

Hydrologic responses to climate change: considering geographic context and alternative hypotheses

Julia A. Jones*

Department of Geosciences Oregon
State University Corvallis, OR 97331
USA

*Correspondence to:

Julia A. Jones, Department of
Geosciences Oregon State University
Corvallis, OR 97331 USA.
E-mail: jonesj@geo.oregonstate.edu

One of the most significant consequences of climate warming is the likely change in streamflow as a result of warming air temperatures. Hydrologists have responded to the challenge of understanding these effects. Many recent studies quantify historical trends in streamflow and usually attribute these trends to climate warming, via altered evapotranspiration and snowpack (Figure 1.a). However, without questioning the fundamental reality of a warming climate, hydrologists should also consider biotic and social processes whose omission may produce misleading interpretations about climate change effects on hydrology. The aim of this commentary is to raise awareness of ecological and social processes that may confound the interpretation of climate effects on hydrology, to review how the geographic context of streamflow records affects interpretation of the climate signal, and to suggest a 'checklist' of working hypotheses that can be used to structure studies of streamflow responses to climate change.

A wide variety of trends in streamflow have been detected and attributed to climate change and variability, but a few themes dominate the literature. The most common studies report earlier snowmelt, a shift to earlier streamflow timing, altered spring maximum flows, and/or intensified summer drought (Adam *et al.*, 2009; Barnett *et al.*, 2008; Brabets and Walvoord, 2009; Burn *et al.*, 2010; Cuo *et al.*, 2009; Hamlet *et al.*, 2007; Hodgekins *et al.*, 2003; Hodgekins and Dudley, 2006; Huntington *et al.*, 2004; Jefferson *et al.*, 2008; Knowles *et al.*, 2006; Lee *et al.*, 2004; Mote *et al.*, 2003; Shepherd *et al.*, 2010; Stewart *et al.*, 2005; Stewart, 2009; Wilson *et al.*, 2010; Xu *et al.*, 2009). These studies focus on mountainous regions or near-polar latitudes of the Northern Hemisphere, and the relationships among warming, snowmelt, and streamflow vary with geographic location, elevation, and latitude. Another frequent finding is a trend of increased streamflow (annual, winter, and/or spring) associated with increased precipitation or temperature, or both (Andreadis and Lettenmaier, 2006; Birsan *et al.*, 2005; Chen *et al.*, 2006; Gautam *et al.*, 2010; Johnston and Schmagin, 2008; Lins and Slack, 1999; Liu *et al.*, 2010; Milliman *et al.*, 2008; Peterson *et al.*, 2002; St. George, 2007; Wilson *et al.*, 2010; Xu *et al.*, 2009; Zhang *et al.*, 2001; Zhang and Schilling, 2006). The flow quantiles affected vary, with some studies reporting increased low flows (Liu *et al.*, 2010) while others project increased flood risk (Allamano *et al.*, 2009, but see Wilby *et al.*, 2008). The climate-streamflow trend literature also contains considerable discussion of methods. Most studies use the Mann-Kendall non-parametric test (Hirsch and Slack, 1984; Helsel and Hirsch, 2002). Moreover, there is broad recognition that trends can be confounded with long-term climate cycles (Burn, 2008; Huntington *et al.*, 2004; Lee *et al.*, 2004; Marengo, 2009; St. George, 2007; Weider and Boutt, 2010; Woo *et al.*, 2006) and that trends are sensitive to the start date of the record (e.g. Wilby *et al.*, 2008). These latter issues are not addressed in this commentary.

Received 6 January 2011
Accepted 14 January 2011

Three factors may produce misleading interpretations about climate change effects on hydrology. These factors, which are relevant to interpretations from statistical analyses as well as models of streamflow trends are: (i) vegetation responses to past disturbances, (ii) vegetation responses to climate variability, and (iii) changes in human water use associated with water management infrastructure, human behaviour and population growth (Figure 1.b–d.).

Vegetation responses to past disturbances may produce gradual trends in water yield that may be misconstrued as climate change effects (Figure 1.b). Past disturbances may be anthropogenic, such as forest management and land use conversions, or ‘natural’ disturbances including fire, windthrow, volcanic eruption, and insect outbreaks. Most hydrologists are familiar with the idea that vegetation treatments influence streamflow, but the effect of succession following disturbance in watersheds labeled as ‘unregulated’, ‘reference’, or ‘control’ is less recognized. Nevertheless, vegetation change is continual and these changes have the potential to produce streamflow trends. For example, in New England (Hubbard Brook), forest harvest shifted snowmelt and peak streamflow to several weeks earlier while three to four decades of forest regeneration shifted snowmelt and streamflow back by several weeks (Jones and Post, 2004). Cumulative forest clearing associated with exurban expansion may therefore also influence the timing of snowmelt and peak streamflow, but be misconstrued as climate change effects. Gradual forest succession may reduce streamflow in ‘reference’ watersheds that were disturbed in the past, as shown by gradual decreases in summer streamflow several decades after replacement of older forest with young forest plantations (Hicks *et al.*, 1991; Swank *et al.*, 2001; Hornbeck *et al.*, 1997; Jones and Post, 2004), as well as by declining streamflow after conversion of deciduous to conifer forest (Swank *et al.*, 1988). Gradual forest succession after fire, windthrow, insect outbreaks, or volcanic disturbances also may produce gradual increases or decreases in streamflow (e.g. Major and Marks, 2006; Scatena *et al.*, 1996; Swank and Crossley, 1988). Thus, changes in forest species and age classes in both managed and unmanaged forests may produce changes

in streamflow that are similar in rate and magnitude to those that have been attributed directly to climate change. Many ‘unregulated’ streamflow gages are downstream of forests, so trends in streamflow from these locations may be the result of climate change, responses to past forest disturbances, or both. As record lengths at many ‘reference’ or ‘control’ watersheds become long enough to detect climate-related trends, they also are likely to capture effects of vegetation succession.

Vegetation responses to climate variability may permit ecosystem water use to be resilient to stresses associated with climate warming, resulting in no streamflow response to changing climate (Figure 1.b). Vegetation responses occur at multiple temporal and ecological scales, ranging from the leaf to the ecosystem, and the second to the century. Drought adaptations (e.g. stomatal conductance, Farquhar and Sharkey, 1982) permit certain species or plant functional types to limit transpiration in response to increased temperature or vapor pressure (e.g. Schwinning and Ehleringer, 2001). As a result, drought may produce relatively small interannual changes in stand-level transpiration (Oishi *et al.*, 2010). This phenomenon is consistent with the finding that evapotranspiration may be nearly invariant at the interannual timescale in undisturbed watersheds, as shown by the strong linear relationship between annual precipitation and streamflow evident in a range of diverse undisturbed forest ecosystems (Post and Jones 2001). Moreover, over successional time scales, vegetation mortality (e.g. van Mantgem *et al.*, 2009) may help maintain relatively constant whole-ecosystem transpiration. Thus, ecosystems have multiple mechanisms to adjust to changes in temperature and moisture, which may result in no detectable trends in streamflow even when climate is changing.

It has long been recognized that human actions influence streamflow, and these influences may confound interpretations of climate change effects in many ways (Figure 1.c). Changes in human water use include effects of infrastructure for water management, such as flood control and water supply, as well as changes in human land use, population density, and behaviour. Structures such as dams, reservoirs, and canals have influenced the timing, and perhaps the magnitude, of streamflow in many locations by storing and withdrawing water from streams in one location or time period, and returning it to the system at another location and/or in another time period. Globally streamflow trends are quite different in managed *versus* unmanaged rivers (Milliman *et al.*, 2008). In many regions of the USA, accumulated storage capacity in reservoirs over the period since 1940 (Graf, 1999) and dam operations for flood control and irrigation have decreased maximum flows and increased

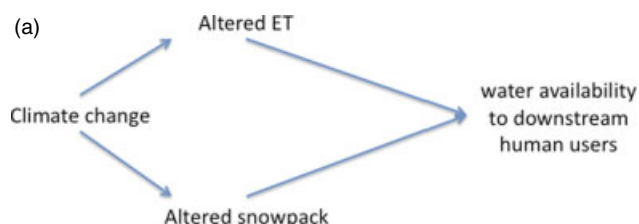


Figure 1.a. Many studies of streamflow response infer a direct relationship between climate change, snowpack and evapotranspiration, and water availability to downstream human users

INVITED COMMENTARY

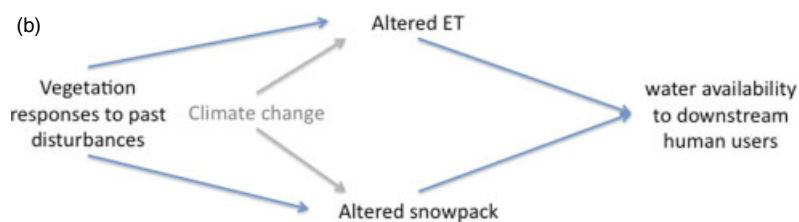


Figure 1.b. Vegetation responses to past disturbances can produce gradual trends in ET and snowpack that may be misconstrued as climate change effects

minimum flows (Poff *et al.*, 2007). Agriculture and urbanisation may produce increasing or decreasing trends in streamflow. For example, groundwater pumping and supplemental dry season irrigation has increased lowflows in the US high plains (Kustu *et al.*, 2010). In the US Midwest, summer lowflows have declined but winter lowflows have increased in watersheds dominated by irrigated agriculture, but both summer and winter lowflows have increased over the same period in watersheds dominated by increasing urban water effluent discharge (Wang and Cai, 2010). Similar trends are apparent near San Antonio in the arid southwest of the USA, where streamflow over a period of rapid urbanisation has declined upstream of the city, but increased downstream (Sahoo and Smith, 2009), and in the northwest USA, where irrigation has reduced flows over the past century in the Columbia River (Naik and Jay, 2005). Landcover changes had a greater effect on streamflow than climate in the lowlands of a large river basin in the US Pacific Northwest (Cuo *et al.*, 2009). Thus, many forms of gradual change in water infrastructure, management, and human use have produced trends in streamflow that may be correlated with, but not directly caused by, climate change.

Geographic context determines the likelihood that one or more of these biotic and social processes (Figure 1.b–d.) confounds our ability to detect effects of climate change on hydrology. The geography of watersheds creates a paradox for studies of climate change effects on hydrology: to avoid the possible effects of flow regulation as a confounding factor, many studies utilize records from rivers that are ‘unregulated’ (lacking dams). However, these are typically low-order, headwater drainage basins often far removed from human populations: 317 undammed

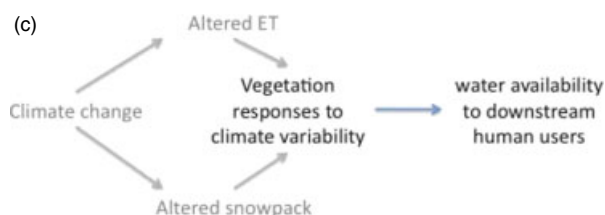


Figure 1.c. Vegetation responses to climate variability can produce no change in streamflow, despite climate change

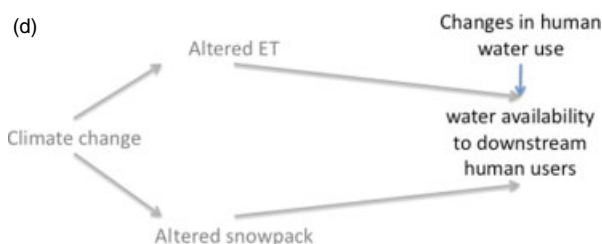


Figure 1.d. Changes in human water use through infrastructure and water management, human population and behavior influence streamflow trends in ways that can be misconstrued as climate change effects, even in ‘unregulated’ basins

reference basins in the USA had a median drainage area of 623 km², and 89% of these basins were ≤5th order (Poff *et al.*, 2007). Climate-related streamflow trends in these ‘unregulated’ basins may be overwhelmed by vegetation responses to past disturbances, or ecosystem adjustments to climate variability. Thus, all records of streamflow reflect some combination of factors that may confound interpretations of climate change effects.

Perhaps the climate change hydrology literature has focused on spring snowmelt because it is easier to detect than other climate change effects, which may be more biologically or human mediated. Direct climate warming effects on hydrology probably are most readily detected from streamflow records near glaciers or snowpacks whose melt behaviour is altered by warming, but where streamflow is relatively little affected by vegetation adaptations (e.g. above treeline, or where flow is groundwater-dominated, see Jefferson *et al.*, 2008). Also, direct climate warming effects on streamflow probably are most readily detected for times of year in which vegetation is relatively unable to respond (e.g. where snowmelt changes precede leafout in deciduous forests, see Campbell *et al.*, 2010).

Outside of these settings, vegetation responses to past disturbances, climate variability, and changes in human water use may be used as a checklist of alternative hypotheses, in addition to the physical process responses to climate change, to evaluate streamflow trends. Hydrologists can explore questions such as: “How does the magnitude and timing of climate change effects on streamflow compare with streamflow responses to vegetation disturbance?” “How do climate change effects on hydrology in headwater

basins compare with the streamflow responses to river regulation, land use, or population change in the downstream basins to which they contribute?” “What regions might be expected to have the least/greatest response of hydrology to climate change, given the biotic, social, and climate factors?”

Consideration of climate change effects on hydrology has led to reflection and renewal in hydrologic research and may greatly enrich the domain of ecohydrology. To understand climate change, hydrologists are turning to long-term records as a source of insights about a broad suite of hydrologic processes and responses. Although analyses of past streamflow trends have many limitations, when formulated with appropriate consideration to multiple processes, such analyses can greatly extend our understanding of the multiple factors that influence water availability and timing.

Acknowledgements

This comment benefitted from NSF support to the HJ Andrews Long-Term Ecological Research project, US Forest Service support of long-term streamflow record archiving (<http://www.fsl.orst.edu/climhy/>), and discussions with FJ Swanson and participants in a Long-Term Ecological Research (LTER) Synthesis workshop funded by the LTER Network Office.

References

- Adam JC, Hamlet AF, Lettenmaier DP. 2009. Implications of global climate change for snowmelt hydrology in the twenty-first century. *Hydrological Processes* 23: 962–972.
- Allamano P, Claps P, Laio F. 2009. Global warming increases flood risk in mountainous areas. *Geophysical Research Letters* 36: L24404, DOI:10.1029/2009GL041395.
- Andreadis KM, Lettenmaier DP. 2006. Trends in 20th century drought over the continental United States. *Geophysical Research Letters* 33: L10403, DOI:10.1029/2006GL025711.
- Barnett TP, Pierce DW, Hidalgo HG, Bonfils C, Santer BD, Das T, Bala G, Wood AW, Nozawa T, Mirin AA, Cayan DR, Dettinger MD. 2008. Human-induced changes in the hydrology of the western United States. *Science* 319: 1080–1083.
- Birsan M-V, Molnar P, Burlando P, Pfaundler M. 2005. Streamflow trends in Switzerland. *Journal of Hydrology* 314: 312–329.
- Brabets TP, Walvoord MA. 2009. Trends in streamflow in the Yukon River Basin from 1944 to 2005 and the influence of the Pacific Decadal Oscillation. *Journal of Hydrology* 371: 108–119.
- Burn DH. 2008. Climatic influences on streamflow timing in the headwaters of the Mackenzie River Basin. *Journal of Hydrology* 352: 225–238.
- Burn DH, Sharif M, Zhang K. 2010. Detection of trends in hydrological extremes for Canadian watersheds. *Hydrological Processes* 24: 1781–1790.
- Campbell JL, Ollinger SV, Flerchinger GN, Wicklein H, Hayhoe K, Bailey AS. 2010. Past and projected future changes in snowpack and soil frost at the Hubbard Brook Experimental Forest, New Hampshire, USA. *Hydrological Processes* 24: 2465–2480.
- Chen Y, Takeuchi K, Xu C, Chen Y, Xin Z. 2006. Regional climate change and its effects on river runoff in the Tarim Basin, China. *Hydrological Processes* 20: 2207–2216.
- Cuo L, Lettenmaier DP, Alberti M, Richey JE. 2009. Effects of a century of land cover and climate change on the hydrology of the Puget Sound basin. *Hydrological Processes* 23: 907–933.
- Farquhar GD, Sharkey TD. 1982. Stomatal conductance and photosynthesis. *Annual Review of Plant Physiology* 33: 317–345.
- Gautam MR, Acharya K, Tuladhar MK. 2010. Upward trend of streamflow and precipitation in a small, non-snow-fed, mountainous watershed in Nepal. *Journal of Hydrology* 387: 304–311.
- Graf WL. 1999. Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research* 35(4): 1305–1311.
- Hamlet AF, Mote PW, Clark MP, Lettenmaier DP. 2007. Twentieth century trends in runoff, evapotranspiration, and soil moisture in the western United States. *Journal of Climate* 20: 1468–1486.
- Helsel DR, Hirsch RM. 2002. Statistical methods in water resources. In *Techniques of Water-Resources Investigations of the United States Geological Survey*, Book 4 Hydrological analysis and interpretation, Chapter A3. US Geological Survey.
- Hicks BJ, Beschta RL, Harr RD. 1991. Long-term changes in streamflow following logging in western Oregon and associated fisheries implications. *Water Research Bulletin* 27(2): 217–226.
- Hirsch RM, Slack JR. 1984. A nonparametric trend test for seasonal data with serial dependence. *Water Resources Research* 20(6): 727–732.
- Hodgkins GA, Dudley RW, Huntington TG. 2003. Changes in the timing of high flows in New England over the 20th century. *Journal of Hydrology* 278: 244–252.
- Hodgkins GA, Dudley RW. 2006. Changes in the timing of winter–spring streamflows in eastern North America, 1913–2002. *Geophysical Research Letters* 33: L06402, DOI:10.1029/2005GL025593.
- Hornbeck JW, Martin CW, Eager C. 1997. Summary of water yield experiments at Hubbard Brook Experimental Forest, New Hampshire. *Canadian Journal of Forest Research* 27: 2043–2052.
- Huntington TG, Hodgkins GA, Keim BD, Dudley RW. 2004. Changes in the proportion of precipitation occurring as snow in New England (1949 to 2000). *Journal of Climate* 17: 2626–2636.
- Jefferson A, Nolin A, Lewis S, Tague C. 2008. Hydrogeologic controls on streamflow sensitivity to climate variation. *Hydrological Processes* 22: 4371–4385.
- Johnston CA, Schmagin BA. 2008. Regionalization, seasonality, and trends of streamflow in the US Great Lakes Basin. *Journal of Hydrology* 362: 69–88.
- Jones J A, Post DA. 2004. Seasonal and successional streamflow response to forest cutting and regrowth in the northwest and eastern United States. *Water Resources Research* 40: W05203, DOI:10.1029/2003WR002952.
- Knowles N, Dettinger M, Cayan D. 2006. Trends in snowfall versus rainfall for the Western United States. *Journal of Climate* 19: 4545–4559.
- Kustu MD, Fan Y, Robock A. 2010. Large-scale water cycle perturbation due to irrigation pumping in the US High Plains: A synthesis of observed streamflow changes. *Journal of Hydrology* 390: 222–244.
- Lee S, Klein A, Over T. 2004. Effects of the El Niño–southern oscillation on temperature, precipitation, snow water equivalent and resulting streamflow in the Upper Rio Grande river basin. *Hydrological Processes* 18: 1053–1071.
- Lins HF, Slack JR. 1999. Streamflow trends in the United States. *Geophysical Research Letters* 26: 227–230.
- Liu D, Chen X, Lian Y, Lou Z. 2010. Impacts of climate change and human activities on surface runoff in the Dongjiang River basin of China. *Hydrological Processes* 24: 1487–1495.

- Major JJ, Mark LE. 2006. Peak flow responses to landscape disturbances caused by the cataclysmic 1980 eruption of Mount St. Helens, Washington. *GSA Bulletin* 118(7/8): 938–958, DOI:10.1130/B25914.1.
- Marengo J. 2009. Long-term trends and cycles in the hydrometeorology of the Amazon basin since the late 1920s. *Hydrological Processes* 23: 3236–3244.
- Milliman JD, Farnsworth KL, Jones PD, Xu KH, Smith LC. 2008. Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951–2000. *Global and Planetary Change* 62: 187–194.
- Mote PW, Parson EA, Hamlet AF, Keeton WS, Lettenmaier D, Mantua N, Miles EJ, Peterson DW, Peterson DL, Slaughter R, Snover AK. 2003. Preparing for climatic change: the water, salmon, and forests of the Pacific Northwest. *Climatic Change* 61: 45–88.
- Naik P, Jay DA. 2005. Estimation of Columbia River virgin flow: 1879 to 1928. *Hydrological Processes* 19: 1807–1824.
- Oishi AC, Oren R, Novick KA, Palmroth S, Ka GG. 2010. Interannual invariability of forest evapotranspiration and its consequence to water flow downstream. *Ecosystems* 13: 421–436.
- Peterson BJ, Holmes RM, McClelland JW, Vorosmarty CJ, Lambers RB, Shiklomanov AI, Shiklomanov IA, Rahmstorf S. 2002. Increasing river discharge to the Arctic Ocean. *Science* 298: 2171 (2002), DOI:10.1126/science.1077445.
- Poff NL, Olden LD, Merritt DM, Pepin DM. 2007. Homogenization of regional river dynamics by dams and global biodiversity implications. *Proceedings of the National Academy of Science (PNAS)* 104(14): 5732–5737.
- Post DA, Jones LA. 2001. Hydrologic regimes of forested, mountainous, headwater basins in New Hampshire, North Carolina, Oregon, and Puerto Rico. *Advances in Water Resources* 24: 1195–1210.
- Sahoo D, Smith PK. 2009. Hydroclimatic trend detection in a rapidly urbanizing semi-arid and coastal river basin. *Journal of Hydrology* 367: 217–227.
- Scatena FN, Moya S, Estrada C, China JD. 1996. The first five years in the reorganization of aboveground biomass and nutrient use following Hurricane Hugo in the Bisley Experimental Watersheds, Luquillo Experimental Forest, Puerto Rico. *Biotropica* 28(4a): 424–440.
- Schwinning S, Ehleringer J. 2001. Water use tradeoffs and optimal adaptations to pulse-driven ecosystems. *Journal of Ecology* 89: 464–480.
- Shepherd A, Gilb KM, Rood SB. 2010. Climate change and future flows of Rocky Mountain rivers: converging forecasts from empirical trend projection and down-scaled global circulation modeling. *Hydrological Processes* 24: 3864–3877.
- St. George S. 2007. Streamflow in the Winnipeg River basin, Canada: Trends, extremes and climate linkages. *Journal of Hydrology* 332: 396–411.
- Stewart I, Cayan DR, Dettinger MD. 2005. Changes toward earlier streamflow timing across western North America. *Journal of Climate* 18: 1136–1155.
- Stewart IT. 2009. Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrological Processes* 23: 78–94.
- Swank WA, Crossley DA. 1988. Forest Hydrology and Ecology at Coweeta. *Ecological Studies*, vol. 66. Springer-Verlag: New York.
- Swank WT, Swift LW, Douglass JE. 1988. Streamflow Changes Associated with Forest Cutting, Species Conversions, and Natural Disturbances. I In *Forest Hydrology and Ecology at Coweeta. Ecological Studies*, vol. 66. Swank WA, Crossley DA, (eds). Springer-Verlag: New York; p. 297–312. 1988.
- Swank WT, Vose JM, Elliott KJ. 2001. Long-term hydrologic and water quality responses following commercial clearcutting of mixed hardwoods on a southern Appalachian catchment. *Forest Ecology and Management* 143: 163–178.
- Van Mantgem PJ, Stephenson NL, Byrne JC, Daniels LD, Franklin JF, Fule PZ, Harmon ME, Larson AJ, Smith JM, Taylor AH, Veblen TT. 2009. Widespread increase of tree mortality rates in the western United States. *Science* 323: 521–524.
- Wang D, Cai X. 2010. Comparative study of climate and human impacts on seasonal baseflow in urban and agricultural watersheds. *Geophysical Research Letters* 37: L06406, DOI:10.1029/2009GL041879.
- Weider K, Boutt DF. 2010. Heterogeneous water table response to climate revealed by 60 years of ground water data. *Geophysical Research Letters* 37: L24405, DOI:10.1029/2010GL045561.
- Wilby RL, Beven KJ, Reynard NS. 2008. Climate change and fluvial flood risk in the UK: more of the same? *Hydrological Processes* 22: 2511–2523.
- Wilson D, Hisdal H, Lawrence D. 2010. Has streamflow changed in the Nordic countries?—Recent trends and comparisons to hydrological projections. *Journal of Hydrology* 394: 334–346.
- Woo M-K, Thorne R, Szeto KK. 2006. Reinterpretation of streamflow trends based on shifts in large-scale atmospheric circulation. *Hydrological Processes* 20: 3995–4003.
- Xu C, Chen Y, Hamid Y, Tashpolat T, Chen Y, Ge H, Li W. 2009. Long-term change of seasonal snow cover and its effects on river runoff in the Tarim River basin, northwestern China. *Hydrological Processes* 23: 2045–2055.
- Zhang X, Harvey KD, Hogg WD, Yuzyk TR. 2001. Trends in Canadian streamflow. *Water Resources Research* 37(4): 987–998.
- Zhang Y-K, Schilling KE. 2006. Increasing streamflow and baseflow in Mississippi River since the 1940s: Effect of land use change. *Journal of Hydrology* 324: 412–422.