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

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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.

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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

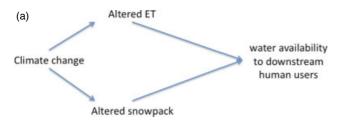


Figure 1.a. Many studies of streamflow response infer a direct relationship between climate change, snowpack and evapotranspiration, and water availability to downstream human users

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

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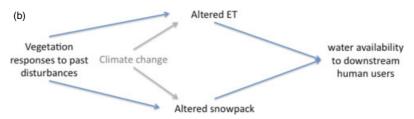


Figure 1.b. Vegetation responses to past disturbances can produce gradual trends in ET and snowpack that may be misconstrued as climate change effects

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

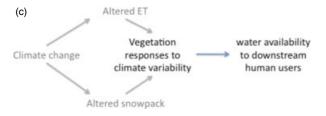


Figure 1.c. Vegetation responses to climate variability can produce no change in streamflow, despite climate change

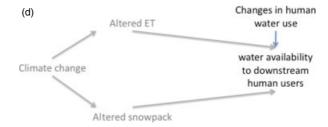


Figure 1.d. Changes in human water use through infrastructure and water management, human population and behavior influence streamflow trends in ways that can be misconstrued as climate change effects, even in "unregulated" basins

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.

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