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Revised manuscript entitled: Widespread potential loss of streamflow into underlying aquifers across USA

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Most rivers exchange water with surrounding aquifers[1,2]. Where groundwater levels lie below nearby streams, streamwater can infiltrate through the streambed, reducing streamflow and recharging the aquifer[3]. These 'losing' streams have important implications for water availability, riparian ecosystems, and environmental flows[4-10], but the prevalence of losing streams remains poorly constrained by continent-wide in-situ observations. Here we analyze water levels in ~4.2 million wells across the contiguous United States and show that nearly two-thirds (64%) of them lie below nearby stream surfaces, implying that these streamwaters will seep into the subsurface if it is sufficiently permeable. A lack of adequate permeability data prevents quantifying these flows, but our analysis nonetheless demonstrates widespread potential for streamwater losses into underlying aquifers. These potentially losing rivers are more common in drier climates, flatter landscapes, and regions with extensive groundwater pumping. Our results thus imply that climatic factors, geological conditions, and historic groundwater pumping jointly contribute to the widespread risk that streams lose flow into their surrounding aquifers instead of gaining flow from them. Recent modeling studies[10] have suggested that losing streams could become common in future decades, but our direct observations show that many rivers across the USA are already potentially losing, highlighting the importance of coordinating groundwater and surface water policy.

Hydraulic gradients and subsurface permeability control the exchanges of water between aquifers and rivers[1-3], increasing streamflow where groundwaters feed rivers (‘gaining rivers’), and decreasing streamflow where river waters seep into underlying aquifers (‘losing rivers’). Distinguishing gaining rivers from losing rivers is important for (a) protecting aquatic habitat[4-10], (b) estimating groundwater recharge[11], (c) quantifying fluvial nutrient cycling[12] and river primary productivity[13], (d) understanding how stream networks and landscapes evolve[14], (e) predicting where polluted groundwater may enter stream channels[15], (f) assessing CO_2 release from streams[16-18], (g) evaluating stream vulnerability to climatic variations[19], and (h) managing groundwater and surface water resources[1-10,20].

Our current understanding of gaining and losing reaches is based on local-scale studies (e.g., Fig. 1a) and hydrological models. Local-scale studies of gaining rivers show that groundwater can feed streams via spatially diffuse seeps and focused discharges at springs[15]; conversely, studies of losing rivers demonstrate how groundwater withdrawals can induce streamwater seepage into underlying aquifers[3]. Both groundwater influxes to streams and streamwater seepage into aquifers can be inhibited by low-permeability sediments[21,22]. The 77 local-scale studies we reviewed (Supplementary Table 1) suggest that losing rivers may be more common in drier landscapes and flatter terrain, especially where groundwater pumping is extensive (Fig. 1b). Local-scale studies are the foundation for our understanding of groundwater interactions with surface waters, providing conceptual frameworks that are relevant beyond just these individual field sites[23].

Because the large spatial gaps between these local-scale studies (Fig. 1a) make it difficult to assess the prevalence and spatial extent of losing versus gaining rivers, attempts to predict gaining and losing conditions at continental scale generally rely on hydrological models to simulate stream-aquifer exchanges[10,24,25]. These continental-scale models can be challenging to verify, however, because the necessary input variables (e.g., groundwater recharge and pumping rates) and model parameters (e.g., subsurface permeability) are difficult to constrain. Moreover, evaluating model outputs requires comparing them to the "ground truth" of densely distributed observations, which have been previously unavailable at continental scale.

[Fig. 1 about here]

Assessing stream-aquifer exchanges across the United States requires combining the strengths of the two approaches outlined above: using field observations to measure the local relationships between streams and their aquifers, but doing so at continental scale to reveal large-scale patterns and processes. Here we analyze millions of well water level observations to evaluate the prevalence and spatial distribution of potentially gaining and losing rivers across the contiguous United States, and to test how the prevalence of potentially losing streams is shaped by climate, physiography, and groundwater pumping. Here, we use the term "losing" to refer to streams whose water levels lie above those in adjacent wells, and thus could potentially drain into their underlying aquifers; however, we stress that the magnitude of any actual streamflow losses will depend on the permeability of the subsurface.

Millions of water level observations

We analyze groundwater level measurements in ~4.2 million wells across the United States (Supplementary Figs. 5-7). All water levels were measured when the wells themselves were not being actively pumped, but they may be affected by pumping in nearby wells. Most of the water level measurements were compiled from 64 unique state or sub-state databases of well completion reports[26-28] (Supplementary Table 5). Water levels recorded in these well completion reports are consistent with those in nearby monitoring wells, implying that these data reflect prevailing groundwater levels at the time of observation (see ref.[28] and Supplementary Fig. 4). We emphasize that our dataset inherently over-represents areas where hydrogeologic conditions have been disturbed by pumping, because well water levels can only be measured where wells have been drilled.

We identified gaining and losing streams by comparing the elevation of each well water level to the elevation of the nearest stream (e.g., Fig. 2a-c, see Methods). We converted each well's water level (below the land surface) to its elevation (above sea level) using digital land surface topography[29] (see Methods). Next, for each well, we obtained the elevation of the nearest point on the nearest stream from the National Hydrography Dataset[29]. We then compared the water level elevations in the well and the nearby stream to distinguish potentially gaining streams (i.e., where the well water level lies above the nearest stream; Fig. 2a) from potentially losing streams (i.e., where the well water level lies below the nearest stream; Fig. 2b). Although these water level differences can identify potentially gaining and losing streams, quantifying stream-aquifer fluxes would require high-resolution three-dimensional permeability data that are presently unavailable at continental scale. This lack of high-resolution hydrogeologic data also means that we cannot resolve two-dimensional cross sections of groundwater flow fields, and thus cannot capture flow patterns in some complex aquifer systems.

Even the best national-scale US digital elevation datasets[30] (i.e., 10 m and 30 m resolution) usually capture the elevation of streambanks rather than the water surfaces themselves. We therefore estimated the water-surface elevation by subtracting the corresponding bank height of each stream segment[31] in the National Hydrography Dataset from the mapped stream elevation[29] (Supplementary Section S4). We limited our analysis to wells within 1 km of the nearest streambank, and to wells no deeper than 100 m below ground (see sensitivity analyses in Supplementary Sections S4.1-S4.2).

Losing rivers are common near wells

Nearly two-thirds (64%) of our ~4.2 million wells have water levels that lie below their nearest stream, implying a hydraulic gradient that will drive seepage from the channel into the underlying aquifer, provided that the channel contains water and the subsurface is sufficiently permeable (Fig. 2c). Among river segments with at least one well nearby, nearly two-thirds (64%) represent potentially losing rivers, as indicated by water-surface elevations that lie above more than half of all nearby well water levels (Fig. 3). Because we can only analyze river segments with at least one well nearby (~580,000 segments, representing 22% of all National Hydrography Dataset segments), our results inevitably reflect regions where wells pump groundwater, and we cannot quantify the prevalence of potentially losing rivers where wells are absent.

Our results show that well water levels that lie below nearby stream surfaces—indicative of losing streams—are common across much of the contiguous United States. These results are robust across a suite of sensitivity analyses (Supplementary Sections S4.1-S4.5), including (a) reducing the well depth threshold from 100 m to 25 m, (b) reducing the well-to-streambank distance threshold from 1 km to 250 m, and (c) repeating our analysis with 10 m instead of 30 m digital elevation data. Our results also generally agree with dozens of local-scale studies of gaining versus losing rivers, providing further confidence in our main findings (Supplementary Tables 2-4; Supplementary Fig. 3).

Because the great majority of our study wells were drilled for groundwater extraction rather than water level monitoring, our analysis is weighted toward irrigated and populated areas with groundwater pumping. Well water levels that lie below nearby stream surfaces are common in areas with longstanding groundwater depletion, such as California's Central Valley, the central and southern High Plains, and the Mississippi Embayment (Fig. 2). Our analysis also reveals a substantial likelihood of losing rivers in regions that are not widely considered to be groundwater depletion hotspots, including Midwestern states near the Great Lakes, Idaho's Snake River Plain, central Washington State, and Oregon's Willamette Valley (Fig. 3).

By contrast, well water levels frequently lie above nearby stream surfaces—consistent with gaining rivers—in the northeastern United States, much of Appalachia, and west of the Atlantic

Seaboard Fall Line dividing the coastal plain from the uplands in North and South Carolina. Well water levels also lie above nearby streams in many high-relief landscapes, such as the Rocky Mountains of Colorado, the Oregon Coast Range, and the Cascade Mountains (Fig. 2).

[Figs. 2 and 3 about here]

Climate, topography and pumping

Our meta-analysis of 77 local-scale studies (Supplementary Table 1) suggests that losing rivers may be more common where climate conditions are drier, topographic slopes are flatter, and groundwater withdrawals are greater (Fig. 1b). These hypotheses are confirmed, at continental scale, by our analysis of 4.2 million wells and their nearest stream segments (Fig. 4). The fraction of well water levels lying below the nearest stream—consistent with losing rivers—is significantly correlated with county-scale averages of groundwater withdrawals[32] (Spearman rank correlation $\rho = 0.32$), topographic slope[29] ($\rho = -0.33$) and precipitation divided by potential evapotranspiration[33] ($\rho = -0.38$; all correlations are statistically significant at $p < 0.0001$). Although these correlations exhibit considerable scatter (Supplementary Fig. 24), they suggest that all of these variables substantially influence the prevalence of losing streams at continental scale.

These three explanatory variables are also themselves inter-related, since groundwater use is more common in arid regions and in flatter landscapes where irrigated agriculture is more widespread. These interrelationships can be taken into account by multiple regression on the rank transforms of each variable[34]. The resulting partial regression coefficients (β=0.22 for groundwater withdrawals, β=−0.33 for precipitation divided by potential evapotranspiration, and β=−0.22 for topographic slope; all statistically significant at $p < 0.0001$) estimate the rank correlations between the prevalence of losing rivers and each explanatory variable, while accounting for its correlations with the other explanatory variables. These statistical relationships support the hypotheses that losing streams are (i) more common in arid climates than in humid climates (Fig. 4b), (ii) more common in flatter landscapes than in steeper terrain (Fig. 4c), and (ii) more common in areas where groundwater withdrawals are higher (Fig. 4d). Although slope, pumping and aridity all correlate significantly ($p < 0.0001$) with the proportion of well water levels that lie below the nearest stream, the high fraction of unexplained variance suggests that other factors may also play important roles in stream-aquifer exchanges (R^2=0.27; see also Supplementary Fig. 24).

[Fig. 4 about here]

Groundwater-streamwater exchanges

Near-stream groundwater pumping can deplete streamflow by either (i) withdrawing groundwater that would otherwise seep into the stream, or (ii) lowering the hydraulic head below the stream surface, creating the potential for the stream itself to drain into the underlying aquifer[1,3]. Our analysis shows that this second and more extreme scenario—in which groundwater levels lie below streams—already dominates many areas where groundwater wells are widespread. This finding remains largely unchanged even when we restrict our analysis to well water levels measured between 1940 and 1980, implying that losing rivers have been common for decades across much of the contiguous United States (Supplementary Section S4.3). Whereas recent model simulations[10] have projected that losing streams may become more common in future decades, our data demonstrate that they are already prevalent here and now.

Our analysis demonstrates the significant ($p < 0.0001$) relationship between groundwater pumping and losing streams across the USA (Fig. 4). Groundwater-use data[32] are highly uncertain across most of the United States[35] because few jurisdictions mandate metering and reporting[36]. Better groundwater-use data might reveal a stronger correlation between groundwater withdrawals and losing streams. For example, the correlation between pumping and losing streams strengthens from $\rho = 0.32$ to $\rho = 0.72$ if we consider only counties within Kansas, where extensive groundwater-use data are available[37] and climate and topography are more uniform than across the nation as a whole (Supplementary Fig. 16).

Although our analysis cannot be directly translated into management prescriptions for individual river reaches, it demonstrates that losing rivers are widespread and it identifies conditions under which they are more prevalent. Losing streams tend to be more common where climate is drier and topography is flatter (Fig. 4), implying that natural climatic and geologic conditions are important controls on the direction of flows between aquifers and streams. Our continent-wide data support a conceptual model of streamflow generation[19] in which streams gain flow in steeper headwaters, only to lose flow to groundwater recharge in alluvial fans in mountain foothills. For example, well water levels often lie above nearby streams in mountain headwaters, but below these same rivers farther downstream (e.g., the Arkansas River draining Colorado's Rocky Mountains, or the Cosumnes River draining California's Sierra Nevada; Fig. 3c). These examples suggest that losing rivers may recharge aquifers that in turn may support irrigated agriculture and groundwater-dependent ecosystems in lowland basins (e.g., ref.[38]).

Groundwater reserves are being drawn down in numerous aquifers across the United States, accounting for 11% of global groundwater depletion[39]. If water tables continue to decline in these aquifers, losing rivers will become more widespread. Our data imply that just 2 m of additional water table drawdown would increase the fraction of well water levels lying below nearby streams from 64% to 74% (Supplementary Figs. 19-20), thus substantially increasing the prevalence of losing rivers.

Almost half (48%) of our well water levels are within five meters of the nearest stream-surface elevation, implying that modest changes in groundwater levels can substantially alter the rate or direction of flows between aquifers and streams. In some jurisdictions, groundwater pumping permit applications are evaluated for their likely effects on streamflow[40], providing an opportunity to avoid or limit streamflow depletion. In some regions, aquifer recharge from excess surface flows has been used to offset groundwater withdrawals[41,42]. Our work shows that losing rivers are prevalent across the contiguous United States, emphasizing the widespread importance of managing groundwaters and surface waters as the interconnected resources that they are[1].

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Figure captions

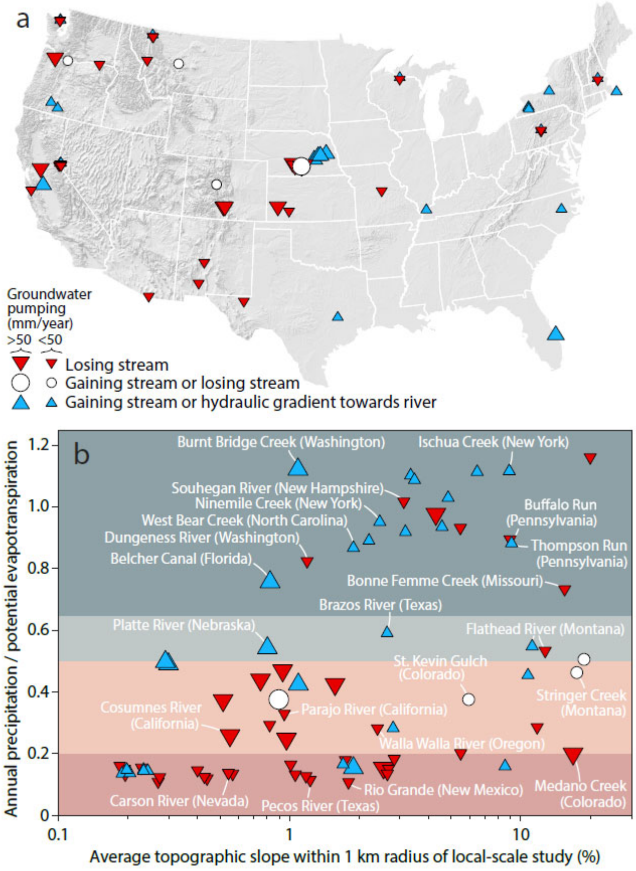

Fig. 1. Local-scale studies of stream-aquifer exchange. (a) Red downward-pointing triangles represent studies documenting ‘losing’ conditions. Blue upward-pointing triangles represent studies documenting (i) a hydraulic gradient from the aquifer toward the river, and/or (ii) seepage of groundwater into the stream (‘gaining conditions’). White circles represent studies where it was unclear whether gaining or losing conditions prevailed. Larger versus smaller symbols indicate whether estimated county-averaged groundwater withdrawals were greater or less than 50 mm/year, respectively, in 2015 (ref.[32]). (b) Losing versus gaining conditions plotted in the context of topographic slope[29] on the horizontal axis and the ratio of precipitation to potential evapotranspiration[33] on the vertical axis. Background shades represent different climate classifications, ranging from arid (light red shading) to humid (greenish-blue shading). Losing reaches are more common in flat and arid regions and gaining reaches are more common in steep and humid areas, but both gaining and losing reaches are found at almost all combinations of aridity and topographic steepness. For an expanded version see Supplementary Figs. 1 and 2; for primary references for each local-scale study see Supplementary Table 1.

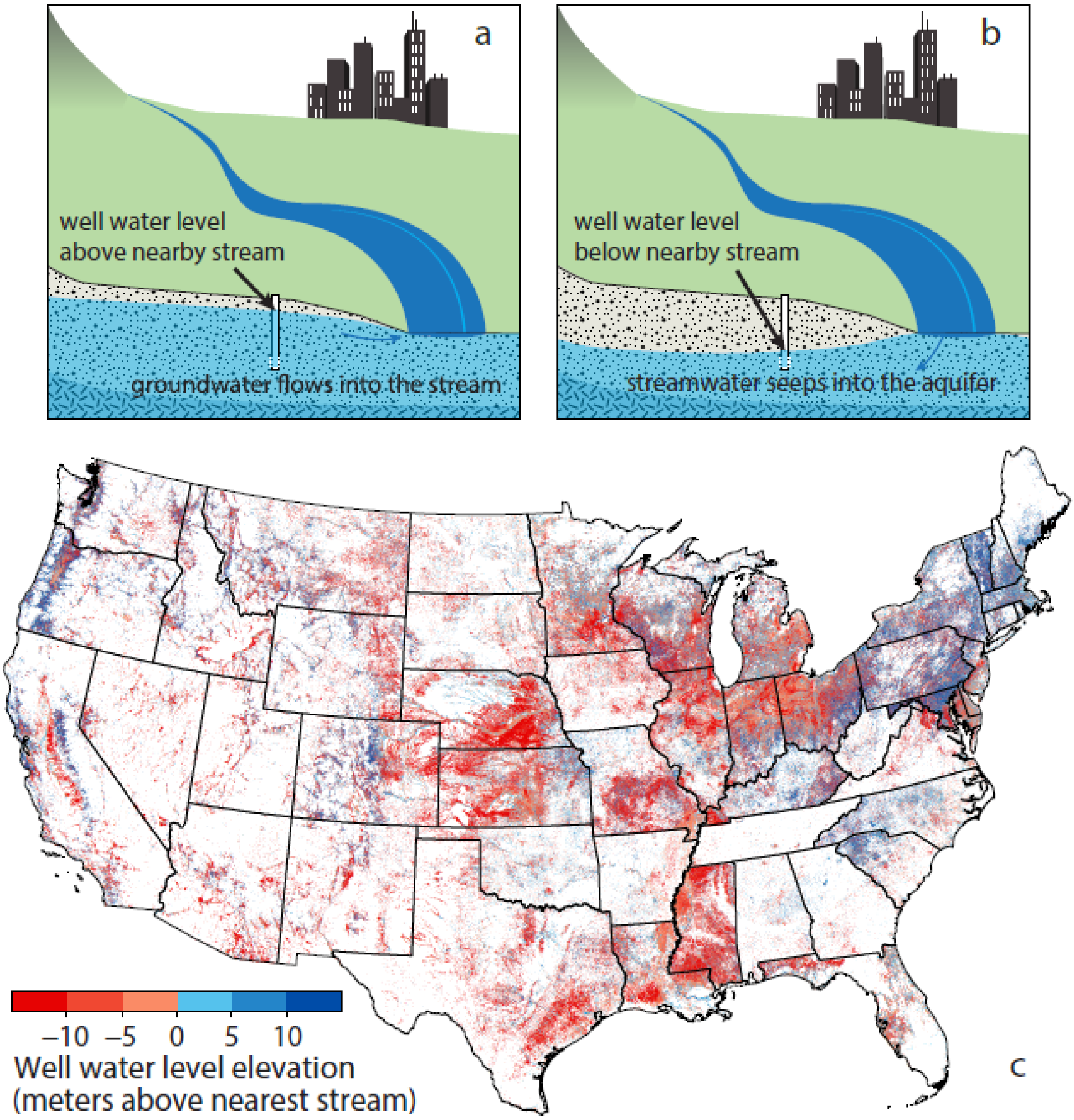

Fig. 2. Comparison of well-water and stream-surface elevations. (a) Cross-section of a gaining stream and its aquifer; the near-stream water table is higher than the stream surface, driving groundwater flow toward the stream. (b) Cross-section of a losing stream and its aquifer; the near-stream water table is below the stream surface, and groundwater flows away from the stream. (c) Calculated differences between each near-stream well water elevation and the elevation of the nearest stream. Only wells within 1 km of a river and shallower than 100 m are shown (totaling ~4.2 million wells). Most well water levels lie above stream surfaces in the northeastern United States and in some high-relief areas (dark blue; see schematic in panel (a)). Most well water levels lie below stream surfaces in central California, the Great Plains and the Mississippi Embayment (dark red; see schematic in panel (b)).

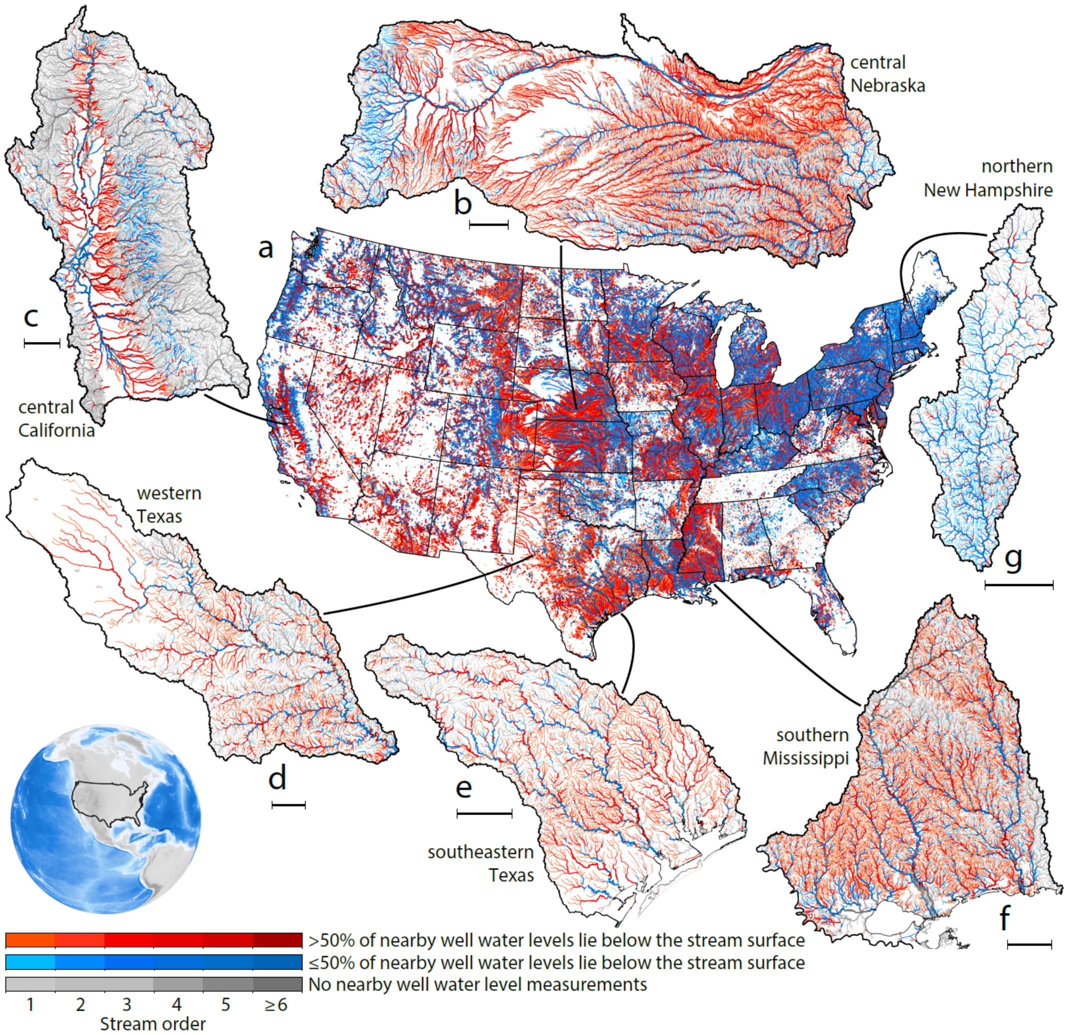

Fig. 3. Prevalence of potentially losing and gaining rivers across the USA. National Hydrography Dataset stream segments are colored according to the fraction of nearby wells with water levels that lie above or below the stream surface. Blue lines represent National Hydrography Dataset stream segments where half or more of nearby (<1 km) wells have water levels that lie above the nearest stream surface. These potentially gaining streams are prevalent in the northeastern states and in areas with high topographic relief. Red lines represent stream segments where more than half of nearby wells have water levels that lie below the nearest stream surface. These potentially losing streams are common in drier climates and flatter landscapes, and where groundwater pumping rates are high (e.g., western Texas). Lower-order stream segments are more likely than higher-order stream segments to be potentially losing (Supplementary Fig. 25). (a) We present ~580,000 stream segments across the contiguous United States, representing 1.7 million kilometers of river segments in total. (b-g) Six maps surrounding the main figure magnify selected regions: (b) central Nebraska, (c) central California, (d) western Texas, (e) southeastern Texas, (f) southern Mississippi, and (g) northern New Hampshire. Each horizontal scale bar depicts 50 km. For alternate displays of these data see Supplementary Figs. 21-23.

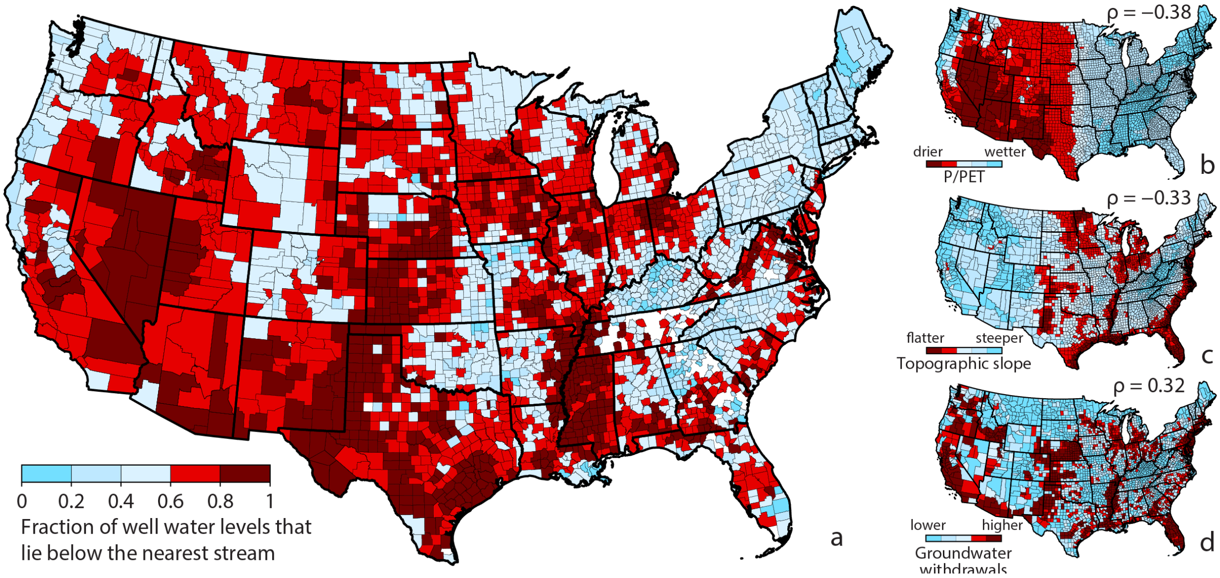

Fig. 4. The prevalence of losing conditions in relation to climatic aridity, topographic slope and groundwater withdrawals. (a) The fraction of wells with water levels that lie below the nearest stream across US counties. Red and blue shades indicate high and low prevalence of losing conditions. (b-d) County-averaged precipitation divided by potential evapotranspiration[33] (P/PET), topographic slope[29], and annual groundwater withdrawals[32]. Rank correlations between these county-scale data and the prevalence of losing conditions (panel a) are shown above the maps in panels (b-d); all are statistically significant at $p < 0.0001$. Corresponding scatterplots are presented in Supplementary Fig. 15.

Methods

Extensive details regarding sensitivity analyses, methodology, and data descriptions are available in the Supplementary Information (see also refs. [43-89]).

Well-water Elevations Versus Nearby Stream Elevations

We analyzed water level observations from 4.2 million wells[26-28] that are (i) no more than 1 km from the bank of the nearest river (as determined by the distance from the well to the river centerline from the National Hydrography Dataset[29], minus half of the estimated channel width[43] at that location), and (ii) no more than 100 m below the land surface (to avoid analyzing well water levels in deeper aquifers that are less likely to reflect stream-aquifer connectivity; Supplementary Fig. 6). We converted well water levels (below the land surface) to elevations (above sea level) by subtracting them from the land surface elevation[29] at each well.

For each well, we identified the nearest stream segment in the National Hydrography Dataset (version "NHDPlusV2", ref.[29]), and extracted the elevation of the stream as recorded in the digital topographic data that accompany the NHDPlusV2 Dataset. We adjusted for streambank height, under the assumption that our digital elevation and hydrography data primarily capture the elevations of valley floors and floodplains rather than water surfaces (see Supplementary Fig. 5). Bankfull depth estimates[31] are available for nearly all stream segments in the National Hydrography Dataset. In cases where rivers are wide enough that the National Hydrography Dataset and digital elevation data capture the water surface elevation, our bank height adjustment further lowers the water surface in our calculations, making our estimate of the fraction of losing rivers conservative. We calculated the difference between each well water elevation and the elevation of the nearest point on the nearest stream (Fig. 2 and basis for statistics in Fig. 4) straightforwardly as: well water elevation minus nearest stream surface elevation (corrected for riverbank height).

County-Scale Geospatial Analyses

For each county, we calculated the fractions of well water levels lying below the nearest stream (Fig. 4a), and compared them to county-averaged values of three potential explanatory variables: (i) annual precipitation divided by potential evapotranspiration[33], (ii) topographic slope[29], and (iii) annual groundwater withdrawals[32] (estimated groundwater withdrawals[32] for the year 2015 normalized by county area; see Supplementary Fig. 18). These comparisons are made at the county scale because groundwater withdrawal data are only available at this scale across the United States[32]. Our county-level analysis omits counties with less than n=3 wells reporting at least one water level measurement. Our findings are not substantially changed if we re-run our county-level analysis with thresholds of 5, 10, 20, 30, 40 or 50 wells (Supplementary Table 16). Similarly, our correlations remain robust if we analyze 50 km by 50 km grid cells instead of county-level data (Supplementary Fig. 17).

Limitations to our analyses

Because no locally relevant, high-resolution three-dimensional database of permeability exists at continental scale, only the potential for rivers to lose or gain (rather than the fluxes of actual losses or gains) can be evaluated with confidence across the USA. Another limitation of our analysis arises from the lack of water level time series for most wells; because most of our wells have just one water level measurement, we cannot evaluate temporal variations in gaining versus losing conditions, nor can we assess the impact of seasonal fluctuations in climate and groundwater withdrawals on stream-aquifer exchanges. Furthermore, imprecise well location data and the coarseness of the digital elevation data we analyze (30 m by 30 m, or 10 m by 10 m) will lead to uncertainty in land surface elevations and, therefore, in our estimate of hydraulic heads, although these uncertainties should not substantially bias our assessment of the relative prevalence of losing and gaining conditions.

Sensitivity Analyses

We tested the sensitivity of our results to assumptions embedded in our analysis (Supplementary Fig. 8), namely: (i) the maximum distance of wells from their nearest river bank, beyond which they are considered too far to provide insights into groundwater-river connectivity (Supplementary Section S4.1), (ii) the maximum depth of wells, beyond which they are considered too deep to represent shallow unconfined aquifer systems (Supplementary Figs. 10-12; Supplementary Section S4.2; for a comparison of well depths and the depths of the top of the shallowest screen interval see Supplementary Fig. 9), (iii) the time intervals during which well water level measurements were made (Supplementary Fig. 14; Supplementary Section S4.3; time-series of total USA groundwater pumping in Supplementary Fig. 13), (iv) the spatial resolution of digital elevation and hydrography data (Supplementary Section S4.4), and (v) the impact of imperfections in river polylines and land-surface elevation data in river valleys (Supplementary Section S4.5). Our results are robust across this suite of sensitivity analyses (Supplementary Sections S4.1-S4.5).

Data availability

Well water level datasets are available from state and sub-state agencies. Some states only share their groundwater-well data through requests to their various agencies or through public records requests. We have permission to share state-wide groundwater well construction data for California, Colorado, Idaho, Kentucky, Mississippi, Montana, Nevada, Oklahoma, South Carolina, Texas, Utah and Washington, and we share these data as a supplementary file. Websites for direct download and contact information for requesting access to the original well completion report data for all states are detailed in refs.[26-28] and summarized in Supplementary Table 5. Monitoring well water level data are available from the US Geological Survey (waterdata.usgs.gov/nwis/inventory) and California's GAMA Program (gamagroundwater.waterboards.ca.gov/gama/gamamap/public). We have posted tables used to generate the spatial data shown in Figs. 3 and 4 as supplementary files.

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Code availability. Requests for code linked to the described geospatial analyses can be directed to H. Seybold (hansjoerg.seybold@usys.ethz.ch)