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# Detection of long-term change in hydroelectric reservoir inflows: Bridging theory and practise

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## SUMMARY

We studied long-term monotonic trend in inflow volume to 20 reservoirs, plus a measure of system-wide hydroelectric power potentially available for generation, in British Columbia, Canada. The primary analysis involved application of a linear method with explicit signal-to-noise ratio ($S:N$) estimation to monthly and annual mean inflows over the period of record common to all basins, providing a broad and convenient overview of changes across the hydroelectric system. Additional analyses then investigated the sensitivity of the results to methodological choices, focussing on annual inflow volume for eight indicator basins and system power. In these auxiliary analyses, alternative data selection and processing schemes were explored: full period of record for each indicator basin; residual after Pacific Decadal Oscillation signal removal; and data from streamgauges on catchments within or near each indicator basin. Alternative analysis techniques were also applied: nonparametric Spearman rank correlation with adjustment for serial dependence; change point detection using Mann–Whitney sliding window analysis; and visual assessment of data low-pass filtered using polynomial fits of various orders. Finally, we studied changes in year-to-year water supply variability, employing a split-sample approach implemented using a standard $F$-test; a nonparametric Ansari–Bradley test; and a novel Monte Carlo-based test on the Shannon entropy, a measure of hydroclimatic information content. The results provided no substantial evidence for decreased annual water supply and pointed to some increases; seasonal inflow pattern shifts were also detected for many basins, in particular a wintertime flow increase. The split-sample tests yielded no evidence for shifts in the volatility and predictability of annual inflow. One of the more intriguing and perhaps broadly important findings was that methodological choices ultimately made little difference to final outcomes.

## 1. Introduction

BC Hydro is a government-owned corporation acting as the primary provider of power to the ~4.5 million residents of the Canadian province of British Columbia. As 90% of this power comes from hydroelectric generation, delivery of abundant, low-cost energy in a socially, environmentally, and economically sustainable way is tied to the province's water resources. However, river flows are sensitive to climatic variability and change. Rainfall, winter snowpack, and summer glacial melt are key drivers of BC Hydro's reservoir inflows. Thus, climatic trends might not only affect demand (by changing per capita winter heating or summer cooling loads, for instance), but also the supply of hydroelectric power available. As such, a thorough examination of the possible impacts of climate change to reservoir inflows is prudent.

Empirical trend analysis of historically observed reservoir inflows is a key component of any attempt to address the implications of climatic changes to hydroelectric generation potential, for several reasons. First, and most simply, it is important to occasionally take stock, both at the operational level and at the organizational or corporate level, of the changes (be they natural or anthropogenic) that have occurred in reservoir inflows – the ultimate source of revenue for a heavily hydroelectric-based power utility. The broader significance of such information is reflected, for instance, in a directive given to BC Hydro by an independent government oversight body, the British Columbia Utilities Commission (BCUC), to perform trend assessment of historical reservoir inflows (M. Rucker, BC Hydro, pers. comm., 2010).

Second, the results of such analyses provide the closest thing available to a "ground truth" about the nature of hydroclimatic

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changes, and against which inflow projections developed using general circulation models (GCMs) of global climate (along with downscaling and process-oriented watershed models) might be compared. Although highly sophisticated and potentially valuable for long-term energy planning purposes, model simulation studies are based on a variety of environmental models and greenhouse gas (GHG) emissions scenarios, all of which are in turn based on an array of assumptions and subject to much uncertainty. Indeed, the major goal of such modeling studies should be to characterize and quantify future uncertainty of inflow under possible future climatic changes, rather than to provide a precise prediction. As such, empirical, data-driven analysis of observational records from the recent past – that is, an evidence-based look at what has actually happened under historical climatic changes – can add much value by providing solid grounding and context. For example, prior statistical analyses of historical streamflow datasets within the general study area of the current project have revealed the importance of watershed glacial cover in controlling long-term streamflow trends (Fleming and Clarke, 2003; Stahl and Moore, 2006), which in turn provides guidance to the types of process-based models that are required for credible assessments of potential future hydroclimatic trajectories.

Third, it can be risky to jump to conclusions regarding the direction and strength of changes in a given river on the basis of observed broad patterns in climate, or by generalizing outcomes from statistical analyses of other river basins. Prior climate trend analyses in BC have outlined general shifts in temperature and precipitation regimes over past decades. Smaller bodies of work have similarly been developed for river flow or other hydrologically salient variables in one or more areas of the province. Examples include Whitfield and Taylor (1998), Whitfield and Cannon (2000), Whitfield (2001), Cunderlik and Burn (2002), Zhang et al. (2000, 2001), Fleming and Clarke (2003), Stahl and Moore (2006), Rodenhuis et al. (2007), and Fleming (2010). However, no study to date has systematically assessed long-term trends in the inflows to BC Hydro reservoirs specifically. This is a notable limitation, as various meteorological driving forces combine with local-scale terrestrial hydrologic properties in complex ways to generate net hydroclimatic signals. Unlike most meteorological variables, streamflow is not a continuous spatial field. Rather, it is determined by both broad-scale climatological forcing and very local-scale terrestrial factors. The practical consequences can be considerable: for instance, profoundly different (indeed, even opposite) long-term water resource responses to uniform changes in climatic forcing have been observationally detected between adjacent basins due to differences in watershed glacier cover, as alluded to above (Fleming and Clarke, 2003; Stahl and Moore, 2006; Hodgkins, 2009; Dahlke et al., 2012). The implication, then, is that if one needs to know how inflow to a given hydroelectric reservoir has been responding to historical climatic shifts, particularly in the strongly heterogeneous geophysical environments of British Columbia, ideally one should specifically study that basin.

There is no standard engineering or applied science code of practise for trend analysis or climate change studies, and a review of the research literature suggests many open questions and a lack of methodological consensus, with several techniques or variants thereof in common use. Further, as discussed below, several review articles have explicitly recommended the use of multiple methods to examine the sensitivity of results to such choices. Certainly from a practitioner's perspective, then, due diligence would seem to behoove some form of comparative critical assessment of the performance of available data processing and analysis methods. However, few empirical hydroclimatic trend assessment studies directly consider multiple data processing and analysis schemes. Thus, here we begin by performing a hydroelectric system-wide scoping study of changes in total water supply and its broad seasonal patterns using a relatively straightforward approach, which is also constructed so as to be (relatively) amenable to communications purposes. We then focus on some indicator basins, an integrated measure of hydroelectric generation potential across the system, and some additional hydrometric data resources, using a wide range of data processing and analysis methods, to examine the effects of methodological and data choices upon inferences regarding 20th–21st century changes in BC Hydro's reservoir inflow volumes. As such, our study makes a significant step toward bridging theoretical academic work proposing cutting-edge new methods on the one hand, with the practise of water resource management and long-term hydroelectric resource planning on the other.

## 2. Data

Inflow data used here are a more heavily quality-controlled version of those routinely employed for operational purposes at BC Hydro. These local reservoir inflows are estimated operationally by the Hydrology & Technical Services Group using the Flow Calculation (FLOCAL) system. The method involves a water balance based on reservoir storage (estimated from measured reservoir elevation using a storage curve); reservoir releases as turbine flow (estimated, using rating curves, from data on hourly power generation, on unit status, and on unit head as determined from measured forebay and tailwater elevations); non-power releases through gates (as determined from head on each device and recorded gate positions); and for those plants downstream of another dam, upstream discharge (L. Brownell and S. Matthews, BC Hydro, pers. comm., 2010). For headwater projects, these data give the unregulated inflow volume from the entire upstream basin area. For non-headwater projects, these data give the unregulated local inflows between the dam and the next hydroelectric project upstream. In both cases, emphasis is on water actually delivered by the watershed to the hydroelectric project, rather than water entering the reservoir, as evaporative losses from the reservoir are not estimated. Some potential sources of error in the inflow data include measurement uncertainty in reservoir level, which (in general) grows more important with increasing reservoir size, as a given elevation change would correspond to a progressively larger volume; as well as uncertainty in rating curves and errors or omissions in recorded information, like gate positions. Thus, operationally, the data used to compute reservoir inflows are quality-controlled on a daily basis, with further corrections made on an ongoing basis as the needs arises (L. Brownell, BC Hydro, pers. comm., 2010). Further, the FLOCAL inflow data were comprehensively re-quality-controlled previously during the course of the UBC Watershed Model recalibration project (see Fleming et al., 2010) using regional analysis techniques (Weber, 2001). Combined usable inflow was also considered; this is a rough but useful measure of total inflows across the BC Hydro system potentially available for hydroelectric generation, expressed as equivalent GW h under some simplifying assumptions, and updated monthly by the Hydrology & Technical Services Group.

For the primary analysis (see Section 3.1 below), we used annual time series of yearly mean inflow, and of monthly mean inflows for each of the 12 months of the year. Each of the resulting 13 data series was independently analyzed for each basin. Annual mean inflow (calculated over the water year, spanning October of one calendar year through September of the next and assigned to the second calendar year) captures overall changes in hydroelectric generation potential in dammed rivers, particularly larger interior projects with considerable storage. Averages for individual months trace out possible changes in seasonal distribution and timing of runoff, with implications for reservoir management, aquatic habitat, and