Editorial

Time to Use Dendrohydrological Data in Water Resources Management?

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The problem of managing the Colorado River's resources is a perfect motivating example for any class in water systems analysis. Its sheer size, socioeconomic context, and development history make it "one of the most controlled, controversial and litigated rivers in the world" (Southern Nevada Water Authority 2012). Its development history also points to the critical dependence of our discipline on long and reliable streamflow records: the data upon which the Colorado River Compact was drafted in 1922 were captured during abnormally wet years, resulting in the overallocation of the water rights. How do we know this? From dendrohydrology, a subdiscipline of tree-ring science that uses tree rings to study past hydroclimate. In the specific case of the Colorado River, streamflow reconstructions for the past five centuries also revealed that past droughts were more severe than those contained in instrumental records (Woodhouse et al. 2006).

It was in the Southwestern United States that dendrohydrology started its journey as a predominantly qualitative science (Hardman 1936; Schulman 1945), to further develop as a quantitative science that draws on time series analysis and stochastic modeling (Stockton 1971). Since those early days, streamflow records have been reconstructed in many basins across the globe, extending instrumental records and providing a more exhaustive characterization of the envelope of variability. The reason behind their widespread development lies in the universal physical basis of dendrohydrology: because tree growth depends on the available water budget, one can use data on tree rings as a proxy of the water budget, and then identify an empirical relation linking tree growth to streamflow. Modern dendrohydrology employs multiple *chronologies*, each of which is a dimensionless time series that represents the amount of climate-induced tree growth of a forest stand. Chronologies from multiple forest stands are pooled to capture the regional climate variations that drive the streamflow process (Fritts 1976; Cook and Kairiukstis 1990).

Despite the wide consensus on the importance of streamflow reconstructions, their use in water resources engineering has been piecemeal, more often applied as qualitative guidance than as input to popular models used to design and analyze water resources systems and infrastructure. Documented applications that buck this trend provide a more in-depth understanding of hydroclimatological risks and associated water management practice. For example, Quinn et al. (2020) recently evaluated the vulnerabilities of water users in the Upper Colorado River Basin by forcing the State of Colorado's Stream Simulation Model with hydrological data based on historical conditions, climate projections, and streamflow reconstructions. Their results show that the robustness of water management solutions depends on the hydrological conditions, underlying the importance of considering a broader set of scenarios when assessing water management plans. The potential of dendrohydrological data extends to other applications, such as the estimation of drought return periods (Kwon and Lall 2016), exploration of water supply system yield uncertainty (Sauchyn et al. 2015), drought contingency planning with new plausible stressors (Meko and Woodhouse 2011; Flack et al. 2020), or sizing water reservoirs (Patskoski and Sankarasubramanian 2015). What all these cases have in common is an improvement in the water management insights, regardless of the specific application considered.

The immense potential of dendrohydrology is underlined by three additional facts. First, in all countries, streamflow records are only available for several decades to about 100 years at best (Fig. 1). Second, the aforementioned applications constitute some of the most widely practiced and impactful forms of analysis that a water resources engineer would be asked to perform. Third, several water agencies have shown a strong interest in dendrohydrological data—see case studies in TreeFlow (n.d.) or the recent recommendation made by the USGS (England et al. 2019). Here, we offer an explanation to why the potential of dendrohydrology remains unfulfilled, and present new research directions to help bridge the gap between the science of reconstructing streamflow records and the engineering applications that can benefit from these data.

Barriers to the Widespread Use of Dendrohydrological Data

Why aren't dendrohydrological data regularly used in water resources management? The reasons must be sought in the technical limitations of reconstructions as well as some knowledge gaps between dendrohydrology and water resources communities. We identify four common problems.

Format Is Not Consistent

First, there is a mismatch in the temporal resolution of water resources and streamflow reconstruction models. The former work with daily to monthly decision-making time steps, while the latter are generally annual because they are constrained by the available tree-ring chronologies and their correlation with discharge data (e.g., Ho et al. 2017). In addition, streamflow reconstructions often focus on a specific season, rather than the entire hydrological year.

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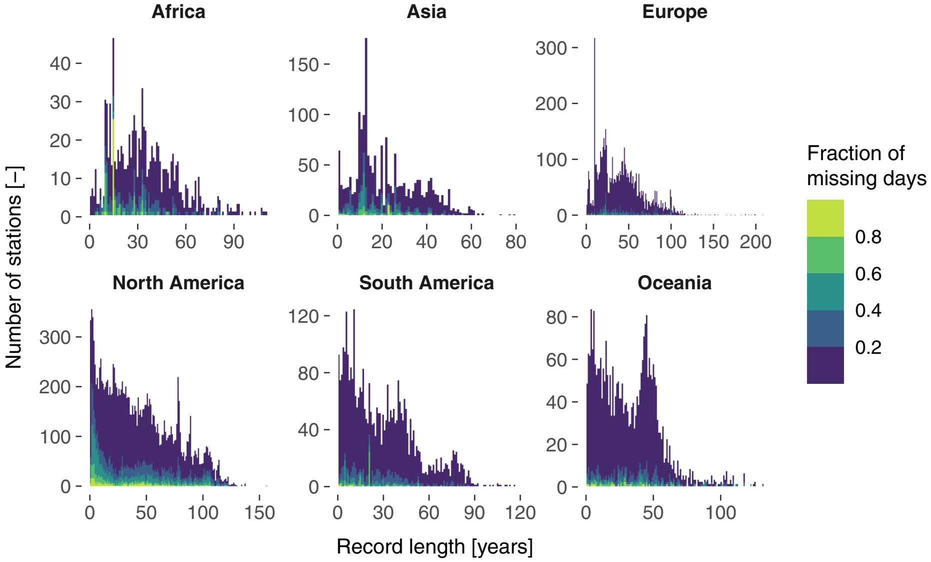

Fig. 1. Global availability of streamflow records, analyzed using the Global Streamflow Indices and Metadata Archive. (Data from Do et al. 2018.)

For example, reconstructions from ring width typically target the growth season (e.g., D'Arrigo et al. 2011), yielding the cumulative discharge during the summer months. Both temporal resolution and continuity of the dendrohydrological data can therefore prevent their direct application in the quantitative decision-making models that dominate the water systems analysis literature.

Accuracy Is Problematic

Reconstructions often fail to capture extremes on the upper tail of the distribution of annual and seasonal flows. In warm regions, for instance, data derived from moisture-limited trees may not reflect saturated overland flow, which is necessary to reconstruct peak discharge events (Nguyen et al. 2020b). Another issue is that reconstructions over large spatial domains may fail to preserve the physical consistency of discharge in a river network. Suppose, for example, that we are modeling streamflow at two tributaries as well as the main stem of a river: the total flow of the tributaries should equal the flow on the main stem. This simple mass balance check is not explicitly accounted for by the vast majority of the reconstruction frameworks, generally based on point-by-point regression (Nguyen et al. 2020b)—where one models the discharge data independently for each station and relies on the proxy network to account for the spatial patterns. Because accuracy is problematic, streamflow reconstructions may generally be considered speculative, and therefore discounted in modeling and decision-making contexts.

Reconstructions Are Not Always Feasible

Reconstructions are limited to pristine catchments or to areas for which naturalized streamflow data are available. The reason for this limitation is that streamflow reconstructions build on the numerical correlation between proxies and discharge data, so they are misled by anthropogenic interventions that alter the natural regime of rivers (e.g., hydropower operations, land use change, or irrigation water withdrawals). Because naturalized streamflow data are not widely available, many river segments across the world are precluded from reconstruction exercises. Paradoxically, it is in these regions with intense water consumption that dendrohydrological data could be most useful.

Our Community Lacks Knowledge of Chronologies

Finally, students in water resources engineering are not exposed to the rigorous analysis that determines the statistical features of tree-ring chronologies. *Detrending* and *prewhitening*, for example, are regularly used to remove multiple competing signals and temporal autocorrelation in raw tree-ring sequences, so that chronologies can be interpreted as evidence of hydrometeorological forcings (Fritts 1976; Cook 1985). But if we do not know which patterns have been deliberately preserved or excluded from the final product, we are liable to misinterpret the relation between chronologies and discharge data. This risk is well exemplified by Coulthard et al. (2020), who show how different detrending methods applied to the same ring width measurements can yield diametrically opposed chronologies, one emphasizing year-to-year variations in tree growth and one emphasizing century-scale variations in climate. An engineer working on the second chronology may erroneously conclude that the relation between annual discharge data and tree growth is weak.

Research Needs for Operationalizing Streamflow Reconstructions

So, how do we bridge the gap between dendrohydrology and water resources management? Here, we focus on the technical limitations of streamflow reconstructions and identify three research areas.

Improving the Format and Accuracy of Reconstructions

A key prerequisite for a water resources management model is the availability of daily to monthly streamflow time series that capture, in a reliable manner, both pluvials and droughts. A fundamental advance in this area could build on the fact that different proxies have different sensitivities to climatic variability. For example, oxygen isotopes often correlate well with peak flow (Xu et al. 2019), while ring widths tend to capture the response to droughts (Gallant and Gergis 2011). One could therefore leverage the correlation between multiple proxies and different target variables to reconstruct subannual flows—a concept recently demonstrated by Rao (2020) and Nguyen et al. (2020a). Because more sampling sites and proxies are being developed (e.g., blue intensity, latewood density), we have an opportunity for creating models that bank on large multiproxy networks to reconstruct subannual streamflow. There are at least two research directions. First, there is a need to extend the spectrum of regression techniques so as to better capture the complex interaction between multiple proxies and discharge data. Linear regression frameworks may remain a cornerstone, but we can easily envision a future in which the modeling toolbox will include nonlinear regression techniques, such as Bayesian regression or state-space models (Rao et al. 2018; Nguyen and Galelli 2018). The next direction would be developing statistical disaggregation techniques that improve the temporal resolution of streamflow reconstruction. Ideally, the disaggregation process should be informed by a proxy network, as recently demonstrated in the monthly reconstructions developed by Stagge et al. (2018).

Developing Alternative Approaches to Streamflow Reconstructions

Future dendrohydrological models may also build on a completely different approach: one could reconstruct time series of precipitation and temperature—instead of streamflow—and use them to force a process-based hydrological model, as shown by Saito et al. (2015), Tozer et al. (2018), and Meko et al. (2020). The approach requires a large amount of data for the model calibration, but it has two advantages. First, process-based models implicitly account for the physical consistency of the reconstructed discharge data. Second, they can represent alterations in the water cycle due to operations of hydraulic infrastructure or land use changes, enabling reconstructions for nonpristine catchments. This approach could be leveraged with state-of-the-art large-scale hydrological and water resource models enhanced with realistic water management representation.

Reconciling Past, Present, and Future Variability

A last important area is the relation between dendrohydrology, water management, and the concept of nonstationarity. Dendrohydrological models build on the assumption that the relationship between proxies and discharge observed in instrumental records holds true over the entire length of the reconstruction. Such stationarity assumption has long been compromised not only by hydraulic infrastructure and land use changes, but also by anthropogenic climate change. In light of this expanded uncertainty, our community has progressively dropped the concept of the static design paradigm (Brown 2010) and developed robust and dynamic planning techniques that adapt to nonstationary trends (Herman et al. 2020). So, shall we still use dendrohydrological data to plan and operate hydraulic infrastructure in a nonstationary environment? In our opinion, the answer is yes. Considering the case of anthropogenic climate change, we have at least two technical challenges. First, we should not limit ourselves to compare the envelopes of reconstructed, observed, and projected streamflow variability. We need data analytics that quantify and reconcile the information contained in multiple power spectra and distributions. With such information, we could put future hydroclimatological risks into a better perspective, or develop a new generation of stochastic streamflow generators. Second, we should use the information provided by streamflow reconstructions to understand and, where possible, reduce the uncertainty in hydrologic projections informed by general circulation models (GCMs). A clear example is offered by the dynamics of the Asian monsoon, which are well captured by climate proxies (Goodkin et al. 2019) but poorly represented by the latest generation of GCMs (Aadhar and Mishra 2020). Streamflow reconstructions could therefore help us identify cases in which GCMs are not fully reliable, narrowing a major source of uncertainty for water resources management applications, such as flood risk management (Ziegler et al. 2020).

Closure

In a well-known—and much debated—editorial on the "death of stationarity," Milly et al. (2008) argued for the need of updating the analytic strategies used for planning grand investments. Twelve years down the line, it appears that our community has been perhaps too preoccupied by this challenge, overlooking the data and knowledge revealed by dendrohydrology. We believe this is an opportune moment for inverting the trend: the studies exemplifying the potential of dendrohydrology for water resources management, the availability of ever-growing multiproxy networks, and the identification of clear research areas are all positive signs that the challenge of closing the gap between dendrohydrology and water resources management is within our reach. We have a wealth of opportunities and reasons for breaking down barriers between the two communities and learning how to "plan forward by looking backward."

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