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TOPICAL REVIEW

In-situ groundwater level monitoring reveals worldwide status, trends and impacts

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Abstract

Groundwater, as the largest storage of liquid freshwater on Earth and a major component of the water cycle, is critical for supporting surface water flow, ecosystems as well as water and food security. Human dependence on groundwater has increased sharply over recent decades, contributing to wealth creation and poverty alleviation. However, anthropogenic activities, including groundwater abstraction and climate change, have modified groundwater dynamics, leading to groundwater level (GWL) changes. We analysed 20 year time series of GWLs in 47 countries distributed across a range of climatic, geographic, hydrogeological and socioeconomic contexts worldwide. Using different indicators based on three time series analysis methods, we show that almost one third of the GWLs trends are declining—thus reflecting overexploitation of groundwater—while GWLs are rising in 18% of wells—not always indicating a recovery but also the consequence of human impact on the environment. Globally, GWLs show a mix of declining and rising trends, however, at regional scale, patterns and hotspots are evident. We also explored the associated impacts of GWL change on humans and ecosystems, by reviewing 28 case study examples. We show that both rising and falling GWLs have substantial impacts on water and food security, ecosystems, infrastructure and socioeconomic wellbeing. Our findings underscore an urgent need for expanding monitoring programmes, protecting groundwater, and defining acceptable impacts to determine sustainable groundwater usage and minimise impacts of GWL change.

1. Introduction

Groundwater represents 99% of liquid freshwater on Earth, is a main component of the hydrological cycle (Gleeson *et al* 2020, Condon *et al* 2021, Xie *et al* 2024) and supports surface water flows and ecosystems (Jolly *et al* 2008, Brunner *et al* 2017, Saccò *et al* 2024). Groundwater is also crucial for humans and has been used to support development of human societies for thousands of years, though groundwater usage has accelerated markedly in recent decades (Holley *et al* 2020, Mace 2022). Today, groundwater supplies 40% of irrigation water (Siebert *et al* 2010), and drinking water for two billion people globally (Margat and van der Gun 2013).

Anthropogenic activities, including climate change, have caused substantial modifications of groundwater processes and behaviour at different spatial scales (Kuang *et al* 2024) challenging the long-term natural 'steady state' in many aquifers. In many regions, groundwater volumes are depleting due to unsustainable abstraction and the effects of climate change (Konikow and Kendy 2005, Green *et al* 2011, Taylor *et al* 2013, Perrone and Jasechko 2019, Scanlon *et al* 2023). Groundwater depletion has caused wells to run dry (Jasechko *et al* 2021) and reduced flow to springs, rivers, wetlands and lakes (de Graaf *et al* 2019, Jasechko *et al* 2021, Rohde *et al* 2021), and has impacted forest density and composition (Kath *et al* 2014). Declining groundwater levels (GWLs) can cause or accelerate land subsidence (Babel *et al* 2006, Bagheri-Gavkosh *et al* 2021, Herrera-García *et al* 2021) and seawater intrusion in coastal areas (Werner *et al* 2013, Jasechko *et al* 2021). Conversely, GWL rise can be driven by either recovery following a period of drought, rising sea levels in coastal areas

(Bosserelle *et al* 2022), or changes in management practices (Buapeng and Foster 2008, Alam *et al* 2021). Rising water tables can cause groundwater flooding and infrastructure damage (Kreibich and Thieken 2008, MacDonald*et al* 2012, Czajkowski *et al* 2018, Becker *et al* 2022), reduced crop growth (Rasmussen *et al* 2023), inhibition of wastewater disposal (Cooper *et al* 2016, Hughes *et al* 2021), and increase the risk of liquefaction following earthquakes (Li *et al* 2025).

Despite the importance of groundwater for humans and ecosystems, effective protection and management of groundwater to ensure its sustainability remains a global challenge (Gorelick and Zheng 2015, Gleeson *et al* 2020, Lall *et al* 2020, Mukherjee *et al* 2021). Certainly, the hidden nature and long response time of groundwater, from days to years to centuries (Cuthbert *et al* 2023), compared to surface water, make it challenging to thoroughly understand groundwater processes, to estimate sustainable abstraction yields and to protect its natural quality. Hence, the consequences of human actions on groundwater can often only be observed many years after the pressure started (Custodio 2002, Molle and Closas 2020). This leads to groundwater being used, in many regions, as a resource with unrestricted or unregulated access (Holley *et al* 2020). It often leaves room for unfounded claims and myths (Mehta 2003, Budds 2009, Urteaga Crovetto 2013) as well as oversimplified and inaccurate assumptions, as defining groundwater sustainable or safe abstraction limit as equivalent to recharge volumes (Custodio 2002, Elshall *et al* 2020, Molle 2023). This further compromises groundwater sustainability, transferring the cost of using groundwater, including externalities as environmental impacts, to future generations (United Nations 2022).

A better understanding of groundwater systems is key to supporting effective management and governance. Knowledge improvement depends on the generation of *in-situ* data through monitoring networks, which have already been established in many countries (IGRAC 2020). *In-situ* measurement of GWL depth in monitoring wells is a foundational component of groundwater monitoring programmes. Consistent, long-term (i.e. multi-decadal) monitoring of water levels can provide insights into flow direction, recharge, storage, discharge, and responsiveness to stressors such as abstraction and drought (Taylor and Alley 2001), as well as the effectiveness of management practices and policies designed to decelerate or reverse depletion (Taylor and Alley 2001). *In-situ* data are also vital for evaluating groundwater models (Stahl *et al* 2010, Beck *et al* 2013, Burek and Smilovic 2022) and satellite-derived estimates of water storage (e.g. based on the Gravity Recovery and Climate Experiment (GRACE) (Li *et al* 2019). An illustrative example of using *in-situ* data to generate information is the World Meteorological Organization (WMO) annual report on the State of Global Water Resources (WMO 2023, 2024, 2025). In WMO (2025), the annual average of GWL for 47 countries was calculated from over 37 000 monitoring stations and ranked against long-term (20- and 10 year) GWLs. This approach provides an annual 'picture' of the status of GWLs worldwide.

Here, we develop deeper analysis of GWL time series, with the aim to provide insights on long-term GWL dynamics and the impacts of GWL change. Although many studies have focused on analysing the impact of human action or climate change on groundwater systems, far less attention has been paid to the impacts of GWL change. Here, we define GWL impact as an observable loss or change at a specific time because of GWL change. It is acknowledged that any continuous groundwater abstraction necessarily leads to impacts on surface water, ecosystems, and groundwater access and use (Molle 2023). While the generation of sufficient knowledge to estimate the sustainable abstraction of groundwater needs decades of observations along with, in general, groundwater development, understanding the impacts of GWL change can inform estimates of how much groundwater abstraction is acceptable in a certain context (Lapuyade *et al* 2020a, Molle 2023). The assessment of GWL trends impacts is complex though, as many hydrogeological, climatological, social, economic and cultural factors influence the type and severity of the impact.

We collated and analysed GWL trends from *in-situ* data collected through 2004–2023 as part of national or regional monitoring programmes in 47 countries. Using a multi-indicator approach, based on three time series analysis methods, we show the status and trends of GWLs and highlight regional patterns of declining or rising trends, and critical hotspots. We also explored how people, communities, societies and ecosystems are affected by GWL change, by reviewing evidence for those impacts in literature. Our study has two main objectives; (i) assess the state and long-term trends of GWLs worldwide and (ii) incorporate our results into a review of local-to-regional scale examples of the impacts of GWL changes on society and ecosystems in a range of climatic, hydrogeological and human contexts.

2. Materials & methods

2.1. Data sources

In-situ GWL monitoring data were collected from national or sub-national monitoring networks in 47 countries. The data were downloaded from the websites of the institutions in charge of groundwater monitoring where available (supplementary table 1). Otherwise, data were requested from the relevant authorities. When data are open or permission was given to share the raw datasets, they were made available on the Global Groundwater Monitoring

Network (GGMN) platform (https://ggis.un-igrac.org/view/ggmn/) (IGRAC 2026). At present, data from 42 of the 47 countries in this study are accessible through GGMN, and the database continues to expand as permissions are granted by data owners and additional datasets become available. For countries whose data are not yet available on GGMN, access may still be possible upon request from the respective data providers.

Data selection and processing

GWL trends and status are commonly assessed using long-term time series of 20 years or more (Sterckx *et al* 2025). For most countries in this study (42 of 47), trends were calculated through 2004–2023 (20 years). However, where 20 years of data were unavailable, a 10 year time series was used, allowing for the inclusion of Brazil, Bulgaria, Costa Rica, Iraq, and Kenya. Countries with datasets shorter than ten years were excluded to ensure comparability. A data gap threshold of 80% was applied (i.e. minimum of 16 years out of 20 or minimum of 8 years with data for 10 year time-series). This threshold allows for broader spatial coverage by retaining a large number of monitoring stations, while still ensuring sufficient temporal coverage for robust trend analysis, as supported by a sensitivity analysis using different thresholds (Sterckx *et al* 2025). Similar thresholds have also been applied in previous groundwater studies (e.g. Dudley and Hodgkins 2013, Samways *et al* 2024).

We did not use specific procedures for outlier removal as, in time series, data are not inherently erroneous, and their treatment often requires a detailed understanding of the hydrogeological context that is unfeasible at a global scale. However, explicitly erroneous data, such as '−9999' or 'exactly 0' values, were identified and removed. Negative values were also excluded unless explicitly linked to artesian wells, as GWLs are expressed as positive depth below ground surface.

After pre-treatment to remove erroneous data, GWL data were resampled to a monthly resolution, either as single measurements or as averages of multiple observations within a given month. Each time series was then divided into 12 sub-series corresponding to each month. The number of data in each monthly sub-series was counted and then ranked in descending order of data availability. Following this ranking, each monthly sub-series was processed sequentially. If a monthly sub-series contained no missing values (complete record across all years), all observations were retained in the final time series. If missing values were present, they were filled using adjacent months: when both the months before and after were available, the missing value was calculated as the average; when only on adjacent value was available, that value was used to fill the gap. Finally, if the number of observations in a monthly sub-series met the predefined threshold, it was selected for trend analysis; otherwise it was excluded. With this protocol, time series with at least one measurement per year were selected, provided that the measurements were taken during the same month(s) each year to avoid inconsistent time series with measurements taken during different seasons. More details about the data processing and selection methodology, including a flowchart of the algorithm and the code (GitHub repository) are provided in the *supplementary information*.

2.2. Indicators

To assess long-term GWL trends and status, we used indicators including the Mann–Kendall test, Sen's slope, and the normalised Sen's slope (change-to-range index, CRI) (table 1).

The Mann–Kendall test was used to identify the statistical significance of monotonic increasing or decreasing trends in GWL time series. To account for serial autocorrelation in the time series, the modified Mann–Kendall test (Hamed and Rao 1998) was applied. Given the complexity of aquifer systems and the high variability of GWL time series related to natural and anthropogenic impacts, a significance level $p < 0.1$ was used instead of the commonly used $p < 0.05$. This relaxation improved the sensitivity of the test and allowed us to identify potential trends that are associated with broader spatial patterns and highlight regions worthy of further investigation. This approach has been applied in previous groundwater studies (e.g. Hodgkins and Dudley 2011, Shanley *et al* 2016).

While the Mann–Kendall test identifies statistically significant trends, it does not quantify the magnitude of changes in GWL. To estimate the rate of change, Sen's Slope (Theil 1950, Sen 1968) was used, which is calculated as the median of the set of slopes between all data pairs. This approach is less sensitive to outliers compared to linear regression, thus providing a more robust estimate of the actual rate of GWL change in m yr^{-1}, offering useful insights into local water balance, potential impacts and policies (Dudley and Hodgkins 2013, Venegas-Quiñones *et al* 2020, Sterckx *et al* 2025).

At the global scale, GWL dynamics are influenced by a range of climatic (e.g. seasonal variability, recharge events, droughts) and hydrogeological factors (confined vs unconfined, fractured or sedimentary rock, karst, etc), under varying levels of human pressure (i.e. groundwater abstraction). Consequently, high Sen's slope estimates can arise in very noisy time series in individual wells simply because of short-term fluctuations instead of a real long-term trend, which can complicate cross comparisons. To address this issue, Sen's Slope was normalised to account for data variability using the CRI (Dudley and Hodgkins 2013). The CRI is calculated as the total GWL change over the study period (Sen's

Table 1. Indicators used for the assessment of GWL trends and status. Note: for Sen's slope and CRI, values for classification are absolute values: negative values indicate declining GWL, positive values rising GWL.

Indicator	Focus	Classification	Limitation
Mann–Kendall test	Statistical significance of trend	P value < 0.1: significant rising/declining trend; P value $\geqslant 0.1$: no significant trend	No measure on trend magnitude
Sen's slope	Magnitude of change (m yr^{-1})	Small change: $<$0.1 m yr^{-1} Moderate change: 0.1–0.25 m yr^{-1} Large change: $>$0.25 m yr^{-1}	May be misleading in highly variable time series
CRI (Sen's slope/IQR)	Relative strength of trend to its own variability	Weak trend: $<$0.5 Moderate trend: 0.5–1 Strong trend: $>$1	Sensitive to very low IQR; may understate strong absolute trends

slope × years of record) divided by the Interquartile Range (IQR, the middle 50% spread of data) of the observations (equation (1)),

$$CRI = \frac{Sen's\, slope \times years\, of\, record}{Interquartile\, Range\ (IQR)}. \quad (1)$$

The CRI highlights the strength of trends relative to its own variability, allowing classification into weak, moderate or strong trends.

Each indicator was used for a different purpose and has limitations that can be overcome using the multi-indicator approach. While the Mann–Kendall test answers '*how certain*' a trend is, CRI further addresses '*how strong*' a trend is accounting for its own variability, and Sen's slope focus on '*how much*' the magnitude of the actual GWL change is, offering critical insights into potential impacts, especially at local scales (table 1).

Additionally, hydrograph analysis was used to better understand groundwater dynamics in specific cases, capturing both long-term trends and short-term fluctuations such as seasonal variations. Since absolute GWLs can differ substantially between monitoring stations, even within the same aquifer, individual GWL time series within a specific analysis unit (e.g. aquifer, basin) were normalised to their long-term average to allow visualisation. Alongside individual curves, an average normalised hydrograph was also plotted to give an overall summarised view of GWL changes within the analysis unit. The hydrographs complement with more information on temporal patterns including seasonality and shorter-term fluctuations. The combination of these approaches enabled a more comprehensive assessment of GWL trends and status and supported the identification of regional patterns and hotspots. Hydrogeological context and aquifer characteristics were considered when assessing the impacts of GWL change in local and regional case-studies.

2.3. Targeted literature review

To understand the impact of GWLs status and trends, we conducted a targeted review of the scientific literature in selected hotspot areas identified from the quantitative analysis based on *in-situ* observations. For each hotspot, we systematically searched scientific databases (Web of Science, Scopus, Google Scholar) using combinations of keywords such as '*groundwater level decline/rise/trend*', '*groundwater depletion*', '*groundwater emergence and flooding*', '*groundwater impact water supply/ecosystem/agriculture/infrastructure/etc*', '*groundwater and subsidence*', '*groundwater level change and water quality*'. Case studies were selected where sufficient evidence of impacts exists. Therefore, the case studies presented here represent specific regions where both GWL monitoring data and scientific publications on impacts exist, with varying spatial scales appropriate to each case study site, as shown in table 2. Case studies were then classified based on their climatic, hydrogeological and human settings as well as the type of impact.

3. Results and discussion

3.1. Global and regional patterns of GWL trends and status

Long-term GWL trends were calculated for 42 844 monitoring wells across 47 countries (list of countries in supplementary table 2). The results were analysed using a combination of significance (Mann–Kendall) and CRI, to identify trends that are statistically significant and strong compared to their own variability, thereby highlighting 'noticeable' long-term GWL changes. Wells with a moderate to strong positive CRI and a statistically significant increasing trend according to the Mann–Kendall test are classified as having a '*rising trend*'. Wells with a moderate to strong negative CRI and a significant decreasing trend are classified as having a '*declining trend*'. Wells with non-significant trends or weak CRI are reported as having '*no trend*'. Globally, GWLs show a mixed pattern: 29% of the wells display *declining trends* and 18% *rising trends* while around half of the wells have *no trend* (53%) (figure 1(a)).

Secondly, the results were analysed based on absolute Sen's Slope to quantify the actual rate of GWL change. Overall, 73% of wells show weak GWL slopes (between −0.1 and 0.1 m yr^{-1}) across countries.

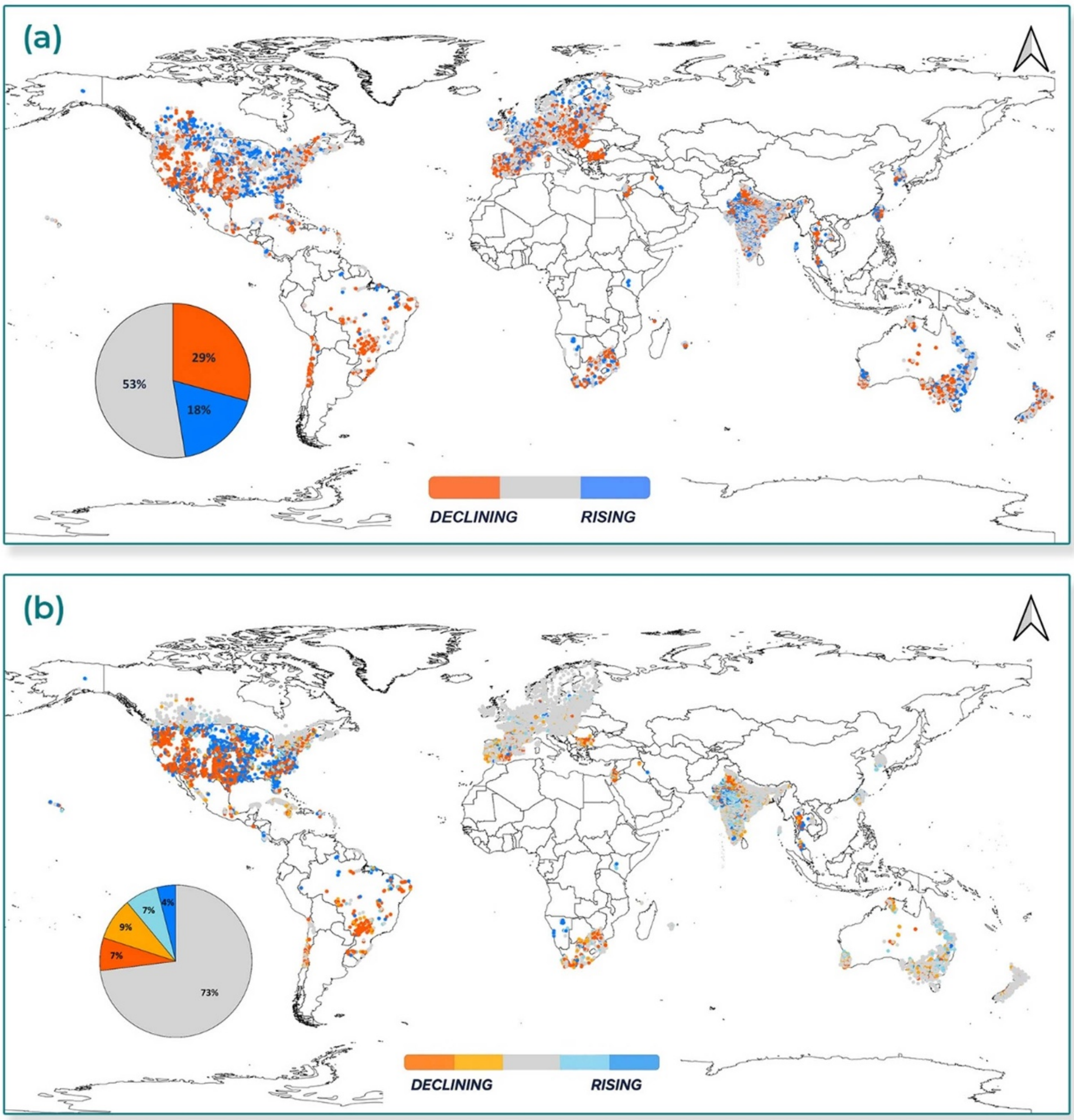

Figure 1. Global GWL trend as assessed by (a) MK and CRI, whereby wells with a moderate to strong positive CRI and a statistically significant increasing trend (according to the Mann–Kendall test) are shown in blue ('rising trend'), while wells with a moderate to strong negative CRI and a significant decreasing trend are shown in orange ('declining trend'). Wells with non-significant trends or weak slopes are shown in grey ('no trend'); (b) absolute Sen's slope. The five categories are based on −0.25; −0.1; 0.1; 0.25 m yr^{-1}.

The rest (27%) shows GWL slopes steeper than 0.1 m yr^{-1}, either declining or rising, of which 16% are declining and 11% are rising (figure 1(b)). Pronounced slopes, such as those below −0.25 m yr^{-1} (strong declining) or 0.25 m yr^{-1} (strong rising), were observed in 13% of the monitoring wells. Extreme change of ±2 m yr^{-1} was found in fewer than 1% of wells (16 countries, with change greater than ±4 m yr^{-1} in six countries) (supplementary table 2).

While GWL trends show a mixed pattern globally, we identify critical hotspots of declining and rising trends. In South America, where data are available only for Brazil and Chile, declining trends occurred in 63% of wells. These two countries also exhibit considerable absolute slopes, with the largest declines observed in northeastern Brazil and in Chile's Central and Norte Chico regions, where many wells show declines exceeding −0.5 m yr^{-1}. In Central America and the Caribbean, most declining trends are concentrated in western and central Cuba, Jamaica, and Guadeloupe, with Jamaica showing pronounced declines exceeding −1 m yr^{-1}. In Mexico, substantial declines are evident in Mexico City, Cuernavaca, south of the capital, and along the northeastern coast facing the Gulf of California, where rates may also surpass −1 m yr^{-1}. In the United States, declines are evident in the western states, across the High Plains aquifer, and along the East Coast, especially in New York, the Washington, D.C. area, and North Carolina. In these areas, declines steeper than −0.25 m yr^{-1} were recorded, and in many cases, the rate of decline is substantially greater.

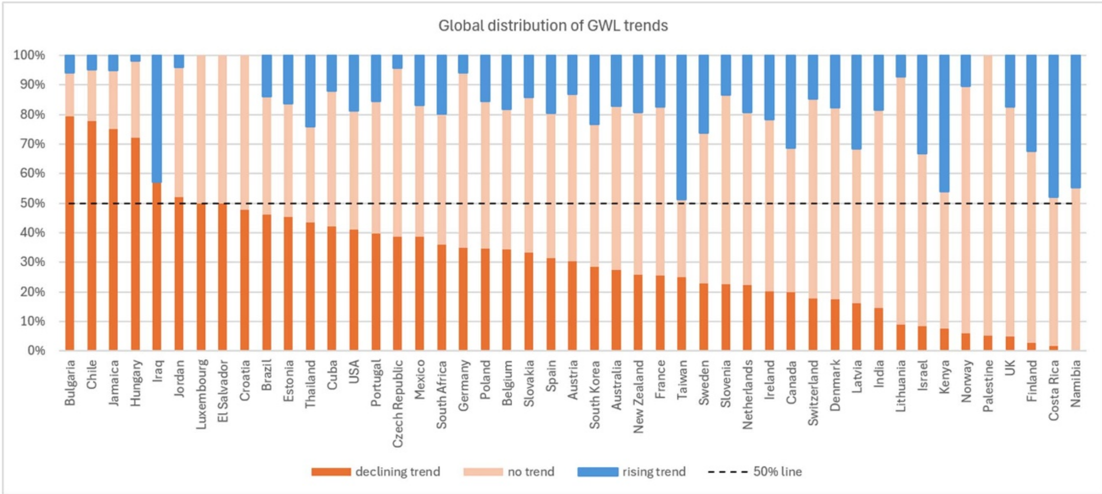

Figure 2. Global distribution of GWL trends per country from combined Mann Kendal and CRI.

Hotspots of declining trends are observed throughout Europe, including southern Portugal and Spain; the Mediterranean coast of Spain and France; Aquitaine and Central and Haut-Rhin regions of France; southeastern Netherlands and northern Belgium; as well as Germany, Hungary and Bulgaria. The magnitude of decline varies between regions. For example, absolute slopes in southern Portugal can reach around -0.5 m yr^{-1}, whereas in southeastern Netherlands most slopes do not exceed -0.1 m yr^{-1}; in southern Spain, slopes are widespread reaching -0.25 m yr^{-1}.

In South Africa, declining trends are common around Cape Town and in the northeast, with slopes exceeding -0.25 m yr^{-1}. In the Middle East, where data are available from four countries, declining trends are also observed, reaching extreme levels in some areas, such as in the A2/B7 aquifer in northwest Jordan where rates approach or even exceed -1 m yr^{-1}. In East and South Asia, pronounced declining trends are particularly marked in northern India (Punjab, Haryana, New Delhi) and in Northwest-central Thailand. In Australia and New Zealand, declining trends are also observed, but generally within -0.1 m yr^{-1}, or in some cases range between -0.1 and -0.25 m yr^{-1}, as in southern Perth and Victoria, and the east of New Zealand's South Island, south of Christchurch.

Rising trends were identified in several regions as in northern Brazil, including the coast near Belém, in Costa Rica's Guanacaste province, and in the United States, in the northern High Plains aquifer, as well as in Florida, Georgia, and North Carolina, along with declining trends. In Canada, most monitoring points, which are distributed across four provinces, also show rising trends, although the slopes are moderate and do not exceed 0.1 m yr^{-1}. Similarly, in Europe, rising trends are found around Aveiro on the northern coast of Portugal, in and north of Paris, France, and in the province of North Holland in the Netherlands. In most cases, the slopes are below <0.1 m yr^{-1}. Exceptions include areas in Spain around Valladolid, Madrid, and the vicinity of Ciudad Real, where rising slopes can exceed 0.25 m yr^{-1}.

In Africa, rising trends are recorded in several wells in northern Namibia (around Grootfontein) and in some wells within the Mukutan Conservancy in Kenya. In the latter region, however, slopes are generally <0.1 m yr^{-1}, and the overall pattern is more mixed. In the Middle East, rising trends occur along Israel's coast, with generally mild slopes not exceeding 0.1 m yr^{-1}. In South and East Asia, rising trends are widespread though mostly moderate (<0.1 m yr^{-1}). Exceptions with higher rising trends occur in northwest India, between the regions of Madhya Pradesh and Rajasthan, and in the central-southern regions of Telangana and Karnataka, where declining slopes exceed 0.25 m yr^{-1}. Similar slopes are also observed in Thailand, around Bangkok and in the southern province of Songkhla. In the Pacific region, both Australia and New Zealand report some rising trends above 0.1 m yr^{-1}, though these are dispersed throughout the countries rather than concentrated in specific areas.

Overall, wells showing no clear trend constitute most of the dataset. In more than half of the countries (28 of 47), at least half of the reporting wells are classified as having 'no trend' (figure 2 and supplementary table 2). Regionally, these wells are most common in Central America and the Caribbean (59%) and in Europe (53%). Notably, 7095 (17%) of wells are not significant according to the Mann–Kendall test but still display a positive or negative slope under the CRI. In 577 wells across 26 countries, these slopes are substantial, exceeding 0.25 m yr^{-1}. By contrast, far fewer cases are found where wells show only a weak slope under the CRI but a significant increasing or decreasing trend and a slope exceeding 0.25 m yr^{-1};

Table 2. Case studies where groundwater level change was impactful.

Case	Region/country	Aquifer (s) name	Lithology of main aquifers (van der Gun 2022)	Climate (Köppen classification, (Beck *et al* 2023)	Main anthropogenic groundwater use	Nb of wells	Sen's slope (m yr^{-1})	Wells with declining trend[a]	Wells with rising trend[a]	Reason for GWL change	Main impacts
1	Brazil	Urucuia aquifer system	Sandstone	Tropical savannah	Agriculture	40	−0.15	38%	5%	Over abstraction	
2	Norte Grande/Chile	Multiple aquifers (see SI)	. Sand and gravel (*detritic*) . Sandstone and conglomerate	Arid, desert, hot/cold	Mining domestic	59	−0.17	75%	17%	Over abstraction	
3	Chile Central and Norte Chico/Chile	Multiple aquifers (See SI)	. Sand and gravel (*detritic*) . Sandstone and conglomerate	Arid, steppe, cold; temperate, dry summer, hot/warm	Domestic agriculture	293	−0.45	78%	2%	Over abstraction exacerbated by prolonged droughts	
4	Mexico City/Mexico	Mexico City metropolitan area aquifers (MCMA)	. Sand and gravel . volcanic	Temperate, dry winter, warm summer	Domestic (megacity)	6	−0.44	83%	0%	Over abstraction	
5	Yucatan peninsula/Mexico	Multiple aquifers (see SI)	Carbonate rocks (Karst)	Tropical savannah	Domestic (incl. Tourism)	42	0.011	5%	24%	Sea level rise	
6	Central region/USA	Central high plains aquifer	Sand and gravel (*Alluvial, dune-based and valley fill deposits*)	Arid, steppe, cold	Agriculture	281	−0.43	81%	0%	Over abstraction	
7	Florida/USA	Floridan aquifer system	Carbonate rocks—Karst (limestone and dolomite)	Temperate, no dry season, hot summer	Domestic agriculture	239	0.024	8%	44%	Sea level rise and rainfall increase	
8	Southeast Sweden	Multiple small aquifers	Sand and gravel (*glacifluvial*)	Cold/temperate, no dry season, warm summer	Domestic agriculture	18	−0.011	56%	6%	Climate change and over abstraction	
9	Denmark	Multiple aquifers (see SI)	. Sand, gravel and clay . Carbonate rocks (chalk and limestone)	Temperate, no dry season, warm summer	Domestic	241	−0.02	17%	18%	Climate change	

(Continued.)

Table 2. (Continued.)

Case	Region/country	Aquifer (s) name	Lithology of main aquifers (van der Gun 2022)	Climate (Köppen classification, (Beck *et al* 2023)	Main anthropogenic groundwater use	Nb of wells	Sen's slope (m yr^{-1})	Wells with declining trend[a]	Wells with rising trend[a]	Reason for GWL change	Main impacts
10	Czech Republic	Multiple aquifers (see SI)	. Sand and gravel . Sandstone and conglomerate . Crystalline and metamorphic bedrocks	Cold, no dry season, warm summer	Domestic	368	−0.01	39%	4%	Climate	
11	Hungary	Multiple aquifers (see SI)	Sand and gravel (*Alluvial, unconfined shallow*)	Cold, no dry season, hot/warm summer temperate, no dry season, hot summer	Domestic	1345	−0.05	72%	2%	Climate change and over abstraction	
12	Bulgaria	Multiple aquifers (See SI)	Sand and gravel	Cold, no dry season, hot/warm summer Temperate, no dry season, hot summer	Domestic	140	−0.15	79%	6%	Climate change and over abstraction	
13	Aquitaine basin/France	Northern Aquitaine basin and Landes Plain	Sandstone Carbonate rocks (limestone)	Temperate, no dry season, warm summer	Domestic (Urban)	443	−0.048	31%	19%	Over abstraction	
14	Southeastern Spain	Campo de Cartagena aquifer—Mar Menor	. Sand, gravel and clay . Sandstone and conglomerate . Carbonate rocks (limestone)	Arid, desert, hot/cold Arid, steppe, cold	Agriculture	12	0.03	33%	42%	Return flow from irrigation	
15	Southern Spain	Almonte-Marismas aquifer system (Doñana)	Sand, gravel and clay	Temperate, dry/hot summer	Agriculture domestic (incl. tourism)	73	−0.08	71%	7%	Over abstraction	
16	Southern Spain	Campo de Dalias aquifer	. Sand, gravel and clay .Carbonate rocks (*dolomites and dolomitic limestones*)	Arid, steppe, hot	Agriculture	13	0.09	8%	54%	Over abstraction	

(Continued.)

Table 2. (Continued.)

17	South Africa	Pietersburg Plateau (part of Limpopo Basin)	Crystalline and metamorphic bedrocks	Arid, steppe, hot	Domestic agriculture	30	−0.15	57%	3%	Over abstraction and climate change	
18	Jordan	A7/B2 aquifer	Carbonate rocks (*Limestone and dolomitic limestone*)	Arid, steppe, hot/cold temperate, dry summer, hot summer	Agriculture	29	−0.63	55%	0%	Over abstraction	
19	Jordan	B4/B5 aquifer	Carbonate rocks (*Limestone, chalk, chert*)	Arid, desert, hot	Agriculture	4	−0.63	100%	0%	Over abstraction	
20	Southern Jordan	Southern Disi-Rum aquifer	Sandstone and conglomerate	Arid, desert, hot/cold	Domestic	3	−0.79	100%	0%	Abstraction of non-renewable groundwater	
21	Jordan Valley	Dead Sea	Sand and gravel Sandstone and conglomerate	Arid, steppe and desert, hot	Agriculture Domestic	28	−0.14	29%	11%	Over abstraction	
22	Punjab/India	Part of Indo-Gangetic alluvial plains	Sand and gravel (*Alluvial*)	Arid, steppe, hot	Agriculture	145	−0.265	63%	12%	Over abstraction	
23	West Bengal/India	West Bengal Aquifer System	Sand, gravel and clay (*alluvial*)	Temperate, dry winter, hot summer (*Darjeeling*) Tropical savannah (*Kolkata*)	Agriculture domestic	416	−0.1	35%	7%	Over abstraction	

(Continued.)

Table 2. (Continued.)

Case	Region/country	Aquifer (s) name	Lithology of main aquifers (van der Gun 2022)	Climate (Köppen classification, (Beck *et al* 2023)	Main anthropogenic groundwater use	Nb of wells	Sen's slope (m yr^{-1})	Wells with declining trend[a]	Wells with rising trend[a]	Reason for GWL change	Main impacts
24	Bangkok/Thailand	Bangkok aquifer system	Sand, gravel and clay	Tropical savannah	Domestic (mega city)	8	0.68	0%	88%	Reduction in groundwater abstraction	
25	Taiwan	Taipei basin	. Sand and gravel . Sandstone and conglomerate	Temperate, no dry season, hot summer	Domestic (mega city)	24	0.09	13%	54%	Over abstraction and further ban on abstraction	
26	Taiwan	Chianan Plain South and North aquifers	Sand, gravel, silt and clay	Temperate, dry winter, hot summer Tropical, savannah	Agriculture (aquaculture)	122	0.13	14%	70%		
27	Western Australia	Gnangara groundwater system	Sand and gravel	Temperate, dry summer, hot/warm summer	Domestic (urban, recreational) Agriculture (horticulture)	154	−0.083	64%	4%	Over abstraction, declining rainfall	
28	Victoria State, Australia	Shepparton irrigation region	Sand, gravels with some clays and silts (*Alluvial*)	Arid, steppe, cold	Agriculture dairying and horticulture)	87	−0.086	51%	4%	Irrigation (including return flow), historical vegetation clearance	
29	Canterbury Region, New Zealand	Canterbury Plains	Unconsolidated gravel (*Alluvial*)	Temperate, no dry season, warm summer	Agriculture (primarily dairying) Domestic	342	−0.05	15%	29%	Over-abstraction. Improved irrigation efficiency/reduced return flow	

[a] Combination of significance (Mann–Kendall) and CRI. The percentage of wells with no trend is not reported in this table.

Legend:

- Negative impacts on: Water supply Agriculture Ecosystem Groundwater quality degradation: Salinisation Contamination Land, assets, infrastructure and health: Land subsidence Flooding
- Positive impacts: Recovery or stabilisation.

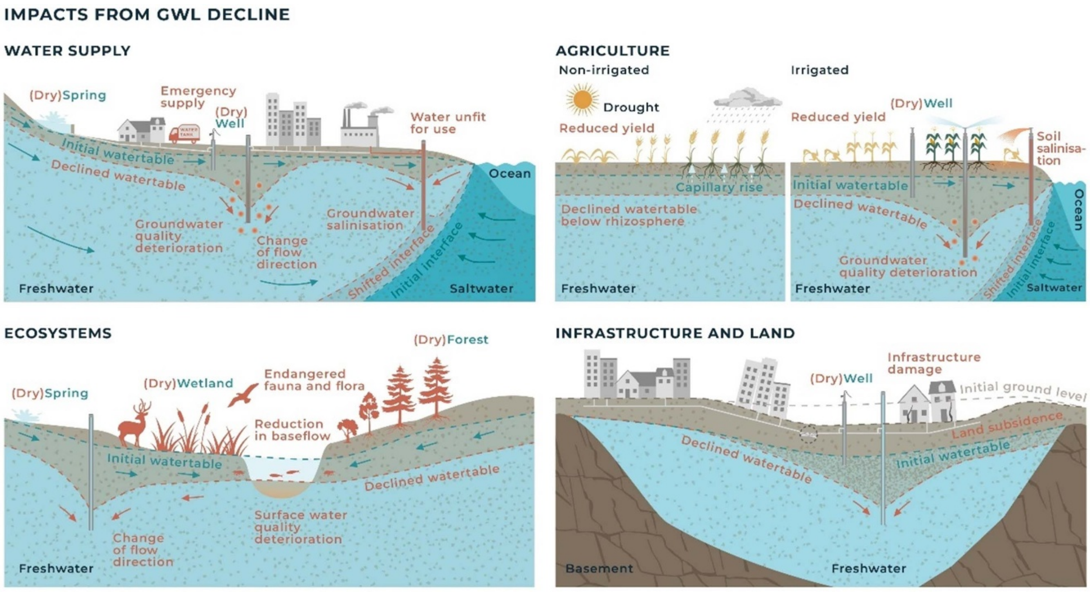

Figure 3. Impacts of groundwater level decline on (upper left) water supply, (upper right) agriculture, (lower left) ecosystems and (lower right) infrastructure and land.

this applies to 44 wells distributed across 13 countries.

3.2. GWL change impacts: case study analysis

Evidence of impacts of GWL change based on *in-situ* monitoring data has generally been under-reported in the scientific literature. Nevertheless, a total of 29 case studies with evidence-based impacts of GWL change have been identified and analysed (table 2).

The impacts of GWL change identified across our case studies allowed for classification into five types of impact (figure 3; table 2): impact on (i) domestic water supply, (ii) agricultural and food security, (iii) ecosystem and environmental services; (iv) infrastructure, land and assets (i.e. subsidence and floods); (v) positive impacts. Additionally, case studies were analysed based on their climatic, hydrogeological and human settings and groundwater demand (table 2). The types and evidence of the main impact of GWL change in the case studies are discussed in the sections below. Further details on the case studies, including regional screenshots showing monitoring stations and trend analysis results, as well as contextual information and reasons of GWL change are provided in supplementary information, *Chapter 4—Case studies.*

3.2.1. Domestic water supply

Approximately half of the world's population rely on groundwater as their primary drinking water source (Margat and van der Gun 2013). Groundwater dependence is intensifying in many of the world's large cities and smaller towns; in rural areas, particularly in developing countries, groundwater can represent the only feasible and affordable source of freshwater (United Nations 2022). Changes in GWL trends and status can compromise quantity and/or quality of groundwater (figure 3), presenting risks to the supplies of hundreds of millions of consumers (United Nations 2022).

3.2.1.1. Impacts on the quantity of domestic water supply

Declining GWLs can directly jeopardise access to groundwater to meet basic domestic water needs. In the **Central and Norte Chico regions of Chile**, groundwater depletion is substantial. Almost 80% of monitoring wells show declining GWL trends with an average drop of 9 m over the past two decades (figure 1, table 2). Groundwater is extracted intensively, for irrigation of cash crops (table grapes, avocados, citrus fruits), mining activities, and for domestic supply for an expanding urban population. In rural areas, the decline in GWLs has caused interruptions in water supply for domestic needs and small-scale agricultural activities (Panez-Pinto *et al* 2017, Duran-Llacer *et al* 2020, Muñoz *et al* 2020, Alvarez-Garreton *et al* 2023). The situation has been recently described as a 'day zero' for affected communities (Alvarez-Garreton *et al* 2023), with water being temporarily or permanently delivered by tanker trucks (Nicolas-Artero and Blanco-Wells 2025). However, the limited quantity supplied by trucks (15 l/person/day) and the questionable quality (Fragkou *et al* 2022, Nicolas-Artero and Blanco-Wells 2025) have had socio-economic impacts including reduced income, and migration to urban centers (Pizarro *et al* 2024).

In **France, the Aquitaine Basin** with the metropolis of Bordeaux and surrounding rural areas rely on 400 wells tapping deep aquifers supplying 97% of its drinking water. Since the 1950's, declining GWLs have reduced the water security of the city and endangered groundwater-dependent ecosystems (Lapuyade *et al* 2020a). Concerns regarding the security of water supply led to resource managers to undertake actions including research programmes and studies to improve groundwater systems knowledge, an extensive GWL monitoring programme, the development of robust groundwater flow models to support regulation, and management policies to control groundwater abstraction (Lapuyade *et al* 2020a, Erostate and Grissac 2025). Despite these efforts, we show that 31% of the monitoring wells display a GWL declining trend through the past 20 years, showing the scale of the difficulties to control groundwater use (figure 1, table 1). Most wells with a declining trend are located in urban areas where the ever-increasing population drives higher water demand, and influences recharge modifications. In this context, it is estimated that around 20% of the groundwater demand will need to be replaced by other water sources (Lapuyade *et al* 2020a).

Even Northern European countries, despite abundant water resources and usually shallow groundwater tables, can be vulnerable to groundwater depletion and water scarcity. In **Southeast Sweden**, about 56% of the monitoring wells show declining trends over the past two decades (figure 1, table 2). While the overall rate of decline remains modest (∼1.1 cm yr^{-1}), the real concern lies in the intensified seasonal fluctuations with pronounced extremes in low and high GWLs, particularly after 2016 (figure 5(a), table 2). The increased seasonal variability is placing rising pressure on groundwater systems especially during dry periods. In the summer of 2017, GWLs reached historic lows in many parts of Sweden, forcing municipalities to impose water consumption restrictions and provide emergency water supply as private wells ran dry (Barthel *et al* 2021, Jaramillo *et al* 2021). Small local water supply systems are impacted much faster and harder by drought than large ones, noting that in Sweden, 1.2 million people use water from private wells all year round, with a similar number relying on small-scale supplies during the summer (Eveborn *et al* 2017).

In the **Limpopo province in South Africa**, groundwater plays a critical role in the domestic water supply to a majority of rural communities, which represents about 90% of the population (Busari 2008). However, widespread declining trends in GWLs have been observed. For instance, in **Pietersburg Plateau**, one of the hydrogeological regions within the Limpopo Basin, about 57% of monitoring wells show declining trends with an average decline rate of 0.15 m yr^{-1} (figure 1, table 2). Such declines, driven by both anthropogenic and climatic variability (Ebrahim *et al* 2019), have increasingly threatened the reliability and sustainability of water supplies. In a participatory study carried out in a community within Limpopo province, Rankoana (2020) found that 85% of participants reported irregular water supply from the main borehole, with local water committee confirming that low borehole productivity often left households without sufficient water for basic household needs (Rankoana 2020).

3.2.1.2. Impacts on the quality of domestic water supply

Besides water scarcity caused directly by GWL depletion, over-abstraction and GWL decline can alter local flow patterns and geochemical conditions, leading to groundwater quality deterioration (figure 3). Changes in groundwater quality can affect domestic water supply, treatment requirements and human health.

In Mexico City, groundwater abstraction since the 1850s has supported the development of the most populous city in North America, now home to 9.2 million people (21 million in the Metropolitan area). Today, groundwater provides 70% of the city's water supply, drawn from wells with depth from 100 to 3000 m below ground level (CONAGUA 2025). However, over-abstraction has caused rapid GWL decline in 83% of the monitoring wells, with an average of ∼0.5 m yr^{-1} (figure 1, table 2). Deteriorating groundwater quality has been a recent and unexpected consequence of GWL decline. Prior to substantial GWL declines observed here, groundwater was under artesian pressure with upward flow from the semi-confined aquifer. However, decades of over-abstraction lowered groundwater heads to below the aquitard, reversing the flow direction and converting the aquifer system from confined to unconfined (Carrera-Hernández and Gaskin 2007). As a result, surface pollutants (salts and chemicals) reach the productive aquifer, leading to the contamination of the city's main water supply (Chaussard *et al* 2021).

In Jordan, groundwater provides ∼57% of the total water used, with 61% of the abstracted groundwater used for domestic water supply (MWI 2023). In the Northern part of the A7/B2 aquifer, lowered GWL (figure 1, table 2) has led to increases in molybdenum and heavy metals (Al Kuisi *et al* 2015). Notably, increasing salinity has also been observed (Salameh 2008, Kaudse *et al* 2016), with increases in total dissolved solids in some wells from around 500 ppm in the early 1970's to over 2000 and even 4000 ppm in the 1990s and 2000s. This groundwater salinisation forced the decommissioning of several wells used for municipal water supply and irrigation (Salameh 2008).

In West Bengal, India, GWLs in the Bengal Aquifer System (BAS) have declined markedly over recent decades (figure 1, table 2). We observed a declining trend of 0.083 m yr^{-1}, with declines observed in 31% of wells. Conversely, rising trends were measured in 8% of wells. The declining trends can largely be attributed to over-abstraction, particularly in agricultural areas and within Kolkata, the capital and largest city of West Bengal. BAS provides almost all drinking and irrigation water for rural communities (Hoque and Burgess 2012) and part of the water supply in Kolkata (Bardhan 2016). Over-abstraction has caused the formation of a groundwater trough in central and south-central Kolkata (Bardhan 2016, Banerjee and Sikdar 2021, Sikdar *et al* 2022), altering the natural flow regime. Instead of discharging towards the Bay of Bengal, shallow groundwater (often polluted with waste water and heavy metals such as chromium and cobalt from tanneries) is drawn into the trough and downwards into deeper drinking water wells (Bardhan 2016, Sikdar *et al* 2022). Excessive pumping has also intensified geogenic arsenic pollution in the BAS (Charlet *et al* 2007, Neidhardt *et al* 2013), impacting both urban and rural areas. Arsenic occurrence in the BAS is highly heterogeneous: polluted and unpolluted wells can be located within meters from each other (McArthur *et al* 2010); while shallow groundwater often exceeds WHO limits for arsenic (10 ug l^{-1}) by 100 times (Burgess *et al* 2010), deeper aquifers generally contain much lower concentrations below the limit. Thus, deeper aquifers (>150 m) are increasingly preferred as a water source (Burgess *et al* 2010). However, deep abstraction induces downwards hydraulic gradients, facilitating transport of arsenic-rich and organic carbon- rich water from the surface into carbon-limited deeper aquifers, leading to reductive dissolution of arsenic-rich minerals (such as Fe (hydr)oxides) and release of arsenic (Burgess *et al* 2010). Consequently, deeper aquifers may no longer be an As-free resource within decades (Burgess *et al* 2010).

Moreover, technological and management changes can further interact with GWL dynamics to create new challenges and risks for water supply. One example is the **Canterbury Plains** (∼17 000 km^2) **in Canterbury region, New Zealand**, where deep aquifers have been exploited for dairy irrigation, which in turn contributes to recharge of shallow aquifers by irrigation return flow in some areas. Region-wide, our data shows a decline of 0.05 m yr^{-1}, a trend driven primarily by intensification of irrigation since the early 2000s, with declines observed in 15% of wells. Recently, regulators promoted more efficient irrigation techniques, with many farms transitioning from flood or border-dyke irrigation to sprinkler irrigation. Although water use became more efficient, recharge of the shallow unconfined aquifer was reduced, contributing to a decline in GWL in some areas (Dench and Morgan 2021). For example, increased water efficiency led to a lowering of GWLs by up to 17 m from 2006 to 2017 in the Hinds-Rangitata Plain (Dench and Morgan 2021). Additionally, improved irrigation efficiency had unintended negative consequences for groundwater quality. Previously, recharge from border-dyke irrigation (with water sourced from deeper aquifers with relatively low nitrate concentrations) diluted nitrate (primarily derived from dairying) in shallow unconfined alluvial gravel aquifers, which have very limited capacity for denitrification. Since conversion to sprinkler irrigation, nitrate concentrations in some shallow aquifers have increased in tandem with GWL declines (Dench and Morgan 2021), posing risks to drinking water supplies, and in some cases exceeding regulatory limits of 11.3 mg l^{-1} nitrate-N (Dench and Morgan 2021).

3.2.2. Agricultural and food security

Groundwater use plays a critical role in agriculture, largely contributing to poverty alleviation and increasing food security by enabling important gains in crop productivity (Fornés *et al* 2005, United Nations 2022). For instance, groundwater has played a pivotal role in improving food security and livelihoods in India (Narayanamoorthy 2007, Fischer *et al* 2022), and in Spain it was central to agricultural modernisation in the 1970s to 1990s (Fornés *et al* 2005). However, the social and economic benefits have come at a cost of aquifer depletion, which in turn causes severe impacts on agriculture and food security (figure 3).

3.2.2.1. Impacts on irrigated agriculture

Irrigated agriculture, especially in dry regions, greatly depend on groundwater pumping (Alley and Alley 2017, Butler and Whittemore 2024). However, the gains in agricultural productivity, increase yields and profit, led to pumping groundwater beyond the natural recharge rates, threatening its long-term sustainability (Steward *et al* 2013). Understanding the adverse impacts of groundwater depletion allows to evaluate whether they outweigh the benefits associated with groundwater use (Tracy *et al* 2019).

A striking example is **the High Plains Aquifer in the United States**, which supplies around 30% of the nation's irrigated groundwater and supports about 20% of the nation's corn, wheat and cotton production (Ajaz *et al* 2020). Critical declines in GWLs have been observed in large portions of the aquifer, particularly in the Central and Southern High Plains. In the Central High Plains, 81% of the wells show GWL declining trends, averaging about 8 m of drop over the past two decades (table 2). The groundwater depletion has pronounced consequences for regional agriculture. The most obvious and direct impacts are the reduced well productivity and the increased pumping costs as the GWLs continue to decline, forcing farmers and water users to drill more wells and deeper to tap groundwater, which further aggregates the depletion situation and financial burdens (Tracy *et al* 2019). The capacity of farmers to sustain irrigated crop yields and production areas, especially in drought years, has decreased (Mieno *et al* 2024). Many producers are shifting from irrigated to rainfed agriculture due to both declining GWLs and rising summer temperatures that reduce irrigation efficiency (Steward *et al* 2013, Nozari *et al* 2024). A study based on more than 30 years of agricultural and hydrologic data in the High Plains region shows that crop yields and overall production decrease nonlinearly with aquifer depletion (Mieno *et al* 2024). Corn, one of the major commercial crops in the region, with corn-fed cattle revenues far overshadowing those from other agricultural sectors, is particularly vulnerable to water shortages. Deficit irrigation (irrigation with water below the full crop requirement to improve water use efficiency, Ray *et al* 2023) have shown to reduce average corn yields by 13%–27% compared to full irrigation (Araya *et al* 2017), and projections suggest a 60% reduction on regional corn yields by 2099 if current irrigation demand and management persist (Cotterman *et al* 2018). Reduced irrigated acreage and lower crop yields threaten the economic viability of local communities; those with limited irrigation capacities and coarse soils are likely to face the most severe impacts (Nozari *et al* 2024).

In Chile Central and Norte Chico, GWL declines in the last decades (figure 1, table 2) have affected not only domestic water supply but also agricultural production, which depends heavily on irrigation with groundwater (Donoso 2021). Pizarro *et al* (2024) demonstrated that agricultural land area expanded from 1996 to 2016 (and likely continuing until 2020–2021 according to the inventories of the Chilean Natural Resources Research Centre (CIREN) for the Coquimbo Region), alongside the continuous decline of GWLs, but suddenly shrunk after 2020–2021, returning to the 1996 agricultural land area. This drastic agricultural land reduction is directly linked to groundwater depletion and to the reduced access to water for sustaining agricultural activities. Similar situation has been observed in the Petorca Basin, where severe groundwater depletion has led to the abandonment of many agricultural areas, including high-value cash crops (Duran-Llacer *et al* 2020).

In Jordan, about one third of the groundwater abstracted is used for irrigated agriculture (MWI 2023). GWL decline occurred in more than half of the monitoring wells of the A2/B7 aquifer over the past two decades (figure 1, table 2), with drawdowns over 100 m since the 1980's (supplementary figure 20). Consequently, water is pumped from ever increasing depths (commonly around 300 m deep and sometimes lower) (Brückner *et al* 2021), impacting the costs of drilling and pumping, which accounted already 15% of the national energy costs in 2018 (NEPCO 2018 in Brückner *et al* 2021). Socio economic impacts go also beyond the increase of the costs to use groundwater as the option to deepen a well and/or to pump groundwater from higher depths is not always possible. The GWLs and saturated thickness are often already too low; or the already low agriculture incomes cannot absorb and justify such investment (deeper drilling) and operational costs (pumping). In such cases, agricultural projects have been abandoned (Salameh 2008).

The state of Punjab in Northwestern India is the country's most agriculturally advanced region and is often referred to as the India's breadbasket. Groundwater use has been pivotal in sustaining the country's food security and alleviating poverty (Kapoor and Anand 2024, Sharma *et al* 2024), but these benefits come at the cost of severe depletion of groundwater resources. Our results show that about 63% of monitoring wells display declining trends, with an average GWL drop of about 20 m over the past two decades (table 2). Groundwater depletion in Punjab has pronounced social implications, spanning from economic concerns to broader societal wellbeing. One direct consequence is the rising cost of groundwater abstraction, putting heavy financial burden on farmers. These costs include deepening existing wells, installing new ones, shifting from centrifugal to more expensive submersible pumps, and increased operation and maintenance costs (Baweja 2017, Srinivasan *et al* 2025). Smallholders are more affected, often incurring 2–3 times higher cost than those with larger landholdings, which in turn exacerbates socio-economic inequalities (Sarkar 2011). In many cases, costs become unaffordable for farmers, leading to reduced investment on irrigation infrastructure and loss of groundwater access (Srivastava *et al* 2017). The reduced access to groundwater, coupled with increased hot and dry monsoon extremes under climate change (Dangar *et al* 2021, Kapoor and Anand 2024) directly affect agricultural practices and crop yields, especially for crops like winter rice and maize which rely on groundwater as the main or only source for irrigation (Bhattarai *et al* 2021). This poses a serious threat to both regional livelihoods and national food security.

In coastal areas, over abstraction of groundwater leads to seawater intrusion into fresh groundwater (Werner 2010, Hussain *et al* 2019). When this happens, groundwater becomes unsuitable for domestic water use but also for irrigation.

The Campo de Dalias coastal aquifer in Southwestern Spain offers a compelling example. The region is characterised by intensively irrigated cash crops agriculture under greenhouses, also known as the plastic sea ('mar de Plastico'). Intensive groundwater abstraction from shallow aquifers intensified in the 1980's, causing rapid salinisation and the shift to deeper aquifers (Custodio *et al* 2016, Pulido-Bosch *et al* 2020). Consequently, GWLs declined in the deeper aquifer while rising in the upper and intermediate aquifers over the past two decades, as observed in 54% of monitoring wells showing ∼2 m rise (figure 1, table 2). Following GWL decline, an important spring, which previously discharged freshwater into the sea from the deeper carbonate, has dried up and seawater intruded into the aquifer (Custodio *et al* 2016), causing groundwater to become too saline for use in irrigation. Nevertheless, the area of greenhouse cultivation has continued to expand, sustained by desalinated seawater and recycled wastewater.

In West Bengal (India), while groundwater depletion (table 2) mainly affects urban areas through impacts on domestic water supply, rural regions face severe consequences for both supply and agricultural production (Guchhait *et al* 2023). Along the east coast of West Bengal, lowering of GWLs caused by over-abstraction, combined with factors including rising sea levels and increased frequency and severity of storm surges, have exacerbated seawater intrusion (Maity *et al* 2018, Sarkar *et al* 2021). In some areas, seawater ingress has led to an acute shortage of freshwater availability, with groundwater now unsuitable for irrigation (Sarkar *et al* 2021). Given the heavy dependency of local population on agriculture for both food production and livelihoods, freshwater salinisation could prove highly detrimental to water and food security in these coastal areas (Behera *et al* 2019).

3.2.2.2. Impacts on non-irrigated agriculture

Agriculture that does not rely on irrigation relies on either rainfall and/or on the direct root uptake or capillary rise from shallow aquifers (Kroes *et al* 2018). The impacts of GWL decline manifest in a different way than in irrigated systems, as lower GWLs reduce the water availability to crops, ultimately lowering crop yields and agricultural productivity (Van Lanen and Peters 2000, Kroes *et al* 2018).

As one of Europe's major cereal producers (Pinke *et al* 2020), **Hungary** is dominated by non-irrigated farming (98% of its arable land) (Süle *et al* 2024). Cereal production (mainly corn and wheat) in continental regions like Hungary are highly sensitive to climate variability (Ray *et al* 2015). Thus, in Hungary, shallow groundwater (median depth of about 3.6 m estimated from monitoring data) is becoming increasingly important in sustaining crop production, but is also threatened by increasing drought frequency, intensity, and duration (e.g. Nosetto *et al* 2009, Rizzo *et al* 2018). During dry periods, rainfed cereals could obtain 50%–100% of their water demand from shallow groundwater (Kahlown *et al* 2005, Yang *et al* 2007). Unlike irrigated systems like the High Plains Aquifer (USA), even relatively modest changes in GWL can affect crop yields. Indeed, the observed widespread GWL decline in Hungary (about 72% of the wells showing a declining trend, with an average decline rate of 5 cm yr^{-1}; figure 1, table 2) has been linked to reduced yield and productivity. For example, an analysis of the Hungarian Plain for 1986–2010 found that corn yields decreased by 11.6% as GWLs declined at rate of 2.24 cm yr^{-1} (Pinke *et al* 2020).

A similar situation is observed in **Bulgaria**, where non-irrigated farming also dominates with irrigation covering <2% of croplands (FAO 2025). Thus, nearly all Bulgarian agriculture depends on rainfall and/or shallow groundwater (median depth of about 4.1 m estimated from monitoring data). The observed groundwater depletion, averaging 15 cm yr^{-1} (table 2) directly affects agricultural productivity, particularly crop yields. Non-irrigated corn systems, which are common across Bulgaria, have experienced yield losses from drought and GWL decline (Popova *et al* 2014, Kazandjiev *et al* 2022). The Hungarian and Bulgarian cases reflect broader global challenges; about 80% of croplands worldwide are rainfed and non-irrigated but also produce ~60% of the world's food (FAO 2025).

3.2.3. Ecosystem and environmental services

3.2.3.1. Aquatic and wetland ecosystems

Long-term GWL decline can cause reduced groundwater discharge to surface waters and the sea, impacting dependent ecosystems (figure 3) (Uchôa *et al* 2024). One example is the **Urucuia Aquifer System in Brazil**, which serves as the main water source in the arid upper reaches of the Sao Francisco River. Over the past decade, GWL declines in the Urucuia Aquifer have averaged approximately 15 cm yr^{-1}, with some wells recording declines of ~1 m yr^{-1} (table 2). Groundwater discharge contributes up to 95% of baseflow in local rivers during the dry season (Eger *et al* 2021). As GWL drops below river levels, rivers begin losing water to aquifers, reducing flow or drying completely (Uchôa *et al* 2024), with major impacts on water availability, riparian ecosystems, and environmental flows. The Urucuia Aquifer and the São Francisco River Basin largely overlap the Cerrado biome in Brazil, one of the global 'biodiversity hotspots', where the depleted aquifer and drying surface water threaten aquatic habitats and the unique ecosystems (Myers *et al* 2000, Lahsen *et al* 2016).

A national-scale study by Uchôa *et al* (2024) showed that streamflow losses to groundwater occurs not only in the Urucuia aquifer but in many Brazilian regions, particularly in dry areas with extensive groundwater pumping. Similar concerns have been documented elsewhere: in the United States, up to two-thirds of rivers are potentially leaking into aquifers (Jasechko *et al* 2024). In Central and Norte Chico regions of Chile, intensive groundwater exploitation has caused the disconnection between aquifers and riverbeds, leading to an important reduction of base flow, sometimes causing rivers to run dry. The lower availability of surface water led to increased groundwater demand, further exacerbating GWL decline (Alvarez-Garreton *et al* 2023, Jódar *et al* 2024). In India, during summer before the monsoon season, volumes of the lower reaches of the Ganges have declined due to lowering GWLs including in

West Bengal (Mukherjee *et al* 2018). Notably, since the onset of irrigation pumping in the 1970s, baseflow declined by 56% to 2016 (Mukherjee *et al* 2018). The lower reaches of the Ganges are crucial for supplying water for drinking and irrigation, allowing transport of goods, and for freshwater ecosystems.

In Northern Chile, large volumes of predominantly non-renewable groundwater have naturally accumulated in endoreic basins, resulting in very shallow, often emerging groundwater in the lower parts of the basins subject to very high evaporation rates and thus forming Salars and salt lakes. This easily accessible groundwater fosters the development of unique groundwater-dependent ecosystems (oasis, Salars, Wetlands) upon which local communities depend. The development of large mining projects since the 1990's, associated with a growing population in urban areas, in this hyper-arid area, has been possible owing to groundwater abstraction (Lictevout and Faysse 2018, Donoso *et al* 2020, Lictevout 2022). Consequently, GWLs have declined over recent decades as shown in 75% of the monitoring wells (figure 1, table 2). While the GWL drop (17 cm yr^{-1}) may appear small with regards to the large volumes accumulated, in this context, a small GWL decline can severely impact ecosystems. As a result, several springs and wetlands have dried up, and grazing areas for cattle (llama, guanaco) have been lost, thus jeopardising the possibility of the native population to remain in their environment (Lictevout and Faysse 2018, Lictevout 2022).

The Marismas of Doñana is a national and international protected natural area located in Southern Spain. The area has a very high ecological value and provides habitat for migratory birds, such as wintering waterfowl, and for fish, amphibians and invertebrates (Scheffer *et al* 2015, Fernández-Delgado 2017, Green *et al* 2018). It is composed of marshlands and sandy areas, with over 3000 ponds and lagoons, many of which are groundwater dependent (Green *et al* 2018, Olías *et al* 2025). Additionally, groundwater sustains the phreatophyte vegetation and a riverine forest, whilst groundwater seepage and discharge through springs are critical for maintaining humidity and sustaining wetland ecosystems, particularly in summer (Manzano Arellano 1999, Custodio *et al* 2009, Green *et al* 2024, Olías *et al* 2025). However, declines in GWLs are increasingly undermining these ecosystems. We observed a GWL decline in 71% of monitoring wells (figure 1, table 2) with accelerating rates in the past 10 and 5 years respectively (figure 5(b)), largely due to groundwater abstraction for irrigated agriculture and tourism (Bea Martínez *et al* 2021). More than half of the ponds have dried up in the last 40 years, with much higher rates near to pumping wells (de Felipe *et al* 2023). The dieback of some trees species (Cork Oak) has been related to fast decline in GWLs, with the drying up of permanent ponds impending their reproduction (Green *et al* 2024). Groundwater discharge to springs and streams have decreased or stopped, leading to surface flows decreasing by nearly two thirds (Suso and Llamas 1993, Munoz-Reinoso 2001, Custodio *et al* 2009, Muñoz-Reinoso *et al* 2020, Green *et al* 2024). Even small GWL declines (average 8 cm yr^{-1}, table 2) can impact vegetation, leading to the replacement of endemic species by more drought resilient xerophytic plant communities (Muñoz-Reinoso *et al* 2020, Díaz-Delgado *et al* 2024, Green *et al* 2024). Other impacts of GWL decline in the Marismas of Doñana include eutrophication, cyanobacteria blooms, and growth of invasive aquatic plants and weeds (Scheffer *et al* 2015).

The Mar Menor, located in Southeastern Spain, is the largest saline coastal Mediterranean lagoon in Europe and a site of high ecological, cultural and economic value (Lillebø *et al* 2015). The lagoon is the outlet of the Campo de Cartagena aquifer system (Baudron *et al* 2014) where GWLs in the shallow unconfined aquifer have been rising (observed in 42% of the monitoring wells; table 2), mainly driven by irrigation return flow and by reduced pumping due to deteriorating groundwater quality (Baudron *et al* 2014). The rising shallow GWLs have increased groundwater discharge into the Mar Menor lagoon through submarine springs (Baudron *et al* 2015), carrying nutrients and other pollutants from agricultural, mining activities and desalinisation brines. Extremely high nitrate concentrations (more than 10 times the EU concentration limit of 50 mg l^{-1}[1]) have resulted in eutrophication of the lagoon, causing ecosystem disruptions such as summer jellyfish blooms (Baudron *et al* 2015, Jimenez-Martinez *et al* 2016, Pérez-Martín 2023). The Mar Menor environmental disaster has also generated substantial socio-economic impacts. The housing market has been affected with a 45% lower return on investment in 2021 than in 2014, corresponding to a loss of more than 4000 million euros (Perez-Quiros *et al* 2022, Lamas Rodríguez *et al* 2023). This represents 'around ten times the gains of changing from dry-farming to irrigated crops' (Perez-Quiros *et al* 2022). Studies have also highlighted broader regional economic impacts of the lagoon eutrophication, including impacts on tourism, on logging, finance, real estate and construction (Maté-Sánchez-Val and Aparicio-Serrano 2023), resulting in an approximate 18% decrease in per capita income (Aparicio *et al* 2024).

In Jordan, discharge from springs has continuously declined since the 1970's with more springs drying up each year. A spring inventory conducted in 2017 (MWI and BGR 2017) reported a total of 361 perennial springs, of which 23 were intermittent and 195 dry. Notably, in some monitoring wells of the

[1] European Union Drinking Water Directive.

A2/B7 aquifer, GWL has declined by >100 m since the 1980's (supplementary figure 20). In the 1980's and 1990's, users of spring water have filed complaints to the Jordanian courts against well owners because groundwater abstraction reduced or caused cessation of springs' discharge (Salameh 2008). An emblematic case is the Azraq wetland and springs, once important spot for migratory birds and desert rich ecosystem (Ramsar 1998) and discharge of the B4/B5 aquifer. Groundwater abstraction, commenced in 1981/82, led to the desiccation of the wetland and springs in the 1990's (Molle *et al* 2017). In our dataset, GWLs have declined by >12 m in the past 20 years in the four monitoring wells positioned near the wetland (figure 1, table 2).

The multi-layer Gnangara groundwater system located in southwestern Australia has also experienced critical GWL declines (table 2). The water table of the shallow unconfined 'superficial' aquifer (known as Gnangara Mound) supports ecosystems including throughflow wetlands and lakes (Bekesi *et al* 2009, McFarlane *et al* 2012). Our results show GWL decline of 0.083 m yr^{-1}, with declines observed in 64% of wells. These declines have caused drying of wetlands and impacted the health of plant communities (Groom *et al* 2000), as well as terrestrial fauna (e.g. amphibians and birds) reliant on healthy groundwater-dependent wetlands and forests for habitat (Davis and Froend 1999, Kavazos *et al* 2020). The observed GWL decline has also led to groundwater quality degradation in the shallow Gnangara Mound aquifer, which is vulnerable to acidification because it is poorly buffered (Clohessy *et al* 2013). Additionally, acid sulphate soils cover more than half of the Gnangara management area (Ward *et al* 2010). When the GWL lowers, exposure to air can release sulphuric acid from fine grained pyrite contained in the soil profile, causing soil acidification and leaching of iron, aluminium, cadmium, and arsenic (Sommer and Horwitz 2009, Ward *et al* 2010, Degens and Thornton 2018). In areas with high drawdown, pH values can fall below 5 at the water table (Appleyard and Cook 2009).

3.2.3.2. Forest ecosystems

In Sweden, the observed decline in GWLs and increased seasonal variability especially summer droughts (table 2) have important impacts on ecosystems, especially forests (Knutzen *et al* 2025). Groundwater supports vegetation either through capillary rise of water from the shallow unconfined groundwater table or direct root uptake from groundwater (Knutzen *et al* 2025). During droughts, reduced GWLs combined with high temperatures cause water stress in trees, leading to crown defoliation, early leaf shedding, and branch death; these stressors reduce tree growth, vitality, and, in severe cases result in mortality (Schuldt *et al* 2016). Notably, boreal forest such as those in Scandinavia, play a critical role in the global climate system by acting as carbon sinks (Masson-Delmotte *et al* 2019). Recent summer droughts in Sweden have triggered widespread water shortages for trees, leading to low tree growth and hotspots of mortality (Aldea *et al* 2024). Species such as spruce, pine and birch, are found to be highly sensitive to summer water deficits with lower GWLs. Since summer is the primary growth period, water shortages during this time are particularly damaging, while winter conditions play only a secondary role (Lévesque *et al* 2014, Zang *et al* 2014, Matisons *et al* 2022). It is also important to note that groundwater depletion tends to have long-lasting effects which can persist well beyond the immediate weather or seasonal cycle, as groundwater recovery after drought is a relatively slow process. This 'drought legacy' could increase the likelihood of recurrent droughts at interannual timescales, resulting in long-term changes in shallow moisture availability and ecosystem resilience (Knutzen *et al* 2025).

In the Czech Republic, more than one third of the monitoring wells show declining trends in GWLs, with an overall average modest decline of 0.01 m yr^{-1} (table 2). A major consequence is the death of vegetation, particularly spruce and pine forests (Dębiec 2021). While the declining GWLs has directly caused water shortage for trees, leading to growth problems and mortality, the impacts extend far beyond. Trees under water stress reduce photosynthesis and limit the production of defensive compounds, weakening their resistance to infestations such as bark beetles (Netherer *et al* 2019, Das *et al* 2025). This has contributed to the spread of bark beetle infestation on a scale which is unprecedented in the history of the Czech Republic. Between 2017 and 2022, the spruce growing stock in the Czech Republic declined by approximately 20%, with certain regions experiencing losses of 40%–60% (Washaya *et al* 2024). This widespread bark beetle infestation is not only a consequence of the drought but also contributes to its aggravation. The need to cut down infested forest has accelerated soil erosion and decreased soil water retention capability, leading to decreased rainwater infiltration and inhibition of the growth of young trees. Moreover, forests play a crucial role in regulating the local microclimate by cooling down the surrounding area. Therefore, reductions in forest cover contributes to an increase in temperature in the region (Dębiec 2021), which in turn aggravates the drought situation.

3.2.4. Infrastructure, land and assets

Changes in GWLs influence not only water availability, but also the stability of land and infrastructure, mainly through land subsidence associated with groundwater depletion and groundwater emergence and flooding with rising GWLs (figure 3). Both processes pose serious risks to infrastructure, land

and assets, often with long-lasting or irreversible consequences.

3.2.4.1. Land subsidence

Mexico City is one of the fastest sinking cities in the world, due to severe land subsidence by tens of cm per year (Carrera-Hernández and Gaskin 2007, Chaussard *et al* 2021, Khorrami *et al* 2023, Zapata-Norberto *et al* 2025). Groundwater abstraction and the induced GWL decline (table 2) have been recognised as one of the main factors contributing to land subsidence, causing a series of cascading effects from infrastructure damage, water access problems and increased poverty levels. Chaussard *et al* (2021) demonstrated a strong correlation between the rate of subsidence, associated to infrastructure fissuring and fracturing, and the lowest socioeconomic portions of the population, leading to not only substandard housing due to damaged infrastructure but also substandard drinking water access due to constant damage to the water supply network. Subsidence rates are expected to persist and are thought to be irreversible, even if GWLs rebound, due to the elastic properties of the aquitard clay formation underlying the city (Chaussard *et al* 2021).

In Kolkata, West Bengal, India, land subsidence has been a persistent issue for several decades (Biswas and Saha 1985, Sikdar *et al* 1996, Chatterjee *et al* 2006, Sahu and Sikdar 2011). In Kolkata, land subsidence is primarily driven by over abstraction of groundwater which caused a decline in piezometric pressure. Under lower piezometric pressure, tensional pressures can develop in the confining material, causing compaction and subsidence (Chatterjee *et al* 2006), leading to degrative impacts on roads, buildings, pipes, and drainage systems. Aside from the impact of GWL decline, the extent of subsidence varies across the city due to the effects of localised intensive pumping and the composition of underlying sedimentary and aquifer material (Chatterjee *et al* 2006).

The Dead Sea provides another striking example of how declining GWLs can trigger severe impacts on land and infrastructure. Under this arid and desertic climate, surface and groundwater resources of the Jordan River Basin have been intensively used since the 1970's to sustain socioeconomic development based on irrigated agriculture. It has resulted in continuously declining inflow volumes into the Dead Sea, which has shrunk through the last four decades. As the lake retreats and associated GWL declines, fresh groundwater replaces saline groundwater, dissolving the geological salt layers, causing widespread sinkholes (Yechieli *et al* 2006, 2016, Ezersky *et al* 2011). More than 6000 sinkholes have been reported, ranging from 1 to 10 m deep, 25–30 m wide and the rate of sinkhole development is increasing each year (Yechieli *et al* 2016, Abelson *et al* 2017). Although no monitoring wells within our dataset are located on the shore of the Dead Sea, wells located in the Jordan Valley upward the Dead Sea show a continuous declining trend over de past 20 years, highlighting the extent of the problem (figure 1, table 2). The environmental, socioeconomic and infrastructure problems in the Dead Sea Basin due to the sinkholes are important but still poorly described. Such examples include: farmers losing their land and leaving the area (Ghor Haditha in Jordan), the closure of large coastal areas along shores of the Dead Sea, damage to buildings, and disruption of industry and tourism (Popperl 2018, Abou Karaki *et al* 2019).

3.2.4.2. Groundwater emergence and flooding

Although most literature focuses on the impacts of declining GWLs, rising GWLs can also be problematic. Rising GWLs are not uncommon in most of the regions as we can observe in our dataset (figure 1). Either because of deindustrialisation or land transformation (Allocca *et al* 2016), leakages and return flow from irrigation, or because of sea level rise (SLR) (Bosserelle *et al* 2022), GWLs rise in shallow aquifers can cause emergence and flooding, potentially resulting in severe negative impacts on water supply, agriculture, ecosystems, groundwater quality, as well as land and infrastructure (figure 4).

In Denmark, rising GWL trends are observed particularly in western regions, with rising rate up to about 0.4 m yr^{-1} over the past two decades. The city of Odense is an example of this dynamic: from the 1950s to 1980s, intensive pumping for drinking water and industry lowered GWLs by over 10 m, creating artificially 'dry' urban conditions. In the 1980s and 1990s, pumping was regulated and reduced to address over-abstraction and pollution risks, leading to a gradual recovery of GWLs to near-surface levels (Laursen and Linderberg 2017, Jorgensen *et al* 2024). Although these groundwater management actions were successful, rising GWLs in shallow aquifers is increasingly leading to groundwater flooding in Denmark. In urban areas, rising GWLs have caused dampening of basements and reduced stability of critical infrastructure such as road trenches and railways; as well as infiltration of groundwater into sewer systems, leading to increased wastewater discharge volumes and higher treatment costs (Laursen and Linderberg 2017, Rasmussen *et al* 2023, Jorgensen *et al* 2024). In agricultural areas, rising GWLs close to the surface have detrimentally affected crop growth and field activities such as ploughing and sowing (Møller *et al* 2018). Unfortunately, the Danish experience highlights a broader lack of awareness regarding risks of groundwater flooding, particularly amongst the municipalities, infrastructure managers and insurance companies, which are insufficiently prepared for hazards posed by rising shallow groundwater tables (Rasmussen *et al* 2023).

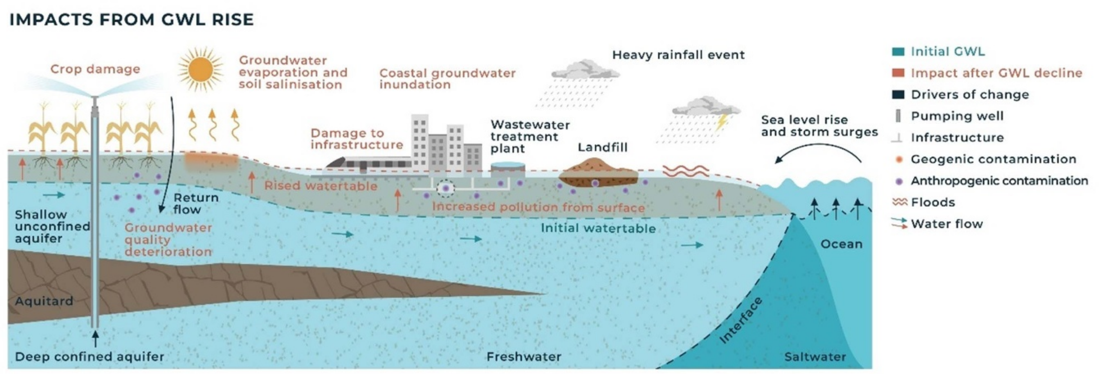

Figure 4. Impacts of groundwater level rise.

In the **Campo de Cartagena aquifer system in Southeastern Spain**, groundwater was intensively used until severe drawdowns threatened the viability of irrigated agriculture (Baudron *et al* 2015). To mitigate this risk, external surface water is transported and used to supplement groundwater. While GWLs in the deep confined aquifers display declining trends, especially during droughts, the GWLs in the unconfined shallow aquifer are rising (table 2), primarily due to irrigation return flows and the cessation of groundwater pumping in the shallow aquifer owing to its poor water quality (Baudron *et al* 2014, Custodio *et al* 2016). Groundwater flooding has affected agricultural land and led to basement flooding, which must be constantly drained (Baudron *et al* 2014).

GWL emergence and flooding due to SLR is a growing concern in coastal areas worldwide (Bosserelle *et al* 2022). Although scientific literature focuses on simulation models to predict the impact of SLR, we present here two case studies based on our dataset. Florida and Southwestern US coastal area is another hotspot of GWL rising trends (figure 1). In the Floridan Aquifer System, more than half of the monitoring wells have rising GWLs trends over the past 20 years (table 2). This rising trend is caused by local SLR rates (Sukop *et al* 2018). In this low-lying coastal region, shallow GWLs are intentionally kept high (i.e. to maintain a seaward hydraulic gradient) to limit saltwater intrusion—through the control of the water level in canals. However, with a reduced and minimal unsaturated zone, GWLs can rise above the ground surface during frequent intense rainfall events (Xiao *et al* 2016, Czajkowski *et al* 2018) leading to flooding. Consequent loss of infrastructure and daily life disruption have caused negative economic impacts, with South Florida being one of the states with the highest number of flooding insurance claims in the United States (Czajkowski *et al* 2018, Davtalab *et al* 2020). Another low-lying coastal area, with highly transmissive karstic aquifer is the **Yucatan Peninsula in Mexico**. Rising GWLs have also been observed in the past 20 years (figure 1, table 2). Approximately 25% of the monitoring wells have a rising trend, while only 5% show a declining trend. Seawater intrusion has occurred along the coast, with shallow GWLs near and sometimes below sea level (Narvaez-Montoya *et al* 2025).

Soil salinisation from shallow saline groundwater is a substantial problem globally, with many examples in semi-arid areas of Australia (Akter *et al* 2021), as in the **Shepparton irrigation Region (SIR)**. The analysis of our dataset shows that GWLs declined in most wells (51%) at an average rate of 0.086 m per/year (table 2), whilst rising trends were only observed in 4% of wells. Despite observed GWL declines, the water table remains very shallow (i.e. <2 m bgl in many wells) as a consequence of vegetation clearance in the late 19th century, to the late 20th century (Heuperman 1999, Gill and Terry 2016), causing a persistent salinity problem (Goulburn Broken Catchment Management Authority 2024). Salinisation led to substantial economic losses and environmental damage in the SIR in the 1970s and 1980s and affected biodiversity, as salt sensitive flora and fauna species are lost or migrate (Goulburn Broken Catchment Management Authority 2024). Additionally, concrete and metal infrastructure can also face damage due to increased corrosion of concrete and metals. Since the late 20th century, several management plans have focused on improving surface and sub-surface drainage in SIR (Heuperman 1999). On local-scales, groundwater pumping is suggested by resource managers as an effective way to quickly lower the water table and minimise impacts (Goulburn Broken Catchment Management Authority 2025).

3.2.5. Positive impacts—GWLs recovery

Bangkok is particularly sensitive to subsidence because it is positioned on an alluvial plain of highly compressible fluvial and marine clays of the Chao Phraya River delta (Lorphensri *et al* 2011). In Bangkok, our results show a rising trend in 88% of monitoring wells, with an average increase of 68 cm per year over the past two decades (figures 1 and 5(c),

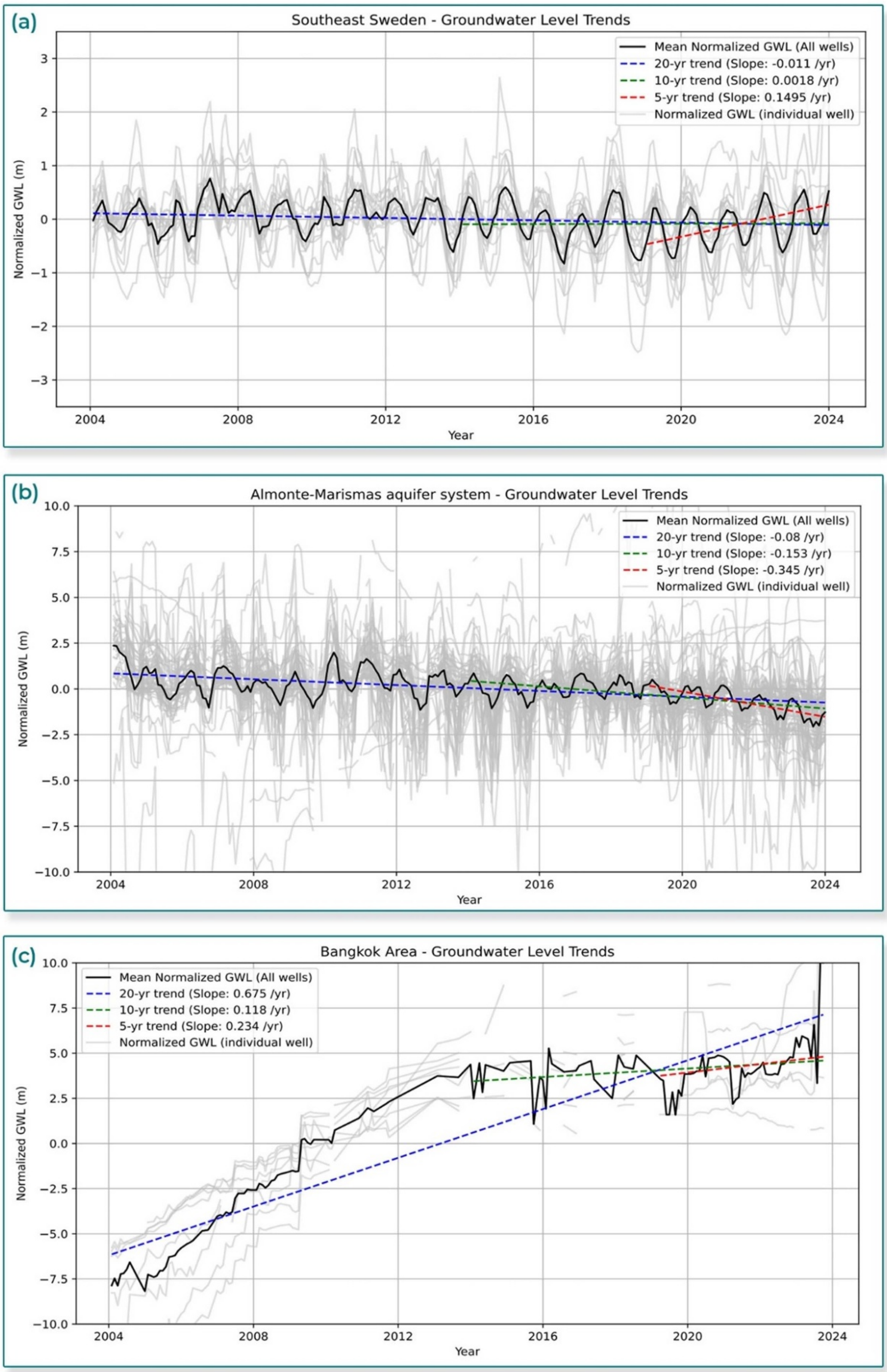

Figure 5. Normalised GWLs hydrographs of monitoring wells in (a) Southern Sweden, (b) Almonte-Marismas (Doñana) aquifer (Spain) and (c) Bangkok area, Thailand.

table 2). This recovery follows a period of groundwater depletion due to over exploitation through the mid-late 20th century (Lorphensri *et al* 2016), whereby GWLs declined by up to 70 m (Nutalaya and Rau 1981, Babel *et al* 2006, Taniguchi *et al* 2009, Ghimire *et al* 2021), causing widespread land subsidence, reduced soil water holding capacity, increased flooding, saline intrusion (Phien-wej *et al* 2006) and further structural failure of buildings and foundations (Ahmed *et al* 2024).

To address overexploitation of groundwater and land subsidence, authorities implemented several highly effective regulatory (e.g. abandonment of supply wells in the city centre) (Lorphensri *et al* 2011) and economic (e.g. tariffs for groundwater use) measures, and decreased groundwater reliance by increasingly using surface water for drinking and industrial activities (Lorphensri *et al* 2016). Owing to GWL recovery, land subsidence rates have declined markedly and are beginning to stabilise (Lorphensri *et al* 2016). Thus, Bangkok is an exemplar of the benefits of consistent application of mitigation measures in addressing GWL decline and associated subsidence (Buapeng and Foster 2008). Nevertheless, GWL recovery has also caused some problems, for example, the land surface in Bangkok is uplifting (Ahmed *et al* 2024), with potential implications for building stability (Ishitsuka *et al* 2014). Further, raised water tables have caused soil deformation and changes in pore water pressure, leading to a reduced stability of existing deep piles installed prior to GWL recovery (Ahmed *et al* 2024, Saowiang and Giao 2021).

Similar situation is observed and described in **Taiwan**. 20 year rising GWLs are observed along the coast. In the **Taipei basin aquifer**, 54% of the monitoring wells have a GWL rising trend, and only 13% are declining (figure 1, table 2). As in Bangkok, intensive groundwater pumping for agriculture and water supply led to groundwater depletion and land subsidence (Chen *et al* 2007, Hwang and Moh 2020). In the early 70's, a government ban on groundwater abstraction was imposed, to restore groundwater storage and control subsidence (Chen *et al* 2007) leading to GWL rise and recovery since 1975 up to 2003 (Chen *et al* 2007, Liu *et al* 2010). We demonstrate that GWLs have continued to rise in the past two decades (table 2). However, high GWLs are now causing seepage problems with infrastructure basements as well as an increased liquefaction risk with strong earthquakes (Liu *et al* 2010). In the Chianan Plain aquifer, Southwest of Taiwan, 70% have a GWL rising trends and 14%, declining.

Groundwater replenishment has also been reported in some parts of **India** (Bhanja *et al* 2017, 2020). Indeed, our results show that, out of the Northern (Punjab) and Eastern (West Bengal) regions, GWLs trends show a mixed pattern of mainly rising and no trends (figure 1). Most of the river basins, except Ganges and Brahmaputra basins, have experienced increased precipitation in the past decades (Bhanja *et al* 2020). Additionally, groundwater management policies, in particular a decrease in governmental subsidies for irrigation electricity, and the increase of surface water use for irrigation promoted by international programmes, have led to groundwater storage recovery in Gujarat (Western India) and in Andhra Pradesh (Southern India) (Bhanja *et al* 2017).

4. Limitations and outlook

4.1. Temporal coverage

Our analysis covers 20 years. In many cases, groundwater abstraction has been ongoing for several decades prior to our analysis, and the trends of the last 20 years may not be representative of longer-term (i.e. multi-decadal) changes in GWL. Decreasing GWLs trends in the last 20 years may be coherent with longer term GWLs decreasing, especially if decreasing, as in the A2/B7 aquifer in Jordan (figure 6(a)). The magnitude of the change may change though, as in in Chile Central and Norte Chico (figure 6(b)). However, the 20 year period analysis may differ from the longer period analysis, especially when either rising or no consistent trend is detected, as in some wells of the Paris basin (figure 6(c)) and in Austria (figure 6(d)). Nevertheless, even when the 20 year period trend differs from the longer period trend, we consider the analysis of impacts still relevant for the period considered (20 years).

4.2. Spatial coverage

Although a growing number of countries are sharing groundwater monitoring data, spatial coverage is still heterogenous, with areas having a high density of monitoring stations (Europe, North America, South Africa, India, Australia and New Zealand) and others crucially lacking data (North Africa, Sub-Saharan Africa, Central and East Asia and some parts of South America). The lack of spatial coverage in our analysis does not necessarily mean that GWL monitoring data does not exist, nor that the data is not shared. In many cases, monitoring stations were excluded because of data quality or time series length. This is the case for Rwanda, The Gambia, Nigeria, Lesotho, Malaysia, Sierra Leone, Somalia, Uganda, Nepal and Madagascar. Moreover, some areas have very few wells and therefore may not be representative of the GWL status and trend of an entire aquifer or region. Many aquifers remain unmonitored or poorly monitored, or, in some cases, data may not be fully accessible. Nevertheless, as groundwater monitoring wells are usually located within exploited aquifers, we consider that the wells included here are likely to reflect the quantitative status of groundwater resources across many regions worldwide.

4.3. Data quality

Data processing does not include the removal of outliers. Removing outliers require a thorough understanding of the local context to identify real outliers from extremes. This is not possible in a study of global scale. Moreover, the analysis of a high number of data points tends to lower the influence of outliers, as it can be observed in the combined hydrographs (figure 5). Overall, the presence of occasional outliers has only a limited effect on the 20 year Sen's slope and

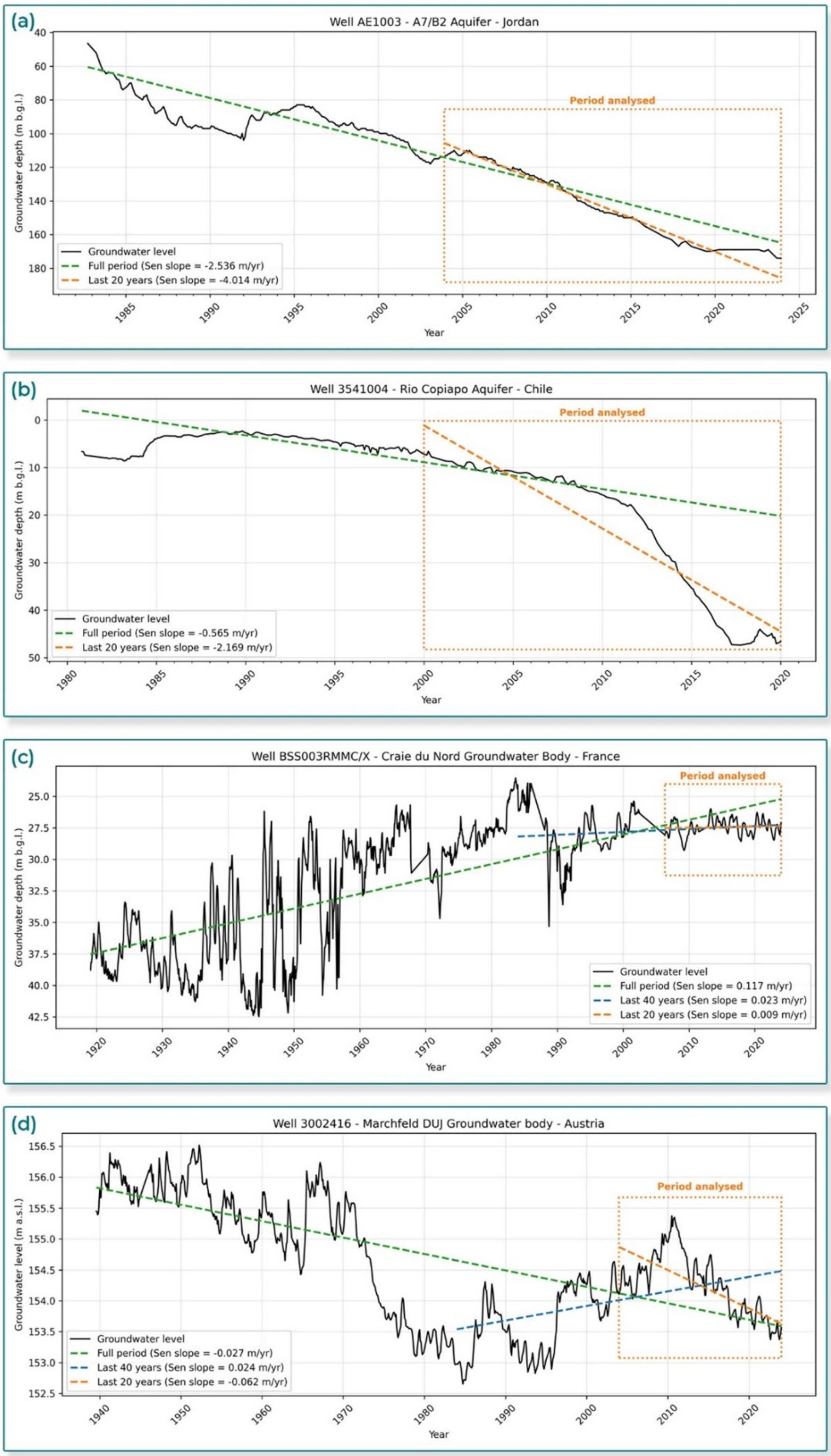

Figure 6. Examples of our 20 year GWLs trends result presented within a context of longer-monitoring. (a) Well in A7/B2 aquifer, Jordan; (b) Well Rio Copiapó aquifer, Chile Central and Norte Chico. (c) Well in Craie du Nord groundwater body, France. (d) Well in Marchfeld groundwater body, Austria.

the Modified Mann–Kendall significance and therefore does not alter the main long-term trend result (Sterckx *et al* 2025).

Finally, the absence, in many cases, of information on the monitoring points and the hydrogeological context (well depth, stratigraphy, aquifer monitored, aquifer delineation) limits the scope for interpretation. However, it does not preclude the identification of larger scale patterns and dynamics in GWL changes.

The status and trends of GWLs should be ideally analysed and interpreted in the context of an aquifer or basin. However, aquifer delineation and characteristics are unavailable for part of the wells in our dataset. Nevertheless, we consider that the identified regional patterns and observed trends in any individual region are likely to show important patterns and GWL dynamic changes associated with impacts, which is the focus of our work.

4.4. Methodological biases

Wells classified as having '*no trend*' does not necessarily exhibit 'stable' GWL behaviour, which would reflect either the absence of anthropogenic impacts (natural state) or sustainable groundwater use and management. Sen's slope assumes that GWLs change in one steady direction. Because of this, it cannot capture more complex patterns. For example, a well may have an historical high GWL, which then drop and remain stable for several years, and later rise again. In this case, the increases and decreases offset each other, and Sen's slope may indicate almost 'no trend' even though the GWL changed significantly. The Modified MK test reduces the effects of autocorrelation, but it still cannot detect sudden shifts or trend reversals and requires enough years of data to produce reliable results. The CRI (slope/IQR) can also be unstable in wells with very low variability, because a very small IQR makes the index extremely sensitive to small changes or noise, which may lead to misleading values.

4.5. Outlook

While expanding the analysis temporally (i.e. beyond 20 years of analysis) would be ideal, as many countries began monitoring much earlier, it would mean excluding many countries, especially countries with developing economies. Nevertheless, data acquisition and sharing is expanding and will allow for improved global-scale analysis.

Recent advances in innovative monitoring and analytical tools offer important opportunities to address the limitations identified in this study. In particular, the increasing availability of real-time monitoring technologies, including low-cost sensors and micro-electromechanical systems (MEMS), which are already implemented in some of the national monitoring networks used in this study, enables continuous, high frequency and reliable groundwater monitoring (Barzegar *et al* 2023). This could support the development of early warning systems for critical conditions (Zhou *et al* 2018, Veness *et al* 2022), such as the 'day zero' scenarios discussed in the Chilean case study.

Satellite-based observations such as the GRACE project provides valuable large-scale information on groundwater changes, offering a complementary perspective that can help address spatial data gaps in regions with limited *in-situ* monitoring, including parts of Africa, Asia, and South America (e.g. Renna Camacho *et al* 2023, Nenweli *et al* 2024, Kashani and Safavi 2025). In parallel, the machine learning (ML) approaches can be applied and combined with *in-situ* and remote sensing data, to enhance the spatial and temporal resolution of groundwater assessments, as well as to support gap-filling and predictive analyses of future changes (Barzegar *et al* 2023, Ali *et al* 2024, Kashani and Safavi 2025).

Nevertheless, *in-situ* monitoring remains indispensable, as it offers critical insights from local to global scales into groundwater dynamics and the drivers of observed changes, which cannot be fully captured by remote sensing or modelling alone. This again highlights the critical need for implementing, improving and scaling *in-situ* groundwater monitoring programmes and data sharing in many regions and countries. This calls for a broader participation of all key stakeholders, i.e. countries, donors, international organisations, researchers, etc. to improve global data coverage, allowing for a continuous refinement on groundwater status assessments over time and supporting evidence-based sustainable groundwater management.

5. Conclusions

We analysed 20 year time series of GWLs in 47 countries distributed across a wide range of climatic, geographic, hydrogeological and socioeconomic contexts worldwide. Based on *in-situ* data, we show that almost one third of the GWLs trends are declining—thus reflecting unsustainable groundwater use. Conversely, 18% are rising which can, in some cases, be a sign of recovery, but, in others, reflect the consequences of human impacts on the environment. Thus, our analysis demonstrates that natural groundwater dynamic has been disrupted in at least half of the analysed monitoring stations.

We also highlight that both rising and falling GWLs have substantial impacts on ecosystems, water security, infrastructure, agricultural activity, and socioeconomic wellbeing, as summarized in figure 7. However, the type and scale of these impacts is determined by a confluence of factors including groundwater dependence and demand, hydrogeological setting, climate, and land-use. Long-term GWL decline typically affects negatively access to water, by causing water sources to run dry, or by increasing the cost of drilling and pumping from a greater depth. Such costs and equipment can be prohibitive, hindering access for groundwater users. Additionally, it has been demonstrated that pumping groundwater from increasing depths lead, in certain cases, to the deterioration of groundwater quality by mobilising natural contaminants or because of seawater intrusion. Deepening GWLs may lead, in some geological and hydrogeological contexts, in particular in

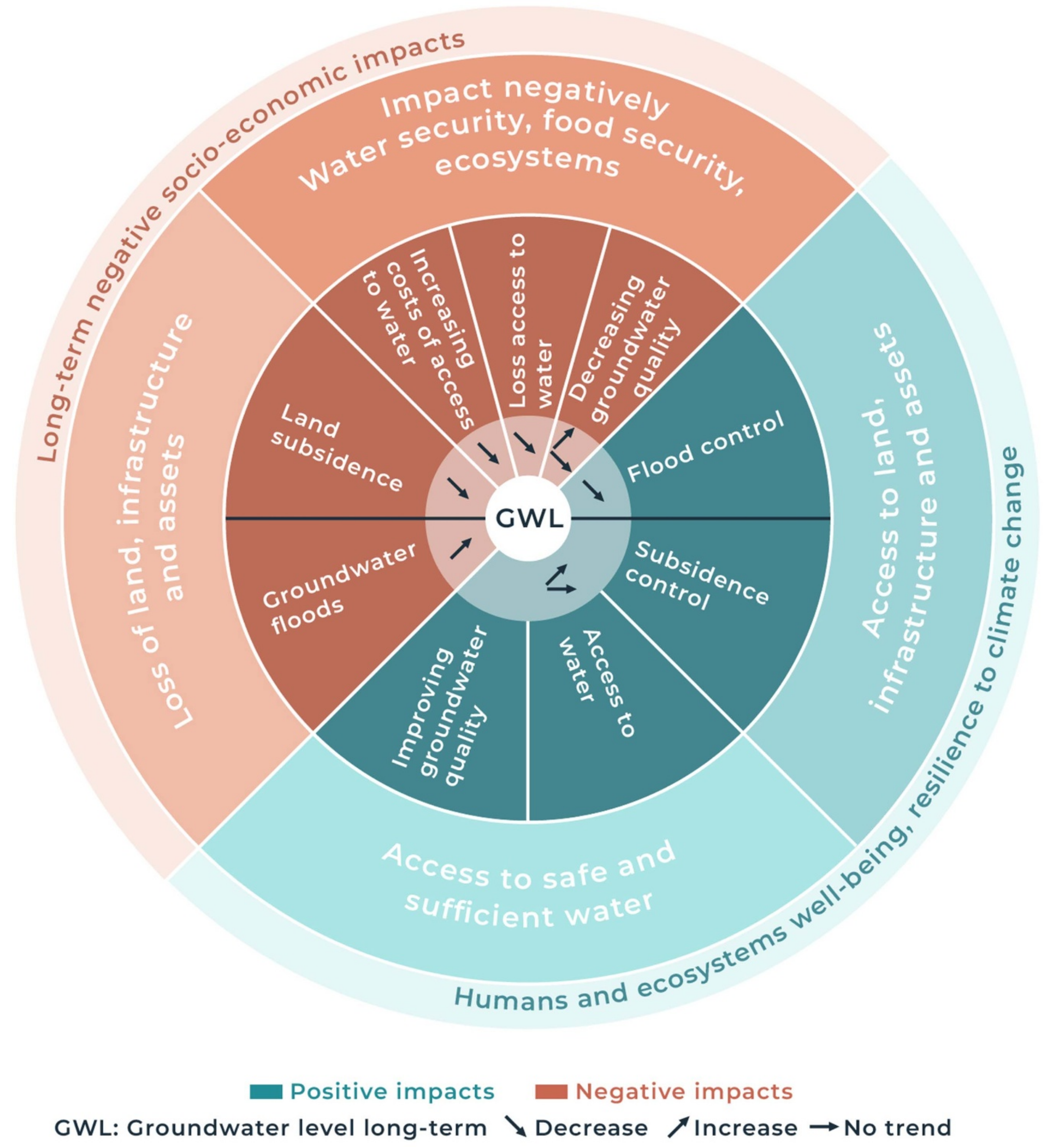

Figure 7. Impacts of groundwater level change on humans and ecosystems

areas overlying soft sediments, to ground subsidence, with consequences for assets, infrastructure and land. Conversely, long-term GWL rise does not necessarily translate to positive impacts. When GWL reaches the ground or is above ground level, flooding can affect infrastructure, agriculture, as well as human and ecosystem health. Nevertheless, positive impacts of GWL recovery have also been documented, although in a minority of cases, specifically in controlling ground subsidence but also in improving water access of communities and farmers.

This work also calls for more reporting on the impacts of GWLs changes. Understanding and analysing the impacts at different scales can support decision-making on which impacts are acceptable, which are not, thus supporting the estimation of sustainable groundwater abstraction. The extent of the impacts of GWL changes in so many aspects of life highlighted in our work underscores the urgent need to integrate and mainstream groundwater in water resources plans, through the conjunctive and integrated management of surface and groundwater, as well as in any development plan, being energy, agriculture, infrastructure or industry. This will allow not only to safeguard water access but also to protect ecosystems sustained by shallow aquifers or springs and sustained river flows.

The analysis can be repeated and improved in the future when data from more national/subnational (and even local) networks are made available. National groundwater monitoring networks are an important source of continuously updated GWL data. Apart from supporting assessments of groundwater status and trends, they enable future comparisons because the data are regularly updated and networks are expected to remain operational. Additional research is required to better understand the patterns of long-term GWL change and associated impacts on humans, ecosystems, and infrastructure.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.58154/6Z0Y-DA34 (IGRAC 2026).

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