Observing Drought-Induced Crustal Loading Deformation Around Lake Mead Region via GNSS and InSAR: A Comparison with Elastic Loading Models

Sonia Zehsaz

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Susanna Werth, Chair
Manoochehr Shirzaei
D. Sarah Stamps
Madeline E. Schreiber

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ABSTRACT

Lake Mead, the largest reservoir in the United States along the Colorado River on the border between the states of Nevada and Arizona, is one of the nation's most important sources of freshwater. As reported by the U.S. drought monitor (USDM), the entire region has been experiencing recurring severe to extreme droughts since the early 2000s, which have further intensified during the past two years. The drought-driven water deficit caused Lake Mead's water volume to decrease to approximately one-third of its capacity, creating a water crisis and negatively affecting soil and groundwater storage across the region. Water deficits have further reduced the mass of water loading on the Earth's crust, causing it to elastically deform. I observe this process from the ground by recording the vertical land motion occurring at Global Navigation Satellite System (GNSS) stations, or from space via Interferometric Synthetic Aperture Radar (InSAR) technology. In this study, I analyze vertical deformation observations from GNSS sites and multi-temporal InSAR analysis of Sentinel-1A/B to investigate the contribution of water mass changes in lake, soil, and groundwater to the deformation signal. To achieve this, I remove the effects of glacial isostatic adjustment and non-tidal mass loads from GNSS/InSAR observations. Our findings indicate that recent drought periods led to a notable uplift near Lake Mead, averaging 7.3 mm/year from 2012 to 2015 and an even larger rate of 8.6 mm/year from 2020 to 2023. Further, I provide an estimate of the expected vertical crustal deformation in response to well-known changes in lake and soil moisture storage. For that, I quantify hydrological loads through two different loading models. These include the application of Green's functions for an elastic, layered, self-gravitating, spherical Earth, and the Love load numbers from the Preliminary Reference Earth Models (PREMs), as well as elastic linearly homogeneous half-space Earth models. I further test various load models against the GNSS observations. Our research further investigates the impact of local crustal properties and evaluates the output of several elastic loading models using crustal properties and different model types under non-drought and drought conditions. For future studies, I suggest a comprehensive analysis of the deformation field InSAR data. Also, rigorous monitoring of groundwater levels is essential to accurately predict changes in water masses based on deformation. In addition, for each data set, I suggest implementing an uncertainty analysis to assess the predictability of groundwater level changes based on vertical loading deformation observed by INSAR/GNSS data around the region. Obtaining such estimates will provide valuable insight into the dynamic interactions of the local aquifers with Lake Mead.
GENERAL AUDIENCE ABSTRACT

The drought has led to a decline of approximately 40 meters in Lake Mead since 1999. During the process of water mass loss from a lake, the crust lifts and extends from the center. However, the water mass loss seen on the lake is not sufficient to explain the movement seen at nearby GPS sites. Hence, the uplift loading of water loss in the form of other hydrological components surrounding Lake Mead needs to be estimated. Here, I analyze several models that best fit the geodetic displacements and try to fill in the gap in deformation observations.
In writing this dissertation, I am honored to dedicate it to my husband, Mehdi Seyyedi, who has provided me with strength, support, patience, and motivation throughout this entire project.

I also dedicate this to my parents, Ali and Mahin Zehsaz, who have always taught me throughout my life to keep God first and then strive for excellence. I thank you for your guidance and love.
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CHAPTER 1. INTRODUCTION

The process of crustal deformation takes place when external forces act on the rocks, leading them to deform or change shape. These forces, known as stress, when acting on an object can arise from various factors, including hydrological processes, glacial isostatic adjustment, and anthropogenic activities like groundwater extraction [2].

Elastic loading is a type of crustal deformation that refers specifically to the changes in the Earth's crust caused by the redistribution of mass, for example, because of hydrological processes such as changes in groundwater levels, soil moisture content, or the filling and emptying of surface water bodies, including reservoirs [5], [6]. In this phenomenon, the crust temporarily changes its shape in response to the applied load. However, once the load is removed, the shape returns to its original state. During the hydrological cycle, variations in continental water storage, encompassing elements such as snow, soil moisture, the atmosphere, ocean, ice sheet, groundwater, and surface water, generate changes in mass and surface pressure and lead to elastic deformation of solid earth [2], [3].

When exploring different types of crustal deformation caused by loading, one area of focus involves the study of elastic loading deformation. The deformation can be effectively measured and monitored using a variety of techniques. Gaining insight into the elastic response of the Earth's crust and its connection with hydrological processes holds significance in comprehending the Earth's dynamics, managing water resources, and evaluating the influence of human activities on the Earth's crust [4], [5].

The elastic Earth response to surface loading manifests itself in both the vertical and horizontal directions. Uplift and subsidence serve as two modes of elastic vertical deformation, emerging in response to shifts in the load affecting the underlying rocks due to hydrological processes. Uplift specifically occurs when the Earth's crust is pushed upward because of a reduction in mass, brought about by diverse factors like drought, excessive use of water resources, or unsustainable alterations in water management practices. Subsidence takes place when the Earth's crust sinks downward because of an increase in mass caused by processes such as replenishing of a lake after a period of drought. When a lake experiences a drought, the water level decreases, and reduced weight of the water on the Earth's crust leads to uplift. When the drought ends and the lake volume increases, the weight of the water on the Earth's crust increases, leading to subsidence because of the elastic response of the crust [6], [7].
It’s also noteworthy that another distinct deformation process, poroelastic deformation, exists. Changes in water pressure and levels within confined aquifers mainly cause it. A reduction (increase) of water level in the aquifer yields subsidence (uplift). Hence, if relevant, this mechanism occurs in the opposite direction compared to elastic deformation. Regions with extensive confined aquifers, such as California’s Central Valley, typically experience significant subsidence rates during drought, caused by sharp declines in groundwater levels due to unsustainable well pumping. Poroelastic deformation in unconfined aquifers due to changes in groundwater levels exists, but it is much smaller and below a measurable amplitude compared to confined aquifers.

Techniques based on space-geodetic data such as the Global Navigation Satellite System (GNSS), and InSAR (Interferometric Synthetic Aperture Radar), enable accurate observation of present-day Earth deformation, and through that provide insight into how hydrological processes impact crustal deformation. Many recent studies employ national and regional GNSS networks, and use 3D station displacements to monitor time-dependent vertical and horizontal crustal deformation caused by hydrological loading [3], [11], [12], [14], [15], [4], [16], [20], [24]. A notable proportion of these studies have concentrated on the precise observation of vertical deformation, facilitated by the utilization of InSAR techniques [14], [21]. These investigations make use of radar images taken from satellites. A noteworthy illustration of such contemporary research endeavors employing InSAR are studies conducted on the northeastern edge of the Tibetan Plateau and in Taiwan [8], [9]. By combining InSAR with other techniques, such as GNSS, a more comprehensive understanding of hydrological elastic crustal deformation has been achieved [16] due to their complementary attributes. InSAR provides high-resolution measurements of surface displacement across extensive regions. For example, Sentinel-1A employs a C-Band Synthetic Aperture Radar (SAR) to generate high-resolution imagery, with individual pixels covering an area of 5 meters by 20 meters. It revisits the same Earth view approximately every 12 days [10]. On the contrary, GNSS provides highly accurate positional data, with precision ranging from sub-decimeter to centimeter-level, depending on the specific technique employed. A combination of both enhances the overall accuracy of ground motion tracking. When employed in conjunction, these methodologies enable researchers to effectively discern the diverse factors impacting crustal deformation, including shifts in groundwater and effects induced by human activities [11], [12].

In the realm of research centered on elastic deformation, hydrological models are also indispensable tools. For example, models such as NLDAS (North America Land Data Assimilation System) and GLDAS (Global Land Data Assimilation System) play a critical role in simulating and
quantifying the amount of water stored in various natural reservoirs, such as soil moisture and snowpack. The estimation of water storage changes provided by these models possesses the potential to function as indicators of deformation. Subsequently, the deformation is monitored and measured through the utilization of GNSS and InSAR techniques. The significance of these models in this context becomes apparent [26], [27].

However, the results obtained from geodetic measurements and model-based estimates show that there is a significant difference in the loading deformation. For instance, the analysis of Dill & Dobslaw (2013) demonstrated that water mass changes as predicted by the Land Surface Discharge Model (LSDM) could only explain 54 percent of the observed vertical displacement at 53 globally distributed GNSS stations [13]. Also, Argus et al. (2017) discovered that models of hydrology underestimate the actual amount of water gained during heavy precipitation periods or lost during drought [14]. The key reason for the significant differences between geodetic measurements and model-based estimates of loading deformation is the fact that variations in the storage of groundwater are notoriously hard to constrain, whereas geodetic observations of surface deformation are sensitive to the loads of vertically integrated water mass which include groundwater [15].

In recent years, several other researchers have specifically studied elastic vertical loading deformation caused by natural processes and anthropogenic pumping. For instance, in the region of the Great Lakes, Argus et al. (2020) conducted a study to determine how the Earth's elastic loading response has been affected by the recent rise in lake levels between 2013 and 2019. By using GPS and GRACE data, they estimated changes to water storage in the Great Lakes basin, resulting in a significant seasonal variation of approximately 100 km$^3$ in land surface water [16]. Also, Li et al. (2020) found that changes in water storage in southern Ontario are correlated with surface deformation based on InSAR data in Erie and Ontario lakes [17]. Moreover, Gahalautet al.'s report states (2017) that GNSS measurements near the reservoir additionally show anomalous fluctuations in response to the seasonal loading and unloading of lake water. Results of an InSAR analysis confirm that there is noticeable subsidence in the neighborhood caused by filling the reservoir seasonally [18].

In the southwestern United States, prolonged and severe periods of drought have substantially affected the Lake Mead reservoir and led to a significant reduction in its water level and volume [19]. The drought has also substantially declined the amount of water stored in soil and underground across the entire region [20]. The central objective of this study is to explore
climate-induced crustal loading deformation and its relationship with fluctuations in water storage within the Lake Mead Basin. In particular, the overarching aim is to quantify water resources using vertical deformation measurements and bridge the gaps between estimates derived from models and those obtained through geodetic observations.

In this research, I address the following questions: (1) During the recent drought, what was the relative partitioning between various water cycle components (e.g., soil moisture content, lake storage)? (2) How does the surface deform when water storage changes in and near Lake Mead? (3) How do GNSS/InSAR observations of loading deformation compare with predictions based on hydrological information (in-situ and model data)? (4) When correcting GNSS/InSAR measurements for the impact of known water storage changes in lake and soil, are the residuals indicators of changes in groundwater storage?

In order to answer these questions, I combine the variations of time-dependent water mass stored in Lake Mead with soil moisture storage around the region, to retrieve the total water variations within this area, not considering groundwater. I use spherical and half-space Earth models to calculate deformation based on elastic loading, considering realistic global (averaged) and local crustal structural properties. Afterward, I compare GNSS observations with the amplitude of modeled surface deformation annually and seasonally, resulting from various components in the hydrological system.
CHAPTER 2. STUDY FIELD, GEOLOGICAL FEATURES, AND DATASETS

2.1. Description of the Study Field

Lake Mead is a man-made reservoir located at the Colorado River, on the border between Arizona and Nevada (as shown in Figure 2.1. below) [21]. It is located on the northeast edge of the Mojave Desert, and on the southwest edge of the Grand Canyon. In the 1930s, it was created with the construction of the Hoover Dam and it is the largest reservoir in the United States in terms of water capacity when measured by volume. It has a maximum depth of 532 feet and a surface area of approximately 248 square miles. The average elevation of the lake is around 1,221 feet above sea level [22]. Named after the American engineer Elwood Mead, Lake Mead is a critical source of water for over 25 million people in Nevada, Arizona, California, and Mexico. The lake's importance is further highlighted by its relationship with the Colorado River Basin and the city of Las Vegas, [23].

The Colorado River basin is a major river system in the western United States, covering an area of approximately 246,000 square miles. It includes portions of seven states: Wyoming, New Mexico, Colorado, Nevada, Utah, California, and Arizona [22]. The Colorado River is the primary source of water for the basin, and Lake Mead is one of the largest reservoirs in the basin, storing up to 26.12 million acre-feet of water. The precipitation in the basin averages 40 millimeters per year and according to the estimates, the annual mean, maximum, and minimum runoff are respectively about 18.6, 29.6, and 6.5 billion cubic meters each year, with approximately 70 percent of Colorado state’s runoff coming from snowmelt [24], [25]. There is a temperature range of -6 degrees to 27 degrees Celsius in the Colorado River basin. Most of the water in Lake Mead derives from snowmelt in the Rocky Mountains, which flows into the Colorado River and eventually into the lake [26].

The city of Las Vegas is in the southern part of the Colorado River basin, near Lake Mead. Its rapid growth and increasing population have significantly stressed the region's water supply, for which the city is heavily reliant on the Colorado River. The Water District of Las Vegas Valley, which supplies water to the city, gets approximately 90% of its water from Lake Mead [27].

Despite its importance as a water supply and power source, according to the US drought monitor, Lake Mead is currently facing a severe and ongoing drought (as seen in Figure 2.2. ) [28]. Several factors have contributed to the drought, including increased temperatures and a decrease in rain and snowfall. As a result, the water levels in Lake Mead have been dropping at an alarming
rate, reaching record lows in recent years. Several years ago in November 1998, there was a peak in the Lake water storage when it reached 1215.76 feet, but the Lake has not reached that level since then (as shown in Figure 2.2.) [19], [20]. Researchers have found that since 1999 because of the prolonged and persistent drought, the lake's surface elevation has decreased by approximately 40 meters, and until July 2023, the lake's water levels were at 1,040 feet, which is 34% of its full capacity, [29], [30].

Studies have shown that drought is a complex phenomenon, the region has wide-ranging impacts beyond just a decrease in the water level of Lake Mead. The drought also reduces all water stocks in the region, including soil moisture and groundwater storage. These impacts highlight the critical importance of effective drought management strategies that consider the complex interplay between all water resources in the region [31].

Figure 2.1. Lake Mead’s location in the United States. (a) Map of the USA indicating Lake Mead’s location. (b) Map showing the location of the lake between the states of Nevada and Arizona, east of Las Vegas.
Figure 2.2. The US Drought Monitor (USDM) and Water Storage Volume Changes of Lake Mead over the Past Decade. There are four major levels of drought intensity recognized by the US Drought Monitor (USDM): D0= abnormal dry, D1= moderate drought, D2= severe drought, D3= extreme drought, and D4= exceptional drought. The graph also shows the changes in Lake Mead’s water volume on a monthly basis over the last few years [32].

2.2. Geological Features

Elastic deformation studies strongly rely on knowledge about the crust's elastic properties. Scientists investigate the geological characteristics of specific regions to gain essential insights into the crust's composition and structure. This research allows them to estimate the elastic parameters of the crust more accurately, which is essential for predicting and comprehending elastic deformation processes. Ultimately, this knowledge is critical for creating precise models that depict how the crust responds to loading.

A study of the geology of Lake Mead's surrounding area was conducted by [33]. In the south of the Lake Mead region, there are the Black Mountains, while in the north there are the Mormon Mountains, which contain the Beaver Dam Mountains. Also, the valley of Vegas lies to the west of Lake and the Colorado River Plateau lies to the east [33]. It consists primarily of crystalline rocks of the Proterozoic period, plutonic rocks from the Mesozoic and Paleozoic periods, sedimentary rocks from the Mesozoic period, intrusive rocks, volcanic rocks from the Cenozoic period Mesozoic and Paleozoic plutonic, Mesozoic sedimentary, intrusive rocks, and Cenozoic volcanic and also surficial deposits [33]. The Colorado Plateau has experienced normal faulting and strike-slip faulting as a result of extensional deformation and sedimentation during the Cenozoic. In recent years, Colorado River system integration has been accompanied by alluvial fan development, dissection formation, and faulting. The major parts of the lake geologically include sedimentary
rocks and also volcanic rocks from the Cenozoic era. The first group of materials is mostly unconsolidated to partially consolidated alluvium, made up predominantly of sand, silt, and gravel in low terraces, washes, streams, piedmont slopes, and alluvial fans [52]. The second category of materials mostly consists of greenish or brownish gray, altered andesite, which ranges from massive to flow-banded with a thickness of 300 meters approximately. Along the original Colorado River bed, the lake bed is covered by continuous sediments, ranging between 10 and 35 meters in depth, and around the bay of Las Vegas and channels of the northern Virgin River, the sediment cover is discontinuous and thinner [34].

On the southwest of the reservoir, the Hoover Dam is located. In this area, the bedrock is composed of crystalline rocks from the Precambrian period overlain and intruded by igneous rocks from the late Cenozoic [34], which cut deep down into the Colorado River. There is also a high degree of faulting and fracturing in this small area, and most surface features contain striae caused by fault movement [54]. The dam’s rocks are formed from volcanogenic sedimentary rocks, clastic sedimentary rocks as well as dikes. It is estimated that these rocks at Hoover Dam are at least 500 meters thick [35].

2.3. Dataset

In order to monitor the security and health of natural ecosystems and human populations, it is vital to accurately estimate changes in water storage, which includes surface water, groundwater, ice and snow over the land surface, soil moisture, and so on [36]. They are predicted by hydrological observations or via simulations of hydrological models (e.g., WGHM, GLDAS, NLDAS, CLM, PCR-GLOBWB 2.0, etc.) [37]. However, there are limited numbers of in-situ measurements and they are often accompanied by large gaps in temporal and spatial datasets, specifically for surface and groundwater [38]. Further, hydrological models are also subject to limitations in terms of model uncertainties, data availability, temporal and spatial resolution, model validation, and model complexity, all of which impact the accuracy of model predictions [39]. Besides this, models like these often cannot take into account the effects of human water abstraction on water storage as well [14], and [40].

As an alternative, geodetic deformation data derived from two different space-borne techniques, namely GNSS and InSAR, based on the assumption that they show the response of the elastic solid Earth to water mass gain and loss, can produce maps of water mass change. Tidal
loading displacements are routinely corrected during GNSS data processing, however, other short-term deformation signatures from geodetic time series must be eliminated with sufficiently accurate hydrological models in order to allow such order motions to be identified confidently on millimeter or even sub-millimeter per year basis [41]. These include non-tidal loading on solid Earth’s surface because of constant redistribution of oceanic, atmospheric, and far-field continental water masses.

It is important to emphasize that GNSS-driven models have sufficient temporal coverage to show seasonal variations in crustal deformation. In small basins, however, its spatial resolution is not adequate for capturing elastic signals. Therefore, it is for this reason that basin-scale, elastic surface loading processes are less understood than large-scale seasonal variations in surface loading. Interferometric SAR (InSAR) has a higher spatial resolution than GNSS, but its line-of-sight directions (descending and ascending) are limited by the errors in satellite orbits, as well as the large uncertainties regarding phase delays in the atmosphere, including the troposphere and ionosphere [42].

It is common in studies to use Green’s functions either to calculate forward the predicted deformation response to water mass changes [43] or to invert geodetic corrected vertical displacements to solve for the change in water volume [14], [44], and [42]. Here, I quantify different hydrological resources using vertical deformation measurements and try to fill in the gaps between model-based estimates and geodetic measurements based on the datasets described in the following sections.

### 2.3.1. Geodetic Deformation Data

#### 2.3.1.1. Geodetic GNSS Data

I used the recently released IGS14 GNSS product from the Nevada Geodetic Laboratory (NGL) at the University of Nevada, Reno for the P006 GNSS station which is the closest station in the Lake Mead region and affected by the largest amount of crustal deformation because of drought (as seen in Figure 2.3.) [45]. Compared to its predecessor, in this new solution, a lower RMS total is achieved and models of the troposphere at high resolutions are used to determine precise positions for the sites [46]. I used the vertical daily displacements recorded from January 2008 to December 2022. The coordinate for the P006 is also given in Table 2.1.
<table>
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<th>Height</th>
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<td>P006</td>
<td>114° 27' 25.2&quot; W</td>
<td>36° 09' 14.4&quot; N</td>
<td>365.216 m</td>
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Table 2.1. The Coordinate of Geodetic P006 Site Used for this study.

2.3.1.2. Geodetic InSAR Data

To generate a deformation map over the lake area, I conducted advanced multi-temporal processing of large SAR image sets between December 2014 and July 2022 [47], [48]. The data set included 599 C-band Sentinel-1 images with 6–12 days revisit time, comprising 233 scenes from the descending path 173 [49]. Using the wavelet-based multi-temporal InSAR algorithm by Shirzaei [47], [48], with multi-looking factors of 32 (range) by 6 (azimuth), I got a pixel size of around 75 × 75 meters. I used a Shuttle Radar Topography Mission (SRTM) Digital Elevation Model of 1-arcsecond spatial resolution.

Figure 2.3. The Topographic Map of Study Area, GNSS P006 Site and Measured VLM around Lake Mead. (a) The yellow square represents the location of P006 station on a topo map around Lake Mead. (b) The monthly mean measured vertical land motion (VLM) at GPS site P006 from 2008 to 2023.
(about 30 meters). I estimated the topographic phase and flat earth corrections and eliminated it using precise satellite orbital information. Moreover, I used adaptive wavelet filters and a 2D smoothing spline to remove the spatially correlated and temporally uncorrelated atmospheric delay. After that, I calculated LOS rates by fitting the slopes of each line to the time series of each pixel. A vertical land motion (VLM) deformation map was obtained from LOS InSAR time-series displacements over the Lake Mead region. To validate the relative accuracy of the deformation map, I compared relative vertical velocities and vertical deformation from GNSS with those derived from InSAR over the same period. This comparison resulted in standard deviations of 1.3526 mm per year and 5.031 mm respectively, for the period from 2014 to 2022 (as shown in Appendix A).

2.3.2. Hydrological Data

2.3.2.1 Lake Water Storage

According to several climatic, empirical, and as well as statistical models, the Colorado River has experienced decreased runoff since 2000 [50], [24] [51], [52]. At the same time, Lake Mead's water level also has consistently dropped as of the year 1998 (as seen in Figure 2.2.). I retrieve the monthly data from the California Data Exchange Center (CDEC) [53]. In order to make the Lake Mead map, the Twichell, Cross, and Belew shapefile data was used [54].

2.3.2.2. Soil Moisture Storage from NLDAS and GLDAS Models

NLDAS (North American Land Data Assimilation System) and GLDAS (Global Land Data Assimilation System) are both data assimilation systems that combine various observational datasets with land surface models to provide accurate and consistent information about land surface conditions. However, there are some key differences between the two systems. NLDAS focuses specifically on the North American region. The models and assimilation techniques used in NLDAS are tailored to this specific geographic area. The spatial resolution of NLDAS is higher within its North American domain, providing more detailed information for that specific region [55]. GLDAS provides global coverage. It encompasses land areas all around the world. They incorporate data from various sources.
on a global scale and use models that work across different climates and landscapes. It has a coarser spatial resolution because of the need to cover the entire globe, resulting in less detailed information compared to NLDAS within its domain [56].

In this study, to retrieve the total water mass loading on the crust surrounding the lake, I need to combine water storage changes in the Lake Mead basin with soil moisture storage in the region. For this, I obtained data for soil moisture storage [kg/m²] at the depth of 2 meters (from the top) by the NLDAS-2 monthly Noah model. These datasets span from Jan 1979 to the present and have a 1/8th degree grid spacing and temporal resolution of once a month. NLDAS-2 monthly Noah model data are generated using NLDAS-2 hourly Noah model data, which is referred to as the accumulation of snowfall, subsurface runoff, rainfall, snow melt, total evapotranspiration, and other variables over the course of the month. It is important to note that NLDAS Noah conceptualizes four layers of soil moisture with thicknesses of 10 cm, 30 cm, 60 cm, and 100 cm (from top), for a total depth of two meters for the total soil column. The four soil layers share the same soil texture and therefore use the same soil parameter values for each layer [55], [57].

The GLDAS Catchment land surface model (CLSM) was used to estimate aggregated terrestrial water storage anomalies (sum of soil moisture, canopy water, snow, surface water). Storage predictions from the GLDAS Catchment Land Surface Model L4 are given on a regular 1°×1° global grid with monthly time steps [56].

2.3.2.3. Groundwater Well Levels

To monitor the changes in groundwater storage in drought and non-drought periods surrounding Lake Mead, I obtained the Groundwater well level observations from the United States Geological Survey (USGS) including daily and field water level measurements [58] and also from Arizona Groundwater Site Inventory (GWSI) [59]. Most groundwater well observations reflect a distinct trend of water loss during the recent drought (Figure 2.5), with sites distributed around the Lake Mead region (Figure 2.4.). It is important to say that two aquifers are the principal sources of groundwater in this region: (1) the Basin and Range basin-fill aquifers, and (2) the carbonate rock aquifers. In the United States, the Basin and Range basin-fill aquifers account for the fourth largest principal water supply aquifer system and the first supplier of fresh water
As you can also observe in Figure (2.4), many wells are located in the Basin and Range basin-fill aquifers and only a few are in carbonate rock aquifers.

In the Basin and Range region, aquifers consist of sedimentary materials forming alluvial fans and basin-fill deposits. In the vicinity of the Lake, these aquifers are mainly classified as unconfined [61]. Outside our study area, confined units exist only farther south of the lake. Because poroelastic compaction in unconfined aquifers is of neglectable magnitude, we do not expect significant poroelastic compaction overprinting the elastic deformation near Lake Mead.

**Figure. 2.4.** The topographic map of the study area showing the location of Groundwater well sites (in dark yellow color circles), Basin and range-basin fill aquifers (in green color), and Basin and range carbonate-rock aquifers (in light yellow color) around Lake Mead.
Figure 2.5. Time series of groundwater observations (in meters below land surface) in the vicinity of the lake, acquired from USGS and GWSI, spanning the period from 2014 to 2023.
2.3.3. Regional Deformation Models

2.3.3.1. Non-Tidal Loadings (NTAL+NTOL)

I consider two types of non-tidal loading: 1. non-tidal oceanic loading (NTOL), and 2. non-tidal atmospheric loading (NTAL). Changes in the distribution of specific masses, most notably water and air, lead to deformation in the Earth’s crust and, shift the position of reference points. Atmospheric circulation moves air masses around the Earth, and the resulting variation of atmospheric pressure deforms the crust, which are predicted by NTAL. Further deformation, given by NTOL, occur because of the pressure at the ocean’s bottom, which is affected by three factors: inflows and outflows of ocean water, redistribution of ocean water by atmospheric circulation, and changes in the overall atmospheric mass of the ocean.

In order to remove the effects of NTAL and NTOL from geodetic observations, corrections were downloaded from the Earth-System-Modelling group at the Deutsches GeoForschungsZentrum (GFZ) in Potsdam (ESMGFZ4). Using Earth’s Center of Figure (CF) as a reference frame, ESMGFZ uses Green’s functions to compute the displacements of the site from non-tidal loadings. They provide software that interpolates displacements in local horizontal coordinates for any point with a spatial resolution of 0.5°×0.5°. I used this software to get non-tidal atmospheric, non-tidal oceanic for the years 2000 to 2023 [1], [62], [63], [64].

2.3.3.2. Sea-Level Loading (SLEL)

When oceanic, atmospheric, and hydrological models are combined, their global mass is not conserved. Especially, most oceanic models do not consider mass exchange with the atmosphere and land because they keep their own mass constant. Thus, introducing sea-level variations is essential here in order to conserve mass globally. These sea-level variations are not included in the oceanic contribution NTOL. The sum of NTAL+NTOL+FAR-FIELD+DD+SLEL represents the surface deformation of a global mass-conserving model system. To remove the effects of Sea-Level Loading (SLEL) from geodetic observations, a regular global 0.5°×0.5° grid of corrections, including daily time steps was downloaded from the ESMGFZ products which were produced by GFZ Earth-System-Modeling group [65].
2.3.3.3. Glacial Isostatic Adjustment Loading (GIA)

Glacial isostatic adjustment (GIA) is a viscoelastic delayed response of the solid Earth’s mantle to past ice loading, primarily, since the last glacial maximum, approximately 20 thousand years ago. GIA modeling is challenging because there are many uncertainties in the ice loading history and in the viscosities in lower and upper mantles. GIA manifests in uplift in regions that were covered by ice sheets during that time, and it may reach over 1 cm per year [66]. Subsidence because of GIA occurs on the perimeter and in regions outside of the past ice sheets. The effect, however, diminishes in farther regions, where it amounts to values below a millimeter. This is also the case for the Lake Mead region. However, even in those regions, a small GIA signal can accumulate to measurable values over long time periods. Hence, the geodetic deformation observed at GNSS sites also bears the signature of GIA [67].

I corrected GNSS vertical land motion at the P006 site for glacial isostatic adjustment (GIA) using predictions of vertical velocity (around 0.7 millimeters per year) from the global ICE-6G_C (VM5a) model’s Peltier on a 0.2 x 0.2 degree global grid [68], [69], and [70].
**Table 2.2.** Hydrological models used in this study.

<table>
<thead>
<tr>
<th>Hydrological Component</th>
<th>Model</th>
<th>Temporal resolution</th>
<th>Spatial resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Storage</td>
<td>NA</td>
<td>Monthly</td>
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</tr>
<tr>
<td>Soil Moisture</td>
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</tr>
<tr>
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<td>Daily</td>
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</tr>
<tr>
<td>FAR-FIELD HYDL</td>
<td>GLDAS (CLSM)</td>
<td>Monthly</td>
<td>1°</td>
</tr>
<tr>
<td>GIA</td>
<td>ICE-6G_C (VM5A)</td>
<td>&gt;25kyr</td>
<td>0.2°</td>
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<tr>
<td>Ground Water Well Level</td>
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<td>NA</td>
<td>NA</td>
</tr>
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</table>
Table 2.3. Sources of data collection and model data

<table>
<thead>
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<th>Data</th>
<th>Agency</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>GNSS Time Series</td>
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<td><a href="http://geodesy.unr.edu">http://geodesy.unr.edu</a></td>
</tr>
<tr>
<td>Sentinel-1 Images</td>
<td>Alaska Satellite Facility</td>
<td><a href="https://search.asf.alaska.edu">https://search.asf.alaska.edu</a></td>
</tr>
<tr>
<td>Lake Storage</td>
<td>California Data Exchange Center</td>
<td><a href="https://cdec.water.ca.gov">https://cdec.water.ca.gov</a></td>
</tr>
<tr>
<td>NTOL</td>
<td>The Helmholtz Centre Potsdam (GFZ)</td>
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</tr>
<tr>
<td>GIA</td>
<td>Prof. Peltier, Department of Physics, University of Toronto</td>
<td><a href="https://www.atmosp.physics.utoronto.ca/~peltier/data.php">https://www.atmosp.physics.utoronto.ca/~peltier/data.php</a></td>
</tr>
<tr>
<td>Soil Moisture Content</td>
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<td><a href="https://disc.gsfc.nasa.gov/datasets">https://disc.gsfc.nasa.gov/datasets</a></td>
</tr>
<tr>
<td>Far-Field HYDL</td>
<td>NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC)</td>
<td><a href="https://disc.gsfc.nasa.gov/datasets">https://disc.gsfc.nasa.gov/datasets</a></td>
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</table>
CHAPTER 3. METHODS

Hydrological elastic loading is the process of crustal bending because of changes in water masses weighing on the crust. Changes of water masses occur in all compartments of the water cycle, namely in soil, lakes and rivers, aquifers, and snow cover. A loss of water mass in either of these compartments yields a relief of weight on the crust and consequently an uplift of the Earth’s surface. The opposite occurs if the water mass accumulates [43]. The water cycle dynamically interacts with the atmosphere, the oceans and the geosphere, hence, the amount of water mass in an area is changing on various time-scales from sub monthly to decadal lengths [71]. Annual variations are typically the largest. However, interannual variations in water availability, e.g., caused by drought or wet periods, as well as by human impacts, can cause significant changes on inter-annual to decadal time scales and therefore might cause a crustal elastic loading response [72]. Many previous works established the framework and applied models for calculating the deformation of an elastic body under surface loads [73], [74], [75], [76], [77], [78], [79], [80], [81], [43], [82]. During the past decade, experts in Earth sciences have become increasingly interested in this topic. They follow the widespread recognition that geodetic measurements are useful as a tool to observe solid Earth’s dynamics that are driven by changes in the climate systems, including the hydrosphere, atmosphere, and cryosphere [83], [84], [85], [86]. In recent years, the elastic response to these environmental loading cycles has been done and developed at global as well as at local scales. Typically, in most geophysical applications either a self-gravitating, layered, elastic sphere with a fluid core on the global scale (by Farrell-1972) [43] or a linearly, homogeneous elastic half-space on the local scale (by Becker-2003) [87], [88], [82] is the preferred framework. Both methods and their implementation are explained in the following sections.

3.1. Global Spherical Model

The solution for a layered, elastic, self-gravitating sphere has wider applicability, and its formalism is appropriate for large aperture loads, or for calculating deformation at great distances from the load, where great means a significant portion of the Earth’s radius. Commonly, either point loads or disk loads are invoked in these treatments. There is often an invalidity to the point load formalism near the nominal point load, such that the disk load formalism provides more flexibility. Therefore, this approach is the easiest way to describe a load change or distributed load by representing it as one or more disk loads, and often many more disk loads [89]. This solution
has been further developed using Legendre polynomials expansions, their derivatives, and the load Love numbers. These numbers are commonly denoted by the symbols \( k_n \), \( h_n \), and \( l_n \), and they describe the radial, vertical, and also horizontal elastic properties of the model domain, here, the Earth’s crust. These numerical values are quantified by applying Earth density models.

The Preliminary Reference Earth Model (PREM) is a widely used elastic model for studying spherical loading effects on the Earth's surface because of its comprehensive representation of the Earth's internal structure into distinct regions like the mantle, crust, inner core, and outer core [90]. It provides a detailed characterization of Earth layers’ properties, including elastic properties, attenuation, density, pressure, and gravity, as a function of depth. Besides the original PREM model (complete), there are also two alternative PREM models named "hard" and "soft". These models are modifications of the original PREM model. The "hard" model assumes that the Earth's mantle is more rigid than the original PREM model, while the "soft" model assumes that the mantle is less rigid. Furthermore, generally, all the models assume radial symmetry, meaning it considers variations in Earth's properties as a function of depth from the center of the Earth outward. On the other hand, this radially symmetric PREM model cannot be precise in the outermost fifty kilometers of the Earth due to the extreme level of heterogeneity in the uppermost mantle and especially in the crust (Fig 3.1a).

In the following equations based on the Farrell theory [43], [72], the vertical \( S_{up} \) (positive = up) and horizontal displacements \( S_{away} \) (positive = away from the load) are given as a result of gravitational potential assuming that a uniform disc of mass is placed, on the surface of a self-gravitating, spherical, elastic Earth [43], [72].

\[
S_{up} = \sum_{n=0}^{\infty} \frac{h_n \Gamma_n}{g (2n + 1)} \frac{4\pi G a}{g (2n + 1)} P_n(\cos \theta)
\]  

\[
S_{away} = \sum_{n=0}^{\infty} \frac{l_n \Gamma_n}{g (2n + 1)} \frac{4\pi G a}{g (2n + 1)} \frac{d P_n(\cos \theta)}{d \theta}
\]

Where \( G \) is Newton's gravitational constant, \( \theta \) is the angular distance away from the center of the mass load, \( h_n \) and \( l_n \) are load Love numbers, \( g \) is the gravitational acceleration at the Earth’s surface, \( \alpha \) is the angular radius of the disk, and \( P_n \) represents the Legendre polynomial. Also, the value of \( \Gamma_n \) is determined using the following equation:
3.2. Half-Space Model

In contrast, another approach, often defined at the local level, predicts the displacements induced on a horizontal surface by uniform vertical pressure applied over arbitrary polygonal regions in a linearly homogeneous elastic half-space. It is noteworthy that this model represents a useful tool in the sense that it allows one to get an analytical solution for the mass loadings with non-trivial geometrical shapes. By combining Gauss' theorem with recent potential theory results, for example, one can get formulas that allow the displacements at an arbitrary point in half-space to be evaluated solely based on the polygonal boundary of the loaded region. [88].

Actually, one can use a half-space model that has a single layer, ignores Earth’s curvature, but where one can set crustal elastic parameters including the Young’s elastic modulus (E) and Poisson’s ratio (ν) to locally representative values. This solution allows for a more realistic evaluation of displacement distribution by considering the relevant Poisson's ratio and elastic modulus of the region in their characterization of the Earth’s properties and achieves a considerable simplification in data handling since they are possible to avoid the tiling of complex regions by the simple load shapes, such as circles or rectangles, for which analytical solutions are currently available in the literature (Fig 3.1b) [87].

The equations for the vertical displacements of the Earth’s surface $d_z$ and horizontal directions $d_x$ and $d_y$ are [88], [91]:

$$
\begin{align*}
\begin{pmatrix} d_x \\ d_y \end{pmatrix} &= -\frac{P_z}{4\pi\nu} \sum_{i=1}^{n} \left( \frac{y_{i+1} - y_i}{x_i - x_{i+1}} \right) \left( \frac{\mu}{\lambda + \mu} S_{1i} + S_{2i} \right) \\
\end{align*}
$$

(4)

$$
\begin{align*}
\frac{d_z}{dz} &= \frac{P_z}{4\pi\nu} \oint_{\Omega} \frac{\rho^\nu}{(\rho - \rho^0)^{1/2}} ds + \frac{P_z}{4\pi(\lambda + \mu)} \left[ \oint_{\Omega} \frac{(\rho^0 - z)^{1/2} \rho^\nu}{\rho^0} ds - z\alpha(0) \right] = \frac{P_z}{4\pi\nu} I_3 \\
&\quad + \frac{P_z}{4\pi(\lambda + \mu)} \left[ I_4 - z\alpha(0) \right] \\
\end{align*}
$$

(5)

It should be mentioned that this algorithm considers the elastic surface displacements generated by an applied pressure equivalent to one-meter water depth (h) in a Lake Mead polygon.

$$
\Gamma_n = \frac{1}{2} [P_{n-1}(\cos x) - P_{n+1}(\cos x)] \text{ for } n > 0 \\
\Gamma_0 = \frac{1}{2} (1 - \cos x)
$$
shape of the area. I also set the surface pressure $p = \rho gh$ where $\rho = 1000 \text{ kg.m}^{-3}$, and gravity acceleration $g = 9.82 \text{ m.s}^{-2}$. As a result, based on this algorithm, the displacement field along two surface directions $x$ and $y$ are evaluated.

![Diagram](image)

**Figure 3.1.** Crustal Loading Models. (a) Spherical Model PREM parameter Wahr et al, (2013). (b) Half space Model Young Modulus $E$, Poisson Ratio $\nu$ D’Urso et al. (2013)

### 3.3. Model Implementation

In this study, at the first step, the application of Farrell’s (1972) physical theory [43] was used to model the 1D elastic loading displacements caused by variations in surface mass. I performed calculations of loading deformation using the equation and physical model presented by Wahr et al. (2013) [72] (Equations 2 and 3). Based on where and how much the water mass or load was, I calculated how the Earth’s surface responds.

After the removal of a uniform disc load characterized by a radius of 20 kilometers and a water thickness equivalent to 1-meter, distinct vertical (represented by the orange curve) and horizontal (indicated by the blue curve) displacements occur within the Earth’s crust (Figure 3.2). This process induces deformation, causing neighboring points on the Earth’s surface to move upward and away from the center of the disc. The results are graphed as a function of the distance from the center of the disc. To highlight the outcomes, a vertical dot-dashed line is used to mark the edge of the disc. Notably, the most significant uplift occurs precisely at the center and then rapidly declines as the distance from the center increases. This decline continues until approximately twice the radius of the disc from the center. Following this, there is a deceleration
in the pace of reduction as the distance extends further, resulting in a prolonged, non-zero decline (Figure 3.2). It is important to mention that the calculations are based on the Preliminary Earth Model (PREM), a reference established by Wahr. J in 2013.

![Graph](image)

**Figure 3.2** As a result of the removal of a uniform disc load of radius 20 kilometer and water thickness of 1 meter equivalent, vertical (positive upward) and horizontal (positive away from the disc center) displacement of the crust occurs. The results are presented as a function of the distance to the disk center. The disc's edge is marked by a vertical dot-dash line. The vertical dot-dashed line marks the edge of the disc. Also, the results are calculated for Preliminary Earth model reference PREM [derived by Wahr. J, 2013].

I (forward) modeled the elastic response of the solid Earth to surface water mass unloading and loading with MATLAB software, encoding the Green's function described above. I further used different elastic parameters for the spherical Earth, including PREM complete, PREM hard, and PREM soft. To achieve this, I estimated the deformation effect of the mass loading/unloading by representing Lake Mead as 34 disks with a radius of 1.75 km (Figure 3.3).

Also in the second phase of this research, to compute the deformation of Earth's crust subject to surface loads based on the half-space model, I used the algorithm of D'Urso et al. [91]. Their solution generalizes Bevis and Becker's work [82] by providing formulas for the calculation of displacements in linearly homogeneous elastic half-space in response to a vertical pressure uniformly applied over arbitrary polygonal regions. I applied and tested 21 half-space models according to the different Earth properties, including different elastic modulus values ranging between 0.35e11 and 0.95e11 pascal (N / m²) and also different values of Poisson's ratio ranging between 0.2 and 0.4 to estimate the loading response around the lake Mead.
The Harmonic Regression Model is a vital statistical tool for analyzing time series data characterized by recurring patterns. These patterns can manifest over various intervals, such as daily, weekly, or yearly cycles. This study applies a harmonic regression model to discern the trends within time series data. The harmonic regression model used in this study is expressed as follows:

\[
Y = b_1 + b_2 \frac{X - \min(X)}{365} + b_3 \cos \left( \frac{2\pi}{365} X + b_4 \right)
\]

Where:
- \( Y \) represents the dependent variable, which constitutes the value I seek to predict.
- \( X \) is the independent variable representing the time
- \( b_1, b_2, b_3, b_4 \) are the parameters of the model that need to be estimated from the data.

To be more specific, \( b_1 \) is a term known as the intercept representing the baseline level of the dependent variable when \( X \) is at its minimum value. \( b_2 \) is responsible for modeling the linear trend component scaling the linear effect of time \( (X) \) on the dependent variable. The function of \( \cos \left( \frac{2\pi}{365} X + b_4 \right) \) captures the periodic component of the data. It has a period of 365 days, as indicated by the \( \frac{2\pi}{365} X \) term. \( b_3 \) scales the amplitude of the cosine wave. It controls the magnitude of the seasonal or periodic effect. The inclusion of \( b_4 \) permits an adjustment of the phase of the cosine wave, thereby enabling a precise fit to the data.
The model's parameters \([b1, b2, b3, b4]\) have to be estimated to minimize the discrepancy between the model's predictions and the observed data points. To determine the parameter solution, I chose a numerical approach that was implemented via the nonlinear regression operator “Nonlinear Model” in MATLAB.

3.5. Conversion of Line-of-Sight (LOS) InSAR Measurements to Vertical Land Motion

For this study, I employed descending images captured by Sentinel-1A, resulting in Line-of-Sight (LOS) displacement data. To convert InSAR measurements from the LOS direction into vertical deformation, I utilized the following equation [92]:

\[
VLM = \frac{LOS}{\cos \theta}
\]  

Where:
- \(VLM\) represents the vertical deformation.
- \(LOS\) denotes the Line-of-Sight displacement obtained from InSAR measurements.
- \(\theta\) signifies the incident angle of the radar wave.

It’s important to note that this equation assumes the deformation is exclusively vertical, disregarding any potential horizontal motion. This conversion enables us to compare GPS-derived vertical land motion with vertical land motion derived from InSAR data acquired along the LOS direction [92].
CHAPTER 4. RESULTS AND DISCUSSIONS

4.1. Observation of Hydrological Loading

Based on the corrections provided by the Deutsches GeoForschungsZentrum (GFZ), I removed non-tidal atmospheric loading (NTAL), non-tidal ocean loading (NTOL), and also sea-level loading deformation from the GNSS vertical observations at P006 from 2008 to 2022 [13]. To accomplish this, I used a CF (center of figure of the Earth) frame for all the corrections.

I acquired terrestrial water storage anomalies from the global hydrological GLDAS-CLSM model (based on the Global Land Data Assimilation System) as the whole surface water, snow, soil moisture [56]. Further, I computed global loading displacements in the far field beyond the Lake Mead region through the integral convolution of the surface load expressed by the pressure of the terrestrial water storage anomalies (covered by 15153 disks around the globe excluding the Lake Mead region) and with appropriate Green's functions [43], [72]. Subsequently, I subtracted these calculated displacements from the GNSS vertical observations at P006.

GNSS readings near Lake Mead contain a long-term GIA signal. I removed this effect from the vertical land motion (VLM) at P006 by applying GIA model predictions. I got the data from the global GIA model ICE-6G_D and subtracted GIA trends from the GNSS time series [70].

In Figure 4.1a, the red graph shows the raw and uncorrected GNSS monthly observations for the site at P006, which is of particular interest because it is very close to the lake boundary. The yellow dashed line shows the estimated GIA-based vertical deformation rate at P006. Figure 4.1b shows the effects of NTOL (yellow graph), NTAL (light blue), SLEL (dark blue) as well as FAR_FIELD (green) at the GNSS site P006.

Figure 4.1a shows the deformation impact of GIA alone, of GIA + NTAL + NTOL + SLEL, and of GIA + NTAL + NTOL + SLEL + FAR_FIELD loading combined, which are printed in blue, dashed black, and solid black, respectively. Based on that, I noted that the GIA significantly affects the long-term trend, by 0.7 mm/year and its contribution is considerably large at the GNSS site P006. I also noted that NTAL + NTOL + SLEL + FAR_FIELD loadings are of much lower amplitudes and none of them had any significant trend. The respective corrections were relatively small, less than 10% of the signal (as shown in Figure 4.1b below). To be more specific, I observed that all the NTOL, NTAL, and also SLEL loadings had seasonal components but the entire variability of total loading of NTAL + NTOL + SLEL is generated by NTAL, and almost no signal was induced by both NTOL and SLEL. I
further noted that the far-field loading has clear inter-annual changes, and it is likely the most important correction after GIA.

---

**Figure 4.1.** Various Non-Tidal and Hydrological Far-Feld Loading Effects. (a) raw and uncorrected GNSS at P006 (in red), glacial isostatic adjustment (in yellow), corrected GNSS for only GIA (in light blue), corrected GNSS for GIA, NTOL, NTAL, and also SLEL (in dashed black line), corrected GNSS for GIA, NTOL, NTAL, SLEL, and also Far-Field HYDL (in solid black line). (b) non-tidal atmospheric (in light blue), non-tidal oceanic (yellow), water storage exodus to the sea (in dark blue), and hydrological far-field effect (in green).

As shown in Figure 4.2, after removing all of the aforementioned loading effects (NTAL + NTOL + SLEL + GIA + FAR_FIELD), I compared the original P006 vertical land motion time series (in red color) with the results of the corrected ones (in black color). There were no considerable differences observed after applying the corrections except for GIA, which showed that the impacts from non-tidal and terrestrial global loading were negligible. However, the GPS time series corrected at P006 (in black color) now only showed the water mass loading effect and some errors.
By applying a harmonic regression model (Chapter 3, Equation 6) to this corrected GPS signal, I estimated the uplift trend during recent drought periods. Consequently, the region surrounding Lake Mead experienced an uplift of around 7.3 mm/year during 2012-2015 and of around 8.6 mm/year from 2020 to 2023. This shows that the ongoing drought caused a slightly larger mass loss rate than the drought that occurred from 2012 to 2015 (Figure 4.3).

![Figure 4.2](image1.png)

**Figure 4.2.** Comparison between raw, uncorrected GNSS observations (in red color) and corrected final one (in black color) at the P006 site.

![Figure 4.3](image2.png)

**Figure 4.3.** Trend estimation (highlighted in red) of the corrected GPS signal (depicted in black) at the P006 site shows uplift during recent drought periods: from 2012-2015 and from 2020-2022.
4.2. Modeling of Hydrological Loading

Our next step was to determine how much of the uplift during the drought periods was caused by the lake volume decline, and how much was caused by water loss in other storage compartments such as soil moisture or groundwater surrounding the lake. To achieve this, we conducted modeling of the deformation caused by the loading of Lake Mead, as well as the modeled deformation resulting from changes in soil moisture. This modeling considered various Earth structure models, including PREMs [93], and half-space models [87], [88], [91].

In Figure 4.4, the modeled loading deformation of Lake Mead water storage is illustrated. Three representations are provided based on different models: PREM complete (dark blue), PREM hard (green), and PREM soft (light blue) all for site P006. The corrected GPS signal observed at P006 is highlighted in red.

![Figure 4.4. Comparison between the corrected GNSS (in red color) with the modeled lake mead loading deformation derived with PREM model Hard (in green color), Soft (in light blue color), Complete (in dark blue color).](image)

Time/Year

Vertical Displacement (mm)
Similarly, we conducted modeling for the loading deformation of soil moisture storage using all PREM models. Figure 4.5 exhibits consistent results obtained from each of these models, including PREM complete, PREM hard, and PREM soft, all for site P006, indicated by the black signal. The corrected GPS signal observed at P006 is highlighted in red.

![Figure 4.5](image)

**Figure 4.5.** Comparison between the corrected GNSS (in red color) with the modeled soil moisture (NLDAS) storage loading deformation derived with PREM model Hard, Soft, and Complete (in black color). Here, no significant differences were observed between three different kind of spherical PREM models.

Additionally, it's noteworthy to highlight findings from figures 4.4 and 4.5, which illustrate the variability in loading deformation attributed to different soil moisture and lake water storage components. In broad terms, our observations indicate that lake water storage tends to exert a primary influence on surface deformation, at station P006. Conversely, soil moisture contributes significantly less to the overall surface displacement at this particular location.
Furthermore, I calculated the cumulative modeled loading deformation, incorporating both the lake and soil moisture storage based on PREMs, which include the PREM model hard (in grey color), PREM model soft (in dark blue color), and PREM model complete (in light blue color), as illustrated in Figure 4.6. The corrected GPS signal observed at P006 is also highlighted in violet.

Figure 4.6. Comparison between the corrected GNSS (in violet color) with the modeled soil moisture (NLDAS) plus lake water storage loading deformation derived with PREM model Hard (in grey), Soft (in dark blue), Complete (in light blue).

In addition, in Figure 4.7, we employed an alternative approach to model only lake loading deformation at site P006. This involved using various half-space models, each represented by distinct, colorful signals. These models were characterized by a range of parameters, notably Young’s modulus, which varied between 0.35e11 and 0.95e11 pascals (N/m²), and Poisson ratio values spanning from 0.2 to 0.4.
4.3. Quantitative comparison between model and observation

After conducting hydrological loading modeling using spherical models, I proceeded to analyze and compare the corrected GNSS signal at site P006 with the modeled deformation caused by Lake Mead’s water storage using various PREM scenarios. Figure 4.4 illustrates this comparison, depicting the corrected GPS signal in red, alongside the loading deformation models based on PREM complete (dark blue), PREM hard (green), and PREM soft (light blue) for the P006 site. Similarly, Figure 4.5 presents the comparison of the corrected GPS signal (red line) with the modeled deformation resulting from soil moisture storage loading, incorporating all PREMs (black) for site P006. Furthermore, in Figure 4.6, I’ve showcased the collective modeled deformation attributed to lake and soil moisture storage loading based on the PREM model hard (grey), PREM model soft (dark blue), and PREM model complete (light blue). This is contrasted against the

Figure 4.7. Comparison between the corrected GNSS (in black color) with the modeled lake mead loading deformation derived with 21 Half-space model with different elastic modulus (E\text{lp}) values ranging between 0.35e11 and 0.95e11 pascal (N / m²) and also different Poisson ‘s ratio (v\text{lp}) values ranging between 0.2 and 0.4.
corrected GPS data at P006, highlighted in violet. Moreover, in Figure 4.7, I delved into a comparison between the corrected GNSS data (depicted in black) and another modeled deformation resulting from Lake Mead loading that was generated using 21 Half-space models (depicted in color) with different elastic modulus (Elp) values ranging between 0.35e11 and 0.95e11 pascal (N/m²) and also different Poisson’s ratio (vlp) values ranging between 0.2 and 0.4.

Considering only lake and soil moisture mass changes, I could evaluate the best-fitting load model in this region. However, groundwater loading, which I did not have data on, may be present, especially during drought. This made the selection of the correct model more complicated, and I wanted to estimate it as an unknown component. Therefore, I started with a simple comparison of all the load models versus corrected GNSS observations at P006. I estimated the difference between the measured and modeled time series as RMS (root-mean-square) deviation. The results are presented across three distinct time categories, encompassing both drought and non-drought periods. These outcomes are depicted in Figures 4.8, 4.9, and 4.10. Specifically, category (A) spans from 01/2008 to 12/2013 (Figure 4.8), category (B) encompasses the timeframe from 01/2014 to 01/2020 (Figure 4.9), and category (C) covers the period from 01/2008 to 08/2021 (Figure 4.10). There are green dots on these figures that show the Root Mean Square Deviation (RMSD) values derived from all PREM models. As well as that, the cyan, blue, and red dots on the figures represent the RMSD values derived from various half-space models with Poisson’s ratios of 0.2, 0.3, and 0.4 respectively.
**Figure 4.8.** RMSD between modeled loading deformation derived from PREM and half-space models with GNSS observation at P006 from 2008/01 to 2013/12 (A).

**Figure 4.9.** RMSD between modeled loading deformation derived from PREM and half-space models with GNSS observation at P006 from 2014/01 to 2020/01 (B).
Based on the findings presented earlier in Figures 4.8, 4.9, and 4.10, the Root Mean Square Deviation (RMSD) values—representing the difference between the time series obtained from measurements and models—exhibit consistent results across different time spans for a variety of elastic models, including both half-space models and the global PREM models. It's worth noting that the RMSD reaches its lowest point in instances involving half-space models characterized by an elastic modulus (E) surpassing 75 e+9 Pascal, as well as in cases featuring the global hard PREM model.

I further examined these results from another perspective. As depicted in Figure 4.11, I obtained the residual time series between the loading models and the observed mass load. I focused on the 2012-2015 drought, which is highlighted by a gray background. During this drought, I observed that some of the load models predicted negative trends (C) in the residuals. If I assumed these residuals source from groundwater, the remaining subsidence in the residuals would suggest that groundwater recharges for some load models. However, this scenario is extremely unlikely. Hence, it is much more probable that these models overestimate the lake loading. It should be noted that the spherical models all showed subsidence in residuals during drought. Some load models led to no trend (A) during the drought. While this may be another valid scenario,

**Figure 4.10.** RMSD between modeled loading deformation derived from PREM and half-space models with GNSS observation at P006 from 2008/01 to 2021/08 (C).
it also raises the possibility that there was no significant groundwater loss if these load models are accurate. In addition, a few models showed an uplift (B) in the residuals during drought, which left a possibility for groundwater loss during drought, which is what I expected.

Figure 4.11. This plot (from Werth, AGU 2023) [1] is showing the remaining residuals derived by subtracting all hydrological loading deformation from the GNSS observations at P006 during the drought. The hypothesis is that the groundwater signal is preserved in the residual time series. (A) suggests a no trend (no groundwater component). (B) suggests a positive trend (groundwater loss, or underestimated lake loading). (C) suggests a negative trend (recharge during drought (unlikely), or overestimated lake loading).

To make a certain decision, I needed to gather more information about groundwater storage changes in the region by collecting well-level records near the lake (as shown in Figure 2.5.). In addition, I evaluated the signal only at the GNSS observation site at P006. However, I also needed to evaluate the spatially distributed pattern of the loading response, in addition to the amplitude. Thus, Sentinel-1 SAR images were analyzed with the WabInSAR technique to determine the deformation of the Earth’s surface surrounding the lake.

As shown in Figures (4.12) and (4.13), you can observe the first results of this process (VLM velocity mm per year) showing spatial maps of vertical land motion for the non-drought period between 2016-2020, and also for the drought period between 2020-2022. During the recent drought, the entire region around the lake shows a consistent loading response in the form of uplift surrounding the lake (Figure 4.13.). Conversely, the non-drought period is not characterized by uplift around the lake (Figure 4.12).
**Figure 4.12.** This plot is showing the deformation map derived by the Sentinel-1 A/B dataset during the non-drought period between 2016/10 and 2020/09 (VLM velocity mm/yr).

**Figure 4.13.** This plot is showing the deformation map derived by the Sentinel-1 A/B dataset during the drought period between 2020/10 and 2022/04 (VLM velocity mm/yr)
CHAPTER 5. CONCLUSION AND FUTURE STUDY

This study focuses on the estimation of elastic loading deformation induced by diverse variations in water mass within the Lake Mead region. These variations encompass alterations in the water levels of Lake Mead, changes in regional soil moisture, as well as shifts in global water mass beyond the boundaries of the Lake region. In the initial stages of this study, I formulated four key questions: (1) During the recent drought, what was the relative partitioning between various water cycle components (e.g., soil moisture content, lake storage)? (2) How does the surface deform when water storage changes in and near Lake Mead? (3) How do GNSS/InSAR observations of loading deformation compare with predictions based on hydrological information (in-situ and model data)? (4) When correcting GNSS/InSAR measurements for the impact of known water storage changes in lakes and soil, are the residuals indicators of changes in groundwater storage? My research has yielded insightful answers to these questions, which I will now present as the main conclusions outlined below:

- The results regarding the first question suggest that the main factor contributing to ground deformation in the Lake Mead region is caused by climate-related influences, i.e. due to season and drought-driven water mass changes. Most of the storage change can be attributed to fluctuations in lake levels, while changes in soil moisture content account only for a small portion, likely less than ~10%, to the storage changes. It’s imperative to note that a decline in groundwater levels is observed in the area, suggesting a reduction in groundwater storage; however, the precise extent of this decline remains unknown due to the lack of dense groundwater well measurements.

- In response to my second question, my research findings indicate that during the severe drought in the Lake Mead Basin, when both the water level of the lake and the surrounding hydrological components, such as soil moisture and groundwater, undergo substantial reductions, the Earth’s crust exhibits an instantaneous elastic due to decrease of the water mass loading on the Earth’s crust. I have observed this gradual uplift using advanced techniques such as GPS and InSAR. According to my estimates, throughout recent drought periods, the vicinity of Lake Mead experienced an uplift of approximately 7.3 mm/year from 2012 to 2015 and of around 8.6 mm/year from 2020 to 2023. This observation suggests that the ongoing drought has resulted in a slightly higher mass loss rate than the drought experienced between 2012 and 2015.
Regarding the third question, my study involved a comprehensive analysis of GNSS observation at the P006 site concerning loading deformation, encompassing nontidal loading effects from the atmosphere, oceans, sea-level variations, and far-field hydrological loading, as well as the influence of glacial isostatic adjustment (GIA). I eliminated the contributions of nontidal and GIA effects from the GNSS observation. Subsequently, this corrected observation was compared with predictions derived from hydrological models, which integrated both in-situ data and model-generated information. My analysis unveiled that the long-term trend was significantly impacted by glacial isostatic adjustment, contributing to a rate of 0.7 mm/year, with the most pronounced influence observed at the GNSS site P006. In contrast, non-tidal atmospheric loading (NTAL), nontidal ocean loading (NTOL), sea-level variations (SLEL), and far-field hydrological loading exhibited lower loading amplitudes and did not display discernible trends. These corrections were relatively modest, accounting for less than 10% of the signal. Notably, far-field loading demonstrated evident inter-annual fluctuations, suggesting its potential significance as a correction factor, especially when investigating temporal variations following the GIA effect.

In addressing the last question, my analysis based on the obtained loading models has shown consistent behavior in the residuals for the GNSS time series at the P006 site across various time periods. Notably, the lowest residuals were observed for the half-space models with $E > 75 \, e+9$ Pascal. Additionally, all the spherical models consistently displayed negative trend residuals in the time series during drought periods. These negative trend residuals strongly suggest a higher likelihood that these models tended to overestimate the loading originating from the lake. Furthermore, some half-space load models displayed no trend residuals during drought, suggesting that substantial groundwater loss may not occur if these models accurately reflect the conditions. On the other hand, a subset of models revealed the uplift in the residual time series during drought, implying the potential for groundwater loss. Therefore, although our findings allow us to eliminate certain models due to their illogical outcomes, we emphasize the need for a precise understanding of the elastic parameters in the lake's surrounding region to accurately predict changes in groundwater storage.

To facilitate certain decision-making in selecting the optimal loading model and guiding future investigations, I recommend incorporating a thorough uncertainty analysis for each data
set to determine the predictability of groundwater storage changes based on observations of vertical loading deformation from GNSS and InSAR surrounding the lake. Furthermore, to quantify groundwater loss effectively, a valuable suggestion for forthcoming research endeavors is the examination of data from the Gravity Recovery and Climate Experiment and its follow-on mission (GRACE/FO), alongside InSAR data. Such estimates will provide an important insight into the dynamics of Lake Mead’s interactions with local aquifers.
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APPENDIX A: FIGURES SHOWING A STANDARD DEVIATION BETWEEN VERTICAL DEFORMATION OF GNSS TIME SERIES WITHIN THE NETWORK AND THOSE DERIVED FROM INSAR OVER THE SAME PERIOD OF TIME FROM 2014 TO 2022

Figure A.1 The STD between vertical deformation of GNSS and those derived from InSAR time series.

Figure A.2. The STD between vertical velocities of GNSS and those derived from the InSAR time series.
APPENDIX B: FIGURES SHOWING THE MAP OF ANNUAL AND SEMI-ANNUAL AMPLITUDE OF ELASTIC LOADING RESPONSE OF LAKE WATER AND SOIL MOISTURE STORAGE DERIVED BY SPHERICAL PREM (COMPLETE) MODEL.

Figure B.1. The deformation map shows the semi-annual amplitude (mm) of the elastic loading response of lake water + soil moisture storage derived by the PREM (complete) model from 2012 to 2020 (location of GNSS stations in white triangles surrounding the lake).

Figure B.2. The deformation map shows the annual amplitude (mm) of elastic loading response of lake water + soil moisture storage derived by the PREM (complete) model from 2012 to 2020 (location of GNSS stations in white triangles surrounding the lake).
APPENDIX C: FIGURES SHOWING THE MAP OF ANNUAL AND SEMI-ANNUAL AMPLITUDE OF ELASTIC LOADING RESPONSE OF LAKE WATER AND SOIL MOISTURE STORAGE DERIVED BY HALF-SPACE MODELS WITH DIFFERENT EARTH STRUCTURES AND PROPERTIES.

Figure C.1. The deformation map shows the semiannual amplitude (mm) of elastic loading response of lake water + soil moisture storage derived by the half-space model from 2014 to 2022 (E=0.35e+11 Pascal and v=0.3).

Figure C.2. The deformation map shows the annual amplitude (mm) of elastic loading response of lake water + soil moisture storage derived by the half-space model from 2014 to 2022 (E=0.35e+11 Pascal and v=0.3).
Figure C.3. The deformation map shows the semiannual amplitude (mm) of elastic loading response of lake water + soil moisture storage derived by the half-space model from 2014 to 2022 (E=0.45e+11 Pascal and v=0.3).

Figure C.4. The deformation map shows the annual amplitude (mm) of elastic loading response of lake water + soil moisture storage derived by the half-space model from 2014 to 2022 (E=0.45e+11 Pascal and v=0.3).
Figure C.5. The deformation map shows the semiannual amplitude (mm) of elastic loading response of lake water + soil moisture storage derived by the half-space model from 2014 to 2022 (E=0.55e+11 Pascal and \( v=0.3 \)).

Figure C.6. The deformation map shows the annual amplitude (mm) of elastic loading response of lake water + soil moisture storage derived by the half-space model from 2014 to 2022 (E=0.55e+11 Pascal and \( v=0.3 \)).
Figure C.7. The deformation map shows the semiannual amplitude (mm) of elastic loading response of lake water + soil moisture storage derived by the half-space model from 2014 to 2022 (E=0.65e+11 Pascal and v=0.3).

Figure C.8. The deformation map shows the annual amplitude (mm) of elastic loading response of lake water + soil moisture storage derived by the half-space model from 2014 to 2022 (E=0.65e+11 Pascal and v=0.3).
Figure C.9. The deformation map shows the semiannual amplitude (mm) of elastic loading response of lake water + soil moisture storage derived by the half-space model from 2014 to 2022 (E=0.75e+11 Pascal and \( v=0.3 \)).

Figure C.10. The deformation map shows the annual amplitude (mm) of elastic loading response of lake water + soil moisture storage derived by the half-space model from 2014 to 2022 (E=0.75e+11 Pascal and \( v=0.3 \)).
Figure C.11. The deformation map shows the semiannual amplitude (mm) of elastic loading response of lake water + soil moisture storage derived by the half-space model from 2014 to 2022 (E=0.85e+11 Pascal and v=0.3).

Figure C.12. The deformation map shows the annual amplitude (mm) of elastic loading response of lake water + soil moisture storage derived by the half-space model from 2014 to 2022 (E=0.85e+11 Pascal and v=0.3).
Figure C.13. The deformation map shows the semiannual amplitude (mm) of elastic loading response of lake water + soil moisture storage derived by the half-space model from 2014 to 2022 (E=0.95e+11 Pascal and v=0.3).

Figure C.14. The deformation map shows the annual amplitude (mm) of elastic loading response of lake water + soil moisture storage derived by the half-space model from 2014 to 2022 (E=0.95e+11 Pascal and v=0.3).