Paradox of Peak Flows in a Changing Climate

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Almost all observational studies report that extreme precipitation in the U.S. has increased in magnitude over the last several decades (Groisman et al. 1999, 2014; Kunkel et al. 2013). Although such studies differ regarding the geographic influence of trends (Mass et al. 2011), the consensus on extreme precipitation (i.e., short-term events with a 5% exceedance probability or less) is surprisingly unequivocal. The American Meteorological Society (AMS) *2013 State of Knowledge* report on extreme precipitation (Kunkel et al. 2013) states that "There is strong evidence for a nationally averaged upward trend in the frequency and intensity of extreme precipitation events . . . " and that the in situ measurement network is considered "adequate to detect such trends." In a slightly more recent study, Groisman et al. (2013) reported that the very heavy precipitation rates (in the upper 5% of all records) have increased over approximately two-thirds of the eastern U.S. during the last 30 years, whereas the number of days with maximum daily convective available potential energy (CAPE) values exceeding 1,500 J/kg has increased ~30% in the same period during the spring season. Although the potential causes of this increasing trend may be multifactorial, the most recent AMS report also indicates increasing atmospheric water vapor as a leading causative factor (Kunkel et al. 2013).

Despite the overwhelming consensus on the rising trend of extreme precipitation rates, the response of peak stream flow is not as unequivocal. Although regulation of surface flow, increasing imperviousness, and altering infiltration rates through land cover change are some of the many ways peak flow distribution can be impacted during a stationary precipitation regime, a clear signal of the rising trend of extreme precipitation may be expected in peak flow records. However, the paradox of peak flow is that any rising trend in peak flows is much more elusive to observe over statistically significant locations. Vogel et al. (2011) analyzed as many as 14,000 U.S. streamflow records and found statistically significant increases in flood risk at only approximately 10% of the stations. They also attributed most of this increase to hydrologic changes in land cover (increasing imperviousness, and hence, increased surface runoff generation) rather than global warming. Villarini et al. (2009) analyzed 50 stream flow stations with more than a century-long record of flow observations using sophisticated methods for change point detection, trend analysis, and nonstationarity. However, they concluded that "it is easier to proclaim the demise of stationarity of flood peaks than to prove it through analyses of annual flood peak data."

Hydrologic extremes are the foundation of most design, operation, and risk management of water management systems that currently serve society. Yet, the current hydrology that traditionally models only the natural laws of physics of a watershed has become increasingly limited in its ability to provide relevant answers for emerging changes that are observed (Vogel 2011). This is because traditional hydrology continues to assume that the extensive replumbing of the natural water network, along with changes to land cover and hemispheric forcing of climate change attributable to extensive human activity, are only an external forcing rather than an integral part of the coupled human–natural system.

The massive but gradual redistribution of water through artificial reservoirs, numerous irrigation schemes, land cover change, and urbanization since the early 1900s has resulted in a nonnegligible contribution to increased moisture availability and altered atmospheric convergence patterns overland in the U.S. (Puma and Cook 2010; DeAngelis et al. 2010). For example, USGS records (Kenny et al. 2009) indicate an increase in irrigation acreage from 35 million acres (in 1950) to 65 million acres (in 2005). The latter is equivalent to a withdrawal of 144 million acre-ft (or 177 km^3) of surface and ground water per year that evaporates directly to the atmosphere [and may be recycled as precipitation (Eltahir and Bras 1996)], and likely balances any increases in peak flow attributable to rising precipitation rates. Similarly, approximately 75,000 artificial reservoirs were built in the U.S. during the last century, with a total capacity almost equaling one year of mean runoff (Graf 1999, 2006; Global Water Systems Project 2008). The cumulative effect of these extensive impoundments has been to triple the average residence time of surface water from 0.1 years (in 1900) to 0.3 years in 2000 (Vorosmarty and Sahagian 2000), an aspect that clearly has not received attention during the assessment of peak flow trends. Similar large-scale alterations have happened to the natural land cover in the U.S., which have modified both hydrologic behavior (water partitioning) and radiative behavior (energy partitioning) in nonnegligible amounts (Pielke et al. 2011).

The explicit consideration of the human replumbing of natural water systems may only explain part of the peak flow paradox. For example, global warming may intensify evaporative fluxes and initiate regional drying of soils. This would compensate for increasing precipitation rates through increased abstraction of precipitation and potentially lowering of peak flows. Thus, the hydrologic engineering community may need to employ a multifactorial approach involving, as a fundamental premise, the human impact (feedback) on local-to-regional weather and climate that have been researched for over many decades (Pielke 2001, 2009; Mahmood et al. 2010), but overlooked in most studies of hydrologic extremes (Hossain et al. 2012). Understanding the causative factors behind the historical evolution of extreme precipitation and peak flow is probably the most urgent priority for current hydrologists to adapt the design and operation of infrastructure. Through an investigation of the combined role of this land–atmosphere feedback owing to artificial redistribution of water, land cover change and climate change, one may postulate that the paradox of peak flows not having responded in sync with rising extreme precipitation may be better understood. Consequently, this approach may allow the hydrologic engineering community to understand how peak flow patterns, which are used in the frequency analysis and design of many infrastructure, are likely to change in future, given that the replumbing of watersheds will continue. Incidentally, a new term has recently been coined to address such changing nature of hydrology attributable to human impacts. It is designated "hydromorphology" and is defined analogously as the geomorphological approach to hydrology (Vogel 2011).

There appears to be a need to shift research and education from traditional hydrology to one that addresses hydromorphology for better understanding of this paradox of peak flows. At minimum, this likely entails the consideration of a hydrology curriculum that recognizes the full coupling of the human–natural system with atmospheric feedback (and models), surface–ground-water interactions, global and regional climate, and interactions with the human management of water resources. Similarly, research would involve the use of atmospheric, hydrologic (surface and ground) models coupled explicitly with water management and redistribution modeling. Currently, there appears to be no such comprehensive modeling tool in place that can allow the pursuit of hydromorphology. However, some recent studies, such as that of Biemans et al. (2011), that have aimed to understand the global impact of human management of water by physical systems on local hydrology appears quite promising. If more of such model development work continues along this direction, the hydrologic community will one day have the tools required for understanding the hydromorphology of peak flows in the 21st century. In summary, the causes of alteration to peak flow distribution are multifactorial; it may be time for hydrologic engineers to apply a hydromorphological approach rather than the purely hydrologic approach of the past.

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