LETTERS
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Substantial proportion of global streamflow less than three months old

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Biogeochemical cycles, contaminant transport and chemical weathering are regulated by the speed at which precipitation travels through landscapes and reaches streams[1]. Streamflow is a mixture of young and old precipitation[2], but the global proportions of these young and old components are not known. Here we analyse seasonal cycles of oxygen isotope ratios in rain, snow and streamflow compiled from 254 watersheds around the world, and calculate the fraction of streamflow that is derived from precipitation that fell within the past two or three months. This young streamflow accounts for about a third of global river discharge, and comprises at least 5% of discharge in about 90% of the catchments we investigated. We conclude that, although typical catchments have mean transit times of years or even decades[3], they nonetheless can rapidly transmit substantial fractions of soluble contaminant inputs to streams. Young streamflow is less prevalent in steeper landscapes, which suggests they are characterized by deeper vertical infiltration. Because young streamflow is derived from less than 0.1% of global groundwater storage, we conclude that this thin veneer of aquifer storage will have a disproportionate influence on stream water quality.

Calculating the time water takes to move through the landscape is crucial for predicting the retention, mobility and fate of solutes, nutrients and contaminants. Although time lags between pulses of precipitation and pulses of streamflow are calculated at gauging stations around the world[4], they measure the celerity of hydraulic potentials rather than the velocity of the water itself[5], which can be orders of magnitude slower[6,7]. Instead, our current understanding of streamflow age is based primarily on the time required for conservative geochemical tracers (for example, Cl^-, ^{18}O or ^{2}H) measured in precipitation to appear in the stream. Two types of streamflow age calculations are commonly reported: storm event hydrograph separations, which partition streamflow into 'event' water derived from the current storm versus 'pre-event' water derived from catchment storage, and the non-storm period mean transit time required for precipitation to reach the stream.

Although storm event hydrograph separations have provided snapshots of event versus pre-event water for dozens of small ($<100\,km^2$) research watersheds[8], they tell us nothing about streamflow age during the large fraction of time when rain is not falling. Alternatively, mean transit times of typically ~1–5 years have been calculated for ~100 small, intensively studied headwater catchments using seasonal fluctuations of stable isotopes in precipitation and streamflow[3,9]. Unfortunately, recent work has shown that these mean transit time estimates are susceptible to aggregation errors[10], implying that true mean transit times have been underestimated, potentially by large factors.

Although seasonal cycles of ^{18}O in precipitation and rivers are unreliable metrics of mean transit times, they can reliably measure the fraction of young streamflow, defined here as precipitation that traverses the watershed and reaches the stream in less than 2.3 ± 0.8 months. Recently Kirchner[10,11] has shown that this young streamflow fraction can be quantified even in catchments that are heterogeneous and nonstationary. Stable-isotope-based young streamflow estimates are derived from the natural seasonal cycle of $\delta^{18}O$ in the hydrosphere (where $\delta^{18}O = ([^{18}O/^{16}O_{sample}]/[^{18}O/^{16}O_{standard\ ocean\ water}] - 1) \times 10^3‰$). Precipitation $\delta^{18}O$ values are often characterized by pronounced seasonality, especially in continental interiors (Supplementary Fig. 1), due to seasonal shifts in temperatures and atmospheric vapour transport pathways that alter rainout-driven fractionation[12,13]. Stream water $\delta^{18}O$ values usually follow similar seasonal cycles, but are damped and phase-shifted relative to precipitation inputs because of storage and mixing in lakes, soils and aquifers[3,14,15]. By comparing the seasonal $\delta^{18}O$ cycles of precipitation and streamflow, we estimate the fraction of young streamflow in 254 global rivers, spanning larger spatial scales than most previous field applications of stable isotope tracer techniques (see Methods).

Our global analysis shows that young streamflow represents roughly one-third of global river discharge and is relatively widespread in world rivers. The young streamflow fraction in our 254 rivers averages 26%, with a median of 21% (10th–90th percentile range of 4–53%; Fig. 1). The flow-weighted young streamflow fraction is 34%, calculated on the basis of 190 of our watersheds where discharge data are available. Three-quarters of our study rivers have more than 10% young streamflow, and the great majority (89%) of them have more than 5% young streamflow.

Small (<5%) young streamflow fractions are found downstream of large natural lakes and reservoirs (such as in the Göta älv below Vänern, Sweden, the Aare River below Lake Thun, Switzerland, and the Missouri River below Garrison Dam, USA), consistent with their long retention times. Conversely, young streamflow fractions greater than 50% are found in lower-relief, free-flowing rivers, including the Yangtze (central China, upstream of Three Gorges Dam), Chenab (northern Pakistan) and Negro Rivers (Amazon Basin, Brazil), but are uncommon globally (11% of study rivers).

The observation that most (89%) rivers have substantial (>5%) young streamflow fractions has important implications for

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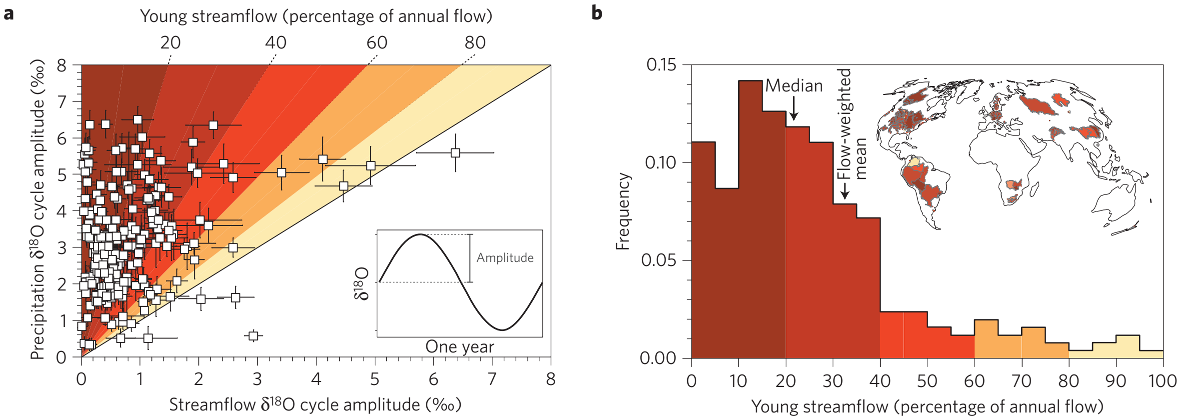

Figure 1 | Fractions of young streamflow in global rivers. a, Comparison of the seasonal cycle amplitudes of river $\delta^{18}O$ and precipitation $\delta^{18}O$ for our study watersheds (error bars are one standard error). The colour fan depicts the fraction of young streamflow, defined as precipitation that enters the stream in less than 2.3 ± 0.8 months. **b**, Histogram of these young streamflow fractions. The median young streamflow fraction is 21%, with a 10th–90th percentile range of 4–53%. The flow-weighted mean young streamflow is 34%.

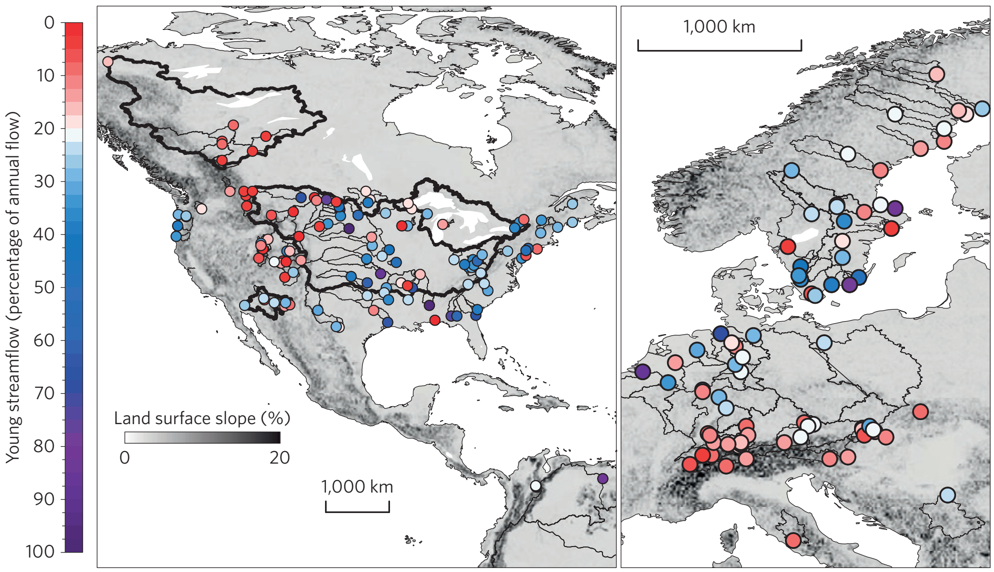

Figure 2 | Fractions of young streamflow in North American (left) and European (right) rivers. Thin black lines delineate catchment boundaries and coloured points mark the locations of river sampling stations, with colours indicating the young streamflow fraction. Blue and red points indicate rivers with more and less young streamflow than the global median, respectively. Thick black lines for North America delineate the Mackenzie, Colorado, Mississippi and St Lawrence drainage systems. Greyscale shading represents topographic slope.

contaminant transport. Spectral analyses of conservative tracers have demonstrated that catchment transit time distributions have long tails, implying that catchments retain soluble contaminants for long time spans and slowly release them to surface waters[16,17]. Our study shows that although catchments can indeed retain pollutants for long time spans—the so-called 'sting in the tail' of the age distribution[18]—another 'sting' can come at the other end of the age distribution, where these same catchments will also rapidly transmit a significant fraction of soluble pollutant inputs to the stream[16]. The prevalence of young streamflow in global rivers means that, even if the mean transit times of typical watersheds are long (~years to decades[3,19]), they can also convey pollutant inputs to surface waters over much shorter timescales (~2 months or less). In summary, most catchments have substantial fast and slow drainage components, and thus can transport a substantial fraction of soluble contaminants rapidly to the stream, while retaining another fraction in the catchment for years or decades[16,17].

The spatial pattern of young streamflow fractions in North America and Europe, where most of our sites are located (Fig. 2), suggests that young streamflow is less prevalent in steep, mountainous catchments than in lower-gradient landscapes. This visual impression is confirmed by the significant negative correlation (Fig. 3) between the young streamflow fraction and the logarithm of the average topographic gradient across our 254 study watersheds (Spearman rank correlation $\rho = -0.36$, $p < 0.0001$). Such a correlation could potentially arise spuriously, if the steeper catchments were found primarily in mountain regions with large snowpacks that melt in the summer, thus contributing a 'winter' isotopic signature to summer streamflows and damping the seasonal isotopic cycle. To test for this artefact, we excluded all catchments where the long-term average February snow-water equivalent[20] exceeds 10% of mean annual precipitation, and found that the correlation becomes, if anything, even stronger ($\rho = -0.39$, $p < 0.0001$).

The greater prevalence of young streamflow in flatter terrain may reflect greater agricultural development, and its concomitant increase in rapid runoff, in low-gradient regions. This hypothesis is consistent with patterns we observe across our 254 sites; the fraction of cropland in each catchment is significantly correlated

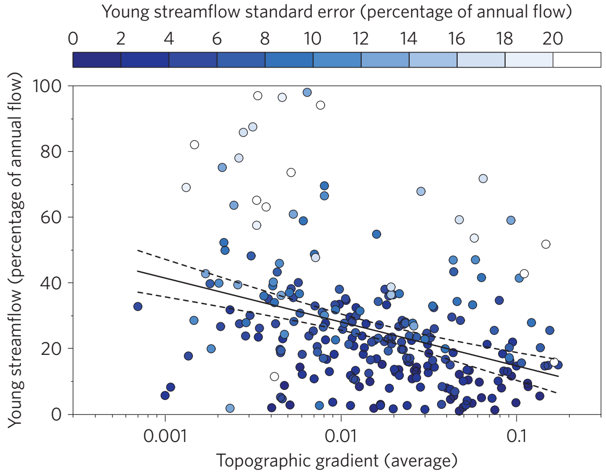

Figure 3 | Young streamflow and topographic slope in 254 watersheds. Steeper watersheds tend to have less young streamflow (unweighted regression marked by solid line; dashed lines show the 90% confidence intervals). Although it is statistically significant ($p < 0.0001$), the relationship between young streamflow and the logarithm of topographic slope shows substantial scatter, indicating other catchment characteristics also influence young streamflow. Calculated young streamflow standard errors are indicated by the colour scale (see colour bar; standard errors expressed as a percentage of discharge).

with the young streamflow fraction ($\rho = -0.30$, $p < 0.0001$), and unsurprisingly is also inversely correlated with average catchment slope ($\rho = -0.38$, $p < 0.0001$).

Conversely, the reduced prevalence of young streamflow in steeper terrain suggests that steeper landscapes tend to favour deeper vertical infiltration rather than shallow lateral flow. A tendency for greater infiltration in mountainous watersheds may seem counterintuitive, but is consistent with conceptual models of runoff generation[21] and groundwater flow[22] that suggest that topographic roughness drives long groundwater flow pathways that bypass first-order streams. Smaller young streamflow fractions in steep regions may also reflect the tendency for rock stresses in steep landscapes to fracture bedrock, enhance permeability, and promote deep infiltration[23]. This hypothesis is supported by the fact that young streamflow fractions are negatively correlated with average water table depth[24] ($\rho = -0.26$, $p < 0.0001$) and bedrock permeability[25] ($\rho = -0.15$, $p < 0.02$) across our 254 watersheds, and both water table depth and bedrock permeability are significantly greater in steeper catchments ($\rho = 0.73$, $p < 0.0001$ and $\rho = 0.24$, $p < 0.0002$, respectively). Less young streamflow in mountain catchments, in turn, implies that soluble nutrients will be less likely to be shunted quickly to surface waters, and thus more likely to be biodegraded by chemical reactions. Furthermore, to the extent that steeper landscapes are characterized by deeper infiltration and longer groundwater residence times, one would expect them to also be characterized by greater concentrations of weathering products in streamwater[26].

Although topographic gradient provides the strongest correlation with young streamflow fractions in our data set, the fraction of unexplained variance is large, suggesting that other variables also play a significant role. We observe no significant correlations between the young streamflow fraction and catchment size, annual precipitation, bedrock porosity, population density, or the fraction of catchment area comprised of pasture land or open water. Other previously identified controls on stream water age may be important at regional scales, such as slope aspect[27], soil drainage class[28], bedrock geology[29] or precipitation seasonality[28]. Previous studies have shown that some of these characteristics are strongly correlated with stream water age, but usually only in specific climates or geologic units, and only for small numbers of sites (typically less than 10 catchments, compared to 254 in our analysis).

Because porosity and permeability decrease rapidly with depth below the surface[30], young streamflow is likely to be generated primarily from a thin layer at the top of the aquifer, where porosity and permeability are greatest. From the young streamflow fraction, we can quantify the volume of this 'short-term aquifer storage' without requiring measurements of aquifer properties (see Methods). Expressed as an equivalent water depth, this short-term aquifer storage ranges from <1 to <55 mm (10th–90th percentile range; median <14 mm) among our study catchments. By contrast, global groundwater stored in the uppermost 2 km of the crust averages[30] ~180 m of equivalent depth. Thus short-term aquifer storage, across our sites, constitutes roughly 0.0005–0.03% (median 0.008%) of global average groundwater storage in the upper 2 km of the crust. This 2 km threshold is somewhat arbitrary; if instead we consider only groundwater stored in the uppermost 100 m of the crust (~15 m of equivalent water depth[30]), we find that short-term aquifer storage still comprises a small fraction (roughly 0.007–0.4%; median 0.09%) of this much shallower groundwater storage.

This tiny short-term storage volume implies that young streamflow will be many orders of magnitude younger than most groundwater stored in typical catchments. Because the global average groundwater volume[30] of ~180 m is itself nearly three orders of magnitude greater than global annual runoff[4] of ~280 mm yr^{-1}, this result is not surprising. Nonetheless, it provides one of the first quantitative measures of the partitioning of storage that actively contributes to streamflow over monthly timescales. This short-term aquifer storage generates, per unit volume, much more streamflow than older catchment storages. Thus, aquifer-stream connectivity is strongest in this thin veneer of short-term aquifer storage, where biogeochemical reactions will disproportionately influence stream water quality.

Our analysis provides the first estimates of young streamflow in global rivers. We show that this young streamflow comprises ~1/3 of global runoff and is pervasive in streams worldwide. Thus, even where mean transit times are years or decades, watersheds can transmit substantial fractions of soluble contaminant inputs to streams over much shorter time spans. The young streamflow fractions presented in this study provide a benchmark for testing how well hydrologic models simulate the movement of water through the landscape, which is a better test of model realism than solely comparing simulated versus observed stream hydrographs[5]. Our analysis reveals that streams draining steeper catchments have less young streamflow than flatter catchments, and that catchments with greater fractions of cropland have greater young streamflow fractions. These findings imply that flatter landscapes with large cultivated areas may be more likely to transmit acute pulses of fertilizer and pesticide inputs to streams in relatively short time spans (~2 months). Our analysis also shows that a tiny fraction (<0.1%) of continental aquifer volume generates roughly one-third of river discharge, implying that biogeochemical reactions in this thin veneer of highly connected aquifer storage will have disproportionate impacts on stream water quality.

Methods

Methods and any associated references are available in the online version of the paper.

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References

1. Dunne, T. & Leopold, L. B. *Water in Environmental Planning* 818 (Freeman, 1978).

2. Horton, J. H. & Hawkins, R. H. Flow path of rain from the soil surface to the water table. *Soil Sci.* **100,** 377–383 (1965).
3. McGuire, K. & McDonnell, J. J. A review and evaluation of catchment transit time modeling. *J. Hydrol.* **330,** 543–563 (2006).
4. Dai, A. & Trenberth, K. E. Estimates of freshwater discharge from continents: latitudinal and seasonal variations. *J. Hydrometeorol.* **3,** 660–687 (2002).
5. McDonnell, J. J. & Beven, K. Debates—The future of hydrological sciences: a (common) path forward? A call to action aimed at understanding velocities, celerities, and residence time distributions of the headwater hydrograph. *Wat. Resour. Res.* **50,** 5342–5350 (2014).
6. Sklash, M. G. & Farvolden, R. N. The role of groundwater in storm runoff. *Dev. Water Sci.* **12,** 45–65 (1979).
7. Brown, V. A., McDonnell, J. J., Burns, D. A. & Kendall, C. The role of event water, a rapid shallow flow component, and catchment size in summer stormflow. *J. Hydrol.* **217,** 171–190 (1999).
8. Klaus, J. & McDonnell, J. J. Hydrograph separation using stable isotopes: review and evaluation. *J. Hydrol.* **505,** 47–64 (2013).
9. McDonnell, J. J. *et al.* How old is the water? Open questions in catchment transit time conceptualization, modelling and analysis. *Hydrol. Process.* **24,** 1745–1754 (2010).
10. Kirchner, J. W. Aggregation in environmental systems – Part 1: Seasonal tracer cycles quantify young water fractions, but not mean transit times, in spatially heterogeneous catchments. *Hydrol. Earth Syst. Sci.* (in the press).
11. Kirchner, J. W. Aggregation in environmental systems – Part 2: Catchment mean transit times and young water fractions under hydrologic nonstationarity. *Hydrol. Earth Syst. Sci.* (in the press).
12. Feng, X., Faiia, A. M. & Posmentier, E. S. Seasonality of isotopes in precipitation: a global perspective. *J. Geophys. Res.* **114,** D08116 (2009).
13. Vachon, R. W., White, J. W. C., Gutmann, E. & Welker, J. M. Amount-weighted annual isotopic ($\delta^{18}O$) values are affected by the seasonality of precipitation: a sensitivity study. *Geophys. Res. Lett.* **34,** L21707 (2007).
14. Małoszewski, P., Rauert, W., Stichler, W. & Herrmann, A. Application of flow models in an alpine catchment area using tritium and deuterium data. *J. Hydrol.* **66,** 319–330 (1983).
15. DeWalle, D. R., Edwards, P. J., Swistock, B. R., Aravena, R. & Drimmie, R. J. Seasonal isotope hydrology of three Appalachian forest catchments. *Hydrol. Process.* **11,** 1895–1906 (1997).
16. Kirchner, J. W., Feng, X. & Neal, C. Fractal stream chemistry and its implications for contaminant transport in catchments. *Nature* **403,** 524–527 (2000).
17. Godsey, S. E. *et al.* Generality of fractal 1/f scaling in catchment tracer time series, and its implications for catchment travel time distributions. *Hydrol. Process.* **24,** 1660–1671 (2010).
18. Stark, C. P. & Stieglitz, M. Hydrology: the sting in a fractal tail. *Nature* **403,** 493–495 (2000).
19. Michel, R. L. *et al.* A simplified approach to analysing historical and recent tritium data in surface waters. *Hydrol. Process.* **29,** 572–578 (2015).
20. Pulliainen, J. Mapping of snow water equivalent and snow depth in boreal and sub-arctic zones by assimilating space-borne microwave radiometer data and ground-based observations. *Remote Sensing Environ.* **101,** 257–269 (2006).
21. Frisbee, M. D., Phillips, F. M., Campbell, A. R., Liu, F. & Sanchez, S. A. Streamflow generation in a large, alpine watershed in the southern Rocky Mountains of Colorado: is streamflow generation simply the aggregation of hillslope runoff responses? *Wat. Resour. Res.* **47,** W06512 (2011).
22. Gleeson, T. & Manning, A. H. Regional groundwater flow in mountainous terrain: three-dimensional simulations of topographic and hydrogeologic controls. *Wat. Resour. Res.* **44,** W10403 (2008).
23. Gleeson, T., Marklund, L., Smith, L. & Manning, A. H. Classifying the water table at regional to continental scales. *Geophys. Res. Lett.* **38,** L05401 (2011).
24. Fan, Y., Li, H. & Miguez-Macho, G. Global patterns of groundwater table depth. *Science* **339,** 940–943 (2013).
25. Gleeson, T., Moosdorf, N., Hartmann, J. & van Beek, L. P. H. A glimpse beneath earth's surface: GLobal HYdrogeology MaPS (GLHYMPS) of permeability and porosity. *Geophys. Res. Lett.* **41,** 3891–3898 (2014).
26. Maher, K. The dependence of chemical weathering rates on fluid residence time. *Earth Planet. Sci. Lett.* **294,** 101–110 (2010).
27. Broxton, P. D., Troch, P. A. & Lyon, S. W. On the role of aspect to quantify water transit times in small mountainous catchments. *Wat. Resour. Res.* **45,** W08427 (2009).
28. Sayama, T. & McDonnell, J. J. A new time-space accounting scheme to predict stream water residence time and hydrograph source components at the watershed scale. *Wat. Resour. Res.* **45,** W07401 (2009).
29. Stewart, M. K., Morgenstern, U. & McDonnell, J. J. Truncation of stream residence time: how the use of stable isotopes has skewed our concept of streamwater age and origin. *Hydrol. Process.* **24,** 1646–1659 (2010).
30. Gleeson, T., Befus, K., Jasechko, S., Luijendijk, E. & Cardenas, M. B. The global volume and distribution of modern groundwater. *Nature Geosci.* http://dx.doi.org/10.1038/ngeo2590 (2015).

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Author contributions

S.J., J.W.K. and J.J.M. conceived the idea to analyse young streamflow in global rivers. S.J. and J.W.K. analysed the geospatial and isotopic data set. J.M.W. provided precipitation isotope data. All authors contributed to writing or editing the manuscript text.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to S.J.

Competing financial interests

The authors declare no competing financial interests.

Methods

We compiled a global database of 63,337 precipitation $\delta^{18}O$ measurements collected at 459 weather stations and 14,240 streamflow $\delta^{18}O$ measurements collected from 254 rivers (data from the International Atomic Energy Agency[31–34], the United States Geological Survey[35], and the Canadian and US Networks for Isotopes in Precipitation[36,37]). The study watersheds span 53 countries and cover 27 million km^2, comprising roughly 20% of the globe's ice-free land area. Individual watersheds range in size from 0.25 km^2 headwater catchments (McDonalds Branch) to major rivers draining 3.6 million km^2 (Ob River). Precipitation isotope stations with less than two years of data were excluded, to ensure that each station used in this analysis captures some inter-annual variability in seasonal precipitation $\delta^{18}O$ cycles. We excluded all stream sampling sites with less than ten measurements or with less than eight unique months during which samples were collected. We also omitted catchments with centroids more than 400 km from the nearest precipitation station, to exclude watersheds where the precipitation isotope sampling network was particularly sparse. The median number of isotope measurements for each river sampling site is 21 (lower–upper quartile range of 15–69 samples), and for each precipitation sampling site is 103 (lower–upper quartile range of 57–200 samples). The median number of years of record for each river sampling site is 4 (lower–upper quartile range of 4–6 years) and the median number of years of record for precipitation stations is 5 (lower–upper quartile range of 5–16 years).

Once the data were screened for quality, we quantified young streamflow fractions in each of the remaining 254 rivers. We calculated the best-fit sine and cosine coefficients of the annual cycle of $\delta^{18}O$ at each precipitation and streamflow station by multiple regression[15]. We calculated global grids of the $\delta^{18}O$ seasonal cycle coefficients by interpolating between the precipitation stations. We weighted each station's coefficients by the reciprocal of their squared standard errors (so-called inverse variance weighting), to down-weight stations with larger uncertainties in their seasonal cycle coefficients. Catchment-averaged precipitation cycle coefficients were extracted for each study watershed by flux-weighting the interpolated cycle coefficient grids, thus accounting for spatial variability in precipitation rates[38] across each catchment. We calculated the amplitudes of the river and precipitation $\delta^{18}O$ cycles by taking the square root of the sum of the squares of the cycle coefficients– that is, the square root of ([cosine coefficient]^2+ [sine coefficient]^2). We estimated the young streamflow fraction for each study catchment by dividing the river $\delta^{18}O$ cycle amplitude by the precipitation $\delta^{18}O$ cycle amplitude[10]. Benchmark tests using gamma-distributed travel times show that this ratio accurately reflects the young streamflow fraction (F_{yw}), with errors of $\sim$2% or less for shape factors (α) ranging from 0.3 to 2.0, spanning a wide range of plausible shapes of catchment transit time distributions[10]. However, over this range of shape factors α, the upper age threshold (τ_{yw}) that defines young streamflow shifts by a factor of two, from 1.5 to 3.1 months[10]; this is why we cite the age range of 2.3 ± 0.8 months in our results. Of the 254 rivers, six (representing 2.3% of the total) had greater streamflow cycle amplitude than precipitation cycle amplitude, implausibly implying a young streamflow fraction greater than one. These six sites probably reflect errors in the stream isotope data or the interpolated precipitation cycles. For transparency we present these watersheds in Fig. 1a and in the Supplementary Information. However, we have excluded these six sites from the quantitative results, because we believe they are misleading outliers. We used Gaussian error propagation to carry all measurable uncertainties through our calculations.

Calculated young streamflow fluxes were used to estimate the volume of short-term aquifer storage (STS; units of mm of water equivalent), defined here as the aquifer volume from which young streamflow is derived. The average flux of young streamflow can be estimated as the young streamflow fraction (F_{yw}; dimensionless) times the water yield (Y_w; units of mm yr^{-1}). For this water to reach the stream while it is still young, it cannot be stored in the aquifer for longer than τ_{yw} (where τ_{yw} is 2.3 ± 0.8 months or 0.12–0.25 years). Therefore the upper bound on the aquifer volume that this water passes through can be straightforwardly estimated as:

$$\mathrm{STS} = F_{yw} Y_w \tau_{yw} \tag{1}$$

Equation (1) defines the upper bound on the short-term aquifer volume, because the young streamflow threshold τ_{yw} is the upper bound on the age of water in this volume.

Finally, we explored correlations between catchment characteristics and young streamflow fractions by extracting catchment-averaged values from the following global grids: annual precipitation[38], water table depth[24], permeability and porosity[25], long-term average February snowpack depth[20] (data available from www.globsnow.info), topographic slope (ETOPO1 global relief data available from www.ngdc.noaa.gov/mgg/global), population density (data from sedac.ciesin.columbia.edu/data/collection/gpw-v3) and the fraction of each catchment comprised of cropland[39], pasture land[39] and open water[40].

References

31. Araguás-Araguás, L., Froehlich, K. & Rozanski, K. Deuterium and oxygen-18 isotope composition of precipitation and atmospheric moisture. *Hydrol. Process.* **14,** 1341–1355 (2000).
32. *Global Network for Isotopes in Precipitation* (International Atomic Energy Agency, accessed November 2014); http://www-naweb.iaea.org/napc/ih/IHS_resources_gnip.html
33. Halder, J., Terzer, S., Wassenaar, L. I., Araguás-Araguás, L. & Aggarwal, P. K. The Global Network of Isotopes in Rivers (GNIR): integration of water isotopes in watershed observation and riverine research. *Hydrol. Earth Syst. Sci.* **19,** 3419–3431 (2015).
34. *Global Network for Isotopes in Rivers* (International Atomic Energy Agency, accessed November 2014); http://www-naweb.iaea.org/napc/ih/IHS_resources_gnir.html
35. Kendall, C. & Coplen, T. B. Distribution of oxygen-18 and deuterium in river waters across the United States. *Hydrol. Process.* **15,** 1363–1393 (2001).
36. Welker, J. M. Isotopic ($\delta^{18}O$) characteristics of weekly precipitation collected across the USA: an initial analysis with application to water source studies. *Hydrol. Process.* **14,** 1449–1464 (2000).
37. Birks, S. J. & Edwards, T. W. D. Atmospheric circulation controls on precipitation isotope–climate relations in western Canada. *Tellus B* **61,** 566–576 (2009).
38. New, M., Lister, D., Hulme, M. & Makin, I. A high-resolution data set of surface climate over global land areas. *Clim. Res.* **21,** 1–25 (2002).
39. Ramankutty, N., Evan, A. T., Monfreda, C. & Foley, J. A. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Glob. Biogeochem. Cycles* **22,** GB1003 (2008).
40. Lehner, B. & Döll, P. Development and validation of a global database of lakes, reservoirs and wetlands. *J. Hydrol.* **296,** 1–22 (2004).