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Synopsis

To properly remediate, improve, or predict how hydrological systems behave, it is vital to establish their histories. However, modern-style records, assembled from instrumental data and remote sensing platforms, hardly exist back more than a few decades. As centuries of data is preferable given multidecadal fluxes of both meteorology/climatology and demographics, building such a history requires resources traditionally considered only useful in the social sciences and humanities. In this Feature, Pastore et al. discuss how they have undertaken the synthesis of historical records and modern techniques to understand the hydrology of the Northeastern U.S. from Colonial times to modern day. Such approaches could aid studies in other regions that may require heavier reliance on qualitative narratives. Further, a better insight as to how historical changes unfolded could provide a "past is prologue" methodology to increase the accuracy of predictive environmental models.

Throughout American history water resources have played integral roles in shaping patterns of human settlement and networks of biological and economic exchange. In turn, humans have altered hydrologic systems to meet their needs. A paucity of climate and water discharge data for the seventeenth and eighteenth centuries, however, has left America's preindustrial hydrology largely unstudied. As a result, there have been few detailed, quantifiable, regional assessments of hydrologic change between the time of first European settlement and the dawn of industrial expansion.

As scientists labor to understand present-day hydrologic systems and make predictions about the future, the value of expanding the geographic [1, 2] and temporal scopes [3, 4] of their studies has become increasingly evident. Pollen and tree-ring analyses have helped shed light on past climate and land-use patterns. But other nonscientific sources and methods can be equally revealing and in some cases complement empirical studies [5]. This paper argues that environmental science, particularly that concerned with the human dimensions of water resources, stands to profit from using historical literature and archival sources. By considering work in environmental history, forging closer working relationships between the geophysical and social sciences, and seriously entertaining narratives as a form of evidence, environmental scientists can not only look farther into the past and across broader geographic areas, but they can also more accurately describe the nuances and complexities that define the ways humans have changed the world around them. In this paper, we present the recommendations of a multidisciplinary summer institute that developed

- a conceptual and methodological framework for conducting historical hydrology, and
- suggestions for ways that historical information can be used to inform the hydrologic sciences.

Our intent here is to encourage further work along these or similar lines. We believe that future efforts that build on our framework and draw and expand upon the sources referenced below will produce scholarship of great utility to both environmental and social sciences.

The Institute

Our conceptual model and recommendations were developed during a summer institute representing the first component of a 500-year (past, present, and future) regional analysis of the Northeastern U.S. hydrologic system between Chesapeake Bay and the St. John River, Maine. Hosted by the Massachusetts Institute of Technology, the Northeast Consortium for Hydrologic Synthesis convened an interdisciplinary team of graduate students and early career faculty representing the physical, biological, and social sciences to synthesize existing scientific and historical information to develop a better understanding of American hydrology between 1600 and 1800.

Conceptual Model

To systematize our approach, our team generated a conceptual model that identified four principal drivers of hydrologic change—water engineering, land cover change, climate change, and human decision-making (Figure 1). We define "change" broadly as any adjustment to water stores and fluxes, biogeochemistry, or river morphology. The term "human decision-making" describes the process by which humans acquire, prioritize, and manage resources through both individual and collective decisions that are bounded by social, economic, and cultural patterns as well as physical limitations in the landscape. We consider decision-making an overarching driver because in most cases it strongly influences the others. For example, the extent, intensity, and distribution of land-cover change is clearly dictated by human decisions. The same holds true for water engineering. Although climate is the hydrologic driver that is least directly controlled by human decisions, the human signature is evident across both large and small scales, from industrialization's impact on global climatic conditions to the micrometeorological impacts of land cover change on individual hill slopes.

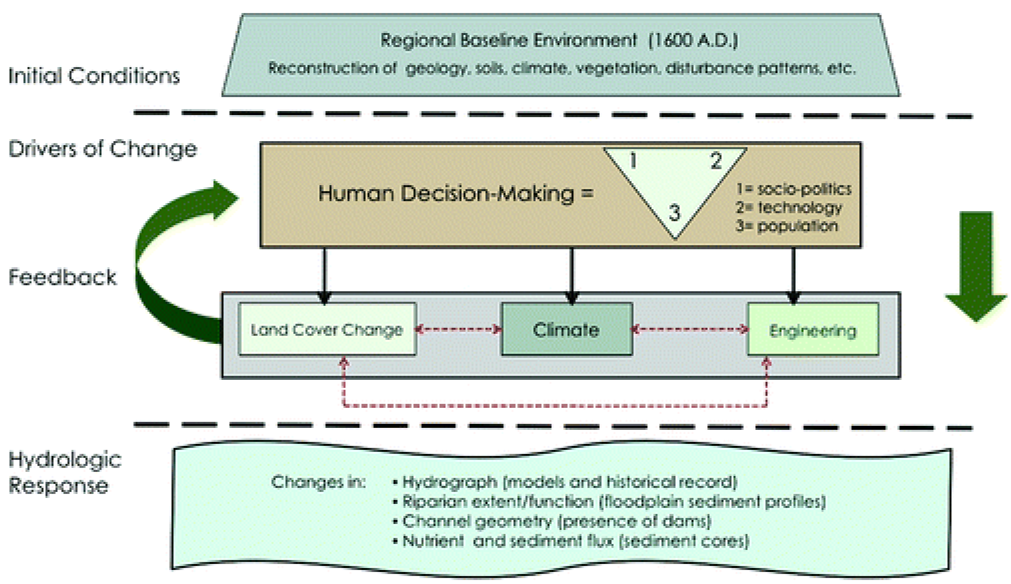

Figure 1. Conceptual model. Graphic by Jonathan M. Duncan.

Our conceptual model identified a baseline environment, which is essential to observing hydrologic change. As Daniel Pauly noted [6], there has often been a tendency among scientists to overlook human signatures on ecological systems of the past. As a result, scientists unwittingly shift their baselines in ways that consider altered ecological systems as "natural". Approximating the date of first permanent European settlement in our region, we established the year 1600 as our baseline. Although we recognized that Native Americans had likely impacted the hydrologic system for millennia prior to European settlement [(7, 8)], historians have observed that Europeans brought to the New World fundamentally different conceptions of nature, which established a whole host of new environmental pressures [(9, 10)], and as a result, we posit, sparked a transformation of the regional hydrologic system. Beginning at the turn of the seventeenth century, Europeans cleared forests [(11)], decimated beaver populations (a species notorious for hydrologic alteration) [(12)], drained meadows [(13)], and built thousands of dams [(14)]. They linked North American commodities to a broader Atlantic World economy, which had far-reaching physical, chemical, and biological repercussions [(9)]. Given this striking example, we recommend that any study of historical hydrology must seriously consider when to begin and how to characterize extant environmental conditions.

Methodological Model

In addition to our conceptual model, we devised a methodological model for our analyses (Figure 2). As a first step, we projected known data sets into a geographic information system (GIS) for visual inspection. We also conducted simulations using hydrologic models, such as the soil and water assessment tool (SWAT). We then calibrated these hydrologic simulations with anecdotal historical information. When possible, we scaled up the results to make subregional or regional assertions. For example, by examining British census records [(15)] and corroborating them with local histories (e.g., [16]) and anecdotal accounts (e.g., [17]), we quantified European population increases and patterns of geographic expansion over time. Based on these data, we estimated patterns of deforestation and the resultant changes to the hydrology at the local scale. This process produced numerous hydrologic "snapshots". By increasing the number and resolution of these snapshots we anticipate the ability to more accurately describe regional conditions. Understanding the human dimensions of water and land use and how those patterns of use varied geographically is integral to this process.

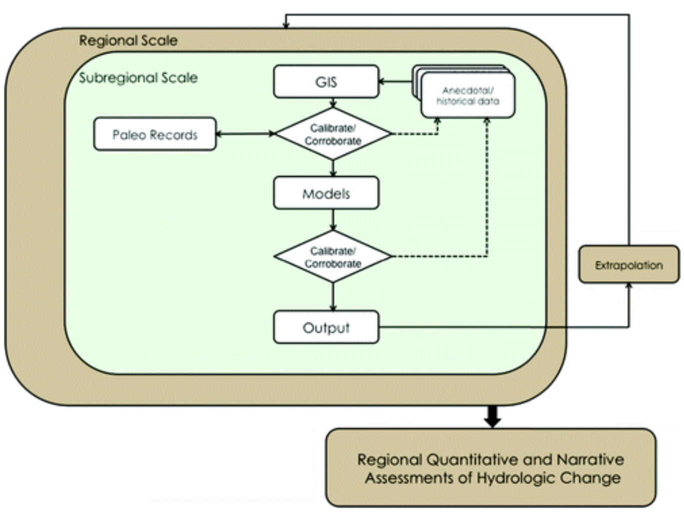

Figure 2. Method of analysis. Graphic by Hyojin Kim.

We systematically applied our methodological model by dividing our region into three geographic and socio-political subregions: New England, the Middle Colonies, and the Chesapeake [18] (Figure 3). We then examined the ways physical variables, such as soil, vegetation, and climate, combined with socio-political factors to influence each subregion's hydrologic development. For instance, in New England, close-knit religious communities with strong central governments concentrated their terrestrial economic efforts on fur trading and timber extraction. The Chesapeake region, conversely, was settled largely by young, unskilled men who cleared trees and planted tobacco fencerow to fencerow. This caused extensive erosion, which dramatically altered river morphologies [19]. Finally, the Middle Colonies were characterized by diverse social, cultural, and religious traditions and feudal-style estate agriculture [18]. This led to deforestation but at a later date than that of the Chesapeake. We recommend that future work increase the resolution of these subregional characterizations by synthesizing individual town histories, many of which provide detailed accounts of land development (e.g., [20–22]). We hypothesize that each subregion will produce distinct patterns of hydrologic change. What follows explains how integration of human decision-making into analyses of land cover change, engineering, and climate change is fundamental to understanding these patterns.

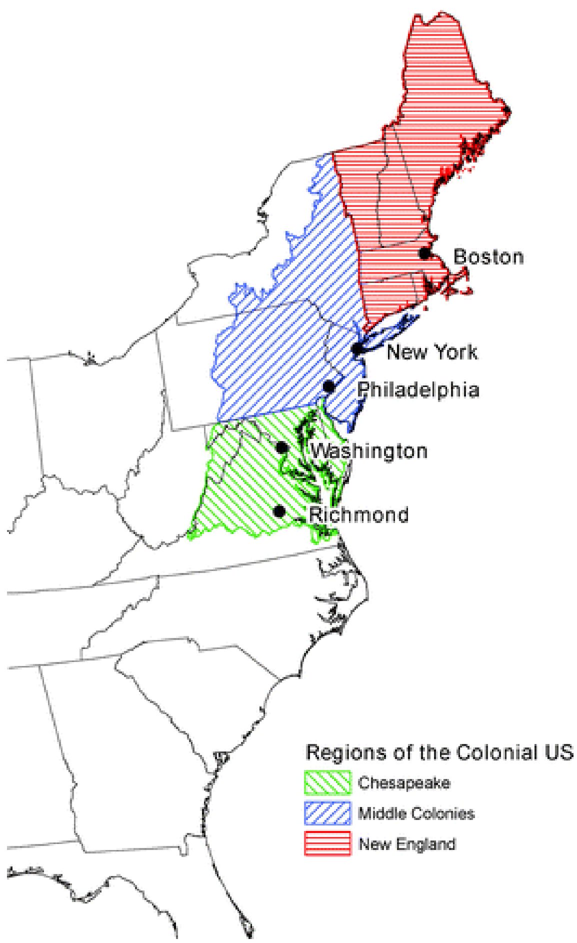

Figure 3. Region of study broken down by subregion. Graphic by Jonathan M. Duncan.

Estimating Land Cover Change

Estimating land cover change is an important part of calculating hydrologic change. Historical studies of land cover change are numerous, spanning local to regional scales and employing different reconstruction techniques. Many reconstructions use sediment cores from estuaries or lakes. Indicators from the cores—such as pollen or charcoal or geochemical signatures—can be used to estimate the land cover change in areas contributing sediment [-23, 24]. Other techniques utilize demographic information and historical accounts to estimate the distribution of land uses and translate this information into land cover maps [25]. Using historical accounts is practical for small scales; larger-scale estimates of historical land cover change have relied mostly on population data [26]. Some large-scale estimates have synthesized multiple lines of evidence (demographic, ecological, historical information, etc.) to produce large-scale maps of land cover [27, 28]. For the colonial era, all of the data sets suggest decreasing forest cover from an almost uniform regional coverage approaching 100% in 1600 to 35−60% (depending on the location) in 1800 [27]. These different types of reconstructions can be integrated into hydrologic calculations—fully coupled, dynamic models or simple back-of-the-envelope calculations—to inform historical hydrologic changes.

Contemporary experiments also provide some direct observations of hydrologic change caused by extreme deforestation. The U.S. Forest Service has conducted a number of deforestation experiments at the watershed scale in the Northeast region, all showing an increase in annual water yield after deforestation because of decreased evapotranspiration [29]. Such present-day analogs can be used to project backward to estimate colonial-era hydrology.

The hydrologic changes resulting from colonial-era deforestation accelerated erosion rates and chemical losses from the landscape. The impact of deforestation on water quality is less well-studied for the colonial era than for the nineteenth century, yet data from sediment cores exist [30, 31]. Contemporary deforestation experiments can also be used to project nutrient losses in the distant past [32]. Sediment erosion data also exist and have been combined with historical information [33], providing insight into the effects of regional deforestation on water quality.

Mining the Historical Record on Human Engineering

Human engineering records tended to be preserved, for they were valuable references for system updates and expansions. These records, in both raw and compiled forms, can illuminate variability in environmental systems and human responses to this variability [34, 35]. For example, the recent suggestion by Walter and Merritts [36] that historical engineering is the primary cause of legacy sedimentation in fluvial systems across the Northeastern U.S. relies on such records. Walter and Merritts [36] used dam safety inspections and historical atlases to document milldam density in southeastern Pennsylvania. These and other data are available through the Inter-University Consortium for Political and Social Research (ICPSR) [37]. Armed with such data and the National Historic Geographic Information System's (NHGIS) [38] organization of the Historic United States County Boundaries (HUSCO) [39], it is possible to reconstruct human engineering at the regional scale.

More detailed information is available for finer spatial scales. This makes it possible to place management decisions concerning wetland drainage into historical context. There are, for example, detailed histories of drainage practices [40], the formation of drainage districts [41], and the implementation of management practices [42]. Fundamentally, engineering is directly controlled by human decisions. The decision-making process, we believe, is as worthy of consideration as the dam or drain that results from those decisions. If we can identify why a management policy was formed, we can more accurately assess its impact.

Reconstructing Colonial Climate

Meteorological data are required to make hydrologic calculations. Even though the colonial era lacked widespread instrumentation and systematic observations of rainfall and temperature, there are other sources of climatic information that can inform historical hydrologic reconstructions. Sporadic instrumental precipitation and temperature records do exist for the late eighteenth century in several locations, including Cambridge, MA, Philadelphia, PA, and New Haven, CT. Throughout our study area, there are also numerous tree-ring reconstruction records [43-46], sediment core examinations [47, 48], pollen studies [49-51], analyses of overwash deposits [52, 53], and historical journals and diaries [54, 55].

By synthesizing these various data, it is possible, we believe, to build a coarse climatic model sufficient for hydrologic analysis. Using existing instrumental records, it is possible to build simple models that estimate temperature and precipitation, and these can be used to create a synthetic record. Approaches such as Monte Carlo sampling can be used to compute uncertainty of the synthetic record, and statistical methods can estimate mean and variability, which can be compared to contemporary data. Moreover, paleorecords can be used to calibrate the synthetic record. Some paleorecords, such as the Palmer Drought Severity Index (PDSI), are based on North American tree-ring reconstructions by Cook and Krusic [56] and cover the period from 1400 to the present; using these data in conjunction with instrumental precipitation records from the U.S. Historical Climatology Network or other more contemporary data sources opens the possibility of backcasting regional conditions. Finally, qualitative materials such as journals and diaries are important sources of climatic information. The 1891 diary of Sidney Perley [57], for example, chronicles, among other extreme events, droughts, snowstorms, hurricanes, and floods in New England between 1600 and 1890, and these date-specific observations can be used to inform hydrologic models.

Based on our preliminary analyses of the data, we hypothesize that precipitation did not experience any discernible region-wide trends over the 200-year period. Despite the strong Little Ice Age signal seen in European records and some U.S. records [58-61] and supported by numerous anecdotal accounts [62, 63] it was difficult to generalize a regional hydrologic trend arising from this event [64]. Because regional hydrology is primarily driven by precipitation rather than temperature, we hypothesize that changes to water stores and fluxes due to climate were minimal. However, a more thorough integration of historical data with climatic models is necessary to either reject or support this hypothesis. Although building a strict reconstruction of climate is difficult, we believe a broader characterization of the climate is possible for the purposes of examining regional hydrologic trends.

Metrics of Hydrologic Change

How then does information about human decision-making, land cover change, water engineering projects, and climate inform the quantification of hydrologic change? We recommend two metrics for quantifying hydrologic change.

The first, a simple water balance, considers precipitation, evapotranspiration, and changes in water storage, which can be used to calculate changes in mean annual river discharge. The second metric, mean water residence time, or the amount of water storage divided by the water flux through that storage volume, can also be used to calculate changes to the amount of water moving through a system. This metric can also inform historical water-quality dynamics. Water residence time is a widely recognized control on nitrogen biogeochemistry, with longer water residence times causing more nitrogen removal from the system [(65)]. Long residence times in water distribution systems increase the potential for bacterial growth during transport of drinking water [(66)]. Thus, if we know how water residence times have changed in the past, we can infer how biogeochemistry or pathogen dynamics may have also changed.

No matter which integrative hydrologic metric is chosen, explicit acknowledgment of uncertainty is vital when working in historical eras (e.g., [67]). Early population estimates and precipitation observations often contain considerable uncertainty. Thus, propagating uncertainty through a hydrologic calculation allows a more robust statement of past hydrologic dynamics. We recommend Monte Carlo techniques, which have the flexibility to accommodate and propagate uncertainty estimates generated from both quantitative and qualitative information.

Conclusions

By synthesizing published scientific studies with contemporary data sets and corroborating those results with the work of environmental historians, we believe it is possible to reconstruct colonial American hydrology on the regional scale. Such an endeavor, we believe, would be of broad utility to the environmental sciences because understanding the ways humans shaped the hydrology of the past is vital to our understanding of the present and future. Our conceptual model centralizes the role of humans in the hydrologic cycle and considers human-induced feedback loops with respect to changes to land cover, engineering, and climate. Furthermore, we propose that integrative hydrologic metrics effectively quantify hydrologic change because they can organize wide-ranging data—both natural and human-induced variations—into numeric results. Using metrics, it is possible to compare, contrast, and even rank the drivers of hydrologic change according to their level of impact over time.

Finally, our work also underscores the importance of forging scholarly ties between the sciences and humanities. For hydrologists, corroborating and calibrating scientific data with historical records and even qualitative historical accounts can increase the accuracy of their work. Our work largely synthesized existing literature and published primary sources, but further analysis and integration of archival historical sources into scientific work is needed and will generate an even more precise picture of the U.S.'s ecological past. For historians, empirical understanding of human−water interactions can shed new light on such topics as patterns of human settlement and competition over resources. Hydrologic models can support historical evidence. The synthetic process—one in which historians, geographers, hydrologists, ecologists, and biologists are forced to grapple with the pressing questions of other fields—encourages scholars to inform their own work with new insights and new perspectives.

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