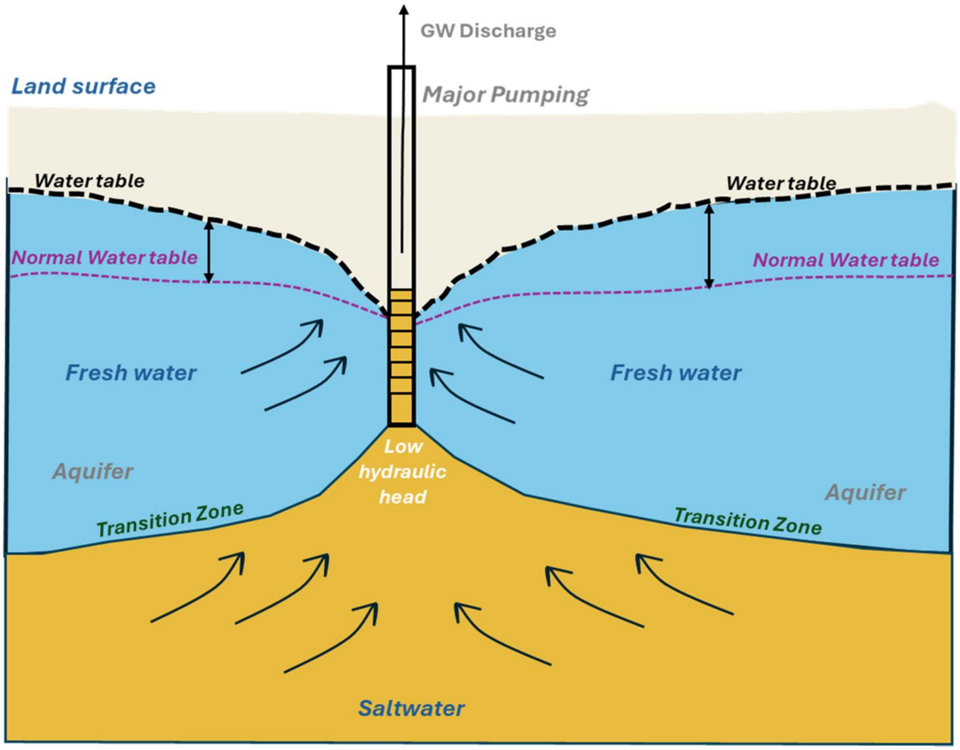

Figure 7. Schematic diagram of seawater intrusion into the coastal aquifer modified after (Reilly and Goodman 1985).

Table 2. Details of constructed dams in zliten area (Hamad 2012).

Wadi	Reservoir capacity Mm^3	Average annual design storage Mm^3 year
Wadi Kaam	111	13
Wadi Tabrit	1.6	0.50
Wadi Al Thiker	2.4	0.50

specific contributions of man-made factors to groundwater upsurge in the study area. Such research will provide valuable insights for developing effective strategies and policies to manage and mitigate groundwater upsurge risks in a sustainable manner. ′

In the vicinity of study area, the presence of dams (Table 2), which regulate surface water flow and store water (Ighwela 2020), may not have directly induce groundwater upsurge. Nevertheless, they can exert indirect influences on the groundwater system. One such effect is the alteration of surface water-groundwater interaction by impacting the groundwater recharge and discharge processes, potentially resulting in elevated groundwater levels and subsequent groundwater upsurge in downstream areas. While dams can indirectly influence groundwater dynamics, their specific contribution to groundwater upsurge is contingent upon various factors. Local hydrogeological conditions, geological formations, and the presence of natural or anthropogenic drainage systems play essential roles in determining the overall impact on groundwater levels and the occurrence of groundwater upsurge (Mancini et al. 2020; Allocca et al. 2022; Alfio et al. 2024).

The Gravity Recovery and Climate Experiment (GRACE) satellite data shows that the water storage trend of Zliten is decreasing but some variations can be observed in the data (Figure 2). The water table depth in the areas of Zliten (where most of the water upsurge events have occurred) is between 25 to 130 m according to Ashmila et al. (2021). It is possible that over the time, overexploitation of the aquifers has disturbed the aquitard and shallow aquifer of the area along with SWI phenomenon, which led the groundwater upsurge due to lower piezometric level, as discussed above. Additionally, the unsaturated zone, extending from the ground surface to the groundwater table, serves as a crucial buffer zone where key hydrological processes occur. These processes include water flow and infiltration, influenced by the moisture content and the medium's properties such as hydraulic conductivity and water retention capacity (Alfarrah and Walraevens 2018; Mahmoodzadeh and Karamouz 2019; El-Hokayem et al. 2023). The unsaturated zone plays a critical role in groundwater flooding, acting as a storage reservoir for water until a saturation threshold is reached. Fluctuations in the system, triggered by antecedent conditions, precipitation events, or anthropogenic disturbances, can drive the groundwater system towards this threshold, ultimately leading to flooding (Bosserelle et al. 2022). An End-Member Mixing Analysis (EMMA) (Christophersen and Hooper 1992) of the water samples (from the affected areas) can further confirm the hypothesis to know the contributions of each end-member i.e. surface water, seawater, groundwater from upstream and or/and from the aquifer.

The study area primarily supports the cultivation of cereal crops, with barley and wheat being the most prevalent. Local communities also cultivate a range of other crops, including vegetables such as tomatoes, peppers, beets, onions, and cucumbers, as well as beans, corn, and fodder. Additionally, a variety of greens, including parsley, coriander, mint, and alfalfa, are grown. While these crops are essential for local livelihoods, excessive water availability can pose challenges. For instance, prolonged periods of waterlogging can negatively impact cereal yields and increase the risk of root rot in vegetables, which has already been reported by media (Al Jazeera 2024). Further research is needed to fully understand the specific impacts of excessive water availability on these crops and to develop strategies for mitigating potential negative effects. Moreover, advance irrigation techniques can be used such as drip-irrigation, tunnel farming, and hydroponic farming, which can turn this disaster to revenue generating opportunity for local residents.

As a long-term solution and to curtail such environmental disasters, a detailed piezometric survey and monitoring along with Ground-Penetrating Radar (GPR) based study is suggested to investigate the water upsurge or groundwater flooding events in Zliten. Conducting piezometric survey and GPR-based study would provide valuable insights into the subsurface characteristics, such as groundwater table levels, soil composition, and potential pathways for water upsurge. One of the limitation of this study is unavailability of piezometric and physio-chemical data of the study area.

6. Conclusions

The preliminary results of this study provided important findings regarding the impact of groundwater storage, SLR, NDVI trends, and the link between rainfall and water upsurge event in the town of Zliten, Libya. The temporal analysis of GWS data over a span of two decades showed fluctuations in subsequent years, the general trend suggested a continued strain on groundwater availability. These initial findings suggest that the potential cause of water upsurge in Zliten can be attributed to short-term increase of GWS due to seawater intrusion. Also, the analysis of SLR trends along the Libyan coastline revealed distinct patterns, with Zliten experiencing an average SLR of 2.8 mm/yr. The higher SLR rates observed in certain regions suggested an increased vulnerability to saltwater intrusion, which might be linked to the recent water upsurge episodes. The study also examined the trends of NDVI within water-logged areas to assess the damage to vegetation and its current health. Furthermore, the analysis of rainfall patterns during the study period showed mostly dry conditions with occasional rainfall events. The time-series analysis since 2014 to 2024 did not reveal any abnormal (intense) rainfall events, indicating no link between irregular rainfall and water upsurge events in Zliten.

Furthermore, the GWF may be influenced by various additional factors, beyond those previously discussed. For instance, the subsurface geological conditions are an important factor to consider, as they can influence groundwater movement and contribute to GWF. On other hand, the composition and structure of the subsurface play a significant role in determining the behaviour of groundwater, affecting its flow patterns and potential for GWR. Moreover, interactions between different aquifer systems, such as confined and unconfined aquifers, might play a noteworthy role. Pressure differentials and preferential pathways for groundwater flow between aquifers can induce changes in groundwater dynamics, contributing to water upsurge phenomena. Anthropogenic factors, specifically excessive groundwater extraction, can alter aquifer levels and flow patterns to cause SWI which intern can potentially triggering groundwater flood. This occurs when the rate of extraction surpasses natural recharge, leading to declining groundwater levels. Excessive extraction or pumping (often driven by increased demand for water) can lower the hydraulic head, reducing the natural gradient that pushes freshwater towards the sea, allowing saltwater to move inland (Figure 7) (Klassen and Allen 2017). This is created by a localized pressure imbalance, causing water to flow towards the extraction site and resulting in GWF. Prolonged extraction can also induce land subsidence, altering hydrogeological characteristics and disrupting drainage patterns, further exacerbating upsurge risks, such cases have been observed in major coastal cities across the globe (Amin et al. 2022; Abdalla et al. 2024; Avornyo et al. 2024; Ohenhen et al. 2024). To understand this phenomenon, a time-series analysis of land subsidence using radar imagery is essential. By analysing radar images over time, changes in land vertical distance can be measured and quantified, providing insights into the extent and impact of excessive groundwater extraction.

Acknowledgements

The authors would like to thank UNOSAT for providing the flooded areas boundaries, NASA's GLAD 2.2 for providing the GRACE satellite data, Climate Hazards Group, UC Santa Barbara for providing CHIRPS rainfall data, and Planet Labs Inc. for providing basic license in the Education and Research programme that granted free access to high-resolution PlanetScope images.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research was supported by the General Research Fund (Project No. PolyU15306224), and the Collaborative Research Fund (Grant No. C5062-21GF) from the Research Grants Council, Hong Kong, China, The Hong Kong Polytechnic University's Start-up Fund for RAPs under the Strategic Hiring Scheme (Project ID: P0044784) and from the Research Institute for Sustainable Urban Development (Project ID: 1-BBG2), The Hong Kong Polytechnic University, Hong Kong, China.

Data availability statement

Data will be made available on request.

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