5-12-2011

Historical Legacies, Information and Contemporary Water Science and Management

Daniel J. Bain
University of Pittsburgh

Jennifer A. S. Arrigo
East Carolina University

Mark B. Green
CUNY City College

Brian A. Pellerin
U.S. Geological Survey

Charles J. Vörösmarty
CUNY City College

Water **2011**, *3*, 566-575; doi:10.3390/w3020566

OPEN ACCESS

water

ISSN 2073-4441
www.mdpi.com/journal/water

Communication

Historical Legacies, Information and Contemporary Water Science and Management

Daniel J. Bain [1,*], Jennifer A. S. Arrigo [2], Mark B. Green [3,4], Brian A. Pellerin [5] and Charles J. Vörösmarty [3]

[1] Department of Geology and Planetary Science, University of Pittsburgh, 200 SRCC, 4107 O'Hara St., Pittsburgh, PA 15260, USA;
[2] Department of Geography, East Carolina University, A-240 Brewster Bldg., Greenville, NC 27858, USA; E-Mail: arrigoj@ecu.edu
[3] CUNY Environmental Cross-Roads Initiative, The City College of New York, New York, NY 10031, USA; E-Mail: cvorosmarty@ccny.cuny.edu
[4] Center for the Environment, MSC 63, Plymouth State University, 17 High Street, Plymouth, NH 03264, USA; E-Mail: mbgreen@plymouth.edu
[5] US Geological Survey, California Water Science Center Placer Hall 6000 J Street, Sacramento, CA 95810, USA; E-Mail: bpeller@usgs.gov

* Author to whom correspondence should be addressed; E-Mail: dbain@pitt.edu; Tel.: +1-412-624-8766; Fax: +1-412-624-3914.

Received: 20 March 2011; in revised form: 30 March 2011 / Accepted: 27 April 2011 / Published: 12 May 2011

Abstract: Hydrologic science has largely built its understanding of the hydrologic cycle using contemporary data sources (*i.e.*, last 100 years). However, as we try to meet water demand over the next 100 years at scales from local to global, we need to expand our scope and embrace other data that address human activities and the alteration of hydrologic systems. For example, the accumulation of human impacts on water systems requires exploration of incompletely documented eras. When examining these historical periods, basic questions relevant to modern systems arise: (1) How is better information incorporated into water management strategies? (2) Does any point in the past (e.g., colonial/pre-European conditions in North America) provide a suitable restoration target? and (3) How can understanding legacies improve our ability to plan for future conditions? Beginning to answer these questions indicates the vital need to incorporate disparate data and less accepted methods to meet looming water management challenges.

Keywords: retrospective assessment; detection; attribution; hydrologic history

1. Introduction

If we are to effectively manage water over the next 100 years and beyond, we need a better understanding of the accumulation of impacts caused by human activities over past centuries. This idea is simple and the underlying principle is generally accepted. However, once the challenge is engaged, the course is not necessarily evident. For example, how does a hydrologist study the period roughly bounded by European settlement in North America and the American Revolution? An almost universal reaction to the prospect of characterizing this era is "What can you do for that period?" There is no gauge data, any other data that exists are sparse if available, and it is assumed the impact of colonial activity could not possibly be more important than more recent changes such as urbanization.

Most hydrologic studies in the U.S. go back less than 100 years, coincident with the availability of stream-gauging data [1]. While these studies reflect the accumulation of human impacts to the hydrologic system, this reflection is often not explicitly recognized. Though historical analysis of human and environmental records may require tools underutilized in contemporary hydrology and geoscience, there are a host of reasons for inspecting past centuries. This piece focuses on three fundamental questions in an attempt to demonstrate the value of incorporating historic hydrologic conditions and the human interactions with these conditions: (1) How is better information incorporated into water management strategies? (2) Does any point in the past (e.g., colonial/pre-European conditions in North America) provide a suitable restoration target? and (3) How can understanding legacies improve our ability to plan for future conditions? We view this effort as analogous to the incorporation of a historical perspective into ecology, which revealed unexpected and important findings including: Historic plowing for agriculture in New England continues to dictate contemporary nutrient cycling [2], the land use status 50 years ago predicts contemporary fish community structure better than contemporary land use [3], and Roman era settlement patterns continue to influence soil fertility and therefore plant community composition in contemporary French forests [4]. A systematic examination of historic hydrologic conditions and the human interactions with these conditions is a powerful way to understand the fundamental coupling of human and hydrologic systems.

2. Human Decisions and Water Use

One of the most important lessons of retrospective assessment of human-water interactions is that data and decision-making are not necessarily well linked [5]. The "correct" course of action is taken sometimes for the right reasons and sometimes for the wrong reasons. The recognition of imperfect decision making structures is a vital outcome of a synthesis of history and hydrologic data. For example, the construction of London's sewer system, while ultimately judged to be a triumphant course of action, arose in a complicated political and scientific environment. The original impetus for the sewer network was likely driven by overblown rhetoric and unfair criticism of urban institutions by individuals such as Edwin Chadwick, and relied on an entirely incorrect understanding of disease vector biology [6,7]. While there are heroes that emerge from the story, scientists who analyzed the data and made correct determinations (e.g., John Snow), the methodology and influence attributed to them has become apocryphal [6,8,9]. When first applied, the retrospectively "right" decision, isolating humans from their waste, was undermined by the fact that dramatically improving hydrologic connectivity between London privy pots and the Thames introduced much more sewage to drinking water sources. Subsequently, the Big Stink in 1858 and a series of deadly cholera outbreaks that killed thousands resulted from this increase in hydrologic connectivity. However, these continued public health problems led to construction of the intercepting sewers and the concepts of the modern sewer network in the early 1860s. The construction of the sewer network was a happy accident: conceived under incomplete information, but fortunately arriving at an appropriate solution given the underlying processes. The construction of the London sewer provides many lessons for those who believe there is a vital role for careful, empirical science in all decision making frameworks. The most important lesson is that integrating science into decision process is not straightforward. An understanding and evaluation of history can provide guidance on how to achieve such integrated decision frameworks.

Disciplines concerned with decision making processes have long recognized the important role of unintended consequences in outcomes arising from application of the ultimate and undoubtedly imperfect decision [10]. However, while many advances in contemporary hydrology have begun as conceptual thought experiments, these thought experiments are not utilized enough to evaluate unintended consequences during the decision application phase, particularly in coupled human hydrologic systems. Some outcomes based on our science that are ultimately detrimental to both the human and hydrologic systems could be avoided with such thinking early on. While early U.S. leaders farmed the Piedmont, they failed to recognize and recall the siltation of harbors following agricultural clearance and developed settlement strategies that led to similar problems in the neighboring Mississippi River system several centuries later. Happ was establishing some of our first monumented stream channel cross-sections across the nation in response to legacy valley sediment [11] at roughly the same time that Gottschalk was recognizing that many early colonial Chesapeake ports had been silted in by the time of the Revolution [12]. The fundamental questions for hydrologists are; the dredging of eastern ports was conducted at a considerable expense, so why were river ports along the Mississippi River being silted in by the 1930s? Why did the Soil Conservation Service arise in 1935 only after multiple major, regional erosive events in the United States? Settlers of these areas, particularly those in the Northwest Territories (*i.e.*, Ohio to Minnesota), had experience with forest clearance and erosion, but could not make the connection to the next region. Does this lagged response result from a failure to think like a basin, a tragedy of the commons, or simple ignorance of the history? Anticipating siltation in the Mississippi Basin would have required understanding of how to transfer knowledge gained from one system to application in another. Do we, as contemporary hydrologists, know when knowledge is transferrable between different systems? Waiting for an accumulation of future changes in water policy is not soon enough to develop adequate data sets to understand transferrable knowledge. Retrospective assessment is a primary and available tool for building knowledge and recognizing past opportunities lost. Without such assessment, we are simply ignoring relevant and vital information.

Too often, our assumption is that most historical decisions about water will remain a mystery. And too often, that assumption remains unchecked, ignoring the available data of all stripes. This is particularly true in humid regions, likely as the hydrologic situation is an embarrassment of riches.

Pre-eminent water historians in the U.S. often work in the arid west, as documentation of water and water shortages is rich in individual accounts and in governmental data collections [13]. This water scarcity is less prominent in the Northeast and therefore less represented in human archives. At the same time, historical evidence points to broad European knowledge and monitoring of climates and landscape for practical and societal purposes (e.g., agricultural [14], navigation [15], *etc.*). Indeed, Europeans were well on their way to monitoring key hydrologic variables by the time of the American Revolution [16], and these efforts have grown into the global leadership in hydrologic characterization from the United States Geological Survey (USGS), the National Oceanic and Atmospheric Administration (NOAA), and others we rely on today. What, then, was the historical importance of water along the Eastern Seaboard? Extensive national hydrologic monitoring arose for a reason, be it for understanding drought, flooding, erosion, or transportation. However, hydrology as a discipline has not participated enough in the discussion of water’s fundamental interactions with historical human systems.

Ultimately, probing the historical role of water in societies allows insight into fixing contemporary water problems that we might reasonably call “hydrologic messes”. The Colorado Basin is probably the most famous example of such a mess in North America [17]. The Law of the River and the societal context driving Colorado River water apportionment were forged by decision makers raised under water use frameworks and humid climates common in the East. On top of this, the allocation of Colorado River water was negotiated during one of the wettest periods in the basin's history [18], leading to an over-allocation of water. During the subsequent periods of more "normal" rainfall, this over-allocation threatens the integrity of the economies built upon the water availability, even more so if forecasts of future drought intensification bear out [19]. Since this agreement grew out of a water management culture forged on the Eastern Seaboard, examination of colonial human behavior, particularly human response to uncertainty, may improve our understanding of how we might amicably fix this over-allocation. At the very least, such an examination will catalog scenarios of uncertainty and identify those scenarios that lead to decisions with particularly deleterious unintended consequences. Retrospective assessment is the only way to gather enough data to allow sophisticated examination of improvements in information and their ultimate impact on water management.

3. The Past as a Management Target

One of the more palpable conceptual hydrological models to arise out of investigations into the interactions between land use change and hydrology is the “urban stream syndrome” [20]. The model suggests that changes in storm hydrographs resulting from increases in impervious surfaces are the primary cause of a host of changes in the channel, changes that degrade habitat for in-stream biota and threaten near-stream infrastructure. Therefore, it follows that by reestablishing pre-urban or even pre-agricultural valley configurations in urban stream systems, we might remove some impacts to in-stream biota, particularly excessive nutrient loadings [21]. Stream restoration consumes a large portion of resources in a relatively limited resource pool, requiring careful work to maximize benefits [22]. However, we must carefully examine the assumptions underlying stream restoration projects, particularly those relying on historic conditions as information for guiding restoration targets. We must not only understand how things were, we also must understand how to accommodate how things have become.

Examination of the historic record, particularly in the Eastern U.S. Piedmont (where much of the work fundamental to the urban stream syndrome model was completed [23,24]) indicates that large parts of the observed geomorphic change occurred before "urbanization" began, driven predominantly by forest clearance and agriculture. The urban stream syndrome assumes that the acceleration of the hydrograph leads to incision and entrenchment of the stream channel. While this assumption is sound in terms of process, it is also easily checked. Indeed, an examination of a wide variety of classic works that rely on return surveys to evaluate channel changes show little evidence of incision following urbanization [25-27], and instead show, in general, entrenched channels that sometimes widen following the hardening of upland surfaces. If channels were incised before urbanization began, did newly urbanized areas simply occupy areas with impaired fluvial systems? In this case, restoration to colonial conditions to address urban stream problems is probably a mistake, as the underlying assumption is not borne out by the data on timing of incision. And further, the conditions arising from urban land cover changes likely remain.

This leads to the essential question, at what point did streams incise? Certainly, in cases where low-head dams played a role in sediment storage [28,29], this incision begins with the breaching of dams whether during the malaria scares in the mid 1800s [30] or in the recent push to re-establish free flowing hydrologic systems [31,32]. However, the accumulation of floodplain sediment occurred throughout the Piedmont, even in areas without extraordinary dam density [33]. In these cases, common to the Piedmont, incision almost certainly began before urbanization. And ultimately, if we fix incision, will the system be fixed? It may boil down to other questions of emphasis and outcome. If streams were largely incised by the turn of the twentieth century, a decade before the emergence of the Haber-Bosch nitrogen fixing process and the subsequent transformation of the nitrogen cycle [34], were these stream channels "broken"? Or are they simply "broken" in terms of nutrient retention once excessive fertilization became part and parcel of our agricultural economy? Re-engineering of fluvial systems under the cover of "restoration" is a deliberate decoupling of language and reality. Most pre-colonial valley forms did not encounter nutrient loadings ubiquitous in contemporary systems. Relying on these forms to address such loadings, will likely cause unintended results.

The impulse to fix systems by simply returning to "the way things were" grows from solid human experience. The strategy can work particularly well in small, simple systems, the same systems that humans are best able to comprehend. If we get too warm or too cold, we can often simply re-adjust the thermostat to a previous position and be comfortable again. However, there is little evidence that this repair strategy scales well. Anyone who has dealt with HVAC (Heating, Ventilating, and Air Conditioning) concerns during building renovations or shared a thermostat with an adjacent office recognizes the poor scaling of this strategy. Despite the lack of evidence that putting things "back" scales well, important regional hydrological management efforts are organized around the goal of putting things back. For example, the Chesapeake Bay Foundation bases its Chesapeake State of the Bay Scorecard on conditions believed to be present when John Smith first explored the Bay in the 1600s [35]. If we are trying to put the Bay back to or near to what it was in 1600, we had better be certain that we understand what we really need to put back. Moreover, we actually need to understand how to engineer systems so that they are not simply "put back", but also compensate for changes driven by radically different contemporary human population densities. Correct understanding and interpretation of boundary conditions are fundamental to effective decisions about hydrologic systems.

Retrospective assessment is the only way to characterize these conditions and the trajectories of the systems they drive.

4. Confronting Models with Historical Data

Hydrologic dynamics are non-stationary [36], evolving with landscape change, climate change, and human engineering [37]. Therefore, making predictions about future hydrologic dynamics requires full consideration of the trends in different hydrologic drivers. These dynamics are best characterized by examining a site's history. For example, restoration requires thinking that was absent during the ascendancy of process-based hydrology. The foundation of evidence used to understand basin response was collected during periods of relatively beaver-free landscapes. This is apparent in our still rudimentary understanding of the cumulative impact of multiple dams on water dynamics in hydrologic networks [38] and the fact that recognition of rerouting of water by dams is still an emerging concept in catchment hydrology [39]. This single and widespread eradication of beaver populations seems like an ideal case to examine catchment response to dam infrastructure removal. While the coupled historical data is admittedly not regular and quantified, we do have some observations that allow evaluation of a model's predictive ability.

In some cases there is a rich documentation and distillation of this history. For example, Perley [40] chronicles a wide range of extreme weather events between 1600 and 1890 in New England. While extreme events are not necessarily the most important hydrologic drivers, the collected anecdotal information can be compared with modeled results. What kind of storm would be necessary to create a 20-foot storm surge in Boston as is reported in 1635 [40]? Such a storm may be hyperbole, and a quick bit of modeling can probably answer that. If a storm producing such a surge occurred, how would the remainder of the New England coast have been affected? Can we use changes in sedimentation rates in this period, coupled with models of the storm to improve our calibration of sedimentary proxies for extreme events? The possible insights allowed by using the historical record to improve and refine our contemporary models, particularly those of extreme events, are important for not only understanding the past, but for predicting the future [41].

The task at hand is a synthesis of our contemporary, process-based observations of hydrologic systems and a confrontation of this understanding with available historic data. We know that deforestation changes the hydrograph and the material fluxes carried by these flows in individual watersheds [42]. However, the impact of these changes on a regional, one-time event, such as that following European colonization of North America, is not well understood (with the possible exception of sedimentation [43]). For example, European alteration to the landscape caused both increased flooding and the drying of small order streams [44]. These changes were likely results that Europeans were unaccustomed to, in some cases due to limited understanding of hydrology and in others as a result of experience gained in the contrasting European climate. A synthesis of these data, both primary and reconstructed from proxies, with simple mechanistic models may point to serious gaps in our understanding of both historic and contemporary hydrology. Consider, if we truncated soil horizons across the landscape, how different were rainfall-runoff response and riparian systems before European settlement? With the demise of the American chestnut (*Castenea dentata*), how different were soil moisture dynamics in the chestnut-free forest? If our models cannot accurately hindcast conditions occurring following these changes, how much trust should we place in the forecasts these models provide?

Finally, building process-based models of these periods may require the incorporation of models not commonly utilized in hydrology. Agent based models have had some success in predicting the complex behavior of human society [45]. Indeed, agent based models do well in predicting things like the location of pueblos in the Mesa Verde region of Colorado based largely on hydrologic inputs [46]. Therefore, rather than construct ten new gauging stations on the Colorado, we might be able to better understand how to fix the Law of the River using an agent based approach. Similarly, a model of detente using agent based simulation might shed light on ways to fix and avoid situations like that caused by New York City and its water treatment plant [47]. Ultimately, by beginning to rigorously examine pre-instrumental period hydrology, we may develop new tools necessary to address such problems.

5. Conclusions

Answers to the three questions posed at the beginning of this article require an approach that synthesizes historical human and biogeophysical information. They highlight the importance of conducting integrated environmental analysis in both contemporary and past time periods. For analysis of the U.S., for example, one can start in 1970 or 1492, and rigorous adherence to this challenging synthesis may lead to similar answers. Perhaps the most important reason for beginning with the distant past is that by starting in contemporary times and working back, the temptation to remain in the hyetograph and hydrograph would be too great. And while these graphs remain important, they are just graphs without the essential context of the accumulation of historical human activities that reside in organized, accessible formats [48,49]. While these rich synthetic data are available and relevant, too often, “history” is used pejoratively, to dismiss work we view as not close enough to our normative science as “natural science.” However, if we allow this tendency to creep, and dismiss history in general, our synthetic answers will not reflect our comprehensive experience with the hydrologic cycle.

Acknowledgements

Thanks to Caroline Hermans, Chris Pastore, and two anonymous reviewers for helpful reviews of this manuscript. This work is funded by NSF-EAR Grant #0854957 to the City University of New York and by the University of Pittsburgh College of Arts and Sciences.

References

1. Hodgkins, G.A.; Dudley, R.W.; Huntington, T.G. Changes in the timing of high river flows in New England over the 20th century. *J. Hydrol.* **2003**, *278*, 244-252.
2. Compton, J.E.; Boone, R.D. Long-term impacts of agriculture on soil carbon and nitrogen in New England forests. *Ecology* **2000**, *81*, 2314-2330.
3. Harding, J.S.; Benfield, E.F.; Bolstad, P.V.; Helfman, G.S.; Jones, E.B.D., III. Stream biodiversity: The ghost of land use past. *Proc. Nat. Acad. Sci.* **1998**, *95*, 14843-14847.

4. Dambrine, E.; Dupouey, J.L.; Laut, L.; Humbert, L.; Thinon, M.; Beaufils, T.; Richard, H. Present forest biodiversity patterns in France related to former Roman agriculture. *Ecology* **2007**, *88*, 1430-1439.
5. Tarr, J.A.; Mc Curley Iii, J.; Mc Michael, F.C.; Yosie, T. Water and wastes: A retrospective assessment of wastewater technology in the United States, 1800–1932. *Tech. Cult.* **1984**, *25*, 226-263.
6. Johnson, S. *The Ghost Map*: *The Story of London*'*s Most Terrifying Epidemic—and How It Changed Science*, *Cities*, *and the Modern World*; Riverhead Press: New York, NY, USA, 2006; p. 320.
7. Sunderland, D. 'A monument to defective administration'? The London Commissions of Sewers in the early nineteenth century. *Urban Hist.* **1999**, *26*, 349-372.
8. Brody, H.; Rip, M.; Vinten-Johansen, P.; Paneth, N.; Rachman, S. Map-making and myth-making in Broad Street: The London cholera epidemic, 1854. *Lancet* **2000**, *356*, 64-68.
9. Snow, S. John Snow: The making of a hero? *Lancet* **2008**, *372*, 22-23.
10. Johnson, C.A. *Blowback*: *The Costs and Consequences of American Empire*; Henry Holt and Co.: New York, NY, USA, 2004; p. 268.
11. Happ, S.C.; Rittenhouse, G.; Dobson, G.C. Valley Sedimentation as a Factor in Sediment-yield Determinations. In *Present and Prospective Technology for Predicting Sediment Yields and Sources*; United States Department of Agriculture (USDA), ARS Pub. 5-40, 1975; pp. 57-60.
12. Gottschalk, L.C. Effects of soil erosion on navigation in upper chesapeake bay. *Geogr. Rev.* **1945**, *35*, 219-238.
13. Worster, D. *Rivers of Empire*: *Water*, *Aridity*, *and the Growth of the American West*; Pantheon: New York, NY, USA, 1986; p. 402.
14. Verosub, K.L.; Lippman, J. Global impacts of the 1600 eruption of Peru's Huaynaputina volcano. *Eos Trans. AGU* **2008**, *89*, 141-142.
15. Wheeler, D.; Suarez-Dominguez, J. Climatic reconstructions for the northeast Atlantic region AD 1685–1700: A new source of evidence from naval logbooks. *Holocene* **2006**, *16*, 39-49.
16. Brown, R.H. The first century of meteorological data in America. *Mon. Weather Rev.* **1940**, *68*, 130-133.
17. Adler, R.W. *Restoring Colorado River Ecosystems*: *A Troubled Sense of Immensity*; Island Press: Washington, DC, USA, 2007; p. 311.
18. Woodhouse, C.A.; Gray, S.T.; Meko, D.M. Updated streamflow reconstructions for the Upper Colorado River Basin. *Water Resour. Res.* **2006**, *42*, W05415.
19. Seager, R.; Ting, M.F.; Held, I.; Kushnir, Y.; Lu, J.; Vecchi, G.; Huang, H.P.; Harnik, N.; Leetmaa, A.; Lau, N.C.; *et al*. Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* **2007**, *316*, 1181-1184.
20. Walsh, C.J.; Roy, A.H.; Feminella, J.W.; Cottingham, P.D.; Groffman, P.M.; Morgan, R.P. The urban stream syndrome: current knowledge and the search for a cure. *J. N. Amer. Benthol. Soc.* **2005**, *24*, 706-723.
21. Craig, L.S.; Palmer, M.A.; Richardson, D.C.; Filoso, S.; Bernhardt, E.S.; Bledsoe, B.P.; Doyle, M.W.; Groffman, P.M.; Hassett, B.A.; Kaushal, S.S.; *et al*. Stream restoration strategies for reducing river nitrogen loads. *Front. Ecol. Environ.* **2008**, *6*, 529-538.

22. Bernhardt, E.S.; Palmer, M.A.; Allan, J.D.; Alexander, G.; Barnas, K.; Brooks, S.; Carr, J.; Clayton, S.; Dahm, C.; Follstad-Shah, J.; *et al*. Ecology-synthesizing U.S. river restoration efforts. *Science* **2005**, *308*, 636-637.
23. Hammer, T.R. Stream channel enlargement due to urbanization. *Water Resour. Res.* **1972**, *8*, 1530-1540.
24. Wolman, M.G. A cycle of sedimentation and erosion in urban river channels. *Geogr. Ann. Ser. A-Phys. Geogr.* **1967**, *49A*, 385-395.
25. Yorke, T.H.; Herb, W.J. *Effects of Urbanization on Streamflow and Sediment Transport in the Rock Creek and Anacostia River basins, Montgomery County, Maryland*, 1962-*74*; U.S. Geological Survey: Washington, DC, USA, 1978; p. 71.
26. Leopold, L.B.; Huppman, R.; Miller, A. Direct observation of rates of geomorphic change: 41 years of direct observation. *Proc. Am. Phil. Soc.* **2005**, *149*, 349-371.
27. Colosimo, M.F.; Wilcock, P.R. Alluvial sedimentation and erosion in an urbanizing watershed, Gwynns Falls, Maryland. *J. Am. Water Resour. Assoc.* **2007**, *43*, 499-521.
28. Phillips, J.D. A short history of a flat place: Three centuries of geomorphic change in the Croatan National Forest. *Ann. Assoc. Am. Geogr.* **1997**, *87*, 197-216.
29. Walter, R.C.; Merritts, D.J. Natural streams and the legacy of water-powered mills. *Science* **2008**, *319*, 299-304.
30. Kirby, J.T. *Poquosin*: *A Study of Rural Landscape and Society*; University of North Carolina Press: Chapel Hill, NC, USA, 1995; p. 293.
31. Stanley, E.H.; Doyle, M.W. Trading off: the ecological removal effects of dam. *Front. Ecol. Environ.* **2003**, *1*, 15-22.
32. Hart, D.D.; Johnson, T.E.; Bushaw-Newton, K.L.; Horwitz, R.J.; Bednarek, A.T.; Charles, D.F.; Kreeger, D.A.; Velinsky, D.J. Dam removal: Challenges and opportunities for ecological research and river restoration. *Bioscience* **2002**, *52*, 669-681.
33. Bain, D.J.; Brush, G.S. Early chromite mining and agricultural clearance: Opportunities for the investigation of agricultural sediment dynamics in the Eastern Piedmont (USA). *Am. J. Sci.* **2005**, *305*, 957-981.
34. Erisman, J.W.; Sutton, M.A.; Galloway, J.; Klimont, Z.; Winiwarter, W. How a century of ammonia synthesis changed the world. *Nat. Geosci.* **2008**, *1*, 636-639.
35. *Chesapeake Bay Foundation 2007 State of the Bay*; Chesapeake Bay Foundation: Annapolis, MD, USA, 2007; p. 12.
36. Milly, P.C.D.; Betancourt, J.; Falkenmark, M.; Hirsch, R.M.; Kundzewicz, Z.W.; Lettenmaier, D.P.; Stouffer, R.J. Climate Change: Stationarity is dead: Whither water management? *Science* **2008**, *319*, 573-574.
37. Vörösmarty, C.; Lettenmaier, D.; Leveque, C.; Meybeck, M.; Pahl-Wostl, C.; Alcamo, J.; Cosgrove; W.; Grassl, H.; Hoff, H.; Kabat, P.; *et al*. Humans transforming the global water system. *Eos Trans. AGU* **2004**, *85*, 513-514.
38. Singer, M.B. The influence of major dams on hydrology through the drainage network of the Sacramento River basin, California. *River Res. Appl.* **2007**, *23*, 55-72.
39. Constantz, J.; Essaid, H. Influence of groundwater pumping on streamflow restoration following upstream dam removals. *Hydrol. Process.* **2007**, *21*, 2823-2834.

40. Perley, S. *Historic Storms of New England*: *Its Gales*, *Hurricanes*, *Tornadoes*, *Showers with Thunder and Lightning*, *Great Snow Storms*, *Rains*, *Freshets*, *Floods*, *Droughts*, *Cold Winters*, *Hot Summers*, *Avalanches*, *Earthquakes*, *Dark Days*, *Comets*, *Aurora-Borealis*, *Phenomena in the Heavens*, *Wrecks Along the Coast*, *With Incidents and Anecdotes*, *Amusing and Pathetic*; The Salem Press Publishing and Printing Co.: Salem, MA, USA, 1891; p. 341.
41. Denny, M.W.; Hunt, L.J.H.; Miller, L.P.; Harley, C.D.G. On the prediction of extreme ecological events. *Ecol. Monogr.* **2009**, *79*, 397-421.
42. Bormann, F.H.; Likens, G.E.; Pierce, R.; Eaton, J.; Johnson, N. *Biogeochemistry of a Forested Ecosystem*; Springer Verlag: New York, NY, USA, 1977; p. 146.
43. Brush, G.S. Natural and anthropogenic changes in Chesapeake Bay during the last 1000 years. *Hum. Ecol. Risk Assess.* **2001**, *7*, 1283-1296.
44. Cronon, W. *Changes in the Land*: *Indians*, *Colonists*, *and the Ecology of New England*; Hill and Wang: New York, NY, USA, 1983; p. 241.
45. Schelling, T.C. Models of segregation. *Amer. Econ. Rev.* **1969**, *59*, 488-493.
46. Axtell, R.L.; Epstein, J.M.; Dean, J.S.; Gumerman, G.J.; Swedlund, A.C.; Harburger, J.; Chakravarty, S.; Hammond, R.; Parker, J.; Parker, M. Population growth and collapse in a multiagent model of the Kayenta Anasazi in Long House Valley. *Proc. Natl. Acad. Sci.* **2002**, *99*, 7275-7279.
47. National Research Council Committee to Review the New York City Watershed Management Strategy. *Watershed Management for Potable Water Supply*: *Assessing the New York City Strategy*; National Academy Press: Washington, DC, USA, 2000; p. 549.
48. Inter-University Consortium for Political and Social Research. Avalable online: http://www.icpsr.umich.edu/ICPSR/. 2009 (accessed on 17 October 2010).
49. National Historic Geographic Information System. Avalable online: http://www.nhgis.org/ (accessed on 17 October 2010).