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A precipitation shift from snow towards rain leads to a decrease in streamflow

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In a warming climate, precipitation is less likely to occur as snowfall[1,2]. A shift from a snow- towards a rain-dominated regime is currently assumed not to influence the mean streamflow significantly[1,3–5]. Contradicting the current paradigm, we argue that mean streamflow is likely to reduce for catchments that experience significant reductions in the fraction of precipitation falling as snow. With more than one-sixth of the Earth's population depending on meltwater for their water supply[3] and ecosystems that can be sensitive to streamflow alterations[6], the socio-economic consequences of a reduction in streamflow can be substantial. By applying the Budyko water balance framework[7] to catchments located throughout the contiguous United States we demonstrate that a higher fraction of precipitation falling as snow is associated with higher mean streamflow, compared to catchments with marginal or no snowfall. Furthermore, we show that the fraction of each year's precipitation falling as snowfall has a significant influence on the annual streamflow within individual catchments. This study is limited to introducing these observations; process-based understanding at the catchment scale is not yet provided. Given the importance of streamflow for society, further studies are required to respond to the consequences of a temperature-induced precipitation shift from snow to rain.

Natural- and anthropogenic-forcing drive fluctuations in the hydrologic cycle that undermine the assumption that it can be considered stationary[8,9]. One of the most profound and widely anticipated changes in the hydrological cycle is the temperature-induced shift of precipitation from snow towards rain and earlier melt of the snowpack[1,10–13]. Future temperature increases will affect precipitation and snowpacks mostly in the mid to late part of the snow season[2]. A shift from a snow regime towards a rain regime leads to changes in the within-year distribution of streamflow[1,4,5,14], which are associated with a significant impact on human freshwater resources[1,3] and disruptions of ecosystem functioning[1,6,15]. The projected global temperature increase[1] is expected to affect future snowfall[1,2] and consequently the temporal distribution of river water availability will continue to change. Although these impacts of warming on temporal streamflow distribution are acknowledged, the influence of the change in form of precipitation on the long-term mean streamflow is generally assumed to be negligible[1,3–5], or found to be negligible using FLUXNET data[16], or generally not included in simulations[17]. However, mechanistic modelling of a catchment in Sweden suggests that a warmer climate with more rain and less snow can lead to a significant decrease in streamflow[18]. Regardless, this assumption that the long-term water balance is not significantly affected by a precipitation shift from snow towards rain is not yet substantiated by empirical findings at the catchment scale.

Here, we study the role of snowfall for the mean-annual and inter-annual streamflow using data from 420 catchments located across the contiguous United States for the period 1948–2001 (Supplementary Methods). The mean-annual streamflow of catchments is studied by a between-catchment comparison of the long-term (16–54 year, mean 47 year) partitioning of incoming precipitation into evaporation or streamflow. These observations are put in the context of the Budyko hypothesis[7]. This hypothesis assumes that the long-term water balance is primarily a function of the atmospheric supply and demand of water, expressed as the ratio of mean potential evaporation ($\overline{E_p}$) to the mean precipitation ($\overline{P}$). The Budyko hypothesis is a widely used tool to normalize observations among a wide range of climatic settings; it enables the effects of secondary controls on a catchment's water balance to be identified[19]. We examine the influence of the mean fraction of precipitation that falls as snow ($\overline{f_s}$) on the mean streamflow ($\overline{Q}$). Because between-catchment differences in the water balance can be caused by many factors which are correlated with the long-term average snow fraction, we also analyse the inter-annual streamflow of catchments to estimate the annual streamflow variation due to variations in the snow fraction. To conclude, we quantify the sensitivity of streamflow to potential changes in $\overline{f_s}$ that may result from temperature rise.

Figure 1a shows the long-term streamflow measurements of the 420 study catchments in the context of the Budyko hypothesis, and stratified by long-term mean snow fraction ($\overline{f_s}$). Overall, the pattern of observations is consistent with the Budyko curve, with a mean overestimation of the normalized streamflow ($\overline{Q}/\overline{P}$) by just 0.02. Figure 1a also shows that, in general, larger values of $\overline{f_s}$ are associated with lower normalized evaporation ($\overline{E}/\overline{P}$) and higher normalized mean streamflow ($\overline{Q}/\overline{P}$). Figure 1b clarifies this effect by showing the observed streamflow anomaly from the Budyko curve as a function of snow fraction, ($\overline{f_s}$). A linear regression ($p < 0.001$) indicates an average increase in normalized streamflow ($\overline{Q}/\overline{P}$) of 0.37 per unit increase in snow fraction ($\overline{f_s}$) and is robust even if calculated separately across low (0.32) and high (0.34) snow fraction values.

We have assessed the uncertainties in these data and their interpretation. Changes in soil and groundwater storage are orders of magnitude smaller than the other fluxes, and thus considered negligible over a multi-annual period. Inter-annual changes of snow storage are minimal owing to the absence of large areas with perennial snow cover in any of the 420 catchments. Streamflow measurement errors and exchanges with aquifers can bias results of individual catchments, but are unlikely to be strongly correlated to the snow fraction. The above uncertainties are thus unlikely to result in a misinterpretation of the observed patterns in the context of the Budyko hypothesis.

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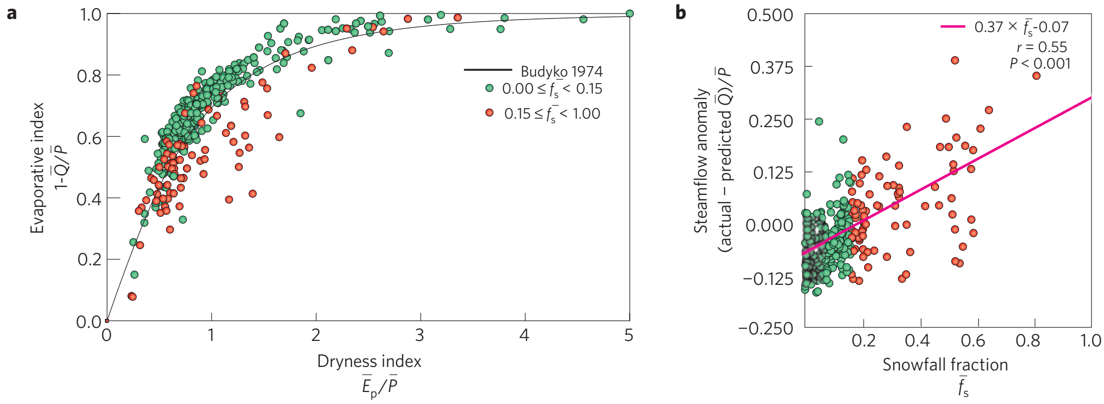

Figure 1 | Mean annual streamflow and streamflow anomaly in the context of the Budyko hypothesis, stratified by snow fraction. The observed long-term streamflow and precipitation measurements are placed in the context of the Budyko hypothesis. The Budyko hypothesis states the mean streamflow is primarily a function of the catchment's annual precipitation and potential evaporation as shown by the black line in **a**. Departures below the Budyko curve for catchments with a significant fraction of the precipitation falling as snow indicate that an increased fraction of precipitation as snowfall is associated with higher streamflow, as clarified by the linear regression in **b**.

The mean partitioning of precipitation into streamflow and evaporation is partly governed by controls that may be spatially correlated with the long-term snow fraction. These controls may consist of chiefly natural (for example, topography) and anthropogenic factors (for example, agricultural development), which are likely to differ between colder and warmer catchments[20]. Furthermore, the Budyko framework does not examine if the mean streamflow within a catchment is sensitive to changes in the $\overline{f_s}$. Therefore, we extend the analysis with a study of the inter-annual streamflow. We selected catchments with a significant amount of snowfall, while maintaining a large number of catchments (97 catchments with $\overline{f_s} > 0.15$, data length $\geq$28 year). For each catchment, we use linear regressions to investigate whether year-to-year variations in normalized annual streamflow $(Q/\overline{P})$ can be linked to the corresponding variations in snow fraction between years. This analysis expresses the change in streamflow due to f_s changes, which may partly depend on the catchment settings (for example, agricultural development, climate), but are not caused by these factors because inter-annual variations of f_s are, for the majority of catchments, much larger than the shift in mean f_s during the historical period.

Figure 2 shows the sensitivity of normalized annual streamflow to annual snow fraction for the 97 catchments. Sensitivity is defined as the change in normalized annual streamflow $(Q/\overline{P})$ per change in the annual fraction of precipitation falling as snowfall (f_s; Methods). The mean increase of $(Q/\overline{P})$ per unit of f_s is 0.29 (standard deviation 0.21) and 94 of the 97 catchments exhibit a positive value of this sensitivity. This indicates that an increase in the annual f_s is almost always associated with an increase in the annual streamflow, but sensitivities differ per catchment. The results are not significantly influenced by changes in soil-water and groundwater storage variation between years; we established this by repeating the analysis using five-year averages in place of annual averages; the conclusions were unaffected. For five-year averages the mean increase of $(Q/\overline{P})$ per unit of f_s is 0.33 (standard deviation 0.36) and 87 of the 97 catchments exhibit a positive value.

Variations in f_s between years are caused both by fluctuations of the mean winter temperature and the fraction of precipitation falling during the winter period. An identical sensitivity analysis using temperature instead of f_s indicates that, on average, the annual streamflow decreases when the mean temperature for the period 1 November–1 April increases. This holds solely for the set of catchments with high $\overline{f_s}$ values, and is not applicable for the period 1 May–1 October or catchments with marginal snowfall ($\overline{f_s} \leq 0.15$). The results therefore suggest that mean streamflow is not merely related to the timing of precipitation or the associated temperature, but that the form of precipitation also is a determining factor.

To provide a context for the streamflow sensitivity to annual snow fraction, we consider the effect of temperature warming, under the assumption that the observed historical climate series are representative for future scenarios. The historical climate series for the 97 snow-affected MOPEX catchments indicate that a large fraction of precipitation that now falls under the temperature threshold will in future fall at temperatures above that threshold. A 2.4 °C temperature rise (A1T Scenario[1]) for the 97 studied catchments leads to an average 40% decrease in $\overline{f_s}$ (standard deviation 12%). For a 4.0 °C temperature increase (A1FI Scenario[1]), $\overline{f_s}$ reduces by 60% (standard deviation 15%). As shown above, the average change in normalized streamflow is 0.29 per unit of f_s, but varies by catchment. Under the simplifying assumption of an otherwise stationary system, this implies that a 2.4 °C temperature rise, on average, could potentially lead to a decrease of normalized streamflow $(Q/\overline{P})$ on the order of 0.12 times the historical f_s. Given that mean streamflow is in general significantly lower than the mean precipitation the proportional change in actual mean streamflow can be much higher. Although other factors, such as changes in precipitation patterns, can locally compensate for changes in the annual streamflow[21], clearly temperature rise will alter the hydrological cycle. This will require an understanding of catchment function that goes beyond the assumption that systems fluctuate within an unchanging envelope of variability[8], including the need to more comprehensively acknowledge the role of snow for the long-term streamflow patterns.

The observation that a lower f_s is associated with lower streamflow on the annual and mean-annual timescales is restricted here to empirical evidence, and does not reveal the physical processes behind these observations. The inter-catchment comparison in the context of the Budyko hypothesis may be strongly affected by dominant human activities that heavily affect the mean streamflow[20,22], which, depending on the local climate and landscape factors, may lead to smaller or larger changes of the mean streamflow[23]. Yet, by the addition of the inter-annual streamflow analysis, the change in streamflow due to changes in f_s is tested, given (but not caused by) the current state of the catchment. The processes underlying the sensitivity of streamflow changes due to snowfall for individual catchments may be related to differences in water storage dynamics, flow paths and evaporation[18] due to changes in the infiltration capacity of soils, the duration of infiltration periods, the timing of infiltration periods, the evaporation from snow-covered and snow-free soils, the growing

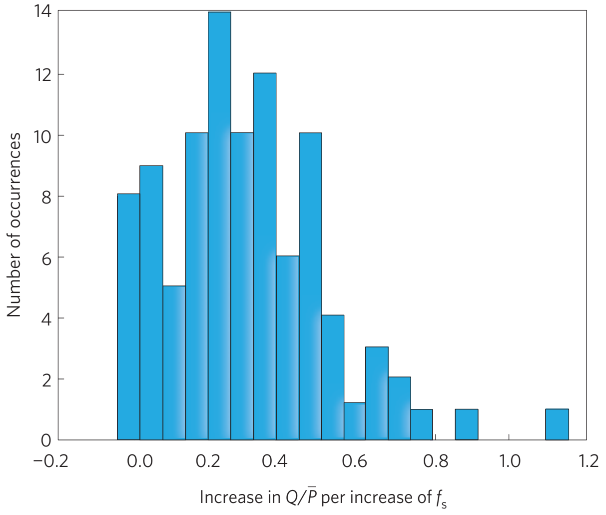

Figure 2 | Sensitivity of annual streamflow to the fraction of annual precipitation falling as snowfall. The histogram shows the change in normalized streamflow ($Q/\overline{P}$) per unit change of the annual snow fraction (f_s) for 97 snow-affected catchments ($\overline{f_s} > 0.15$). Positive values of sensitivity indicate that the annual streamflow of catchments varies (between years) directly with the annual f_s. Years with higher snow fraction, f_s, tend to have higher values of annual streamflow.

season length, the soil moisture regime, the potential evaporation, amongst other factors. Given the diversity of catchments in our sample, each with its own internal heterogeneity, the mechanisms connecting snow to mean streamflow are likely to result from combinations of factors and may vary from site to site, as well as depending on human influences, topography and vegetation of the catchment. Further work is needed to clarify which hydrological processes are the main contributors to the sensitivity we have presented.

In summary, this study uses historical data from a wide range of catchments to investigate the role of the fraction of precipitation falling as snow for the long-term and the inter-annual mean streamflow of catchments. There is evidence that, in the context of the Budyko hypothesis, catchments with a high fraction of long-term precipitation falling as snowfall are characterized by significantly higher long-term mean streamflow than catchments with little or no snowfall. In addition, analysis of inter-annual variability indicates that the annual fraction of precipitation falling as snow has a significant influence on the mean annual streamflow, independent of precipitation amount. Both results indicate that a change in phase of precipitation from snow towards rain significantly decreases the mean streamflow. These results, obtained from an empirical, strictly data-based analysis, are in line with earlier findings inferred from mechanistic modelling[18], but more explicitly isolate the role of snow and show that even for small temperature changes large differences in streamflow may occur. Although the study catchments are restricted to the contiguous United States, the diversity of physiographic and climatic settings, and the number of catchments used, suggest that snowfall may affect the mean streamflow in other regions as well. This finding has significant implications for water resource planning, as the projected global temperature rise is expected to lead to significant reductions in f_s in many regions around the world, and our results indicate that this would decrease mean streamflow in these regions, unless other factors compensate[21]. It is particularly relevant to 'water towers'[24] where societally important functions, such ecosystem stability, hydropower, irrigation, and industrial or domestic supply are derived from snowmelt. Associated process explanations have been assessed locally[18], but are not yet generalizable to catchments across a wide range of settings and need to be understood if society is to respond adequately to the consequences of a temperature-induced precipitation shift from snow to rain.

Methods

Data. Data are from 420 catchments belonging to the Model Parameter Estimation Experiment (MOPEX; ref. 25). We eliminated 11 of the 431 catchments of the MOPEX dataset for which less than 15 years of data are available, or for which no potential evaporation estimates are available. Catchments are located throughout the contiguous United States and span four of the five main climate types of the Köppen–Geiger climate classification. The climate type that is not included is Polar. Drainage areas of the catchments vary between 67 and 10,329 km^2. Daily time series of precipitation, temperature, potential evaporation and streamflow are all available for up to 54 years (1948–2001). Potential evaporation is calculated based on the NOAA Pan Evaporation Atlas[26], using the Penman method[27]. The PRISM method[28] was applied for interpolation of the temperature and precipitation values to account for topographic effects when estimating catchment mean precipitation and temperature. Streamflow values were sourced from the United States Geological Survey. The catchments were selected to have a limited anthropogenic influence, and their decadal water balance is not significantly influenced by changes in glacier storage: the perennial snow-covered area does not exceed 3% for individual catchments and is for most catchments non-existent. Annual values used in the analysis are from 1 September to 31 August to minimize the effects of carry over storage of snowfall. The dataset is available online: www.nws.noaa.gov/oh/mopex/mo_datasets.htm

Snowfall estimation. The fraction of precipitation falling as snow (f_s) is approximated using a simple temperature threshold on each day of recorded data[29]. Precipitation on days with an average temperature below 1 °C is considered to be entirely snowfall, whereas on days with temperature above 1 °C, precipitation is considered to be entirely rainfall. The conclusions of the paper are robust to changes in the method of snowfall estimation. Other methods employed are temperature thresholds ranging between −2.0 and 3.0 [°C] and methods that linearly partition precipitation between snow and rain for temperatures between two thresholds (−3.0 and 4.0 [°C], −2.0 and 3.0 [°C], −1.0 and 2.0 [°C]).

Undercatch correction. In the context of the Budyko framework, the precipitation measurements are corrected for mean monthly undercatch. Corrections for undercatch are made according to monthly wind speed and air temperature[30]. A sensitivity analysis with applying undercatch corrections for higher average windspeeds indicated that the positive relation between snowfall and Budyko anomaly still holds for much higher average windspeeds (7.5 m s^{-1}), but becomes less significant (not shown).

Budyko framework. The Budyko curve used for the normalization of the long-term water balances of catchments is as follows:

$$1-\overline{Q}/\overline{P}=\sqrt{\frac{\overline{E_p}}{\overline{P}}\tanh\left(\frac{\overline{P}}{\overline{E_p}}\right)\left(1-\exp\left(-\frac{\overline{E_p}}{\overline{P}}\right)\right)}$$

where $\overline{Q}$, $\overline{P}$ and $\overline{E_p}$ are the long-term [L/T] mean values for the streamflow [L/T], precipitation [L/T] and potential evaporation [L/T]. Similar equations proposed by others[19] will slightly alter the water balance anomalies for individual catchments but yield similar conclusions regarding the influence of snowfall.

Sensitivity of inter-annual streamflow. Sensitivity is defined below as the change in normalized annual streamflow ($Q/\overline{P}$) per change in the annual fraction of precipitation falling as snowfall (f_s). It is well known that annual streamflow often depends strongly on annual precipitation; if precipitation were correlated with snow fraction then a naive approach would result in a spurious sensitivity of streamflow to snow fraction. In the equation below we make the required correction for the effects of correlation between P and f_s. Therefore, sensitivity is approximated by:

$$\frac{\partial(Q/\overline{P})}{\partial f_s}=\frac{dF}{df_s}-\frac{\partial F}{\partial(P/\overline{P})}\frac{dG}{df_s}$$

where

$$Q/\overline{P}=F(f_s,P/\overline{P}) \quad \text{and} \quad P/\overline{P}=G(f_s)$$

and where Q is the annual streamflow [L/T], $\overline{P}$ is the mean annual precipitation [L/T], f_s is the annual fraction of precipitation falling as snowfall [−], and $G(f_s)$

and $F(f_s, P/\overline{P})$ are approximated as functions linearly dependent on their variables. The derivatives are approximated by the slope terms of least squares estimators.

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Author contributions

W.R.B. and R.A.W. designed the study; W.R.B. conducted all the analyses; all authors contributed to interpretations and writing the paper.

Additional information

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Competing financial interests

The authors declare no competing financial interests.