



Berghuijs, W. R., Woods, R. A., & Hrachowitz, M. (2014). A precipitation shift from snow towards rain leads to a decrease in streamflow. *Nature Climate Change*, 4, 583-586.
<https://doi.org/10.1038/nclimate2246>

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1 A precipitation shift from snow towards 2 rain leads to a decrease in streamflow

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6 **In a warming climate, precipitation is less likely to occur as snowfall**
7 **(Solomon 2007, Krasting 2013). A shift from a snow- towards a rain-**
8 **dominated regime is currently assumed not to influence the mean**
9 **streamflow significantly (Barnett 2005, Regonda 2005, Stewart 2005,**
10 **Solomon 2007, Gentine 2012, Godsey 2013). Contradicting the current**
11 **paradigm, we argue that mean streamflow is likely to reduce for**
12 **catchments that have significant reductions in the fraction of**
13 **precipitation falling as snowfall. With more than one-sixth of the Earth's**
14 **population depending on meltwater for their water supply (Barnett 2005)**
15 **and ecosystems that can be sensitive to streamflow alterations (Bunn**
16 **2002), the consequences of a reduction in streamflow can be**
17 **substantial. By applying the Budyko water balance framework (Budyko**
18 **1974) to catchments located throughout the contiguous United States**
19 **we demonstrate that a higher fraction of precipitation falling as snow is**
20 **associated with higher mean streamflow, compared to catchments with**
21 **marginal or no snowfall. Additionally, we show that the fraction of each**
22 **year's precipitation falling as snowfall has a significant influence on the**
23 **annual streamflow within individual catchments. This study is limited to**
24 **introducing these observations; process-based understanding at the**
25 **catchment scale is not yet available. Given the importance of streamflow**
26 **for society, new studies are required to respond to the consequences of**
27 **a temperature-induced precipitation shift from snow to rain.**

28
29 Natural and anthropogenic influences such as climate and land-cover change
30 or long-term fluctuations of the system undermine the assumption that the
31 hydrological cycle can be considered stationary (Milly 2008; Koutsoyiannis
32 2010). One of the most profound and widely-anticipated changes in the
33 hydrological cycle is the temperature-induced shift of winter precipitation from
34 snow towards rain and earlier melt of the winter snowpack (Laternser 2003,
35 Hamlet 2005, Mote 2005, Solomon 2007, Pierce 2008, Barnett 2008). A shift
36 from a snow towards a rain regime leads to changes in the within-year
37 distribution of streamflow (Regonda 2005, Stewart 2005, Solomon 2007,
38 Molini 2011, Godsey 2013), which are associated with a significant impact on
39 human freshwater resources (Barnett 2005, Solomon 2007) and disruptions of
40 ecosystem functioning (Vaganov 1999, Cayan 2001, Westerling 2006,
41 Solomon 2007). The projected global temperature increase (Solomon 2007) is
42 expected to affect future snowfall (Solomon 2007, Krasting 2013) and
43 consequently the temporal distribution of river water availability will continue
44 to change. Though these impacts of warming on temporal streamflow
45 distribution are acknowledged, the influence of the change in form of
46 precipitation on the long-term mean streamflow is generally either assumed to

47 be negligible (Barnett 2005, Regonda 2005, Stewart 2005, Solomon 2007,
48 Gentine 2012, Godsey 2013), or found to be insignificant using FLUXNET
49 data (Williams 2012), or not included in simulations (e.g. Milly 2005).
50 However, this assumption that the long-term water balance is not significantly
51 affected by a precipitation shift from snow towards rain is not yet
52 substantiated by empirical findings at the catchment scale.

53

54 Here, we study the role of snowfall for the mean-annual and inter-annual
55 streamflow using data from 420 catchments located across the contiguous
56 United States. The mean-annual streamflow of catchments is studied by a
57 between-catchment comparison of the long-term (16-54 year, mean 47 year)
58 partitioning of incoming precipitation into evaporation or streamflow. These
59 observations are put in context of the Budyko hypothesis (Budyko 1974). This
60 hypothesis assumes that the long-term water balance is primarily a function of
61 the atmospheric supply and demand of water, expressed as the ratio of mean
62 potential evaporation (\bar{E}_p) to the mean precipitation (\bar{P}). The Budyko
63 hypothesis is a widely used tool to normalize observations among a wide
64 range of climatic settings; it enables the effects of secondary controls on a
65 catchment's water balance to be identified (Dooge 1992, Zhang 2004). We
66 examine the influence of the mean fraction of precipitation that falls as snow
67 (\bar{f}_s) on the mean streamflow (\bar{Q}). Since between-catchment differences in the
68 water balance can be caused by many factors which are correlated with the
69 long-term average snow fraction, we also analyze the inter-annual streamflow
70 of catchments to estimate the annual streamflow variation due to variations in
71 the snow fraction. To conclude, we quantify the sensitivity of streamflow to
72 potential changes in \bar{f}_s that may result from temperature rise.

73

74 Figure 1a displays the long-term streamflow measurements of the 420 study
75 catchments in the context of the Budyko hypothesis, and stratified by long-
76 term mean snow fraction (\bar{f}_s). Overall, the pattern of observations is consistent
77 with the Budyko curve, with a mean overestimation of the normalized
78 streamflow (\bar{Q}/\bar{P}) by just 0.02. Figure 1a also shows that, in general, larger
79 values of \bar{f}_s are associated with lower normalized evaporation (\bar{E}/\bar{P}) and
80 higher normalized mean streamflow (\bar{Q}/\bar{P}). Figure 1b clarifies this effect by
81 displaying the observed streamflow anomaly from the Budyko curve as a
82 function of snow fraction, (\bar{f}_s). A linear regression ($p < 0.01$) indicates an
83 average increase in normalized streamflow (\bar{Q}/\bar{P}) of 0.37 per unit increase in
84 snow fraction, (\bar{f}_s).

85 We have assessed the uncertainties in these data and their interpretation.
86 Precipitation measurements are sensitive to undercatch, especially for solid
87 precipitation (Groisman 1994) and so have been corrected here according to
88 Groisman (1994). Changes in soil and groundwater storage are orders of
89 magnitude smaller than the other fluxes and thus considered negligible over a
90 multi-annual period. Inter-annual changes of snow storage are minimal due to
91 absence of large areas with perennial snow cover in any of the 420
92 catchments. Streamflow measurement errors and exchanges with aquifers
93 can bias results of individual catchments, but are unlikely to be strongly
94 correlated to the snow fraction. The above uncertainties are thus unlikely to

95 result in a misinterpretation of the observed patterns in context of the Budyko
96 hypothesis.

97 Given that the mean partitioning of precipitation into streamflow and
98 evaporation is partly governed by physiographic controls that may be spatially
99 correlated with the long-term snow fraction (e.g. topography, soil, landcover,
100 etc.), and since the Budyko framework does not examine between-year
101 variations in streamflow, we extend the analysis with a study of the inter-
102 annual streamflow. We selected catchments with a significant amount of
103 snowfall, while maintaining a large number of catchments (97 catchments with
104 $\bar{f}_s > 0.15$). For each catchment, we use linear regressions to investigate
105 whether year-to-year variations in normalized annual streamflow (Q/\bar{P}) can be
106 linked to the corresponding variations in snow fraction between years.

107 Figure 2 displays the sensitivity of normalized annual streamflow to annual
108 snow fraction for the 97 catchments. Sensitivity is defined as the change in
109 normalized annual streamflow (Q/\bar{P}) per change in the annual fraction of
110 precipitation falling as snowfall (f_s) (see Methods). The mean increase of Q/\bar{P}
111 per unit of f_s is 0.29 (standard deviation 0.21) and 94 of the 97 catchments
112 display a positive value of this sensitivity. This indicates that an increase in
113 the annual f_s is almost always associated with an increase in the annual
114 streamflow, but sensitivities differ per catchment. The results are not
115 significantly influenced by changes in soil-water and groundwater storage
116 variation between years; we established this by repeating the analysis using
117 5-year averages in place of annual averages; the conclusions were
118 unaffected.

119 Variations in f_s between years are caused both by fluctuations of the mean
120 winter temperature and the fraction of precipitation falling during the winter
121 period. An identical sensitivity analysis using temperature instead of f_s
122 indicates that, on average, the annual streamflow decreases when the mean
123 winter temperature (1 Nov. – 1 Apr.) increases. This holds solely for the set of
124 catchments with high \bar{f}_s values, and is not applicable for summer
125 temperatures (1 May. – 1 Oct.) or catchments with marginal snowfall ($\bar{f}_s \leq$
126 0.15). The results therefore suggest that mean stream flow is not merely
127 related to the timing of precipitation or the associated temperature, but that
128 the form of precipitation also is a determining factor.

129 To provide a context for the streamflow sensitivity to annual snow fraction, we
130 consider the effect of temperature warming, under the assumption that the
131 observed historical climate series are representative for future scenarios. The
132 historical climate series for the 97 snow-affected MOPEX catchments indicate
133 that a large fraction of precipitation that now falls under the temperature
134 threshold will in future fall at temperatures above that threshold. A 2°C
135 temperature rise for the 97 studied catchments leads to an average 35%
136 decrease in \bar{f}_s (standard deviation 11%). For a 4°C temperature increase, \bar{f}_s
137 reduces by 60% (standard deviation 15%). As shown above, the average
138 change in normalized streamflow is 0.29 per unit of f_s , but varies by
139 catchment. Under the simplifying assumption of a system otherwise at steady-
140 state, this implies that a 2°C temperature rise, on average, could potentially

141 lead to a decrease of normalized streamflow (Q/\bar{P}) in the order of 0.1 times
142 the historical f_s . Given that mean streamflow is in general significantly lower
143 than the mean precipitation the proportional change in actual mean
144 streamflow can be much higher. Although other factors, such as changes in
145 precipitation patterns (Groisman 2004, Dore 2005), can locally compensate
146 for changes in the annual streamflow, clearly temperature rise will alter the
147 hydrological cycle. This will require an understanding of catchment function
148 that goes beyond the assumption that systems fluctuate within an unchanging
149 envelope of variability (Milly 2008), including the need to more
150 comprehensively acknowledge the role of snow for the long-term streamflow
151 patterns.

152 The observation that a lower f_s is associated with lower streamflow on the
153 annual and mean-annual timescales is restricted here to empirical evidence,
154 and does not reveal the physical processes behind these observations. The
155 processes underlying the sensitivity of mean streamflow to snowfall may be
156 related to differences in: the infiltration capacity of soils, the duration of
157 infiltration periods, the timing of infiltration periods, the evaporation from
158 snow-covered and snow-free soils, the growing season length, the soil
159 moisture regime, the potential evaporation, amongst other factors. Given the
160 diversity of catchments in our sample, each with its own internal
161 heterogeneity, the mechanisms connecting snow to mean streamflow are
162 likely to result from combinations of factors and may vary from site to site.
163 Further work is needed to clarify which hydrological processes are the main
164 contributors to the sensitivity we have presented.

165 In summary, this study uses historical data from a wide range of catchments
166 to investigate the role of the fraction of precipitation falling as snow for the
167 long-term and the inter-annual mean streamflow of catchments. There is
168 evidence that, in context of the Budyko hypothesis (Budyko 1974),
169 catchments with a high fraction of long-term precipitation falling as snowfall
170 are characterized by significantly higher long-term mean streamflow than
171 catchments with little or no snowfall. In addition, analysis of inter-annual
172 variability indicates that the annual fraction of precipitation falling as snow has
173 a significant influence on the mean annual streamflow, independent of
174 precipitation amount. Both results indicate that a change in phase of
175 precipitation from snow towards rain significantly decreases the mean
176 streamflow. Although the study catchments are restricted to the contiguous
177 United States, the diversity of physiographic and climatic settings, and the
178 number of catchments used, suggest that snowfall may affect the mean
179 streamflow in other regions as well. This finding has significant implications for
180 water resource planning, as the projected global temperature rise is expected
181 to lead to significant reductions in f_s in many regions around the world, and
182 our results indicate that this would decrease mean streamflow in these
183 regions, unless other factors compensate (Groisman 2004, Dore 2005). It is
184 particularly relevant to “water towers” (Viviroli 2007) where societally
185 important functions, such as ecosystem stability, hydropower, irrigation, and
186 industrial or domestic supply are derived from snowmelt. Associated process
187 explanations are not yet available and need to be understood if society is to

188 respond adequately to the consequences of a temperature-induced
189 precipitation shift from snow to rain.

190 **Methods**

191

192 **Data**

193 Data are from 420 catchments belonging to the Model Parameter Estimation Experiment
194 (MOPEX) (Schaake 2006). Catchments are located throughout the contiguous United States
195 and span four of the five main climate types of the Köppen-Geiger climate classification.
196 Drainage areas of the catchments vary between 67 and 10,329 km². Daily time series of
197 precipitation, temperature, potential evaporation and streamflow are all available for up to 54
198 years (1948-2001). Potential evaporation is calculated based on the NOAA Pan Evaporation
199 Atlas (Farnsworth 1983), using the Penman method (Penman 1948). The PRISM method
200 (Daly 2008) was applied for interpolation of the temperature and precipitation values to
201 account for topographic effects when estimating catchment mean precipitation and
202 temperature. Streamflow values were sourced from the United States Geological Survey. The
203 catchments were selected to have a limited anthropogenic influence, and their decadal water
204 balance is not significantly influenced by changes in glacier storage: the perennial snow-
205 covered area does not exceed 3% for individual catchments and is for most catchments non-
206 existent. Annual values used in the analysis are from 1 Sep. to 31 Aug. to minimize effects of
207 carry over storage of snowfall. The dataset is available online:
208 www.nws.noaa.gov/oh/mopex/mo_datasets.htm

209 **Snowfall estimation**

210 The fraction of precipitation falling as snow (f_s) is approximated using a simple temperature
211 threshold on each day of recorded data (e.g., Hock 2003). Precipitation on days with an
212 average temperature below 1°C is considered to be entirely snowfall, while on days with
213 temperature above 1°C, precipitation is considered to be entirely rainfall. The conclusions of
214 the paper are robust to changes in the method of snowfall estimation within reasonable
215 bounds (e.g. other temperature thresholds, or more complex schemes that linearly partition
216 precipitation between snow and rain for temperatures between two thresholds).

217 **Undercatch correction**

218 In the context of the Budyko framework, the precipitation measurements are corrected for
219 mean monthly undercatch. Corrections for undercatch are made according to Groisman
220 (1994).

221 **Budyko framework**

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

$$224 \quad \frac{1 - \bar{Q}/\bar{P}}{\bar{P}} = \sqrt{\frac{\bar{E}_p}{\bar{P}} \tanh\left(\frac{\bar{P}}{\bar{E}_p}\right) \left(1 - \exp\left(-\frac{\bar{E}_p}{\bar{P}}\right)\right)}$$

225 where \bar{Q} , \bar{P} and \bar{E}_p are the long-term mean values for the streamflow [L/T], precipitation [L/T]
226 and potential evaporation [L/T]. Similar equations proposed by others (e.g. Pike, 1964) will
227 slightly alter the water balance anomalies for individual catchments but yield similar
228 conclusions regarding the influence of snowfall.

229 **Sensitivity of inter-annual streamflow**

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

236

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

237

where

238

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

239

240

241

242

243

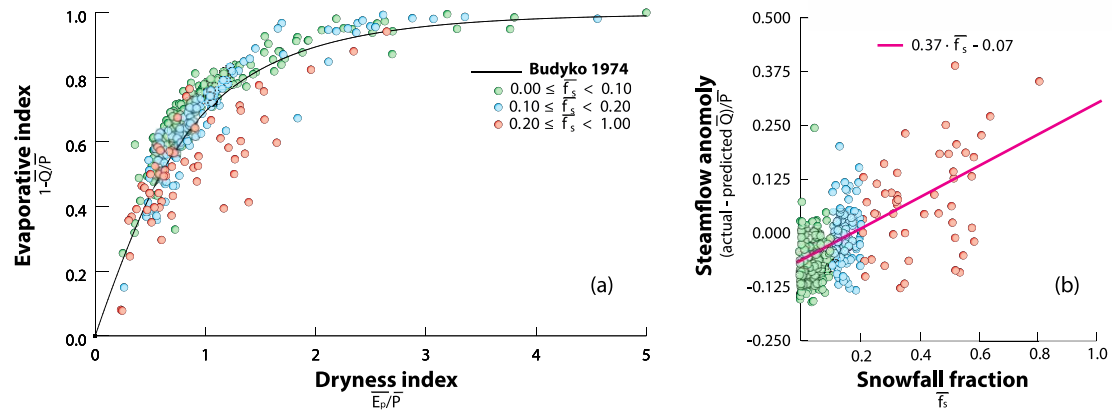
and where Q is the annual streamflow [L/T], \bar{P} is the mean annual precipitation [L/T], f_s is the annual fraction of precipitation falling as snowfall [-], and $G(f_s)$ and $F(f_s, P/\bar{P})$ are approximated as functions linearly dependent on their variables. The derivatives are approximated by the slope terms of least squares estimators.

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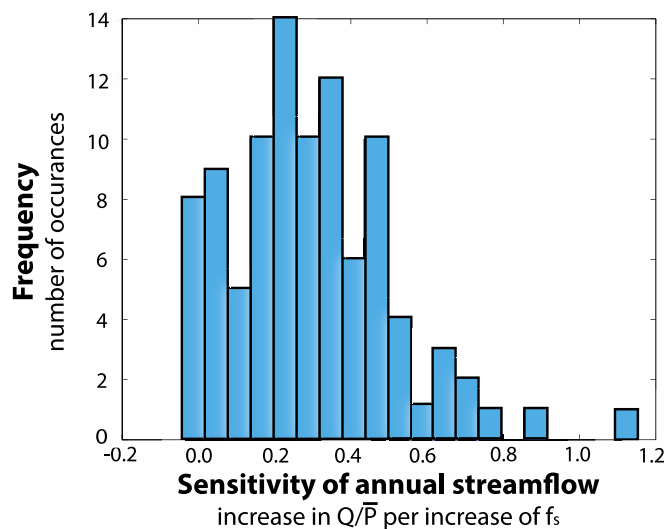
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349

350 **Figure 1: Mean annual streamflow and streamflow anomaly in the**
351 **context of the Budyko hypothesis, stratified by snow fraction.** The
352 observed long-term streamflow and precipitation measurements are placed in
353 context of the Budyko hypothesis. The Budyko hypothesis states the mean
354 streamflow is primarily a function of the catchment's annual precipitation and
355 potential evaporation. Departures below the Budyko curve for catchments with
356 a significant fraction of the precipitation falling as snow indicate that an
357 increased fraction of precipitation as snowfall is associated with higher
358 streamflow.

359



360

361 **Figure 2: Sensitivity of annual streamflow to the fraction of annual**
362 **precipitation falling as snowfall.** The histogram displays the change in
363 normalized streamflow (Q/\bar{P}) per unit of change of the annual snow fraction
364 (f_s) for 97 snow-affected catchments ($\bar{f}_s > 0.15$). Positive values of sensitivity
365 indicate that the annual streamflow of catchments varies (between years)
366 directly with the annual f_s . Years with higher snow fraction, f_s , tend to have
367 higher values of annual streamflow.

368