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Technical Note

Rethinking groundwater-level mapping: The presence of intrinsic vertical hydraulic gradient in confined aquifers

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ABSTRACT

This study investigates the Intrinsic Vertical Hydraulic Gradient (IVHG) and its significant impact on enhancing groundwater-level (GWL) mapping. The IVHG is a fundamental characteristic that is naturally inherent in confined aquifers, reflecting the natural, undisturbed state of vertical hydraulic head variations under equilibrium conditions. Traditionally, GWL mapping has overlooked vertical hydraulic gradients within confined aquifers, assuming that groundwater levels remain constant at any given site within a confined aquifer regardless of well depth. This study identifies an IVHG of approximately 0.07 within the confined Chicot-Evangeline aquifer beneath the Greater Houston area, Texas, and around 0.05 in the underlying Jasper aquifer. This study presents an IVHG-adjusted GWL mapping method that standardizes GWL measurements based on well depth, resulting in more precise and depth-specific GWL contours. This approach offers a critical improvement over conventional methods, providing greater precision in water resource management, conservation planning, and the assessment of land subsidence risks, especially in areas land subsidence has ceased. The IVHG represents the minimum vertical hydraulic head gradient within confined aquifers. In regions where subsidence persists, the IVHG-adjusted method may not fully capture the larger vertical hydraulic gradient, yet it still outperforms conventional mapping by providing a more accurate representation of GWLs at different depths. The findings highlight the need to consider vertical hydraulic gradients in GWL mapping for more precise groundwater assessments and effective management strategies.

1. Introduction

Groundwater is a vital source of fresh water, sustaining agriculture, industry, households, and ecosystems. Accurate groundwater-level (GWL) mapping is essential for managing water resources, mitigating land subsidence, and informing policy development. GWL mapping conventionally relies on contouring techniques that interpolate water levels measured from wells, assuming a uniform hydraulic head across a confined aquifer regardless of depth (e.g., Ramage et al., 2022). This classical approach, akin to generating digital elevation models (DEMs) from topographic data with a single height per site, relies on contouring techniques that interpolate well measurements, without accounting for well depth, often overlooking vertical hydraulic gradients. While effective for broad regional assessments, this method may fail to capture depth-specific variations critical for understanding complex aquifer systems like those in the Gulf Coast region.

Long-term GWL observations in the Greater Houston area, Texas, particularly from co-located and closely-spaced wells screened at varying depths within the confined Chicot-Evangeline aquifer, reveal significant variations in GWL at different depths (e.g., Kasmarek et al., 2015; Wang, 2023; Ellis et al., 2023). Even in areas where land subsidence has ceased over three decades, these vertical variations in GWL remain prominent, highlighting the presence of an inherent vertical hydraulic head gradient within the aquifer system. These findings challenge the traditional notion of equilibrium in confined aquifer systems and suggest the need for a more nuanced approach to GWL mapping.

This study identifies a vertical hydraulic gradient of approximately 0.07 in the confined Chicot-Evangeline aquifer system across the Houston region when the system nears equilibrium, marked by the cessation of permanent land subsidence and approximating an undisturbed natural state. This natural gradient is termed Intrinsic Vertical Hydraulic Gradient (IVHG), reflecting a natural property of confined aquifers. IVHG represents the minimum vertical hydraulic head gradient intrinsic to confined aquifers. Conversely, aquifers experiencing compaction from excessive groundwater withdrawals display vertical hydraulic head gradients greater than the IVHG. The IVHG concept extends beyond the Houston region, offering insights into confined

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aquifer systems worldwide.

2. Study area and data

The Greater Houston region, located in southeastern Texas near the Gulf of Mexico, spans approximately 25,000 km^2 and includes parts or all of approximately 10 counties, with Harris County at its center (Fig. 1). This area has experienced significant land subsidence and groundwater-level decline over the past century, largely due to excessive groundwater pumping, particularly in the mid-20th century (e.g., Gabrysch and Bonnet, 1977; Gabrysch, 1982; Ellis et al., 2023). Overextraction created pronounced cones of depression, leading to widespread subsidence, infrastructure damage, and increased flood risks (e.g., Coplin and Galloway, 1999). In response to the subsidence issues, the Texas State Legislature established the Harris-Galveston Subsidence District (HGSD) in 1975, the Fort Bend Subsidence District (FBSD) in 1989, and several groundwater conservation districts. Those districts have played key roles in managing groundwater use in the Greater Houston area.

Geologically, the region is part of the Gulf Coast aquifer system, composed of unconsolidated Holocene and Miocene sediments. This system includes the Chicot, Evangeline, Burkeville confining unit, and Jasper aquifers, which are critical to the region's water supply (Baker, 1979; Chowdhury and Turco, 2006). The Burkeville Confining Unit, a thick clay-dominated layer within the Gulf Coast Aquifer system, separates the Evangeline and Jasper aquifers in the Houston region, restricting vertical groundwater flow between these units (Young and Draper, 2020). As of the early 2020s, the U.S. Geological Survey (USGS)

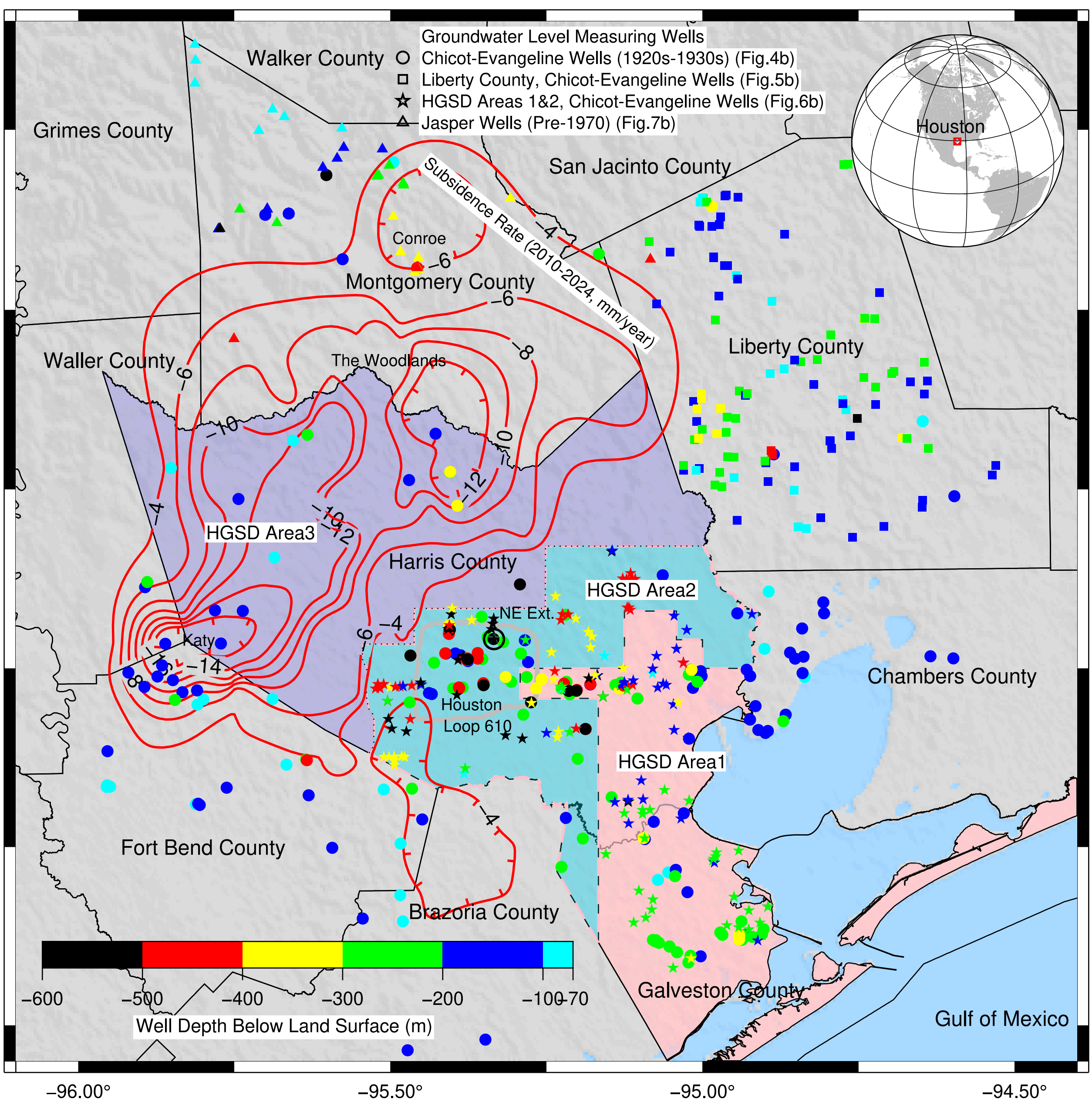


Fig. 1. Map showing groundwater-level monitoring wells used for exploring the Intrinsic Vertical Hydraulic Gradient (IVHG) in the greater Houston area. Contour lines depict recent land subsidence rates (in mm/year) derived from GPS data (2010–2024) (Agudelo et al., 2020; Wang et al., 2022). Marks indicate the locations of wells analyzed for correlations between well depths and groundwater levels, with well depths visually represented by distinct color patterns. The location of the Northeast Extensometer site is marked as NE Ext. Areas 1, 2, and 3 correspond to the current groundwater regulatory zones implemented by the Harris-Galveston Subsidence District (HGSD, 2013).

routinely measures groundwater levels in about 700 wells across the primary aquifers, including the Chicot and Evangeline, Burkeville confining unit, and Jasper aquifers. The comprehensive collection of groundwater level data by the USGS is publicly available through the USGS National Water Information System (NWIS) (USGS, 2024).

GWL monitoring and mapping in the Houston area boasts a long history, dating back to the 1890s. Prior to 1900s, GWLs within the confined Chicot-Evangeline aquifer were much higher than land surface (Wood and Gabrysch, 1965). Since 1977, the USGS has published annual reports that document both short-term fluctuations and long-term trends in GWLs within the Chicot and Evangeline aquifers, respectively, beneath the Houston area, providing valuable insights into the region's hydrological dynamics (e.g., Gabrysch, 1979; Barbie et al., 1991). These maps, updated annually, provide crucial information for forming and revising groundwater management plans. In 2001, the USGS introduced the inaugural GWL map for the Jasper aquifer (Coplin, 2001). Since then, the USGS had annually published GWL maps for the Chicot, Evangeline, and Jasper aquifers beneath the Houston area, respectively (e.g., Kasmarek et al., 2015; Braun and Ramage, 2020).

In 2021, the USGS merged the Chicot and Evangeline aquifers into a single unit for groundwater level mapping (Ramage et al., 2022). This combined unit is referred to as the Chicot-Evangeline aquifer in this study. The thickness of the Chicot-Evangeline aquifer varies from approximately 300 m at the northern boundary of Harris County, gradually increasing to about 600 m in downtown Houston, and reaching up to 1,600 m near the Galveston coast. The upper portion, from the land surface to around 70 m depth, is generally considered unconfined or semi-confined, while the section from 70 m to the base of the aquifer system is classified as confined.

Following this change, the USGS began publishing two sets of GWL maps in their annual reports starting in 2021: one for the confined Chicot-Evangeline aquifer and one for the Jasper aquifer (e.g., Braun and Ramage, 2022; Ramage and Braun, 2023; Ramage, 2024). This new approach, which utilizes a greater number of wells compared to the previous method of producing separate GWL maps for the Chicot and Evangeline aquifers, has resulted in a significant increase in the variation of well depths. Consequently, the impact of the vertical hydraulic gradient on GWL assessments has become more pronounced.

3. Revealing the intrinsic vertical hydraulic gradient (IVHG): Evidence and rationale

3.1. Presence of IVHG

Since the 1970s, the USGS has installed 14 deep borehole Extensometers across the Houston area to monitor land subsidence, with the most recent installation in 2017 in Katy, Fort Bend County (Adams and Ramage, 2024). Each Extensometer borehole also functions as a deep groundwater well, allowing GWL measurements at the bottom of the borehole. In addition, several co-located groundwater monitoring wells, spaced a few meters to tens of meters apart and terminated at varying depths, were installed adjacent to each Extensometer borehole, penetrating different depths of the confined Chicot-Evangeline aquifer system. In general, groundwater wells have a screen window with a height varying from a few meters to several tens of meters at their bottom. The bottom of the screen is typically positioned a few meters above the bottom of the well borehole. For example, the bottom of the Northeast Extensometer borehole is 661 m below the land surface, while the bottom of the screen is 646 m, and the top of the screen is 640 m below the land surface, giving the screen window a height of approximately 6 m (Ellis et al., 2023).

In order to reveal the presence of IVHG, long-history GWL changes within the State Highway Loop 610 are investigated, where measurements in the confined Chicot-Evangeline have remained stable for over two decades as of 2023. Loop 610, a major freeway encircling central Houston, spans approximately 155 km^2 and includes significant urban zones such as the Medical Center, Downtown Houston, the Galleria, and the University of Houston. Refer to Fig. 1 for the study area location. Within this loop, groundwater levels have experienced significant fluctuations over the past century, largely due to extensive groundwater pumping. Historically, the region saw substantial groundwater depletion, which resulted in pronounced cones of depression and contributed to widespread land subsidence. Regulatory efforts and reduced groundwater extraction have allowed groundwater levels to elevate since the 1980s, with stabilization approaching since the mid-2010s (Turco and Petrov, 2015).

Fig. 2 illustrates the long-term GWLs at the Northeast Extensometer site, located northeast of Loop 610, along with a cross-sectional profile of the underlying aquifers. Rapid groundwater level decline in the shallow portion of the confined Chicot-Evangeline aquifer began in the late-1930s, and the rapid land subsidence began in the late-1940s. The maximum drawdown (MDD) of the hydraulic head occurred between the late-1970s and early-1980s, shortly after the implementation of HGSD groundwater regulations in 1976. Pumping-induced subsidence significantly decreased to less than 1 cm per year around 1990 and ultimately ceased in the early-2000s, as indicated by the onset of land rebound. Since the early 1980s, GWLs at various depths have steadily risen, reaching a stable state around 2010. Since then, the GWL time series from these co-located wells have displayed parallel trends, with shallower wells consistently showing higher levels and deeper wells showing lower levels. This stability has persisted for more than a decade, up to 2023, with no signs that groundwater levels at different depths will converge to a single value, contrary to the assumptions often made in conventional GWL mapping.

These observations reveal that the vertical hydraulic gradient is an inherent feature of the confined aquifer system. During the stabilization period from 2010 to 2020, when groundwater levels were at their highest and most stable, a hydraulic head decline of approximately 30 m occurred over a 560-m increase in well depth, resulting in a vertical hydraulic gradient (VHG) of about 0.06. Severe droughts during the summers of 2022 and 2023 in the Houston area led to a significant increase in groundwater pumping (Greuter, 2024), causing a consistent decline in groundwater levels across wells of varying depths, while the VHG remained unchanged.

Fig. 3 depicts the GWL time series at 72 wells within the Loop 610 area and the correlations between GWLs and well depths. All wells are terminated in the confined Chicot-Evangeline aquifer system. The locations of these wells are plotted in Fig. 1. The correlation between GWLs and well depths at three critical time periods are analyzed: (a) predevelopment prior to the 1940s, (b) the period of maximum drawdown (MDD) from the mid-1970s to the mid-1980s, and (c) post-recovery stabilization from the mid-2000s to the early-2020s. These plots vividly illustrate the presence of a VHG with varying magnitude over time in the confined Chicot-Evangeline aquifer system. Even before the 1940s, when significant groundwater pumping had not yet occurred and the aquifers were in a natural or undisturbed condition, the VHG presented in the confined Chicot-Evangeline aquifer system. The VHG peaked (approximately 0.08) during the MDD period from the mid-1970s to the mid-1980s, then gradually declined as groundwater levels rose, stabilizing in the late 2000s when hydraulic equilibrium was attained within the aquifer. This equilibrium is evidenced by the cessation of land subsidence. As of 2023, groundwater levels across multiple depths have remained stable for approximately two decades, yet a VHG of about 0.05 persists. The vertical hydraulic gradient within an equilibrium aquifer system reflects a fundamental characteristic of the confined aquifer system.

3.2. IVHG based on pre-1940 groundwater levels across the Houston area

Intensive groundwater extraction in the Houston area began in the 1940s, primarily targeting the upper and middle sections of the Chicot-Evangeline aquifer system. Prior to this period, groundwater resources

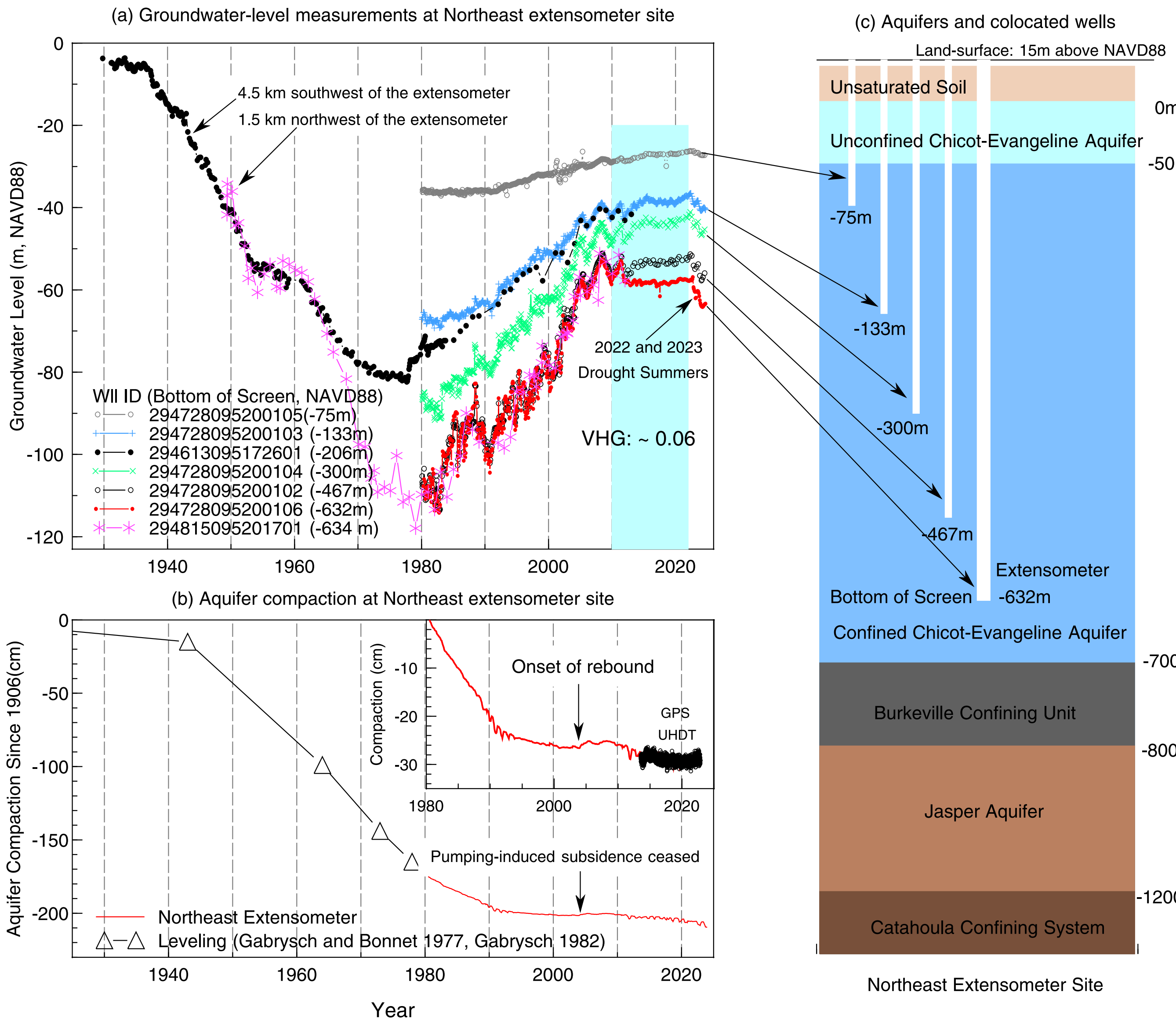


Fig. 2. Groundwater-level measurements and aquifers at the Northeast extensometer site. (a) Groundwater-level measurements at seven closely-spaced wells. Well 294613095172601 (depth: −206 m) and well 294815095201701 (depth: −634 m) are approximately 5.5 km apart. Well 294613095172601 is about 4.5 km to the extensometer site, while well 294815095201701 is about 1.5 km from it. The other five wells are co-located at the extensometer, separated by about one hundred meters. (b) Aquifer compaction from 0 to 661 m below the land surface from about 1906 to 2023, (c) Sketch map of the aquifers beneath the Northeast Extensometer site. Well depth and aquifer information are sourced from the recent USGS report (Ellis et al., 2023).

in the area remained largely undisturbed, with natural recharge rates sustaining a stable hydrological balance. The initiation of extensive extraction activities in the 1940s led to a significant and rapid decline in GWLs within the Chicot-Evangeline aquifer.

Fig. 4a presents GWL measurements from wells with records during the 1920s and 1930s in the Houston area, with the locations and well depths shown in Fig. 1. These GWLs are primarily sourced from the USGS National Water Information System (NWIS). A recent report from the USGS Gulf model identified a group of early GWL measurements from the 1920s to 1930s in the Houston area (Ellis et al., 2023), some of which have not been included in the NWIS database. By integrating GWL data from the 1920s and 1930s, both from the NWIS and the USGS report, a total of 255 wells ranging between 70 m to 700 m below the land surface were analyzed. Since GWLs in the confined aquifer system prior to1940 predominantly reflect a natural equilibrium state across the aquifer, the GWLs measured during the 1920s and 1930s are considered representative of the Chicot-Evangeline aquifer's intrinsic balance, termed in this research as pre-development GWLs.

Fig. 4b demonstrates the relationship between GWLs and well depths, both referenced to the North American Vertical Datum of 1988 (NAVD 88). The elevation of the Galveston coastline being approximately zero relative to NAVD 88. Given that most wells have limited measurements from this period, the average GWL was used for wells with two measurements, while the median GWL was used for wells with three or more measurements to represent the pre-development GWL. A linear regression was applied to examine the correlation between GWLs and well depths, resulting in a slope of 0.07. This suggests an average IVHG of 0.07 within the confined Chicot-Evangeline aquifer, indicating that for every 100-m increase in well depth, the groundwater level deepens by approximately 7 m.

3.3. IVHG derived from GWLs in Liberty County

Liberty County, Texas, located to the east of Harris County, spans an area of approximately 3,200 km^2 (Fig. 1). In contrast to its economically vibrant neighbor, Liberty County has experienced modest economic

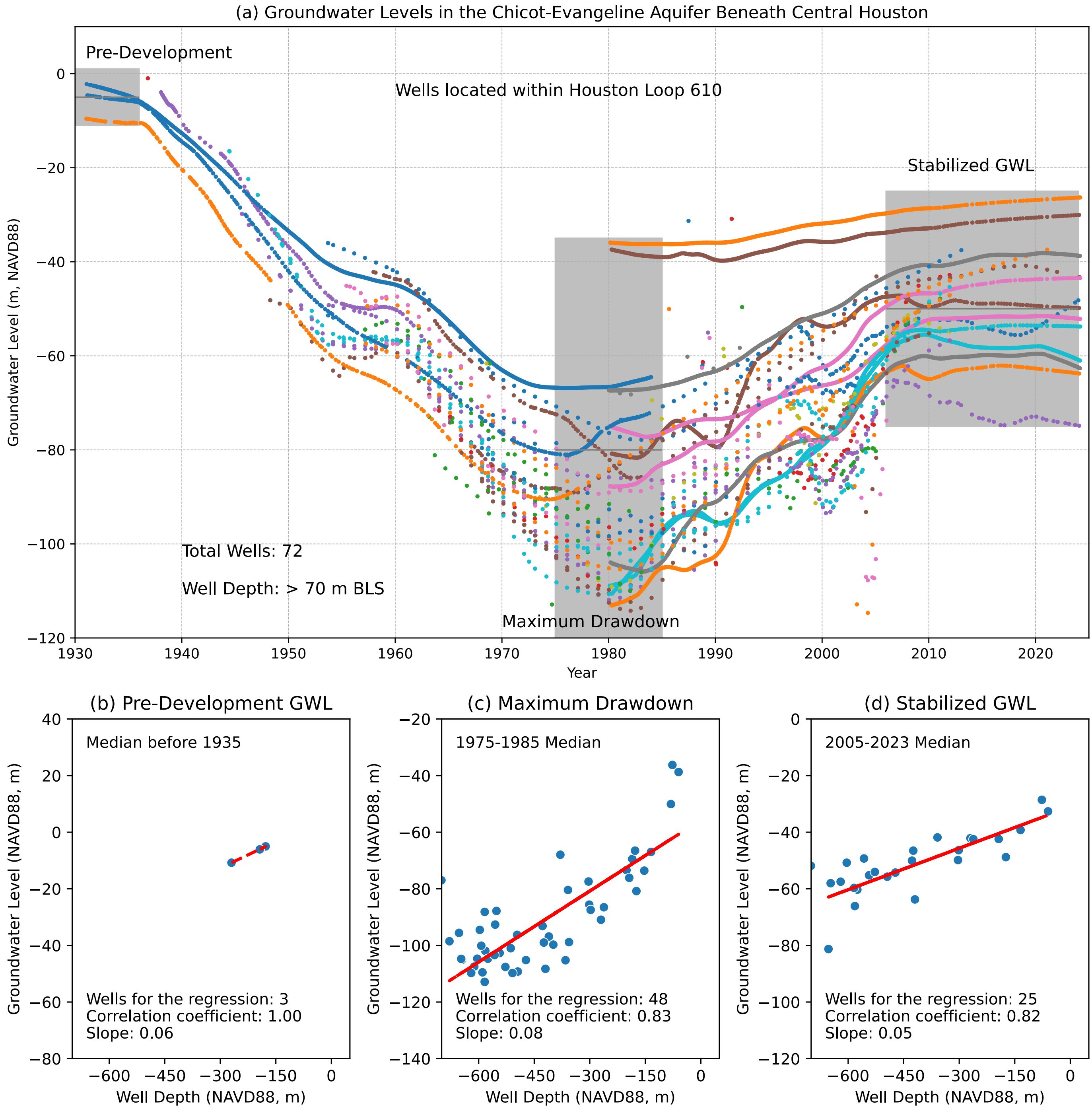


Fig. 3. (a) Groundwater levels (GWLs) within the confined Chicot-Evangeline aquifer beneath central Houston, delineated by State Highway Loop 610. The raw GWL time series have been smoothed to minimize short term variations. (b), (c), and (d) illustrate the relationships between well depths and GWLs within the confined Chicot-Evangeline aquifer during three key periods: pre-development (prior to 1935), maximum drawdown (MDD, 1975–1985), and the stabilization period (2005–2023).

growth, a sparse population, and minimal industrial activity. These factors have resulted in relatively low levels of groundwater extraction over the past century. As of the 2020s, Liberty County, along with its neighboring Chambers County, is the only area within the Greater Houston area where groundwater withdrawals are not subject to regulation. Long-term data from leveling, GPS, and Interferometric Synthetic Aperture Radar (InSAR) studies show minimal land subsidence in the county over the past decades (e.g., Kearns et al., 2015; Qu et al., 2015; Khan et al., 2022; Liu et al., 2022), enabling the maintenance of stable groundwater levels that reflect the area's natural equilibrium.

Fig. 5a illustrates the GWL time series recorded by wells terminated in the Chicot-Evangeline aquifer beneath Liberty County. There was slight groundwater level depletion during the 1970s at a few well sites, but the depletion was much minor compared to that occurred in Harris and Galveston counties during the same timeframe. Overall, there were no remarkable GWL changes during the past century (1930s-2020s) across Liberty County. In contrast to the broader analysis across multi counties as depicted in Fig. 4, the GWLs documented in Liberty County offer a local-scale reference for assessing the IVHG, minimally affected by areal hydraulic variations. Fig. 5b illustrates the relationship between

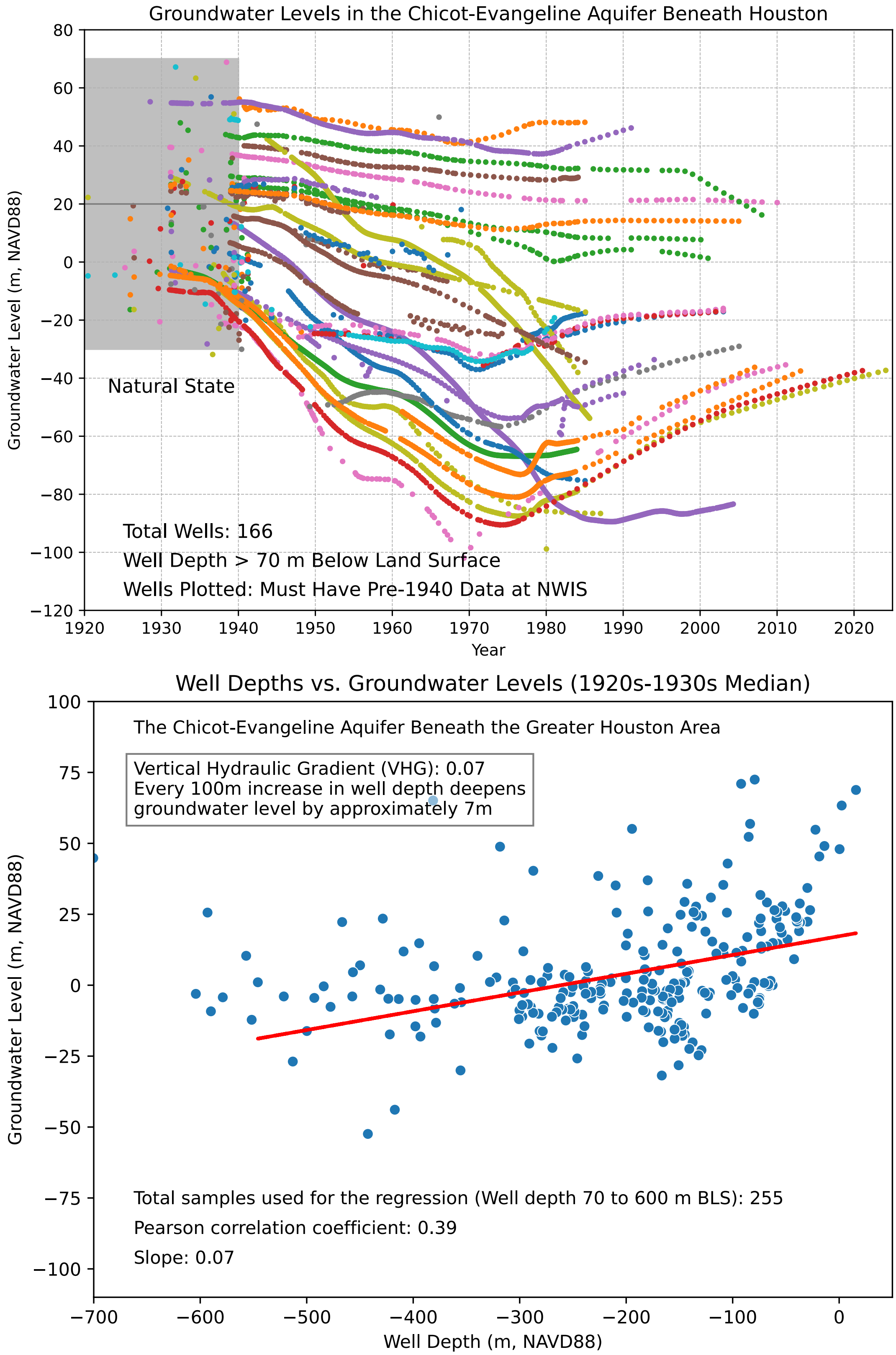


Fig. 4. Presence of the Intrinsic Vertical Hydraulic Gradient (IVHG) within the undisturbed Chicot-Evangeline aquifer beneath the greater Houston area. Panel (a) displays GWL time series from wells with measurements before 1940 (pre-development), while panel (b) illustrates the relationship between well depths and pre-development GWLs (1920s to 1930s) across the greater Houston area.

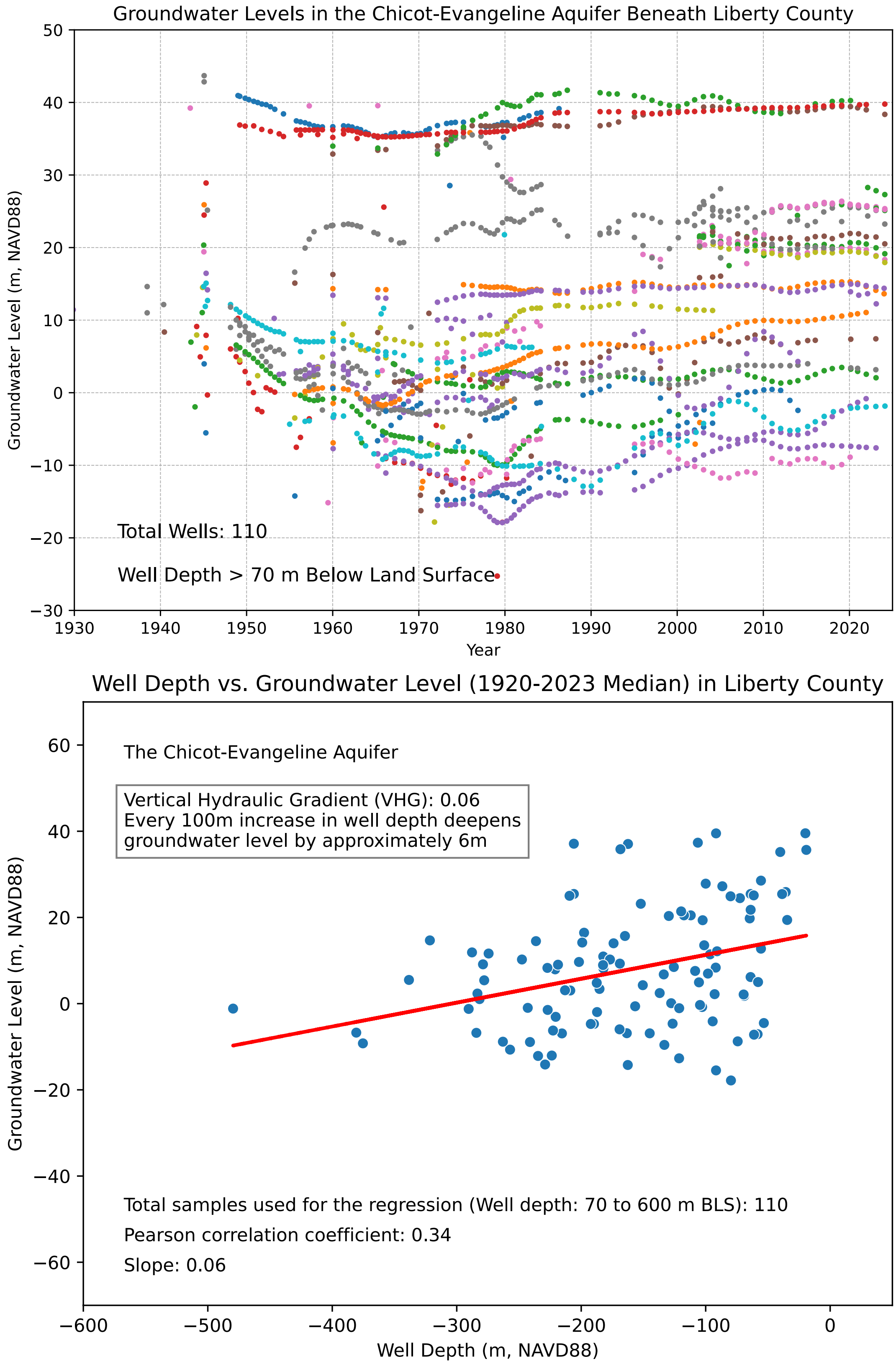


Fig. 5. Presence of the Intrinsic Vertical Hydraulic Gradient (IVHG) within the confined Chicot-Evangeline aquifer beneath Liberty County. Panel (a) displays GWL time series from wells terminated in the confined Chicot-Evangeline aquifer; panel (b) shows the correlation between well depths and average GWLs. The average GWL at each well site is represented by the median of all measurements from that well. The locations of wells used for this correlation analysis are indicated in Fig. 1.

the average groundwater levels at well sites and their respective depths in Liberty County. Here, the GWL is determined by the median of all recorded measurements throughout the history of each well. A linear regression of this dataset reveals a slope of 0.06, indicative of an IVHG presence in the area.

3.4. IVHG in Harris-Galveston subsidence district (HGSD) regulatory areas 1 and 2

HGSD Regulatory Areas 1 and 2 cover approximately 5,100 km^2, encompassing Galveston County and the southeastern portion of Harris County (Fig. 1). The previous mentioned Loop 610 area belongs to the HGSD Area 2. These areas are of particular importance because they have been central to both subsidence mitigation efforts and groundwater management strategies since the establishment of the HGSD in 1975 (Greuter et al., 2021). Defining hydraulic gradients in these areas is key to understanding how hydraulic heads and land subsidence rates vary over time, correlate, and for preventing subsidence reoccurence.

Fig. 6a illustrates the long-term history of GWLs within the confined Chicot-Evangeline aquifer system beneath HGSD Areas 1 and 2. After the introduction of groundwater regulations in the late-1970s, groundwater levels in these areas showed a significant recovery, with levels beginning to rise by the late 1970s. By the 1990s, groundwater levels had exceeded the newly established pre-consolidation head, named as new pre-consolidation head (Wang, 2023). This stabilization led to a substantial reduction in subsidence risk by the mid-2000s, as the Chicot-Evangeline aquifer reached an "overconsolidated" state, effectively preventing further land subsidence as long as groundwater levels remained above the new pre-consolidation head (Wang, 2023; Wang et al., 2024). By 2023, groundwater levels in the Chicot-Evangeline aquifer have remained consistently stable for approximately two decades.

Fig. 6b examines the relationship between current GWLs and well depths in HGSD Areas 1 and 2, using the median GWL from 2010 to 2023 as the representative current level for each well. Wells without data for this period were excluded from the analysis. A linear regression was applied, revealing an IVHG of approximately 0.07. This value is consistent with earlier estimates based on pre-development GWLs across the Greater Houston area (Fig. 4b) and measurements from undisturbed GWLs in Liberty County (Fig. 5b). This consistency across different regions and time periods confirms the presence of the IVHG as a key parameter for understanding the behavior of the Chicot-Evangeline aquifer under varying conditions.

3.5. IVHG quantified in the Jasper aquifer

The Jasper aquifer is a critical source of fresh water in Montgomery County and northern Harris County, with its thickness ranging from approximately 300 m in northern Montgomery County to 500 m in northern Harris County. The upper portion of the Jasper aquifer generally contains freshwater, while the lower portion holds slightly saline (brackish) water (Young et al., 2017). As of the 2010s, the upper portion has become the primary target for freshwater extraction in northern Harris County and southern Montgomery County (Kelley et al., 2018). Groundwater usage in Montgomery County has surged dramatically with population growth since the 2000s, particularly in the municipal sector. While both the Evangeline and Jasper aquifers have been subject to extensive pumping, the Jasper aquifer has been increasingly utilized, contributing to ongoing land subsidence (e.g., Wang et al., 2021).

Fig. 7a presents GWL time series data from wells terminated in the Jasper aquifer beneath Montgomery County and northern Harris County. The time series reveals a marked decline in groundwater levels starting in the 1970s, a period of intensified groundwater extraction. Prior to this, minimal withdrawals from the Jasper aquifer occurred, meaning GWLs before the 1970s largely reflect natural, undisturbed conditions.

Fig. 7b explores the relationship between pre-1970 GWLs and well depths within Montgomery County, using the median GWL from measurements taken before 1970 at each well site. Locations of these wells are shown in Fig. 1. The analysis includes only 35 wells due to the limited availability of pre-1970 data, which may affect the specific IVHG value. However, this does not negate the clear presence of an IVHG within the Jasper aquifer, estimated at approximately 0.05. Despite the smaller sample size, the Pearson correlation coefficient of 0.72 indicates a strong relationship between well depth and groundwater levels. Given the increasing reliance on the Jasper aquifer in Montgomery County and northern Harris County as a vital freshwater source, understanding the presence of IVHG is essential for developing effective groundwater management and conservation strategies.

4. IVHG-adjusted groundwater-level (GWL) mapping

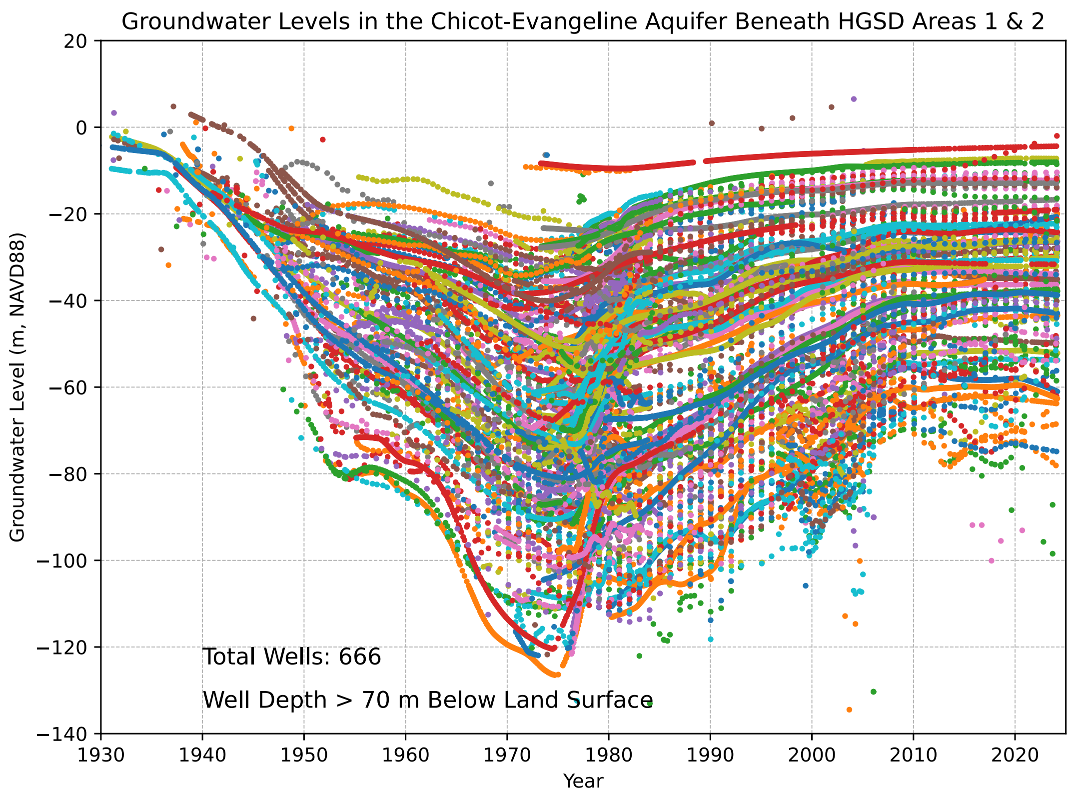
Groundwater level mapping is an essential tool for understanding and managing groundwater resources and land subsidence processes, particularly in regions where groundwater serves as a major fresh water supply. The process typically begins by collecting GWL measurements from a network of monitoring wells across an area of interest during a specific period. Once the data is gathered, common methods for GWL mapping involve interpolating the measured values to generate contour maps that represent groundwater levels across a geographic area. Techniques such as kriging, inverse distance weighting, or spline interpolation are often used to estimate GWL values at locations between measurement points.

GWL maps, particularly those with contour lines, are crucial for both scientific and practical purposes. They provide insights into the direction and rate of groundwater flow, which are key factors in managing water resources and assessing risks like land subsidence, groundwater depletion, and contamination spread. GWL contour maps can also be used to identify recharge and discharge areas, helping water managers make informed decisions about groundwater extraction and conservation practices.

The presence of IVHG in the Chicot-Evangeline and Jasper aquifers challenges conventional GWL mapping, which assumes a single hydraulic head per location regardless of well depth. Integrating IVHG requires normalizing GWL measurements to a uniform depth across the study area. This method enhances GWL map accuracy, improves understanding of aquifer dynamics, and supports advanced groundwater management strategies.

As of the early 2020s, there are about 600 active wells terminated within the confined Chicot-Evangeline aquifer beneath the Greater Houston area. Fig. 8 illustrates the variation of the well depths with respect to the land surface and with respect to NAVD 88. In the Houston area, land surface elevation typically ranges from near sea level (around 1 m) along the Gulf Coast to approximately 40 m in some of the higher inland areas, such as northwest Harris County. The histograms indicate that the well depths vary within a broader range from near land surface to about 700 m below land surface. This comprehensive dataset encompasses measurements from 581 sites with well depth ranging from 70 m to 700 m below land surface (BLS), across the Houston area, providing a broad foundation for detailed GWL mapping.

The key idea of integrating IVHG into GWL mapping is to standardize the GWL measurements collected at wells with different depths to a unified depth. In this study, three common depths were selected, −150 m, −300 m, −450 m with respect to NAVD88, which represent the shallow, middle, and deep portions of the confined Chicot-Evange aquifer, respectively. An example for mapping the GWL at the early 2020s in the Houston area is shown in Fig. 9. The current GWL at each well site is estimated by the median value of all field measurements during the last five years (2019–2023). The Kriging interpolation method is applied to convert discrete GWL measurements into a continuous spatial framework, using a grid resolution of 0.25 km by



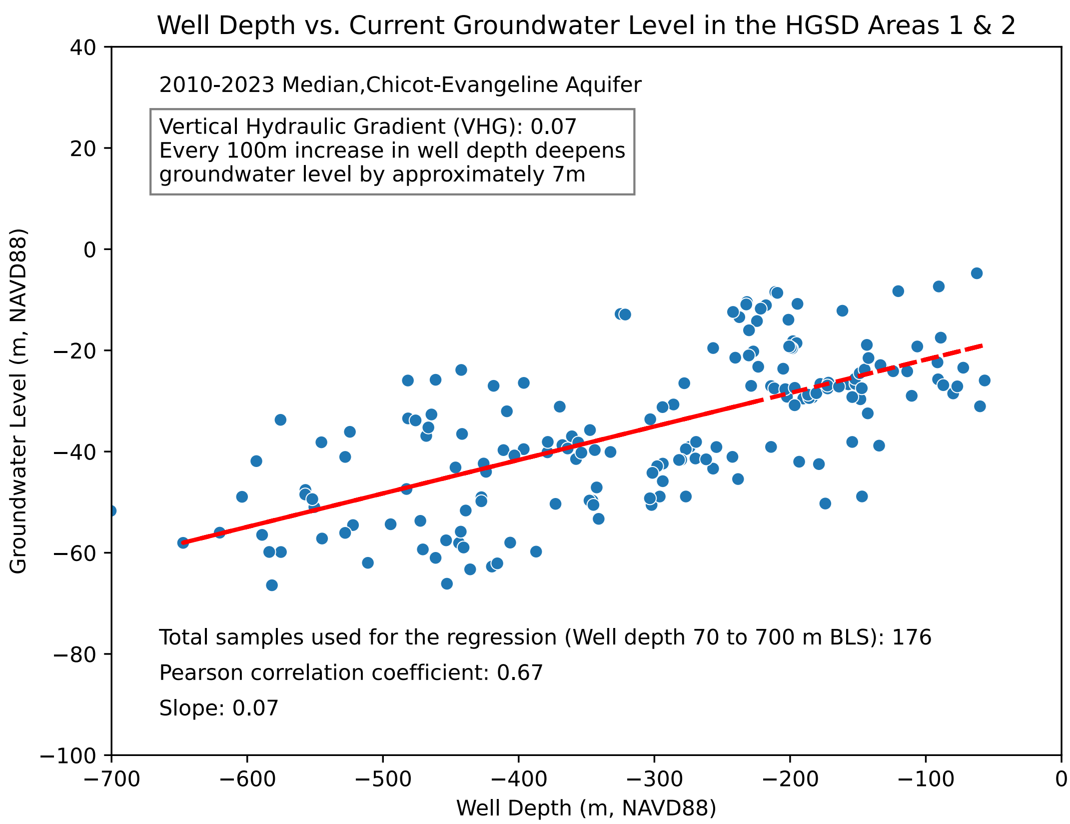
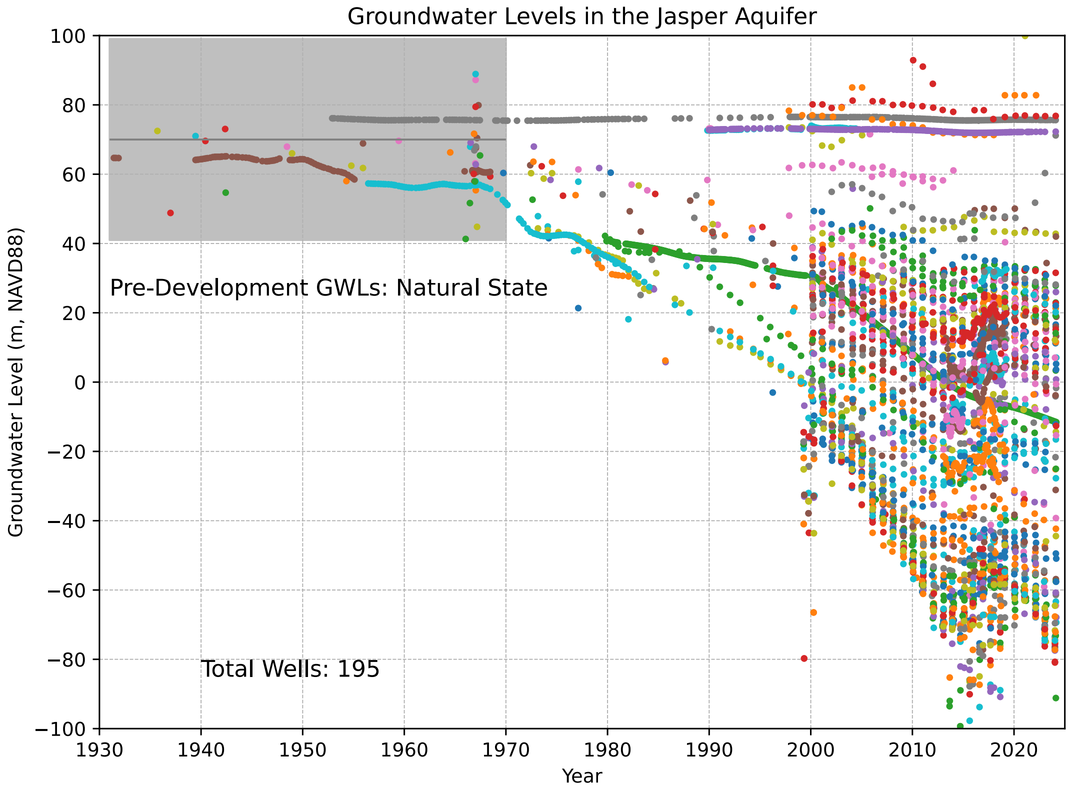


Fig. 6. Presence of the Intrinsic Vertical Hydraulic Gradient (IVHG) within the confined Chicot-Evangeline aquifer under the Harris-Galveston Subsidence District (HGSD) Regulatory Areas 1 and 2. Panel (a) displays GWL time series from wells terminated in the confined aquifer; panel (b) depicts the correlation between well depths and recent GWLs. The recent GWL at each well site is represented by the median of measurements spanning from 2010 to 2023. The locations of wells used for this correlation analysis are marked in Fig. 1.



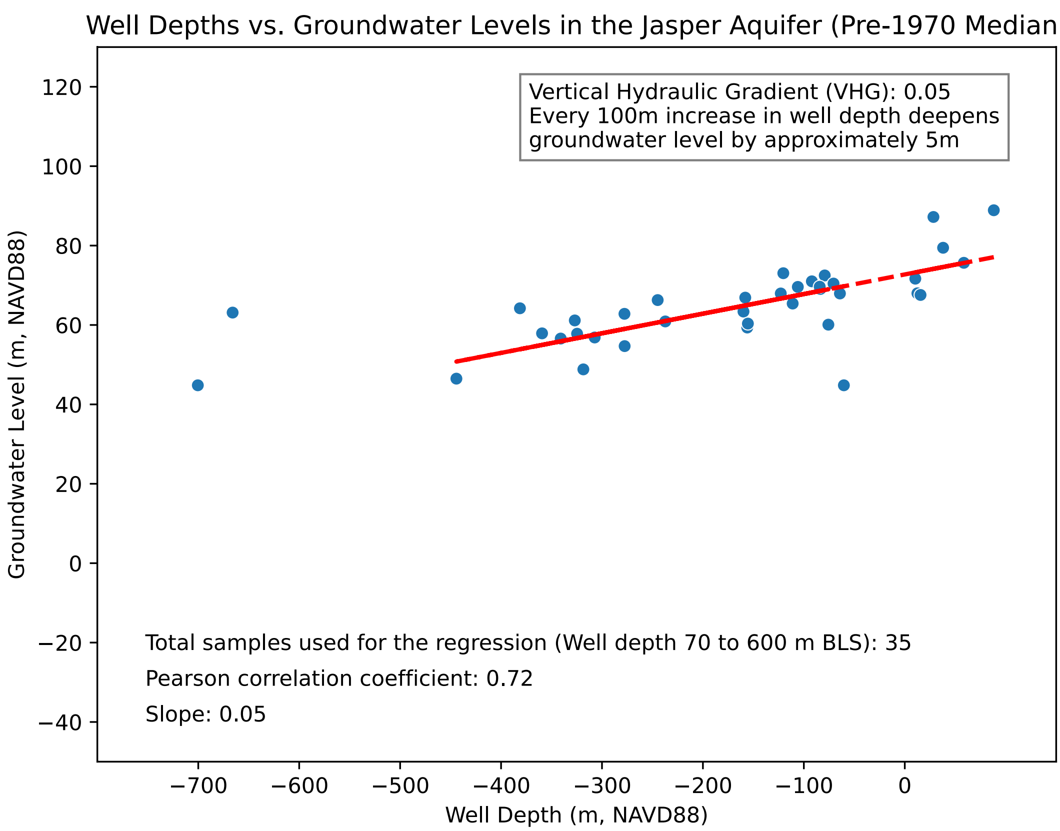


Fig. 7. Presence of the Intrinsic Vertical Hydraulic Gradient (IVHG) within the Jasper aquifer beneath Montgomery County and northern Harris County. Panel (a) displays GWL time series from wells terminated in the Jasper Aquifer; panel (b) shows the correlation between well depths and pre-development GWLs (before 1970). The pre-development GWL at each well site is represented by the median of measurements taken before 1970. The locations of wells used for this correlation analysis are indicated in Fig. 1.

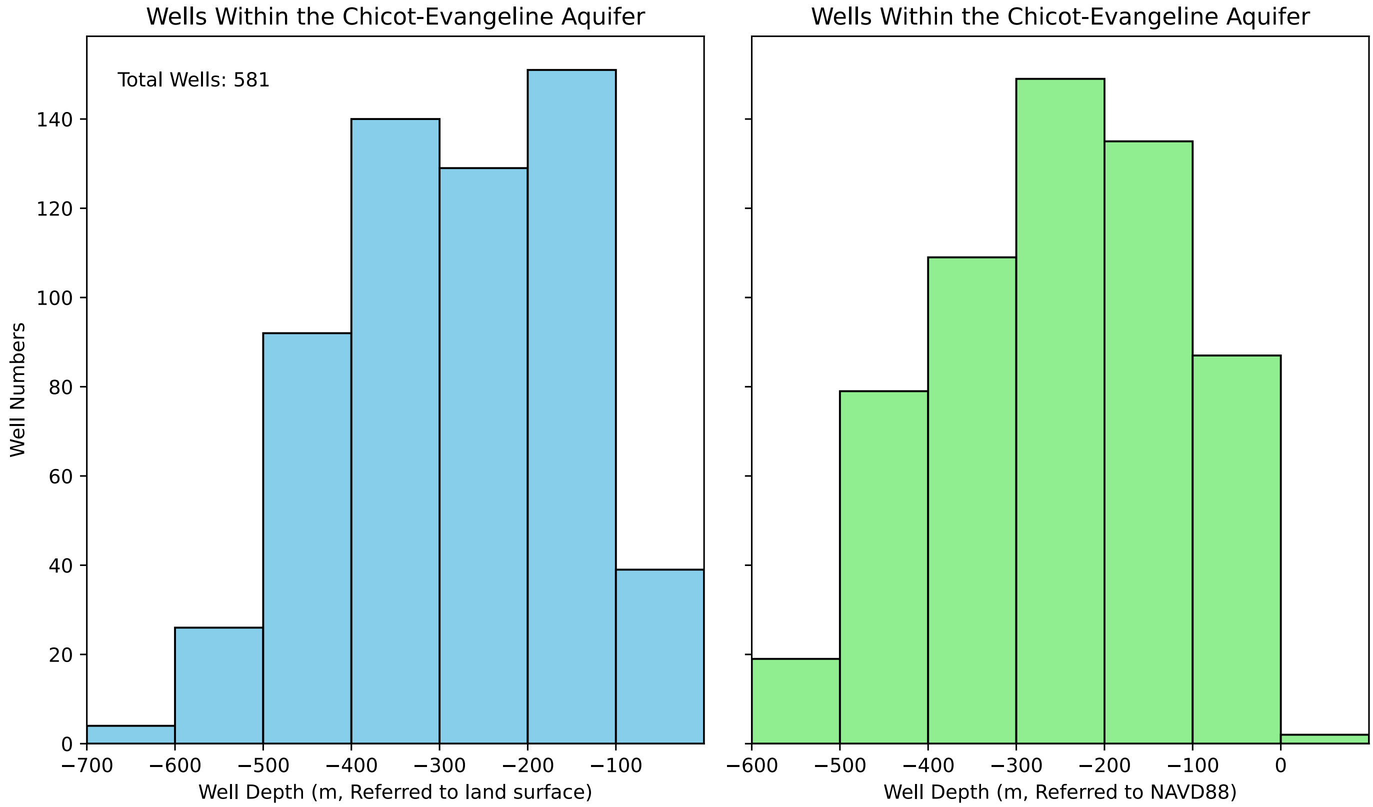


Fig. 8. Histogram showing the distribution of well depths for wells terminated within the Chicot-Evangeline Aquifer beneath the greater Houston area, with groundwater level measurements taken between 2019 and 2023 and depths ranging from 70 m to 700 m below the land surface. Panel (a) categorizes the wells by depth relative to the land surface, while panel (b) categorizes the wells by the elevation of the well bottoms in reference to NAVD88.

0.25 km. This approach is similar to the method used by the USGS for producing its annual GWL contour maps (e.g., Ramage et al., 2022; Ramage, 2024).

Fig. 9a presents the initial GWL map produced using the conventional mapping method, which grids raw measurements from wells across various depths. In contrast, Fig. 9b, 9c, and 9d display the results of IVHG-adjusted mapping at standardized depths of −150 m, −300 m, and −450 m (NAVD 88), respectively. Fig. 10 depicts the GWLs along a cross section from northwest to southeast, as marked in Fig. 9a. The IVHG-adjusted map at the mid-depth of −300 m (Fig. 9c) appears similar to the conventional GWL map (Fig. 9a). The cross section also reveals the similarity. This likeness stems from most wells being near 300 m deep (Fig. 8b), though the conventional method misses notable GWL variations in deeper layers.

The IVHG-adjusted maps (Fig. 9b–9d) and the cross section (Fig. 10) provide a clearer picture of the vertical variations of GWLs. For instance, at a depth of −450 m (Fig. 9d), the cones of depression—areas where groundwater levels have dropped significantly—are much more pronounced compared to shallower depths. This indicates that groundwater levels decline more sharply at greater depths, especially in regions affected by historical groundwater extraction. The conventional mapping method fails to capture this depth-specific variability, leading to a less accurate assessment of groundwater level variations over space. By standardizing GWL measurements at different depths, these maps allow for more accurate evaluations of groundwater storage, depletion, and recharge across various depths of the aquifer. This is essential for effective groundwater resource management, including the identification of safe pumping depths and areas that require focused conservation efforts.

Depth-specific GWL maps enable policymakers to identify areas most vulnerable to land subsidence. For effective subsidence management, administrators can focus on groundwater levels in the deep aquifer layers (Fig. 9d), where excessive withdrawals have historically (1960s–1980s) and currently driven subsidence (e.g., Yu et al., 2014). Areas with GWLs below −60 m are critical targets for pumping restrictions to mitigate ongoing moderate to rapid subsidence (>1 cm/year). The conventional mapping method identifies approximately 326 km^2 with GWLs below −60 m, whereas the IVHG-adjusted method estimates 1,337 km^2 in the deep portion. This suggests the conventional method likely underestimates the extent of effort needed to raise GWLs and curb subsidence.

Beyond improving groundwater management, the IVHG-adjusted mapping method provides new insights into the behavior of confined aquifers. It enables researchers to study the effects of vertical hydraulic gradients on groundwater flow, recharge zones, and interactions between different aquifer layers. This depth-specific information is crucial for developing more accurate models of aquifer dynamics, which are essential for predicting and managing future water use and mitigating environmental impacts.

Overall, the IVHG-adjusted GWL mapping method offers significant improvements over conventional mapping by revealing vertical variations in groundwater levels that are not captured by conventional approaches. The ability to generate multiple GWL maps for different depths (e.g., shallow, middle, and deep) within a confined aquifer system provides a more detailed understanding of groundwater dynamics. This refined approach enhances not only resource management and land subsidence mitigation efforts but also broader environmental and hydrological studies.

5. Discussion and conclusions

5.1. Presence of IVHG and its drivers

This study reveals the presence of IVHG within the confined Chicot-

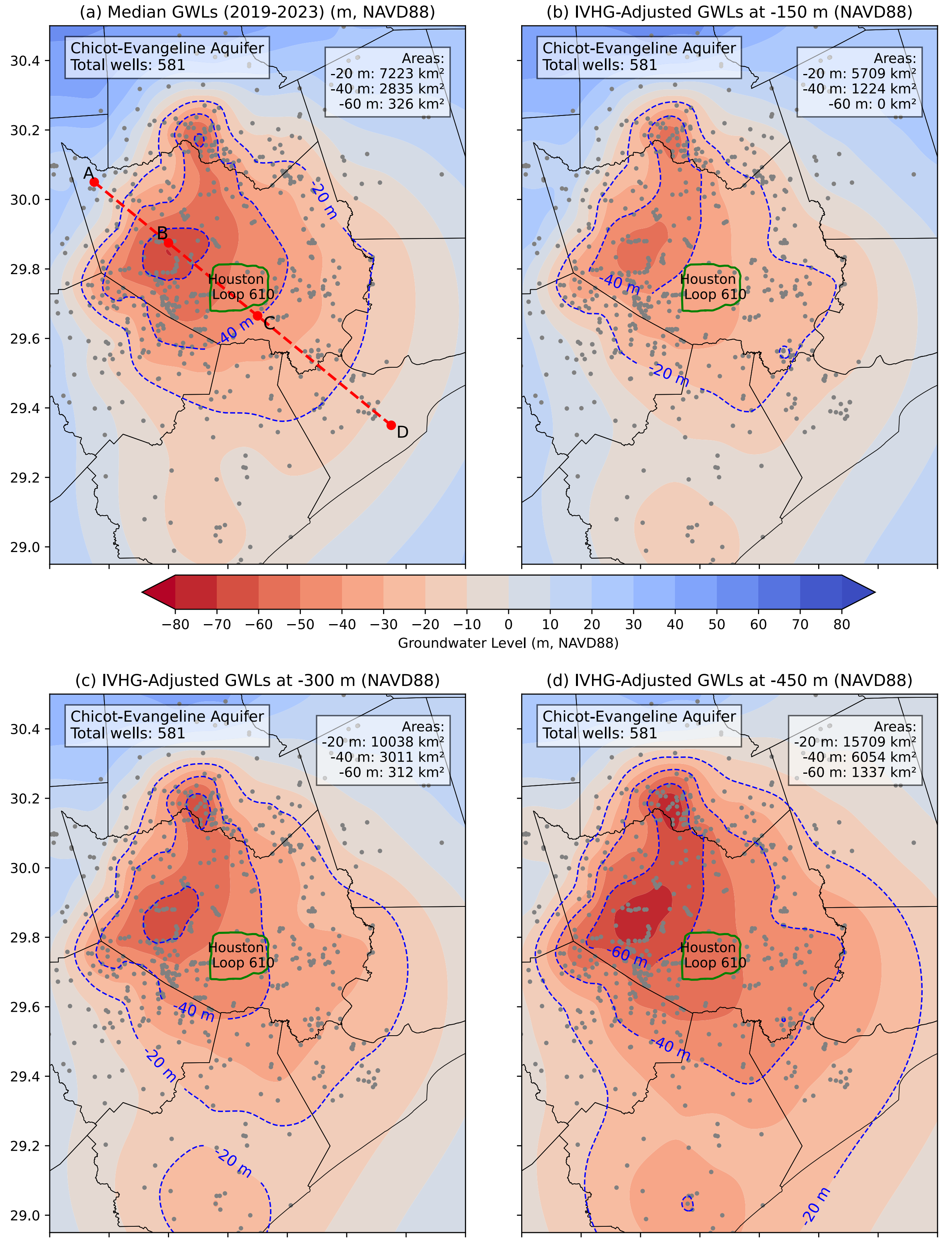


Fig. 9. Contours of groundwater levels (GWLs) in the confined Chicot-Evangeline aquifer, comparing conventional and IVHG-adjusted mapping methods. (a) Current GWL map (median 2019–2023, NAVD88) generated using the conventional mapping method, with the cross-section location (red line, see Fig. 10). (b–d) IVHG-adjusted GWL maps at −150 m (shallow), −300 m (middle), and −450 m (deep), respectively (NAVD88). Dots mark 581 wells used for contouring.

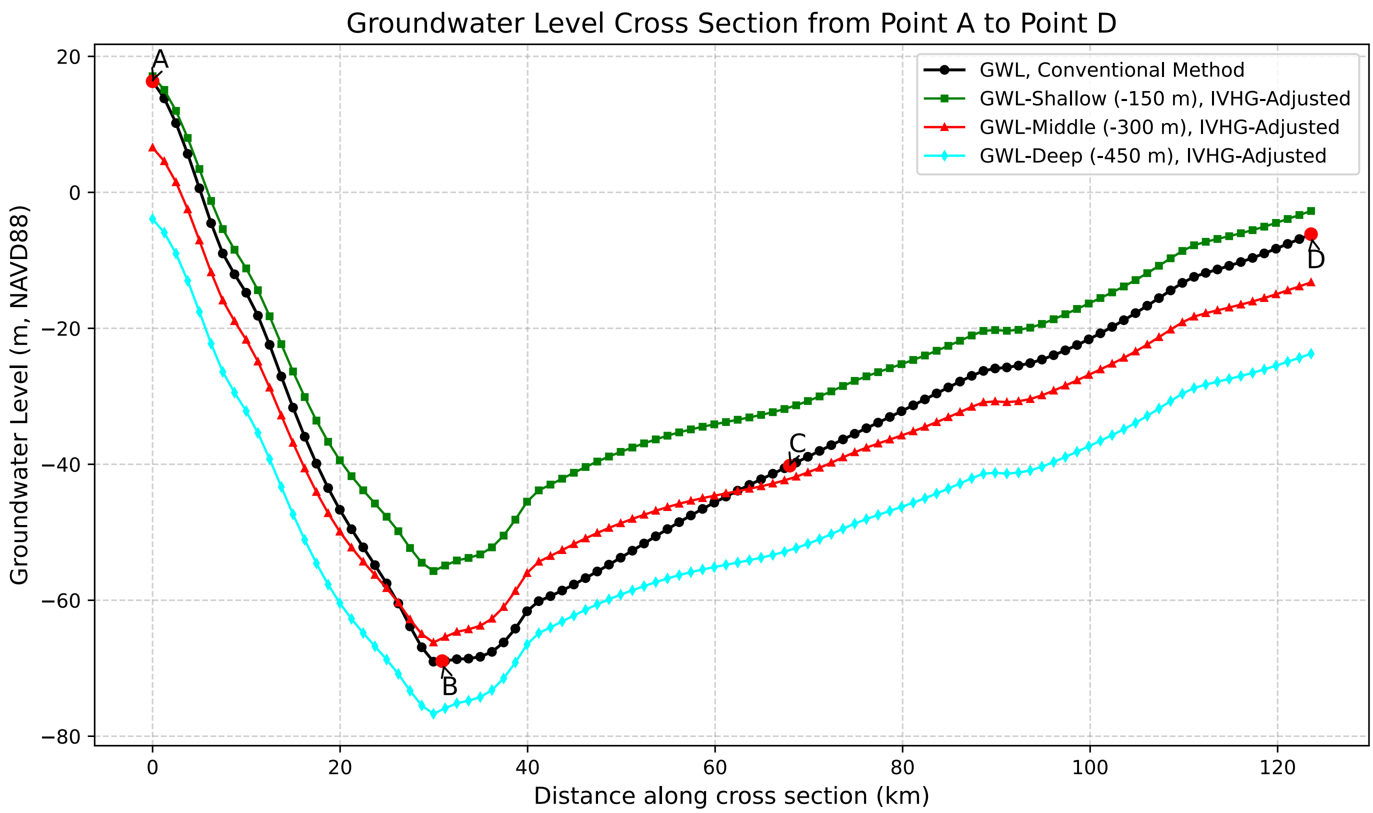


Fig. 10. Cross section comparing groundwater level (GWL) estimates from the conventional mapping method and the IVHG-adjusted method. The latter provides GWL estimates at three depths: −150 m (shallow, Fig. 9b), −300 m (middle, Fig. 9c), and −450 m (deep, Fig. 9d). Profile location and reference points (A, B, C, D) are shown in Fig. 9a.

Evangeline and Jasper aquifers beneath the Greater Houston area. Correlation analyses between GWLs and well depths, drawing on data from the pre-development era (1920s-1930s) across the Greater Houston area, century-long records (1930s-2020s) from Liberty County where no considerable subsidence occurred, and the stabilization period (2010–2023) from the HGSD Regulatory Areas 1 and 2, consistently indicate an IVHG of approximately 0.07 in the confined Chicot-Evangeline aquifer. Similarly, the Jasper aquifer beneath Montgomery County exhibits an IVHG of around 0.05. These findings confirm that IVHG is a natural and inherent characteristic of the confined aquifer systems across the study area, underscoring its significance as a fundamental hydrogeological property. Understanding IVHG is vital for the sustainable management of groundwater resources, as it helps address the uncertainties associated with groundwater level measurements.

The occurrence of IVHG can be attributed to a combination of factors, including discontinuous aquitards, anisotropy in hydraulic conductivity, stratigraphic variability, heterogeneity in aquifer thickness, natural compaction of aquifers, recharge and discharge zones, overlying pressure from the water column, surface water interactions, variations in temperature and water density, geothermal gradients, differences in mineral content and salinity, chemical gradients, paleohydrologic conditions, historical pumping practices, sediment loading and unloading, faulting and fracturing, tectonic activity, and tidal influences in coastal settings (e.g., Hess et al., 1992; Samper et al., 1992; Zlotnik et al., 2011; Manning et al., 2020). These factors collectively drive IVHG by generating vertical differences in hydraulic head, as physical processes—such as fluid pressure gradients from density variations, preferential flow through anisotropic or fractured media, and stress-induced pore pressure changes—create a persistent, natural gradient even under equilibrium conditions.

5.2. *Quantifying IVHG with linear GWL-depth relationships*

To quantify the IVHG, this study examines the relationship between GWLs and well depths in the Chicot-Evangeline confined aquifer system during its equilibrium state, using linear regression to estimate the vertical hydraulic gradient. This approach is grounded in consistent linear trends observed in GWL versus well-depth plots across diverse spatial and temporal scales: pre-development data (pre-1940s) across the Greater Houston area (Fig. 4b), century-long records (1930s–2020s) from Liberty County (Fig. 5b), and recent measurements (2010–2023) from HGSD Regulatory Areas 1 and 2 (Fig. 6b). These plots, spanning equilibrium conditions with minimal pumping, reveal a clear linear relationship, justifying linear regression over more complex models.

The strength of this linearity varies with spatial and temporal factors, as captured by the Pearson correlation coefficient (Pearson's r), ranging from −1 (perfect negative linear relationship) to 1 (perfect positive), with 0 indicating no linear correlation. In wider regions like pre-1940 Houston (Fig. 4b, $r = 0.39$) and over century-long spans like Liberty County (1930s–2020s, Fig. 5b, $r = 0.34$), lower Pearson's r values indicate influences beyond depth—such as areal hydraulic gradients across counties or shifts in land use and climate over time—yet still affirm a detectable IVHG. Conversely, smaller, recent datasets from central Houston (Fig. 3d, $r = 0.82$), HGSD Areas 1 and 2 (2010–2023, Fig. 6b, $r = 0.67$), and the Jasper aquifer beneath Montgomery County (Fig. 7b, $r = 0.72$) show higher r values, as limited spatial extent and shorter timeframes reduce confounding factors. These constrained spatial scales and recent timeframes reduce exposure to confounding regional or historical factors, allowing clearer detection of IVHG dynamics. While not all variability is depth-driven, these consistently positive correlations during the equilibrium state validate linear regression as an effective, practical tool for IVHG mapping, balancing simplicity with robust representation of aquifer behavior.

5.3. Role of IVHG in GWL mapping

This study introduces an innovative GWL mapping methodology that incorporates the IVHG to create depth-specific groundwater-level maps spanning the full vertical extent of a confined aquifer. By standardizing GWL measurements at various well depths, this approach significantly enhances the accuracy of GWL mapping and provides a more nuanced understanding of aquifer dynamics. This method departs from conventional mapping techniques by acknowledging vertical heterogeneity within confined systems, offering a practical tool for hydrogeologists to refine aquifer characterizations.

Incorporating IVHG into GWL mapping yields a standardized, depth-adjusted approach that delivers a more precise depiction of groundwater levels in confined aquifers. This method not only improves aquifer modeling accuracy but also provides essential insights for sustainable groundwater management, land subsidence mitigation, and water conservation planning.

It should be noted that the IVHG-adjusted mapping may not fully account for the vertical hydraulic gradient in areas where moderate to rapid subsidence continues. This is because IVHG represents the minimum vertical hydraulic gradient where subsidence has ceased. In areas where subsidence is ongoing, hydraulic equilibrium within the aquifer system has not been achieved, and the vertical hydraulic gradient is greater than the IVHG, as illustrated in Fig. 3. However, the IVHG-adjusted mapping still results better estimates of hydraulic heads in subsidence areas than conventional GWL mapping, which do not consider the vertical hydraulic gradient.

Given that IVHG is an inherent feature of confined aquifers, the methodologies and insights developed in this study not only advance hydrogeological research but also offer a new framework for managing groundwater resources and mitigating land subsidence more effectively, with broader applicability to confined aquifers in other regions facing similar challenges. Beyond the Houston area, this framework could inform groundwater resource management in other large urban areas suffering from subsidence, such as Beijing, Tianjin, and Shanghai in China, where confined aquifers face pressures from urbanization, groundwater extraction, both natural and anthropogenic recharge, and environmental changes. Future research could extend these findings by integrating IVHG into predictive models, exploring its variability across temporal and spatial scales, and assessing its implications for long-term aquifer sustainability under a changing climate, particularly in regions vulnerable to sea-level rise, drought, or intensified groundwater demand.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Groundwater level data used for this study are sourced from the USGS National Water Information System (NWIS) Web Interface (https://waterdata.usgs.gov/nwis/gw).

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