Rapid groundwater decline and some cases of recovery in aquifers globally

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Groundwater resources are vital to ecosystems and livelihoods. Excessive groundwater withdrawals can cause groundwater levels to decline[1–10], resulting in seawater intrusion[11], land subsidence[12,13], streamflow depletion[14–16] and wells running dry[17]. However, the global pace and prevalence of local groundwater declines are poorly constrained, because in situ groundwater levels have not been synthesized at the global scale. Here we analyse in situ groundwater-level trends for 170,000 monitoring wells and 1,693 aquifer systems in countries that encompass approximately 75% of global groundwater withdrawals[18]. We show that rapid groundwater-level declines (>0.5 m year^{-1}) are widespread in the twenty-first century, especially in dry regions with extensive croplands. Critically, we also show that groundwater-level declines have accelerated over the past four decades in 30% of the world's regional aquifers. This widespread acceleration in groundwater-level deepening highlights an urgent need for more effective measures to address groundwater depletion. Our analysis also reveals specific cases in which depletion trends have reversed following policy changes, managed aquifer recharge and surface-water diversions, demonstrating the potential for depleted aquifer systems to recover.

Groundwater is the primary water source for many homes, farms, industries and cities around the globe. Unsustainable groundwater withdrawals and changes in climate can cause groundwater levels to fall[1–10], making groundwater resources less accessible[17]. Global maps of groundwater storage trends are available[7] from the Gravity Recovery and Climate Experiment (GRACE) satellites, although at a resolution that is too coarse (>150,000 km^2; ref. 19) to detect local changes and inform local management. Measuring multidecadal groundwater-level declines and managing their consequences—including seawater intrusion[11], land subsidence[12,13], streamflow depletion[14–16] and wells running dry[17]—requires in situ groundwater-level measurements from networks of monitoring wells. Such monitoring-well networks have been used at local and regional scales to estimate groundwater recharge[20,21], characterize streamflow depletion[14], evaluate the risk of wells running dry[17] and test whether surface-water diversions[22,23] or market and policy interventions[24] have succeeded in slowing groundwater losses. However, in situ groundwater-level observations have rarely been analysed at the global scale because we lack a global compilation of in situ groundwater-level time series.

Here we compile and analyse in situ measurements of groundwater-level trends in about 170,000 monitoring wells. The measurements provide new constraints on the prevalence of rapid and accelerating groundwater-level declines and their correlation with land use and climatic drivers. Furthermore, the measurements highlight individual cases in which groundwater levels have recovered following policy changes[25] and inter-basin water transfers[26].

Local hotspots of groundwater-level changes

We compiled and quality-controlled groundwater-level time series in monitoring wells from more than 40 countries (see Methods and Supplementary Notes 1 and 2). We calculated twenty-first century trends in depth to groundwater level for about 170,000 monitoring wells with time series that span at least 8 years using Theil–Sen robust regression (Fig. 1; analyses based on alternative regression techniques and on different quality-control thresholds yield similar results; see Supplementary Notes 3, 4, 5 and 6). Positive Theil–Sen slopes indicate deepening groundwater levels (red points in Fig. 1). Trends in groundwater levels often differ substantially from well to well, and local hotspots of groundwater decline can be found even in regions in which nearby groundwater levels are stable or rising, and vice versa (Fig. 1), highlighting the importance of analysing groundwater-level trends at the scales defined by the boundaries of individual aquifer systems.

To evaluate aquifer-scale groundwater-level trends, we manually delineated the boundaries of 1,693 aquifer systems—areas underlain by one or more aquifers—using maps and descriptions from 1,236 local and regional studies (see Methods and Supplementary Note 7). We calculated aquifer-scale groundwater-level trends as the median of the

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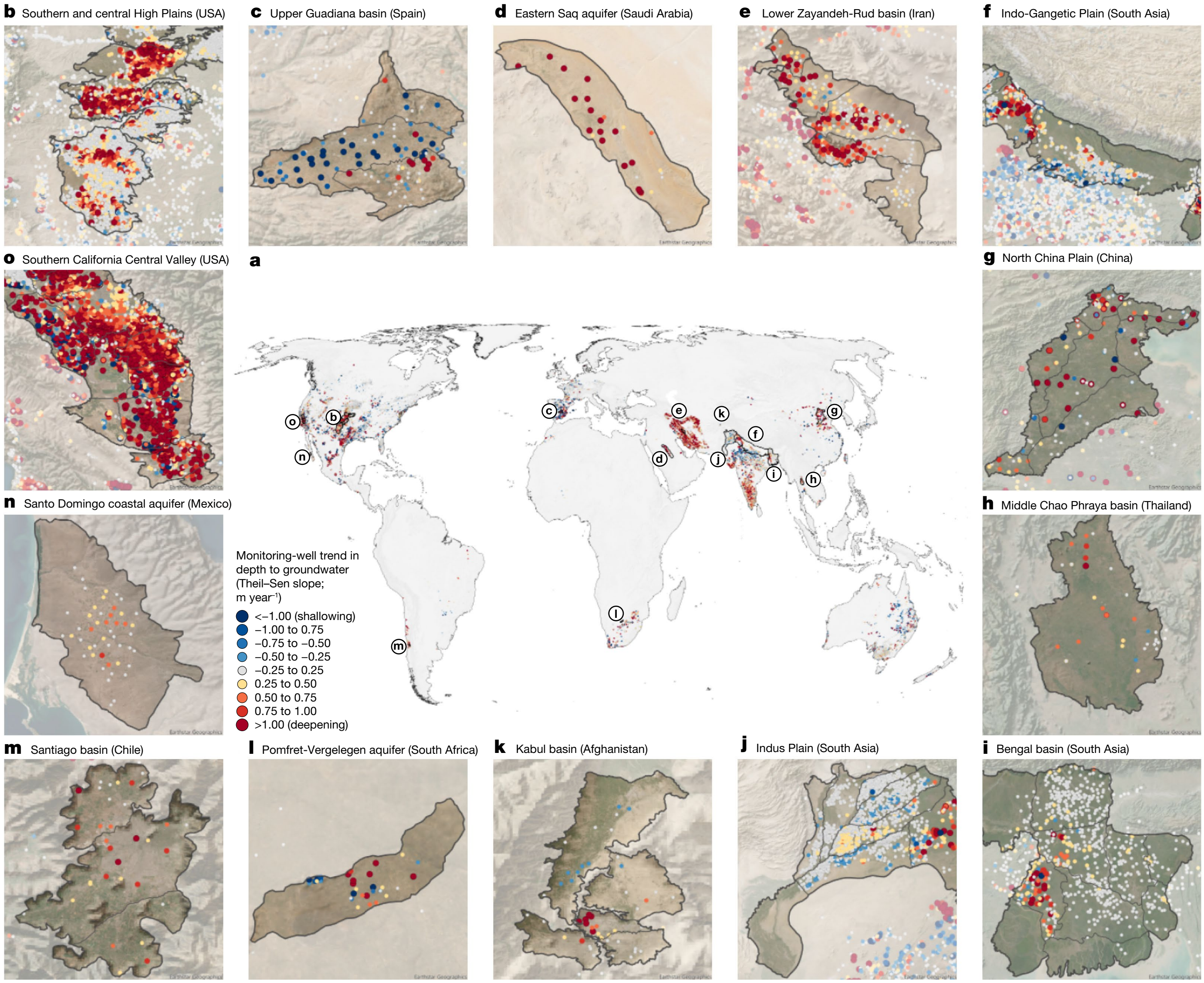


Fig. 1 | Twenty-first century groundwater-level trends in globally distributed monitoring wells. Each point represents one monitoring well, coloured to represent the Theil–Sen trend of annual median groundwater levels during the twenty-first century. Blue and red points indicate shallowing and deepening, respectively, of groundwater levels over time, with darker colours indicating faster rates. **a**, Spatial distributions of groundwater-level trends in globally distributed monitoring wells. **b**–**o**, Regional maps illustrating the substantial spatial variability in groundwater-level trends. Supplementary Notes 16 and 17 show monitoring wells and their groundwater-level trends at subcontinental scales (Supplementary Note 16) and in 207 individual aquifer systems (Supplementary Note 17). Background imagery shown in **b**–**o** from https://www.arcgis.com/home/item.html?id=10df2279f9684e4a9f6a7f08febac2a9.

Theil–Sen slopes of all monitoring wells located within each aquifer system (Fig. 2). Most aquifer-scale groundwater-level trends range from −0.1 to 0.9 m year^{-1} (5th to 95th percentiles), in which negative values represent shallowing groundwater levels and positive values indicate deepening groundwater levels.

Groundwater levels became deeper over time at rates exceeding 0.1 m year^{-1} in 36% of the aquifer systems (617 of 1,693) and exceeding 0.5 m year^{-1} in 12% (210) of them. Aquifer systems that exhibit groundwater-level deepening and are too small to be detected by GRACE satellite observations (for example, southeastern Spain) highlight the value of in situ groundwater-level measurements to complement global-scale insights[5,7,9,19] made possible by the GRACE (see Methods and Supplementary Note 8).

Groundwater levels became shallower over time faster than −0.1 m year^{-1} in 6% of the aquifer systems (97 of 1,693) and faster than −0.5 m year^{-1} in only 1% (13) of them. Some groundwater-shallowing trends may be explained by reductions in groundwater withdrawals, land-cover changes, managed aquifer recharge projects (for example, in Arizona's East Salt River basin[22]) and inter-basin surface-water transfers (for example, the Wanjiazhai water diversion to China's Taiyuan basin[26]).

Accelerating groundwater-level declines

To place twenty-first century groundwater-level declines into context, we compared them with groundwater-level trends during the late twentieth century (1980–2000); this analysis was possible in 542 of the 1,693 delineated aquifer systems (see Methods and Supplementary Note 9).

In 30% of these aquifer systems, groundwater-level declines accelerated, with early twenty-first century groundwater-level declines outpacing those of the late twentieth century (the red points in Fig. 3a; see the red time series in Fig. 3b and Extended Data Fig. 1 for illustrative examples). These cases of accelerating groundwater-level declines are more than twice as prevalent as one would expect from random fluctuations in the absence of any systematic trends in either time period

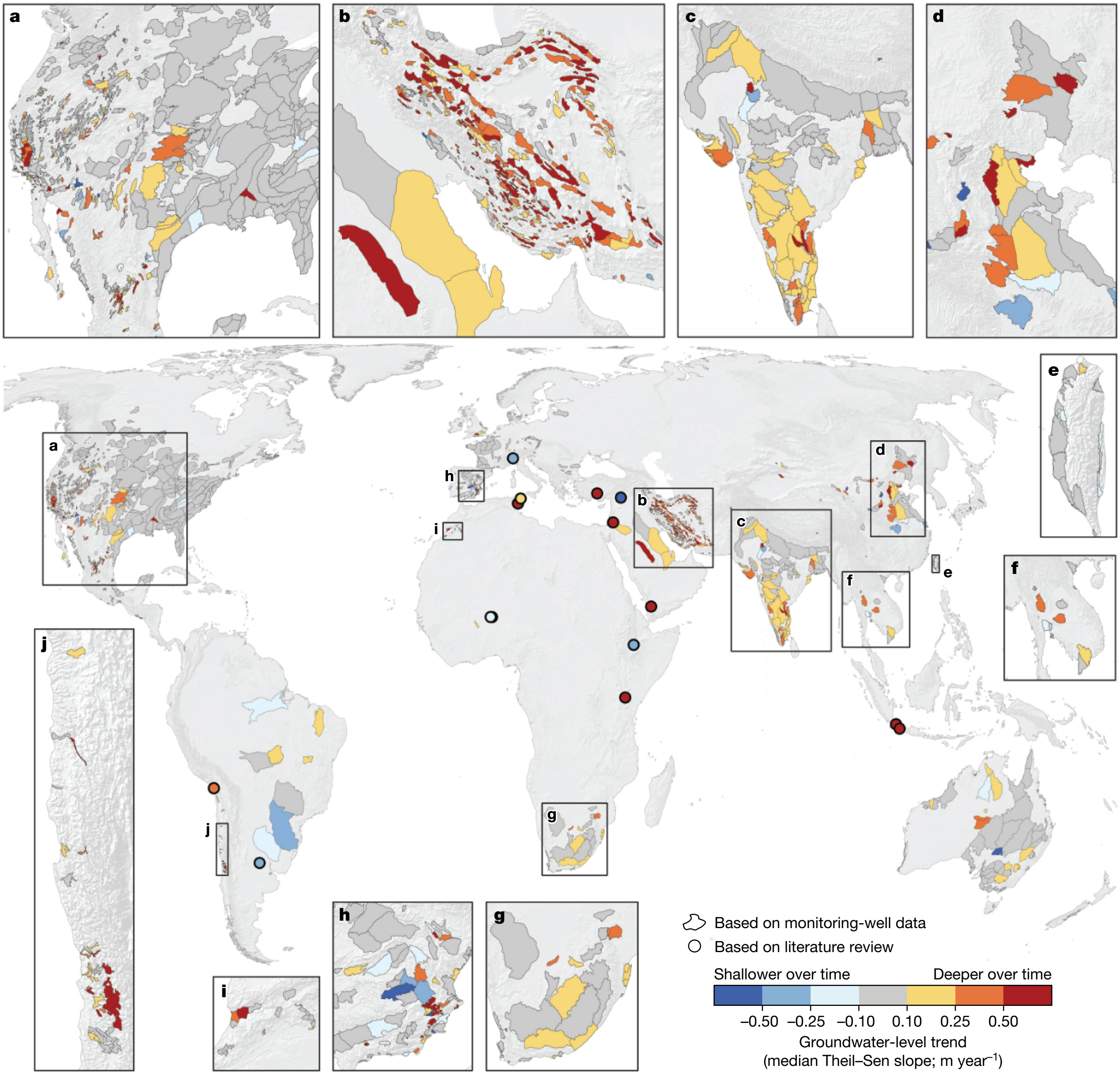


Fig. 2 | Twenty-first century trends in depth to groundwater in 1,693 globally distributed aquifer systems. Each polygon represents one aquifer system. Dark grey represents aquifer systems in which groundwater levels have been relatively stable (median Theil–Sen slope between −0.1 and 0.1 m year^{-1}). Yellow, orange and red represent aquifer systems in which groundwater levels became deeper (median Theil–Sen slope >0.1 m year^{-1}). Blue represents aquifer systems in which groundwater levels became shallower (median Theil–Sen slope of <−0.1 m year^{-1}). Darker colours indicate faster rates. Circular points mark locations for which we lack monitoring-well data but groundwater-level trends have been documented in the literature, with colours indicating the average of the minimum and maximum literature values (Supplementary Note 15). Statistics describing the spatial variability of groundwater-level trends within individual aquifers are presented in Supplementary Note 23. Median Theil–Sen slopes for all 1,693 aquifer systems are tabulated in Supplementary Note 24.

(12.5%; P-value < 0.001 by the binomial test). Furthermore, among all cases in which groundwater levels declined in both the late twentieth and early twenty-first centuries, declines in the early twenty-first century outpaced those in the late twentieth century much more often than one would expect by chance (163 red points versus 107 orange points in Fig. 3a; P-value < 0.001 by the sign test). If we exclude cases in which groundwater-level trends changed by less than 0.1 m year^{-1} between these two periods (that is, considering only points lying outside the grey diagonal band in Fig. 3a), we find that accelerating declines (red points) outnumber decelerating declines (orange points) by a ratio of 5:2 (P-value < 0.001 by the sign test). In summary, groundwater-level declines have accelerated in a substantial share of the analysed aquifer systems.

To test for a potential statistical relationship between accelerating groundwater-level declines and climate variability, we analysed precipitation rates over the past four decades (Supplementary Note 10). We show that most (>80%) of the aquifer systems exhibiting accelerating groundwater-level declines also experienced a decline in precipitation

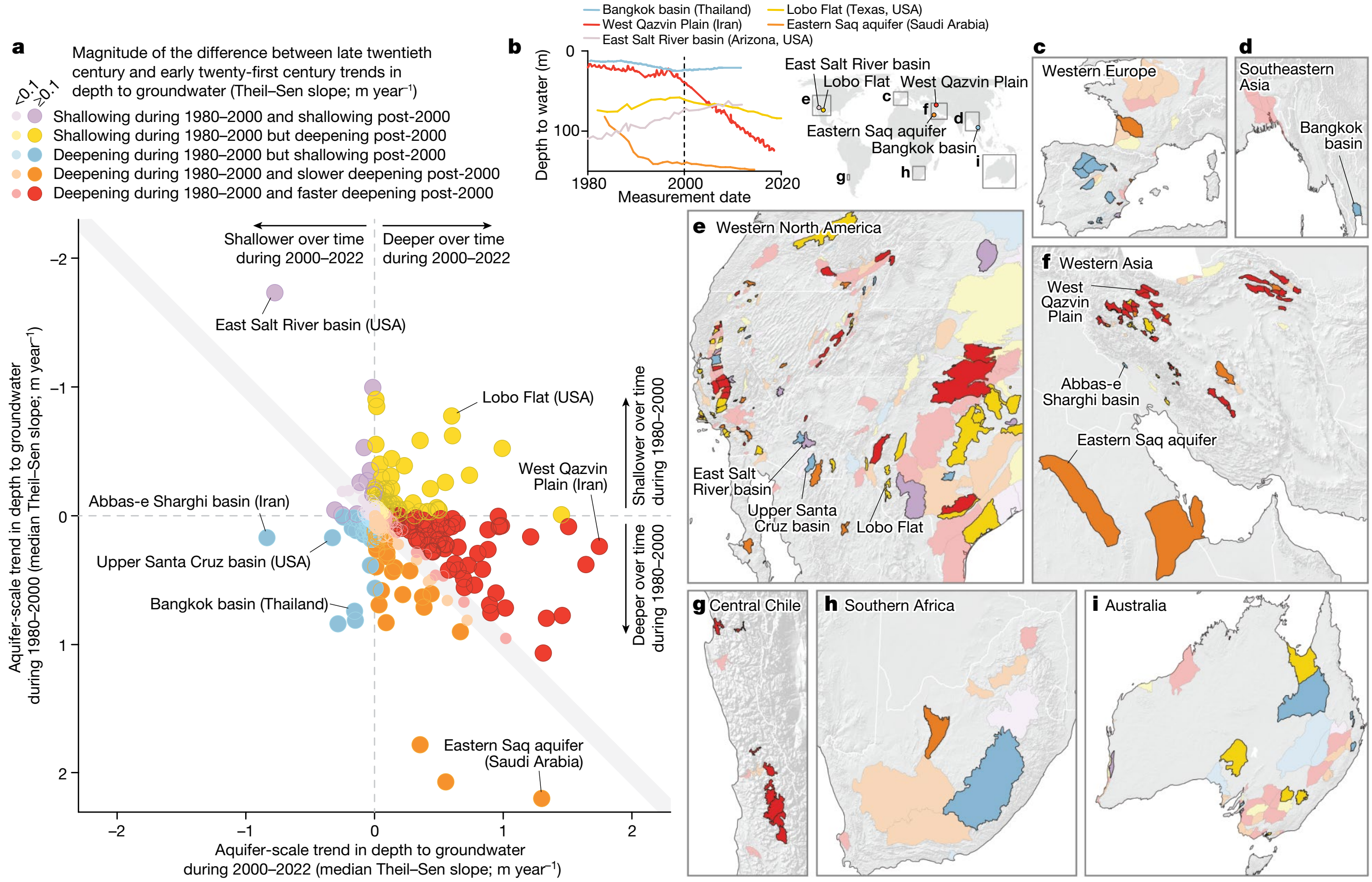


Fig. 3 | Comparison of aquifer-scale trends in depth to groundwater during the late twentieth and early twenty-first centuries. a, Scatter plot of aquifer-scale trends (median Theil–Sen slopes) during 2000–2022 (*x*-axis values) and during 1980–2000 (*y*-axis values). The colour of each point indicates one of the following categories of trends: (1) groundwater levels became shallower during 1980–2000 and continued to become shallower (purple points); (2) groundwater levels became shallower during 1980–2000 but have since become deeper (yellow points); (3) groundwater levels became deeper during 1980–2000 but have since become shallower (blue points); (4) groundwater levels became deeper during 1980–2000 and continued to become deeper but at a slower rate (that is, decelerated deepening; orange points); and (5) groundwater levels became deeper during 1980–2000 and continued to become deeper at a faster rate (that is, accelerated deepening; red points). The intensity of each colour scales with the absolute value (that is, magnitude) of the difference between the late twentieth and early twenty-first century trends in groundwater level (see legend). **b**, Examples of groundwater-level time series illustrating each of our five categories (see legend). **c**–**i**, Maps of aquifer systems categorized by their late twentieth and early twenty-first century trends in groundwater levels (colours correspond to categories in the legend). For an expanded version of this figure, see Supplementary Note 9.

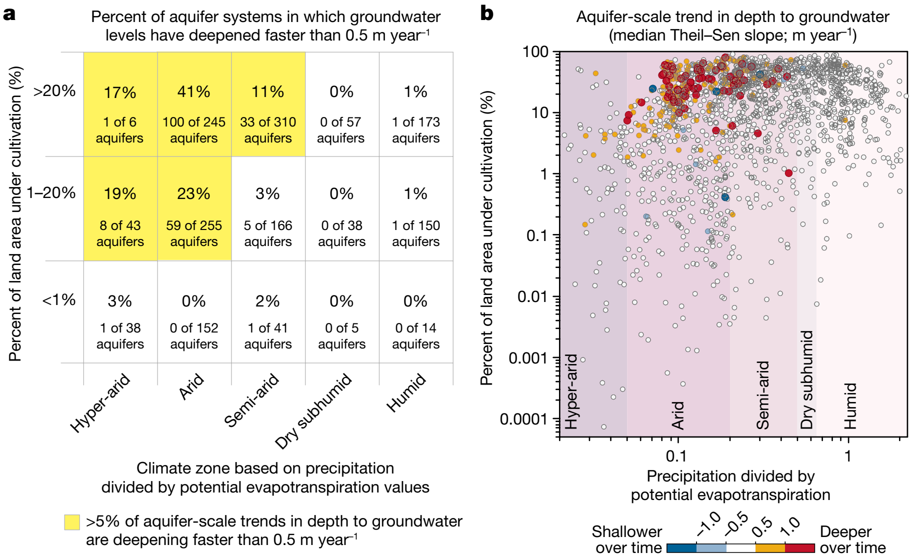
over time (that is, lower average annual precipitation during the early twenty-first century than in the late twentieth century). Declines in precipitation can cause groundwater levels to fall as a result of both indirect impacts (for example, increased groundwater abstractions during droughts) and direct impacts (for example, reduced recharge rates during droughts; see ref. 27). Our finding—that early twenty-first century precipitation rates were lower than in the late twentieth century in most aquifer systems exhibiting accelerating groundwater-level declines—highlights a potential link between decadal-scale climate variability and accelerating groundwater-level declines. Accelerating groundwater-level declines, regardless of their potential drivers, are likely to also accelerate the consequences of those declines, including land subsidence[12,13] and wells running dry[17].

Slowing and reversing groundwater-level declines

Many previous studies[1–10] have highlighted groundwater losses, but the potential for slowing or reversing these losses has received less attention. Our analysis of groundwater levels suggests that long-term groundwater losses are neither universal nor inevitable. Specifically, in half (49%) of the 542 aquifer systems in our analysis, groundwater-level declines have decelerated (that is, slowed; orange in Fig. 3; 20%) or reversed (blue in Fig. 3; 16%), or groundwater levels have continued to rise (purple in Fig. 3; 13%).

In 20% of the aquifer systems, groundwater-level deepening has decelerated, as late twentieth century groundwater declines continued in the early twenty-first century, but at a slower rate (the orange points in Fig. 3a; see orange time series in Fig. 3b and Extended Data Fig. 2 for illustrative examples). Although these cases are outnumbered by those for which groundwater declines have accelerated, they demonstrate that it is possible to slow, and potentially even reverse, groundwater-level declines. For example, our analysis shows marked deceleration of groundwater-level deepening in the Eastern Saq aquifer of Saudi Arabia, possibly owing partly to policies designed to reduce agricultural water demands[28] (see labelled orange point in Fig. 3a, which corresponds to the orange line in Fig. 3b).

In 16% of the aquifer systems, groundwater level declines reversed—defined as cases in which groundwater levels declined in the late twentieth century but rose in the early twenty-first century (the blue colours in Fig. 3; see blue time series in Fig. 3b and Extended Data Fig. 3 for examples). For example, in the Bangkok basin (Thailand), groundwater levels deepened during the late twentieth century but shallowed in



	Hyper-arid	Arid	Semi-arid	Dry subhumid	Humid
>20%	17% 1 of 6 aquifers	41% 100 of 245 aquifers	11% 33 of 310 aquifers	0% 0 of 57 aquifers	1% 1 of 173 aquifers
1–20%	19% 8 of 43 aquifers	23% 59 of 255 aquifers	3% 5 of 166 aquifers	0% 0 of 38 aquifers	1% 1 of 150 aquifers
<1%	3% 1 of 38 aquifers	0% 0 of 152 aquifers	2% 1 of 41 aquifers	0% 0 of 5 aquifers	0% 0 of 14 aquifers

Fig. 4 | Twenty-first century aquifer-scale trends in depth to groundwater in the context of climate and cultivation. a, The percentage of aquifer systems with rapidly deepening groundwater (median Theil–Sen slope steeper than 0.5 m year^{-1}) when categorized by climate conditions and cropland prevalence. Aquifer systems with rapidly deepening groundwater are most common in hyper-arid, arid and semi-arid climate zones (see categories on the *x* axis) and where a larger proportion of land is under cultivation (see categories on the *y* axis). **b**, Scatter plot of aquifer-scale average annual precipitation divided by potential evapotranspiration[39], and the percentage of land area under cultivation[40] (estimated for the year 2015). The colour of each point represents the twenty-first century aquifer-scale groundwater-level trend (median Theil–Sen slope). Blue and red points indicate shallowing and deepening, respectively, of groundwater, with darker colours indicating faster rates. Background shades represent climate zones classified by annual precipitation divided by potential evapotranspiration (that is, *x*-axis values). Several aquifer systems are absent from this plot because either no land is under cultivation (incompatible with the log scale of the *y* axis) or precipitation divided by evapotranspiration values fall outside the shown range of *x*-axis values. For alternative versions of this figure showing these aquifer systems, see Supplementary Note 11.

the early twenty-first century (see labelled blue point in Fig. 3a); this reversal has been attributed[25] to regulatory measures (groundwater pumping fees and licensing of wells). Another example is Iran's Abbas-e Sharghi basin, in which twentieth century groundwater-level declines were reversed by the diversion of water to the basin from the Kharkeh Dam[29]. In other areas, groundwater deepening has been reversed following the implementation of managed aquifer recharge projects[22] (for example, west of Tucson, Arizona; Extended Data Fig. 3). Recharge projects are sometimes only viable where excess surface waters are available, emphasizing the importance of coordinating groundwater and surface-water management[30]. Nevertheless, these examples illustrate that interventions of sufficient scope and scale can reverse declining groundwater trends.

In a further 13% of the aquifer systems, groundwater levels rose in both the late twentieth and the early twenty-first centuries (purple colours in Fig. 3; see purple time series in Fig. 3b and Extended Data Fig. 4 for examples). Some of these cases indicate that aquifers that were heavily exploited before 1980 are recovering. Aquifer recovery can potentially ameliorate the consequences of groundwater pumping (for example, land subsidence[31]). In other cases, however, rising groundwater levels can be problematic. For example, rising groundwaters can lead to flooding of coastal cities[32], waterlogging of farmlands[33] and salinization of groundwaters and soils[34]. Rising groundwater levels may be driven by reductions in groundwater withdrawals[25] or increases in recharge rates owing to land clearing[35,36], irrigation[33] or managed aquifer recharge[37]. Our aquifer-scale groundwater-level trends can help predict where rising groundwater levels may pose challenges.

Although these examples illustrate that groundwater declines can be slowed or reversed, several caveats must be kept in mind. In general, rates of groundwater-level shallowing are much slower than rates of groundwater-level decline. Of the aquifer systems in Fig. 3 with rising twenty-first century groundwater levels (blue and purple points), only 6% are rising faster than −0.2 m year^{-1}. By contrast, of the aquifer systems with deepening twenty-first century groundwater levels (yellow, red and orange points in Fig. 3), 25% are falling faster than 0.2 m year^{-1}. Furthermore, across these aquifer systems, the average rate of twenty-first century deepening (0.2 m year^{-1}) exceeds the average rate of shallowing (−0.05 m year^{-1}) by a factor of four. Thus, rapidly rising groundwater levels are rare, but they demonstrate that aquifer recovery is possible, especially following policy changes[25], managed aquifer recharge[37] and inter-basin surface water-transfers[26].

Groundwater declines in cultivated drylands

Many of the aquifer systems with declining twenty-first century groundwater levels (Fig. 2) underlie drylands, defined[38] as areas in which average precipitation divided by potential evapotranspiration is less than 0.65. Rapidly deepening groundwater levels (faster than 0.5 m year^{-1}) are found in 11%, 24% and 8% of aquifers in climate zones classified[38] as hyper-arid, arid and semi-arid, respectively. Notably, aquifer systems with rapidly deepening groundwater levels are virtually absent (<1%) in humid and dry subhumid climate zones. Our 1,693 aquifer-scale groundwater-level trends exhibit a moderately strong rank correlation with precipitation divided by potential evapotranspiration[39] (Spearman $\rho = -0.40$, P-value < 0.001; Supplementary Note 11 and Methods), implying that groundwater deepening is more common in drier climates (Fig. 4). As well as rapid groundwater-level declines, we also find that accelerating groundwater-level declines are more common in drier climates, especially underlying cultivated lands (Supplementary Note 9), probably reflecting greater reliance on groundwater for irrigation.

Irrigation is estimated to account for 70% of global groundwater withdrawals[18]. A lack of high-resolution, ground-truthed data quantifying groundwater withdrawals for irrigation precludes statistical tests of their correlation with groundwater-level changes over time. However, using high-resolution global land cover data[40], we can test for statistical relationships between land-use patterns and groundwater trends (Fig. 4). Aquifer systems with rapidly deepening groundwater levels (>0.5 m year^{-1}) are relatively common (17%) where more than one-fifth of the land surface is cultivated, but are virtually absent (0.8%) where cultivation accounts for <1% of the land surface. Across the 1,693 aquifer systems, rates of groundwater-level deepening are significantly correlated with the proportion of land under cultivation[40] (Spearman $\rho = 0.17$, P-value < 0.001; Fig. 4). This statistical relationship becomes stronger when we account for the correlation between cultivation and climatic aridity (partial rank correlation coefficient = 0.32, P-value < 0.001; see Supplementary Note 11). Our analyses demonstrate that rapid groundwater declines are most common in cultivated drylands.

Groundwater losses from dryland aquifers pose management challenges. Aquifer recharge is typically slow in drylands[41], meaning that depleted dryland aquifers will generally take longer to recover than aquifers in wetter climates[42], except where recharge rates are artificially increased (for example, seepage from unlined canals in the Indus basin[33]). Moreover, groundwater is often the sole source of perennial drinking water for communities in drylands. As groundwater levels become deeper, shallower wells can run dry[17], compromising local water access. Even where groundwater levels remain stable, groundwater withdrawals can deplete the flow of nearby streams by reducing natural seepage of groundwater to rivers, or even inducing streamwater leakage into underlying aquifers (see discussion of 'capture' by ref. 43). Indeed, leakage from surface waters may replenish pumped aquifers and stabilize groundwater levels at the expense of streamflow. The prevalence of rapid and accelerating groundwater declines in cultivated drylands suggests that, even if management strategies are in place, they have often been insufficient—either in concept or in implementation—to slow or reverse groundwater depletion.

Depleting and recovering groundwater resources

Our analysis of groundwater-level measurements demonstrates that: (1) groundwater levels are declining rapidly (>0.5 m year^{-1}) in many regions (Fig. 2); (2) groundwater declines are accelerating in many aquifer systems around the world (Fig. 3); and (3) both rapid and accelerating groundwater declines are particularly evident in aquifers underlying cultivated drylands (Fig. 4 and Supplementary Notes 9 and 11). Our analysis also identifies cases in which late twentieth century groundwater declines have been reversed in the early twenty-first century (blue points in Fig. 3). However, cases of rapidly rising groundwater levels remain outnumbered by cases of rapidly deepening groundwater levels.

Our results indicate that twenty-first century realities—including climatic trends, hydrogeologic conditions, groundwater withdrawal rates, land uses and management approaches—have resulted in widespread, rapid and accelerating groundwater-level declines. Nevertheless, the compiled in situ observations also capture numerous cases in which declines in groundwater levels have slowed, stopped or reversed following intervention (for example, implementation of regulatory measures[25]). Although our work represents the most extensive analysis of groundwater-level monitoring records so far, it does not cover the globe (see Methods section entitled 'Limitations'). Further, analysed monitoring wells do not represent a randomized sample of global wells and we are only able to analyse groundwater level trends where monitoring data are available. Global maps of groundwater storage changes from GRACE satellite observations[7] suggest that groundwater stores are declining in some regions in which monitoring data are not publicly available and, thus, cannot be evaluated here. GRACE data are also important for characterizing impacts of climate change and variability[9,19,44–46] and evaluating global hydrologic models[47]. Evaluating such models is important because they are widely used to estimate groundwater depletion (see ref. 6 and Table 3 in ref. 48). Our compilation of monitoring-well data could facilitate future efforts to reconcile GRACE-based, model-based and piezometric-based groundwater time series (see refs. 49,50). Combining these diverse data products—and thus exploiting both the high spatial resolution of monitoring-well networks and the global coverage of GRACE[7,9,19] and hydrologic models[2,3,6,16,48]—may yield new insights into the causes, consequences and spatial patterns of groundwater depletion.

Groundwater depletion can threaten ecosystems and economies. Specifically, groundwater depletion can damage infrastructure through land subsidence[12,13], impair fluvial ecosystems through streamflow depletion[14–16], jeopardize agricultural productivity[51] and compromise water supplies as wells run dry[17]. Our methodologically consistent analysis of groundwater-level trends across 1,693 globally distributed aquifer systems demonstrates widespread, rapid and accelerating twenty-first century groundwater-level declines, particularly in cultivated drylands.

Our analysis also documents cases for which groundwater declines have slowed or reversed after: (1) the implementation of groundwater policies; (2) the alleviation of groundwater demand by means of surface-water transfers; or (3) the addition of groundwater storage following managed aquifer recharge projects. To address the growing problem of global groundwater depletion, these kinds of success stories would need to be replicated in dozens of aquifer systems with declining groundwater levels. Thus, our analysis illustrates the potential for depleted aquifers to recover, while demonstrating how much work remains to be done to protect groundwater resources. By documenting global hotspots of groundwater-level decline and recovery, this analysis can inform efforts to address rapid and accelerating groundwater depletion.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-023-06879-8.

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Methods

Delineating global aquifer systems based on literature review of local studies

For each country in our study, we consulted published accounts of local-scale studies[52–1288] (Supplementary Note 7) to delineate 1,693 study areas, each underlain by one or more aquifers and/or low-permeability geologic formations that are, collectively, referred to as an 'aquifer system'. Each aquifer system was delineated by consulting maps and reading descriptions within local-scale reports. Specific steps applied to delineate the boundaries of each aquifer system are detailed in Supplementary Note 7.

Downloading groundwater-level data

Our study focuses on more than 40 countries for which we compiled monitoring-well data. We analysed groundwater-level time series derived from numerous data repositories (dataset-specific details are available in Supplementary Note 1; some of these datasets are described in refs. 1289–1297). The compiled groundwater-level databases span different time intervals and have different measurement frequencies (see heat map plot and global maps showing monitoring-well time series durations and measurement frequencies in Supplementary Note 12).

Quality controlling groundwater-level time series

We completed five pre-processing steps before analysing groundwater-level data. First, we identified replicate groundwater-level measurements, defined as cases in which an identical measurement date and an identical groundwater-level measurement were reported from the same monitoring well; in these cases, we retain only one of these replicates. Second, we identified cases in which several groundwater-level measurements from the same monitoring well reported identical measurement dates. In these cases, we calculated the median among all groundwater-level measurements sharing the same measurement date and the adjacent points in the time series (that is, the median of the group of measurements with identical dates and the measurements immediately preceding and following the same-date measurements); we then kept only the single water-level measurement whose value was closest to this calculated median (Supplementary Note 2). Third, we excluded extreme values of depth to groundwater (that is, >1,000 m and <−1,000 m) and implausibly high groundwater elevations (that is, >8,000 m above sea level). Fourth, we excluded groundwater-level measurements with values of '999', '−9,999' or '0', because some databases used these values as a code for missing measurements (see figures in Supplementary Note 2). Fifth, we excluded outlier values detected by a machine-learning algorithm[1298] (based on an additive regression model[1299]; for details, see Supplementary Note 2.1). This algorithm was applied to each monitoring well with more than 15 groundwater-level measurements, yielding a prediction for each time step and its 99% confidence interval. We defined points to be outliers and excluded them if they fell outside the range defined by the predicted groundwater level ±0.75 times this confidence interval. If a large number of measurements within a monitoring well's time series were classified as outliers, we excluded the entire time series from our analysis (in which a 'large number of measurements' is defined as cases for which there were at least five outliers identified by the machine-learning algorithm and for which these outliers comprise >1% of all measurements in the time series; for visualization, see schematics in Supplementary Note 2). Among the approximately 170,000 monitoring wells presented in Fig. 1, only about 12% had one or more outlier points removed by means of this machine-learning approach, highlighting that this machine-learning approach affected only a small proportion of consulted monitoring wells. Furthermore, a comparison of aquifer-scale trends in depth to groundwater with versus without the use of a machine-learning-based outlier-exclusion procedure suggests that our machine-learning approach had no substantial influence on our findings (see Supplementary Note 13).

Flagging groundwater-level measurements based on rapid increases or decreases

After excluding potential outliers (through the steps outlined in the previous paragraph), we calculated each monitoring well's annual median groundwater levels for each calendar year with at least one measurement. We then visually inspected plots of annual median groundwater levels over time. On visual inspection, we noted that a small number of monitoring wells show 'spikes' in their annual groundwater-level time series, in which a 'spike' is defined as a high-magnitude (absolute value > 20 m year^{-1}) groundwater-level change followed directly by another high-magnitude groundwater-level change in the opposite direction (for example, a high-magnitude groundwater-level deepening trend between two adjacent points in the time series, directly followed by a high-magnitude groundwater-level shallowing trend between two adjacent points). We flagged these data points as potentially suspect. The first or last point in each time series was also flagged if it differed by more than 20 m year^{-1} from the second or next-to-last point. We compared groundwater-level trends with and without these flagged points and observed only trivial differences (Supplementary Note 5: 'Similar aquifer-scale trends obtained with and without flagged measurements'). The results presented in the main text (for example, Fig. 1) derive from annual median groundwater-level time series that exclude the flagged measurements.

Statistical analyses of twenty-first century groundwater-level trends (Figs. 1 and 2)

To evaluate groundwater-level trends since the year 2000, we excluded all previous measurements. Next, we excluded all monitoring wells for which the earliest and most recent annual medians were separated by fewer than 8 years. We calculated trends in annual median groundwater levels for all monitoring wells that met these minimum criteria for analysis (for a similar method, see ref. 1288).

Some data sources report groundwater levels as elevations (metres above sea level) and others report them as depth to groundwater (metres below the land surface, or below the top of the well). In cases in which both were reported, we used the depth to groundwater data. If groundwater levels were only reported as elevations, we reversed the signs of the calculated trends, to obtain trends in depth to groundwater.

Our results in the main text are based on Theil–Sen regression slopes[1300,1301] but we also applied several different regression techniques, including ordinary least squares, iteratively reweighted least squares[1302–1304] and RANSAC (or random sample consensus)[1305], which yielded comparable results (Supplementary Note 3; for non-parametric regression techniques, see Supplementary Note 4 and ref. 1306). We present our results as trends in depth to groundwater, meaning that positive slopes represent groundwater levels becoming deeper over time. We calculated an aquifer-scale groundwater-level trend for each aquifer system by taking the median of the Theil–Sen slopes of all monitoring wells within its boundaries (Fig. 2).

Comparing groundwater-level trends between the late twentieth and early twenty-first centuries (Fig. 3)

To contextualize twenty-first century trends in depth to groundwater, we identified monitoring wells with sufficient data during two periods: the late twentieth century (1980–2000) and the early twenty-first century (2000–2022). Here well time series are 'sufficient' if their earliest and latest annual medians are separated by at least 8 years within a given time interval (that is, 1980–2000 or 2000–2022). There are 45,911 monitoring wells in the compiled dataset with sufficient groundwater-level data for trend analyses during both periods. For these monitoring wells, we calculated Theil–Sen trends in depth to groundwater for the late twentieth century. Next, we grouped monitoring wells located within the same aquifer system and calculated aquifer-scale trends for the late twentieth century (medians of the Theil–Sen slopes for all wells in each system; that is, y-axis values presented in Fig. 3a). Only aquifer systems with at least five monitoring wells for both time periods (1980–2000 and 2000–2022) satisfying the aforementioned requirements were used to compare late twentieth century and early twenty-first century trends in depth to groundwater. Last, we assigned each aquifer system to one of five categories based on its late twentieth century and early twenty-first century trends in depth to groundwater: (1) groundwater levels became shallower during 1980–2000 and continued to become shallower (purple points in Fig. 3a); (2) groundwater levels became shallower during 1980–2000 but have since become deeper (yellow points in Fig. 3a); (3) groundwater levels became deeper during 1980–2000 but have since become shallower (blue points in Fig. 3a); (4) groundwater levels became deeper during 1980–2000 and continued to become deeper but at a slower rate (that is, decelerated deepening; orange circles in Fig. 3a); and (5) groundwater levels became deeper during 1980–2000 and continued to become deeper at a faster rate (that is, accelerated deepening; red circles in Fig. 3a). Further details are available in Supplementary Note 9.

Geospatial analysis of potential explanatory variables (Fig. 4)

To test for statistical relationships between the spatial distributions of environmental conditions and groundwater-level trends, we downloaded two geospatial datasets: (1) long-term mean annual precipitation divided by potential evapotranspiration (the 'CGIAR-CSI Global-Aridity and Global-PET Database'; ref. 39) and (2) the proportion of land area under cultivation (estimated for the year 2015; ref. 40). Next, we averaged each of these geospatial datasets over each of the 1,693 aquifer systems (Fig. 4). We calculated rank correlations between twenty-first century aquifer-scale groundwater-level trends and both of the potential explanatory variables (namely, (1) long-term mean annual precipitation divided by potential evapotranspiration and (2) the proportion of land area under cultivation). We also used multiple regression on the rank transforms of these explanatory variables to account for their covariation (Supplementary Note 11).

Limitations

Our analyses are based on the best available measurements but nonetheless have limitations. Here we detail some of these limitations and evaluate how some may affect our main conclusions.

- Although we have used several steps, as outlined above, to detect and remove outliers, we cannot independently verify the accuracy of all groundwater-level time series. Nevertheless, our analysis is based on several layers of robust estimation (for example, Theil–Sen regression on annual medians), minimizing its sensitivity to unreliable data.
- Groundwater-level data from individual monitoring wells span different time intervals and have different measurement frequencies, as detailed in Supplementary Note 12. Furthermore, about 41% of the analysed monitoring wells have discontinuous time series of annual groundwater levels (for which 'discontinuous' time series are defined as those lacking a groundwater-level measurement for at least one of the calendar years that lie between the earliest and most recent twenty-first century groundwater-level measurements; for an example of a discontinuity in an annual groundwater-level time series, see Supplementary Fig. 3c).
- We could not obtain groundwater-level data for many countries around the globe and our conclusions are only directly applicable where we have data. GRACE satellite data[1307–1311] suggest that groundwater storage has declined in some of the areas in which we lack monitoring-well data (Supplementary Note 8). Further, simulation results from a global model suggest that substantial groundwater depletion may have occurred in some of the countries in which we lack monitoring-well data, so groundwater-level deepening may be even more widespread than our results indicate (refs. 16,1312; Supplementary Note 14). We reviewed published and grey literature[20,427,802,1282,1313–1356] to obtain groundwater-level trends for some of the countries in which we lack monitoring-well data (that is, point data in Fig. 2; details available in Supplementary Note 15).
- We highlight that monitoring wells are not distributed evenly across each aquifer system. Consequently, some locations within aquifer systems are not captured by compiled monitoring-well data (see discussion of Dhaka (Bangladesh) in Supplementary Note 15). The aquifer-scale trends that we present in the main text (Figs. 2–4) do not provide insights into the spatial patterns of groundwater-level trends within individual aquifer systems. The high variability in monitoring-well densities within aquifer systems, as well as the substantial variability in groundwater-level trends even among co-located monitoring wells, are presented in a suite of maps for individual aquifer systems in Supplementary Notes 16 and 17. Specifically, our analysis demonstrates that groundwater-level trends can vary greatly among wells within individual aquifer systems (Fig. 1 and Supplementary Notes 16 and 17), implying that local-scale groundwater-level declines may be even more widespread than our Fig. 2 suggests (Supplementary Note 18). Some of the variability in groundwater-level trends among co-located wells may be partly explained by differences in the depths of nearby monitoring wells, as shallow and deep aquifers can have different groundwater-level trends (see Supplementary Note 19).
- We stress that groundwater-level trends may differ between deeper and shallower wells (for example, ref. 1357) owing to, for example, differences in the depths of nearby wells used to extract groundwater and differences in storage coefficients between unconfined and confined aquifers (see, for example, refs. 1358,1359). Steep groundwater-level trends—both upward and downward—are more common in deeper wells than in shallower wells, possibly due in part to the greater prevalence of confined conditions at deeper depths (discussion and analyses available in Supplementary Note 19). 2D geologic data are available at the global scale[1360], but an accurate high-resolution 3D hydrogeologic dataset remains unavailable for the globe, meaning that key hydrogeologic conditions (for example, whether the monitoring well captures unconfined versus confined conditions) cannot be ascribed for deep versus shallow wells at the global scale.
- We highlight that our approach to delineating boundaries for individual aquifer systems—although based on local-scale studies—potentially introduces inconsistencies, because local norms for delineating aquifer-system boundaries may differ. Further, some (16%) of the 170,000 monitoring wells fall outside the boundaries of the aquifer systems delineated here and, therefore, are excluded from our aquifer-scale statistical analyses. We present groundwater-level trends for monitoring wells both within and outside aquifer-system boundaries in a series of regional-scale maps (Supplementary Note 16).
- It is possible that some of monitoring-well-based time series may be truncated where the monitoring well itself has run dry (see ref. 1361), possibly excluding monitoring wells located in areas experiencing rapid groundwater depletion. We analysed monitoring-well depths and depth to groundwater data for 72,000 wells and conclude that it is possible that a small proportion of the groundwater-level time series was truncated owing to well desiccation (see Supplementary Note 20). Thus, rapid and accelerating twenty-first century groundwater-level deepening may be even more prevalent than our analysis indicates.
- Our main-text results are based on annual median groundwater levels. However, we acknowledge that trends in depth to groundwater can differ when based on measurements made during specific seasons (for example, long-term trends in pre-monsoon depth to groundwater can differ from long-term trends in post-monsoon depth to groundwater; see ref. 1362). We highlight that trends in season-specific groundwater levels may differ from trends in annual median groundwater levels (as presented in Fig. 1), especially where intra-annual groundwater-level variability is changing over time (for example, time series from the Bengal basin in Supplementary Note 21; see also the time series presented in refs. 21,1363,1364).

- The compiled groundwater-level time series do not allow us to infer trends over longer (for example, centennial-scale) time intervals. In some areas, substantial groundwater-level changes took place long before the four decades that we focus on here. For example, there is evidence[1365,1366] that substantial accumulation occurred during the twentieth century in parts of South Asia and that groundwater levels were much deeper at the start of the twentieth century than they are today (see, specifically, Fig. 3b in ref. 1365). Some aquifer systems in our dataset, for example, may have been heavily depleted during the mid-twentieth century, but have exhibited relatively stable groundwater levels (or even shallowing groundwater-level trends) during the twenty-first century. Given the potential for such cases, we make no claim that stable twenty-first century groundwater levels necessarily imply a lack of previous or continuing disturbance.
- We do not make claims about aquifer-specific drivers behind rapid and accelerating groundwater declines (although we do make note of case studies in the literature that have identified important drivers; for example, ref. 25). We acknowledge that groundwater abstractions can perturb flow systems and, in many cases, deplete aquifers. Many of the aquifer systems exhibiting rapid groundwater-level declines are being accessed by wells, as evidenced by recorded well-completion events throughout the early twenty-first century (Supplementary Note 22; data described in refs. 17,1367–1369) and by regional-scale research[108,1370,1371]. Further, we acknowledge that climate variability and change can have both direct impacts on groundwater levels (such as through changes in groundwater recharge owing to, for example, changes in temporal variability in precipitation) and also indirect impacts on groundwater levels (for example, through changes in groundwater demand in response to climate variability, such as increased groundwater withdrawals during drier time intervals; see ref. 27). Available precipitation data[1372,1373] suggest that most of the aquifer systems characterized as exhibiting accelerating groundwater-level declines (that is, red points in Fig. 3) are situated in areas in which early twenty-first century annual precipitation rates were lower than late twentieth century annual precipitation rates (Supplementary Note 10), highlighting that, at a minimum, we cannot rule out an influence of climate variability (direct or indirect) on groundwater-level changes over time.

Data availability

Annual groundwater-level data are available for download in all cases for which we have received permission from a database manager to post data (data are available from Zenodo (https://doi.org/10.5281/zenodo.10003697) and CUAHSI HydroShare (https://www.hydroshare.org/resource/da946dee3ada4a67860d057134916553/)); these datasets include groundwater-level data for: Afghanistan[1289], Austria, Belgium, Brazil, Bulgaria, Canada (Alberta, British Columbia, Manitoba, Northwest Territories, Ontario, Prince Edward Island, Saskatchewan, Yukon), China[1290], Croatia, Czech Republic, Denmark, France[1291], Germany, Guam, Ireland, Israel, Italy, Latvia, Lithuania, New Zealand, Norway, Paraguay, Poland, Slovenia, Sweden, Switzerland and the USA (Groundwater Ambient Monitoring and Assessment Program, U.S. Geological Survey's (USGS) National Water Information System and the Texas Water Development Board). The databases for which we have received written permission to post annual groundwater-level data encompass 59% of annual groundwater-level data analysed here (specifically, we received permission to post 66% ($n = 4,170,802$ of $n = 6,314,793$) of all annual 'depth to groundwater' data and 18% ($n = 190,879$ of $n = 1,049,502$) of all 'groundwater elevation' data). These datasets are specified in Supplementary Table 1 (see column entitled 'Written permission received to post annual groundwater-level data'). Source data for each of the main-text figures are available here. Supplementary tables associated with this work are available at https://doi.org/10.5281/zenodo.10003697. Geospatial data for the 1,693 aquifer systems studied here are available from CUAHSI HydroShare (https://www.hydroshare.org/resource/73834f47b8b5459a8db4c999e6e3fef6/) and Zenodo (https://doi.org/10.5281/zenodo.10003697). Source data are provided with this paper.

Code availability

Analyses presented here do not depend on specific code; the approach can be reproduced following the procedures described in the Methods section.

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Additional information

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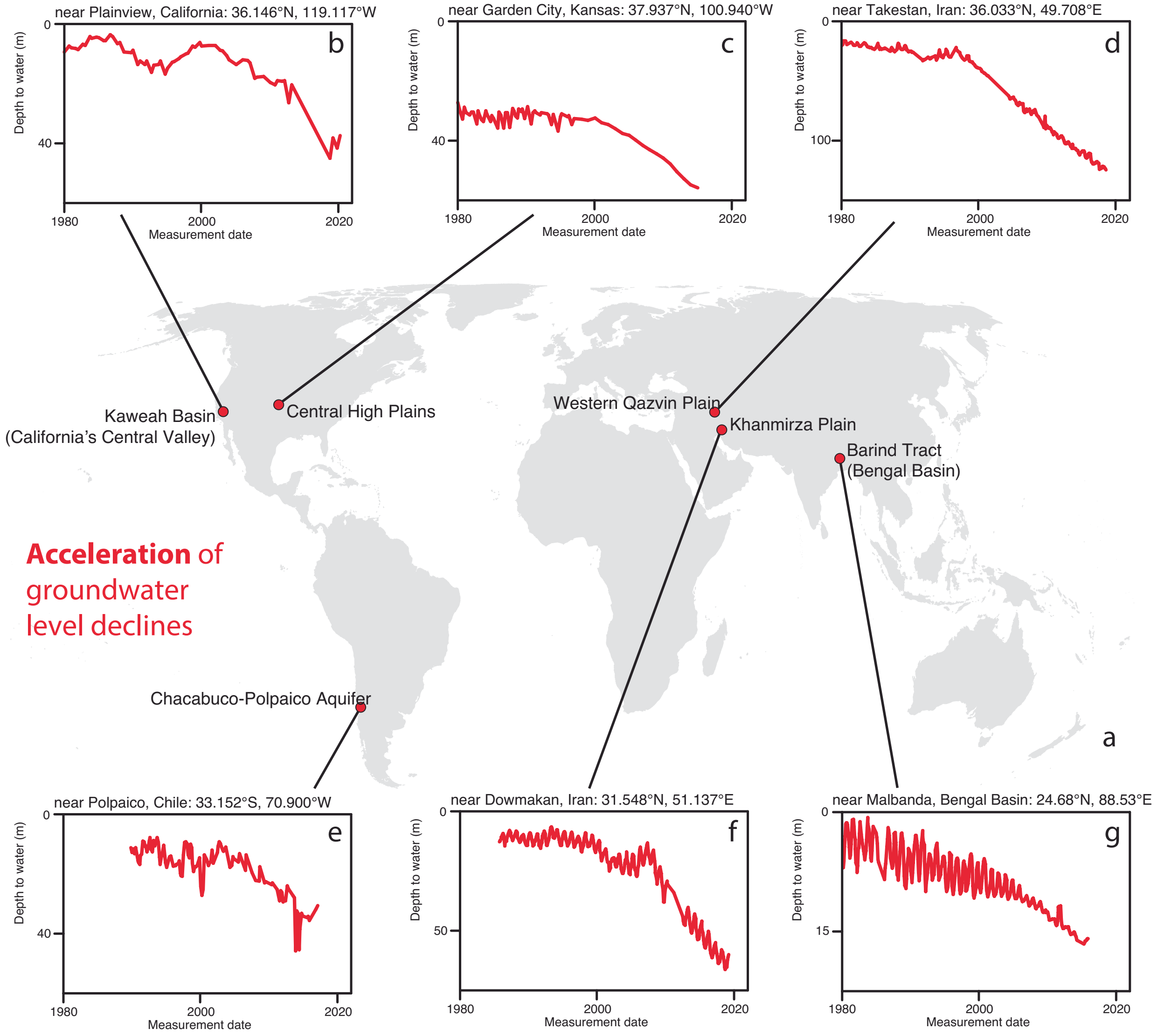
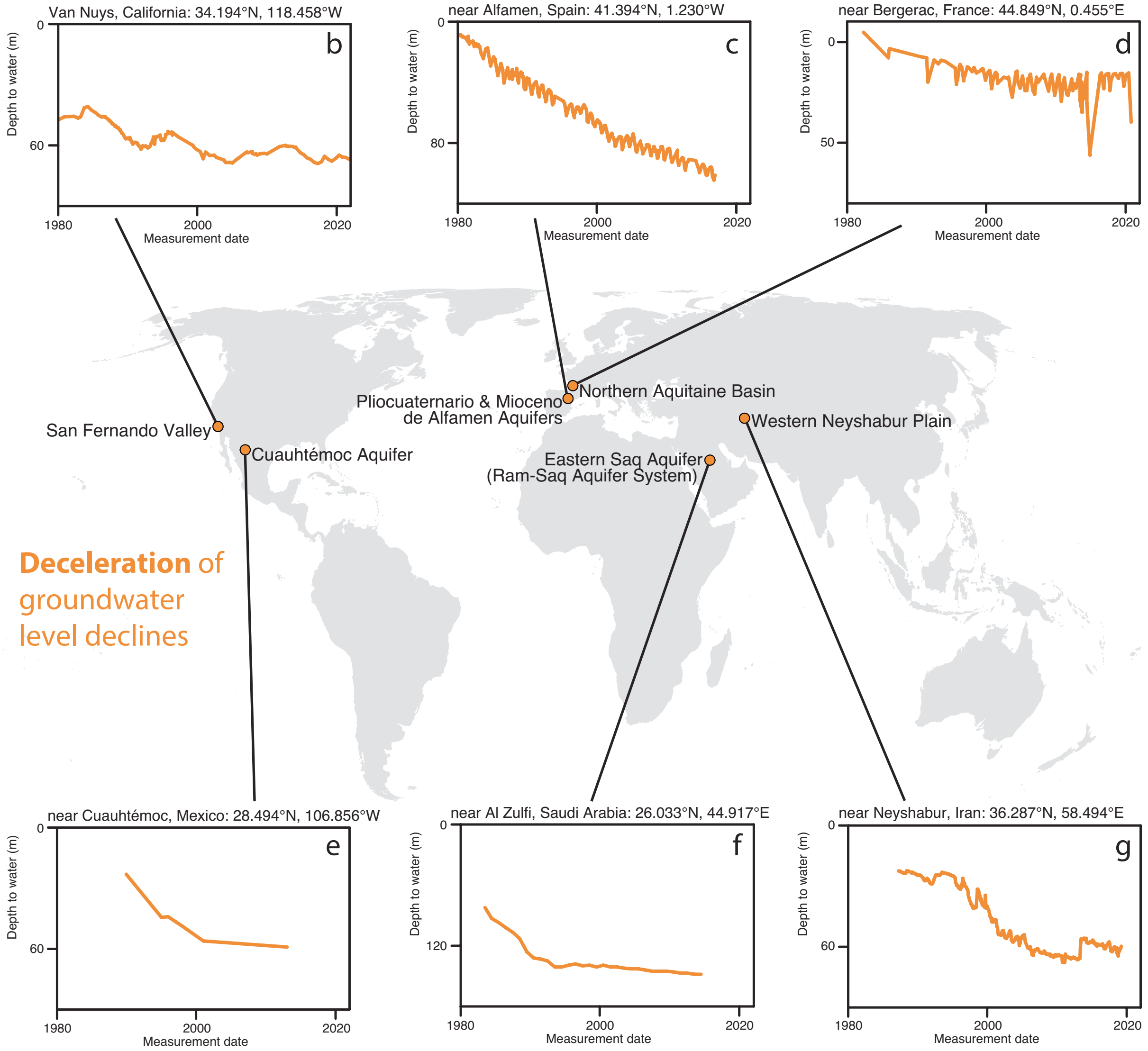
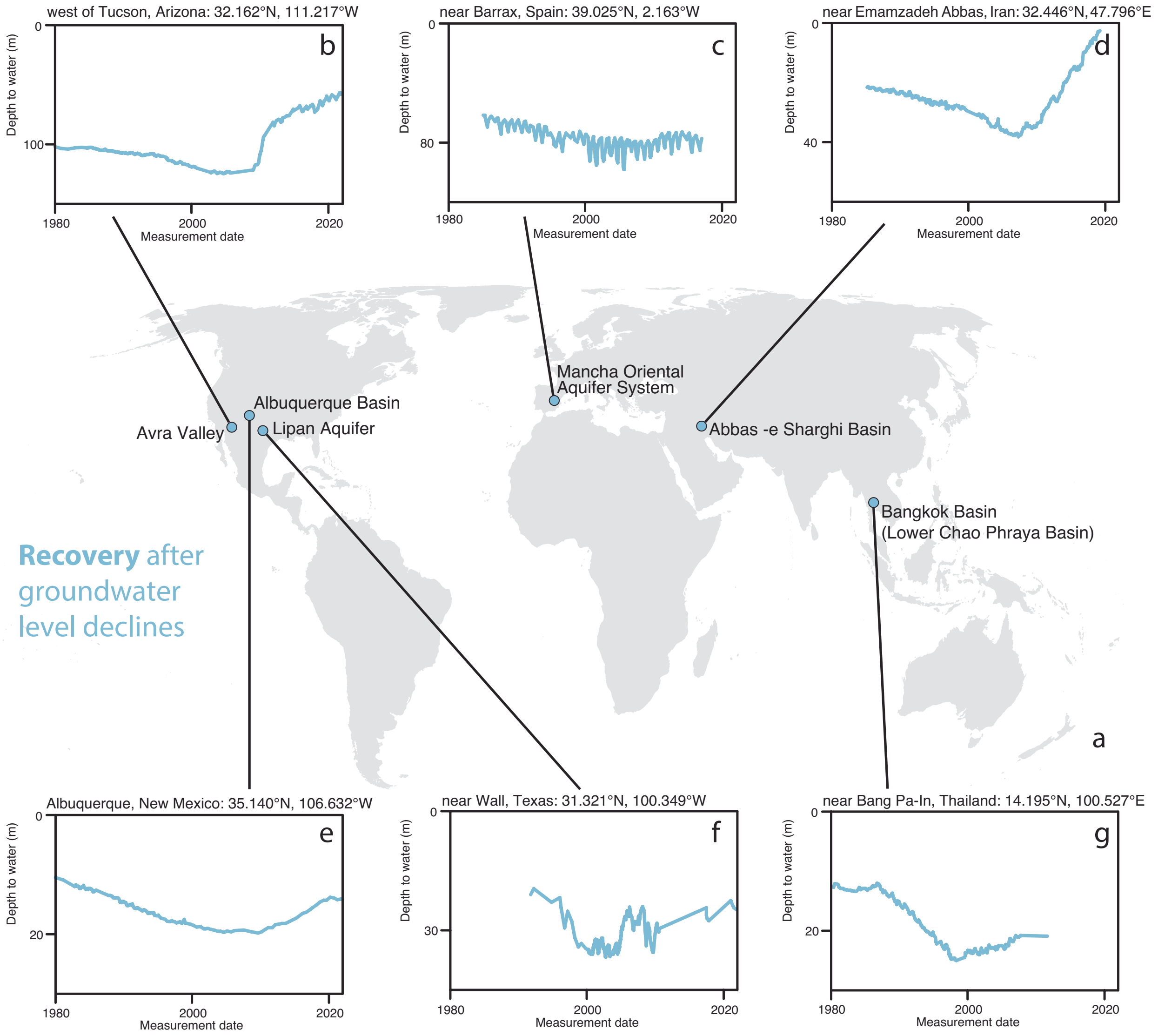


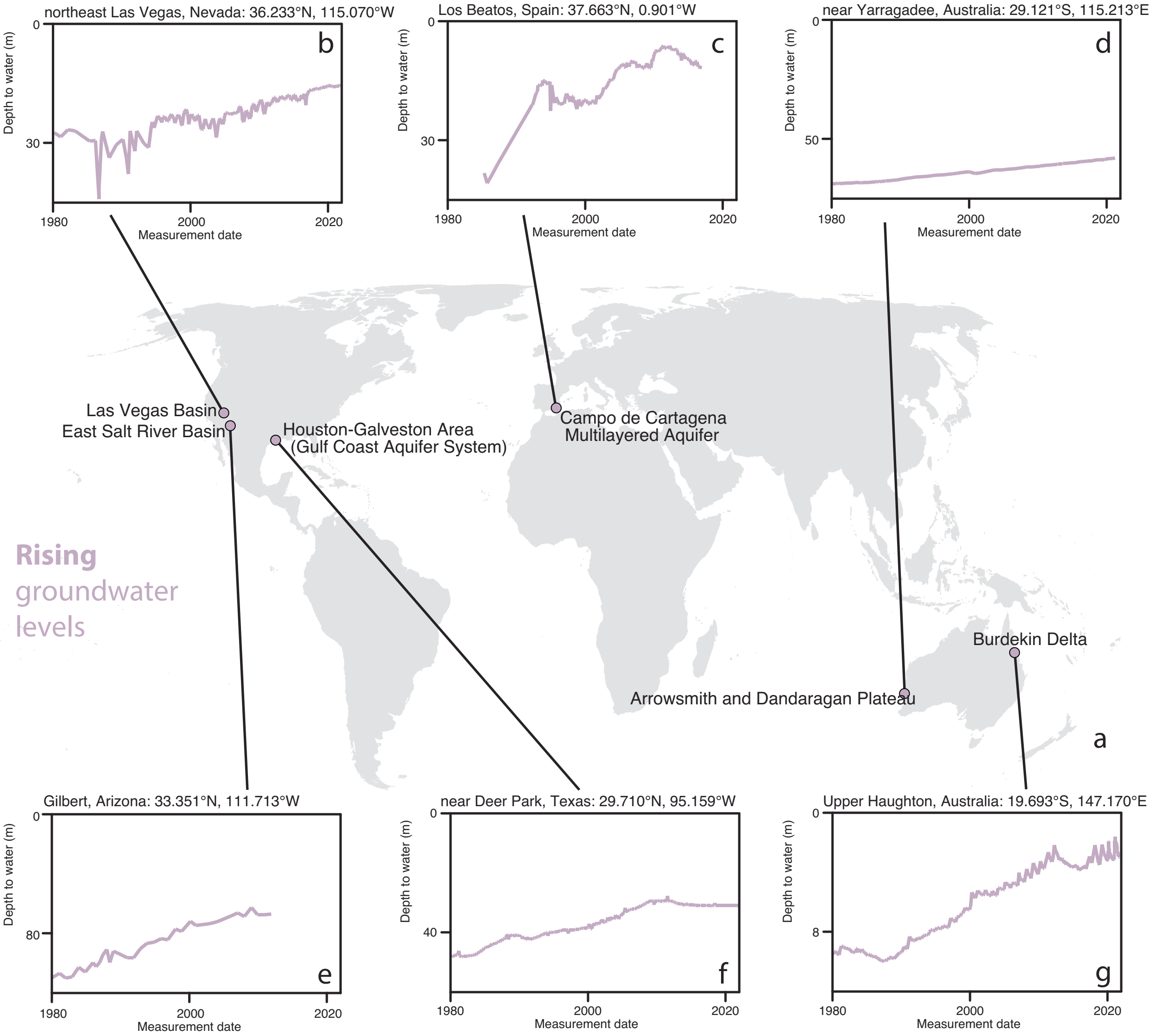
Extended Data Fig. 1 | Illustrative examples of individual monitoring wells that record cases for which groundwater levels declined during late twentieth century and continued to decline at a faster rate in the early twenty-first century (that is, accelerated deepening). a, Global map depicting the locations of the six monitoring wells (that is, each point represents one monitoring well). The aquifer system that each monitoring well lies in is labelled next to each point. **b**–**g**, Measured groundwater-level variations over time for individual monitoring wells. Each panel presents groundwater-level data for a single monitoring well.



Extended Data Fig. 2 | Illustrative examples of individual monitoring wells that record cases for which groundwater levels declined during late twentieth century and continued to decline but at a slower rate in the early twenty-first century (that is, decelerated deepening). a, Global map depicting the locations of the six monitoring wells (that is, each point represents one monitoring well). The aquifer system that each monitoring well lies in is labelled next to each point. **b**–**g**, Measured groundwater-level variations over time for individual monitoring wells. Each panel presents groundwater-level data for a single monitoring well.



Extended Data Fig. 3 | Illustrative examples of individual monitoring wells that record cases for which groundwater levels declined during late twentieth century but rose during the early twenty-first century (that is, cases of groundwater level recovery). **a**, Global map depicting the locations of the six monitoring wells (that is, each point represents one monitoring well). The aquifer system that each monitoring well lies in is labelled next to each point. **b**–**g**, Measured groundwater-level variations over time for individual monitoring wells. Each panel presents groundwater-level data for a single monitoring well.



Extended Data Fig. 4 | Illustrative examples of individual monitoring wells that record cases for which groundwater levels rose during late twentieth century, and continued to rise during the early twenty-first century. **a**, Global map depicting the locations of the six monitoring wells (that is, each point represents one monitoring well). The aquifer system that each monitoring well lies in is labelled next to each point. **b**–**g**, Measured groundwater-level variations over time for individual monitoring wells. Each panel presents groundwater-level data for a single monitoring well.