Advancing the Science of River Low Flows in a Changing Climate

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Introduction

Low streamflow hydrology — the study of minimum flows in rivers — is of critical importance for society. This is because understanding *how low* streamflow will go, and *how often* low streamflows ("low flow" henceforth) will occur, is necessary to meet water needs for municipal supply, irrigation, industry use, river navigation, recreation, and wildlife conservation [Smakhtin, 2001]. Low flows are a sensitive indicator of climate. However, like other areas of water resources, low flow studies have been grounded in the principle of stationarity – that is, the idea that natural systems vary within a known, unchanging range of variability – which has been rendered obsolete by climate change [Milly, 2008]. Low flows describe an important component of water scarcity within the broader issue of hydrological drought, yet there has been a relative paucity of research considering how climate change will affect low flows. This can be partially attributed to the unique challenges in working with low flows. First, there is the data challenge: data are often unavailable (e.g., ungauged basins) or are impacted by human activities (i.e., reservoirs, irrigation). Next, low flows are strongly influenced by groundwater interactions with surface water, for which data are difficult to obtain and analyses therefore rely on models. Finally, what constitutes as "low flow" may be defined differently by users with diverse water needs; for example, some applications may be concerned with average 7-day or 30-day minimum flow, while others may be interested in a particular exceedance probability threshold (e.g., the flow exceeded 75/90/95% of the time). Despite these challenges, there is an urgent need to gain a better understanding of the changing behavior of low flow conditions to support sustainable water management and protect against potential risks and impacts.

Here we describe the major tools that can be brought to bear on these issues to advance the science of low flows for water management decisions, as follows:

Using Hydrological Models

Hydrological models that incorporate land surface characteristics (topography, vegetation, soils) and explicitly account for the governing physical processes of the land surface water budget (soil moisture, evapotranspiration, runoff) are viable tools for advancing low flow research. Hydrological models integrate precipitation and temperature information *together* with the aforementioned characteristics, which enables low flow assessment under both climate and land use changes, and can be applied over areas with limited data. Further, hydrological models offer a means to project "natural" flow data that are otherwise altered by humans, especially via simulating streamflows based solely on meteorology and thus not subject to reservoirs, irrigation, etc. This is important, given that our inspection of 9068 U.S. Geological Survey (USGS) stream gauges in the continental U.S. revealed that data from 6862 have been altered by reservoir storage. Finally, if one wants to consider the impacts of changing land-cover, physically based models offer the *only way* to estimate future low flows in conjunction with future climate projections. Though a limited number of studies have successfully used hydrological models for low flow research [e.g., Wilby and Harris, 2006; Demirel et al., 2013], and non-stationarity [Vaze et al., 2010], the potential remains largely untapped.

There are, however, potential shortcomings to estimating low flows with hydrologic models. First, low flows are strongly influenced by groundwater, but hydrologic models often lack the ability to represent water storage, deep below ground. This can be quantified and potentially overcome by coupling surface and groundwater models [e.g., Rosenberg et al., 2012]. Second, with little exception, hydrologic models are typically calibrated to mean, or even peak flow conditions, rather than to low flows. Model calibration is already limited by the availability of high quality data, but is often overcome by regionalization techniques, that is, transferring parameters from nearby or similar basins based on physiographic features (e.g., topography, vegetation, soils). The process of regionalization is often used to estimate flood frequency parameters, but an analogous approach has not been used to calibrate for low flows. We put forth that a comparable regionalization approach could be developed for low flow characteristics, which would improve upon existing regionalization efforts generally focused on mean conditions, such as that being carried out by the USGS.

Assessing and Incorporating Climate Non-stationarity

Low flows are sensitive to climate, and previous research has indicated that trends in low flow features over time are associated with historical changes in climate [Lins and Slack, 1999]. Further, low flows are influenced by fluctuations in the ocean-atmospheric system [Stahl and Hisdal, 2004]. However, for many stream gauge locations, for example in the U.S. and elsewhere, data are only available for a limited number of years, which may not span the recurrence interval and duration of such fluctuations. Therefore, an integral part of investigating non-stationarity in low flow features also lies in identifying the influence of climate variability at decadal to multi-decadal scales, as previous studies have indicated [Stahl and Hisdal, 2004].

Once the connection with climate is established, there needs to be a way to incorporate those findings into design estimates of low flow. This is critical because current estimates of low flow characteristics do not reflect these shifting risks, rather they are "stationary". For instance, one of the most common low flow indices in the U.S. is the annual average 7-day minimum flow that occurs on average every 10-years (10q7). 10q7 was originally developed to regulate stream pollution, but has since been applied widely. Therefore, the current practice of estimating a single 10q7 value may be inappropriate, especially given recent findings that minimum flows are actually changing in U.S. river basins [Lins and Slack, 1999]. One tool that can be applied to this issue is extreme value theory [Coles, 2001] – a branch of statistics uniquely-geared towards modeling minimum (or maximum) values – which offers a promising means to include climate information (i.e., covariates), such as the El-Nino Southern Oscillation, to quantify how minimum flows vary from year-to-year. Extreme value theory is well suited to studying hydrologic phenomena [Katz et al., 2002] and has been used to look at changing low flows in Europe [Feyen and Dankers 2009], but to our knowledge has not been used with covariates in the study of low flows.

Fostering a Closer Connection with Decision-making

To truly advance low flow science in a non-stationary climate, research directions and outcomes must also reflect the needs and concerns of decision-makers. It has been shown that successful use of climate knowledge requires some level of iteration between knowledge producers and users [Dilling and Lemos, 2011]. For instance, stakeholder involvement was critical to making season-ahead low flow predictions relevant to drought planning for species conservation in Montana [Towler et al., 2013]. In this vein, research initiatives that help to build the capacity to prepare for and adapt to climate variability and change, such as the Western Water Assessment, one of NOAA's Regional Integrated Sciences and Assessments (RISAs), as well as other key efforts to develop closer partnerships between scientists and engineers [Tye et al., 2014] are prime examples of how these feedbacks can occur and should be used to guide future low flow research.

We would like to challenge the scientific community, together with engineers, regional water managers, local drought planners, and state agencies to more actively engage in low flow discourse. Only together can we advance the science of low flows and develop relevant tools to broadly manage the changing risks of low flows in support of sustainable water management in a changing climate.

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