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Social science in a water observing system

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[1] We set forth an argument for the integration of social science research with natural science and engineering research in major research infrastructure investments addressing water science. A program of integrated observation of water resources offers great opportunities to address several environmental "grand challenges" identified by the National Research Council, including climate variability, institutions and resource use, and land use dynamics, and their importance for hydrologic forecasting. We argue that such a program has the potential to advance both water science and the contributing disciplines. However, to realize this potential, it is essential to recognize that social science requires critical infrastructure funding on the scale of advanced research facilities in the natural sciences and engineering.

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1. Introduction

[2] Eight "grand challenges in environmental science" identified by the National Research Council [*National Research Council*, 2001] focus on biogeochemical cycles, biological diversity and ecosystem functioning, climate variability, hydrologic forecasting, infectious disease and the environment, institutions and resource use, land use dynamics, and reinventing the use of materials. To meet these challenges, planning activities are underway for several long-term environmental observing systems. These systems are distinctive because they are candidates for funding through USA/NSF's Major Research Equipment and Facilities Construction (MREFC) account (National Science Foundation, Guidelines for planning and managing the Major Research Equipment and Facilities Construction (MREFC) account, 29 pp., 2005, http://www.nsf.gov/bfa/docs/mrefcguidelines06.pdf) which provides funding for facilities like accelerators and telescopes. The National Ecological Observatory Network (NEON) will deploy sensors "to gather long-term data on ecological responses of the biosphere to changes in land use and climate, and on feedbacks with the geosphere, hydrosphere, and atmosphere" (http://www.neoninc.org/science/overview). The Ocean Observatories Initiative (OOI) will "construct a networked infrastructure of science-driven sensor systems to measure the physical, chemical, geological and biological variables in the ocean and seafloor" (http://www.joiscience.org/ocean_observing/initiative). The Water and Environmental Research Systems (WATERS) Network (http://www.watersnet.org/index.html) [*National Research Council*, 2009a] seeks [*Dozier et al.*, 2009, p. 2]

> to create the infrastructure to transform our water research among multiple disciplines, across temporal and spatial scales, and under uncertainty. The development and deployment of the Network are fundamentally based on science questions about water and how natural, engineered, and social systems alter water quantity and quality throughout our environment and across time.

[3] A compelling feature of the National Research Council's grand challenges is the recognition of humans as inextricable elements of the systems about which we need to learn. Humans are major drivers of, as well as responders to, climate and land use change [*Christensen et al.*, 2004; *Christensen and Lettenmaier*, 2007; *Seager et al.*, 2007; *Barnett and Pierce*, 2008]. Human influences have diminished the accuracy of our historical, physically based capacity for hydrologic forecasting and the planning and investments it enables [*Milly et al.*, 2008]. Our actions perturb biogeochemical cycles and ecosystems that affect the quality of our water, the diversity of wildlife, and the spread of diseases. At the same time, human activities and livelihoods are affected by changes in the quality, quantity, and timing of water flow. The cycle of interaction is completed by human adaptations through various individual behavior, technological innovation, and societal action.

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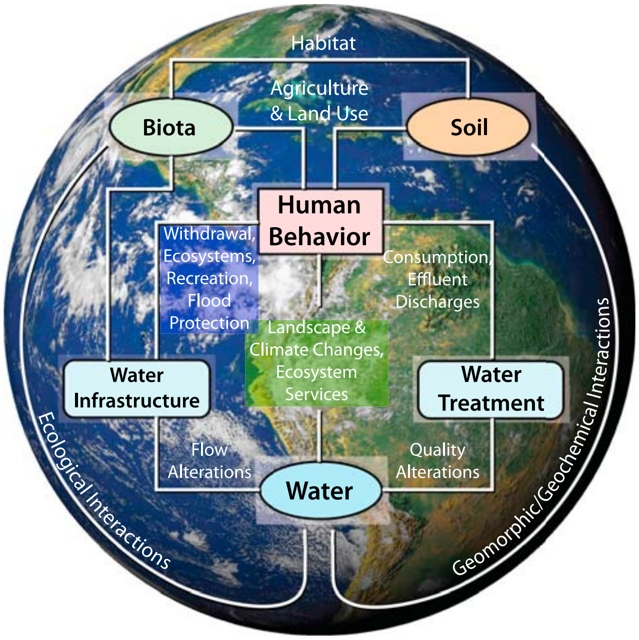


Figure 1. Humans as central actors in the water environment, exerting pressure through land use and water infrastructure and treatment and use and experiencing resulting changes in stores, fluxes, quality, and biota.

[4] The study of interactions between human and natural systems constitutes an important new scientific frontier: sustainability science [*Clark*, 2007]. Sustainability science links science, engineering, and social science to provide a deeper understanding of complex environmental systems and then turns that knowledge into societal action. The intellectual significance of the interactions between human and natural systems also is highlighted by the creation of a new section of the *Proceedings of the National Academy of Sciences* dedicated to this area (http://www.pnas.org/site/misc/sustainability.shtml) and NSF's first standing interdisciplinary program, entitled the Dynamics of Coupled Natural and Human Systems (National Science Foundation, NSF awards 12 grants for research on coupled natural and human systems, press release 07-144, 2007, available at http://www.nsf.gov/news/news_summ.jsp?cntn_id=100447).

[5] While humans are central to and inseparable from many of these scientific grand challenges, the infrastructure requirements of human-oriented research have typically not been included in the scientific infrastructure. For fully integrative research on complex human-natural systems to be undertaken, new mechanisms for coupled investments in social and natural science research infrastructure must be found. That the U.S. scientific arsenal is out of balance with respect to human components is illustrated by a recent report that extols successes in the understanding of climate systems, while arguing for increased investment in integrated social science research to support the decision making systems needed to act on climate knowledge [*National Research Council*, 2009b].

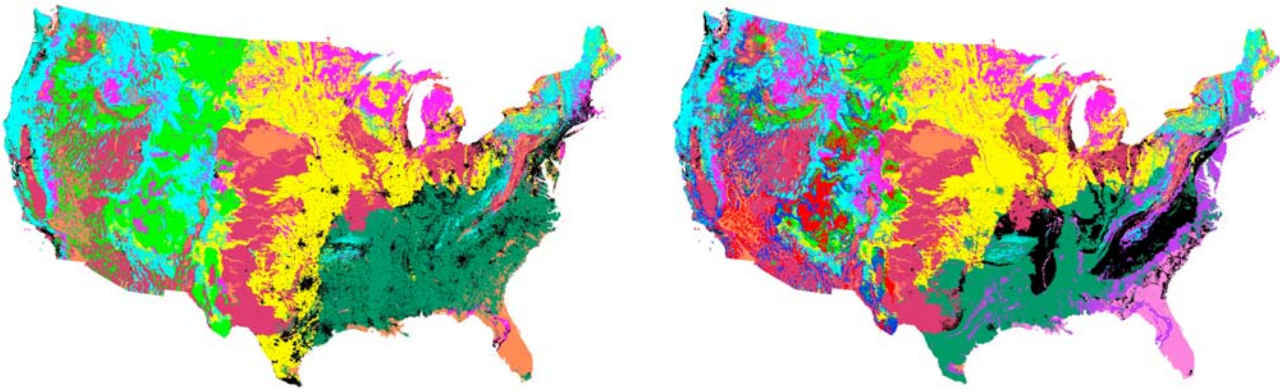
[6] We set forth an argument for why and how social science research should be integrated with natural science and engineering research in major research infrastructure investments addressing environmental grand challenges. We focus on water science research as a specific example of integration not only across disciplines, but also across environmental domains, since climate variability, institutions and resource use, and land use dynamics all affect hydrologic forecasting. Figure 1 illustrates this nexus between humans and the water environment. Figure 1 indicates that water shapes many human decisions, such as the location of cities, transportation of goods, and uses of land, and those decisions in turn modify the movement and quality of water and its attendant ecosystems. Thus, the water environment cannot be fully understood, predicted, or effectively utilized without a deep understanding of the interactions between the hydrosphere and the social sphere over space and time.

[7] We begin by describing what we mean by a water observing system in broad terms and then explain why integrating social science is essential to the overall scientific and societal success of such a system. Next, we illustrate how integrated observation will transform not only water science, but also help answer fundamental social science research questions. In section 5, we identify high-priority social science research infrastructure for an observing system and justify its cost. Finally, we argue that social science research requires investments in infrastructure analogous to the facilities required by (and provided for) the physical sciences and engineering.

2. A Water Observing System

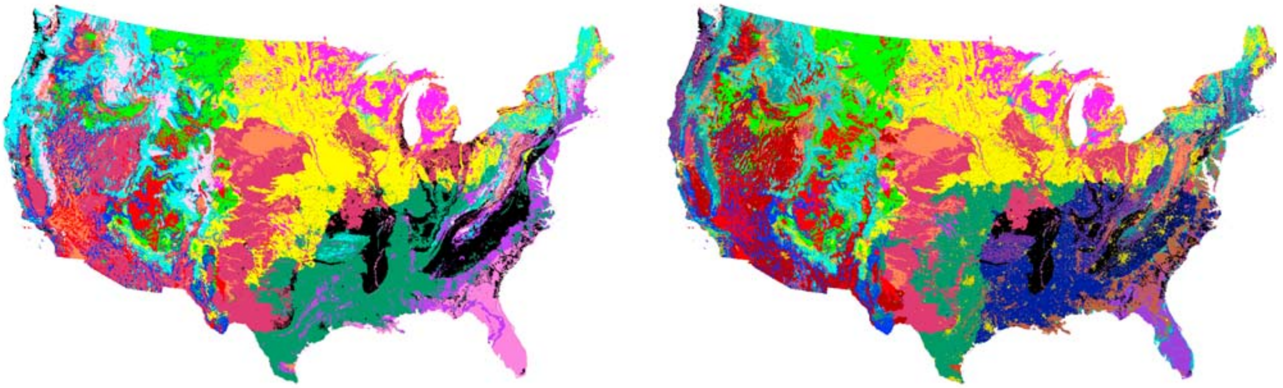
[8] The goal of an integrated water observing system is to transform our understanding of the water environment, comprising its hydrologic, engineering, and social dimensions, through controlled experimentation and observation of uncontrolled environments. We consider these facilities in order.

[9] Experimental watersheds or treatment facilities would enable extensive manipulation of system variables, well beyond the range of artificial manipulations that would be tolerable outside the laboratory. For example, water treatment systems can be tested to discover their most vulnerable components and to evaluate the robustness of emerging technologies and controls. Experimental watersheds or facilities enable a high degree of control over system variation, so only a few would be needed to produce scientifically valid insights. Similarly, facilities for visualization and decision-making experiments would support the controlled examination of interactive strategic games, framing experiments, individual versus group decision-making, tradeoff behavior, and public perceptions of scientific information and models [*White et al.*, 2009]. Controlled experimentation is a leading methodology for the study of human decisions and interactions with applications throughout the social sciences [*Campbell*, 1988; *Smith*, 1994; *Standish et al.*, 2002], including environmental and natural resource applications [*Murphy et al.*, 2000; *Cherry et al.*, 2008]. For example, drawing on studies of energy use [*Seligman et al.*, 1982] to test the effects of information on water using behavior, different forms of real-time sensors and feedback displays on water use and its associated costs might be installed in offices, commercial buildings, and households with simultaneous continuous monitoring of flows [*Aitken et al.*, 1994]. In a laboratory setting, water managers could be immersed in visual simulations of a watershed and asked to make choices about management policies [e.g., *Garrick et al.*, 2008].



8 HIWECs

12 HIWECs



13 HIWECs

20 HIWECs

Figure 2. Groupings of USGS eight-digit hydrologic units into human-impacted water environment classes (HIWECs) according to correlations in underlying hydrologic, climate, and demographic variables, by numbers of categories.

[10] While experimental facilities extend the range of questions that can be addressed, numerous scientific puzzles are not amenable to controlled experimentation. For example, changes in the hydrologic cycle and the emergence of real human institutions must be observed in the field. In these cases, the key to plausible identification of causal relationships is systematic observation across gradients in the essential design variables. The design variables are necessarily limited in number and selected to represent key drivers of hydrologic variation. For instance, they might include annual precipitation, geology, population density, water rights, and land use. Statistical clustering techniques could identify hydrologic units (http://water.usgs.gov/GIS/huc.html) that are similar with respect to these variables [*Ellis and Ramankutty*, 2008]. Following a factorial design [*Box et al.*, 2005], observational facilities could then be located to represent specific clusters. Those facilities would collect more granular data on the design variables plus additional variables such as water flows, quality, demography, social institutions, and infrastructure.

[11] Figure 2 [*Hutchinson*, 2008] illustrates this approach to identifying representative clusters. They use cluster analysis to identify hydrologic units (HUCs), defined by the U.S Geological Survey (http://water.usgs.gov/GIS/huc.html) as being "relatively homogenous with respect to the human influence variables of land cover, population density, and water use; the climate variables of temperature and precipitation; and the physical variables of slope, bedrock permeability, and soil permeability." These HUCs average about 457,000 ha in area. The domain of each design variable is discretized into intervals, and each HUC is assigned to an appropriate category for each variable. The cluster analysis discerns categorical correlations among the HUCs. For example, the analysis might discover a high degree of correlation between low population density, agricultural land uses, humid climate with moderate temperatures, and low slopes combined with high permeability. HUCs with these characteristics might then be assigned to one cluster.

[12] *Hutchinson* [2008] coined the term human-impacted water environment classes (HIWEC) to describe clusters defined by patterns of correlation between hydrologic and social variables. Each map in Figure 2 represents the clustering results for a particular limit on the number of HIWECs. Comparisons between the different maps reveal how the classes change with different limits on the number of clusters.

[13] For our purposes, the delineations shown in Figure 2 are purely illustrative. The point is that selecting observation points through statistical design based on key parameters will ensure systematic variation in these parameters and thereby maximize the information content of the observations. The design strategy should be tested for robustness across different parameter sets and interval definitions within the sets. Once appropriate clusters are determined, the availability of data, facilities, and willing partners would contribute to locating observation nodes.

[14] In addition to the breadth of coverage provided by the watershed observation nodes, a water observing system also provides a useful foundation for multilevel statistical analyses [*Bryk and Raudenbush*, 2002]. The basic node would include instrumentation to measure water stores, fluxes, and constituents. It would be designed to maximize synergies with existing observing systems, such as the stream gauge network (http://waterdata.usgs.gov/nwis) and water use estimates [*Hutson et al.*, 2004] of the U.S. Geological Survey. In addition to the hydrologic observations, households, enterprises, and formal and informal institutions (e.g., municipalities, watershed councils, water management agencies, and virtual environmental networks) would be systematically mapped and observed. Once again, the maps would leverage ongoing population and economic surveys conducted by other organizations, but the data would be geospatially linked to water quantity and quality observations. Within each node, nested observations at different hydrologic and social scales would add variation in the design variables as well as enable the study of scale relationships. Hydrologic instrument clusters could be nested in first-order to higher-order hydrologic units. Socioeconomic observations could be nested from households to census block groups to public utility networks to various levels of political jurisdiction. The two nesting structures can be integrated geospatially, with due recognition of boundary differences. Nested observation would inform our understanding not only of scale relationships in the hydrosphere, but also scale relationships in decision-making structures, from individuals to communities. Importantly, the hierarchical design allows for hypotheses to be tested about the cross-level interactions, for example, how individuals respond to changes in different types of watersheds, or how policies interact with watershed characteristics to affect water quality. Observation over time will also allow for interannual variation in, for example, solar radiation, precipitation, and water use behavior. It also opens the door to systematic data collection around, and analysis of, "natural experiments" created by climatic events, new building codes, land development projects, watershed protection activities, price increases, or other interventions. Although these discontinuities cannot be anticipated with specificity, the collection of both cross-sectional and longitudinal data has a high likelihood of observing numerous discrete perturbations that are amenable to analysis with panel data techniques [*Nauges and Thomas*, 2000; *Renwick and Green*, 2000; *Hsiao*, 2003].

3. Importance of Social Science Observation

[15] Humans are important as both causal and consequential variables in grand challenges in environmental science. In the context of water, the "management" required to balance human needs with ecosystem requirements is not simply a matter of better understanding flows or contaminants, or optimizing engineered systems; it also requires understanding: (1) economic, cultural, and social determinants of water use by individuals, businesses, and other entities, (2) how individual use aggregates to communities and beyond, (3) how social structures, institutions, and engineered technologies mediate water use, and (4) how those structures and technologies adapt to changes in population and climate. Without understanding factors underlying individual and societal decision making, a water observing system will produce science and engineering that is blind to important causes and consequences of stressed water resources and unable to predict human-driven changes in water environments.

[16] The systematic, long-term collection of human system data alongside water quantity and quality data will improve water resource management in at least three ways: water-using behavior, complexity, and uncertainty.

3.1. Water-Using Behavior

[17] Many scientific puzzles surround water-using behavior. For instance, average water use varies enormously across the U.S. and in ways not adequately explained by price, income, household size, climate, infrastructure, and other factors suggested by received economic theory. Investments in fixed assets, such as lawn irrigation systems or distribution system rehabilitation, as well as community norms and information campaigns, affect demand in ways that conventional economic theory largely overlooks [e.g., *Rosenberg et al.*, 2007]. Unraveling these puzzles requires a deeper understanding of the interplay of conflicting social and market norms [*Heyman and Ariely*, 2004; *Shampanier et al.*, 2007; *Ariely et al.*, 2009], of the chronic tension between individual self-interest and collective priorities [e.g., *Ostrom*, 2000], and of the enduring importance of perceptions such as fairness, trust, and entitlement [e.g., *Beierle and Konisky*, 2000]. Additionally, the influences of lifestyles, social pressures, and attitudes need to be understood [e.g., *Kitamura et al.*, 1997].

[18] The study of cognitive and motivational processes is also important for predicting and changing behavior of water users and decision makers. For example, different hypotheses and approaches to understanding the motivators of, and conditions for, water conserving behavior [*Thompson and Stoutemyer*, 1991; *van Vugt*, 2001; *Lehman and Gellar*, 2004; *Wolfe*, 2009] present challenges for those trying to encourage behavioral change. Further, motivators may interact with psychological processes that can obstruct the ability to persuade people to change behavior such as inertia, motivated reasoning, and optimistic biases [*Weinstein*, 1989; *Kunda*, 1990]. Skepticism, confusing language in communications, and innumeracy [*Paulos*, 2001] can reduce understanding and reliance on information about water quality and risk indicators [*Johnson*, 2008]. Moreover, we know little about how findings from studies of water users apply to water managers and decision makers, a highly influential but little-studied group within water management. For example, *Rayner et al.* [2005] and *Lejano and Ingram* [2008] found that organizational and cultural forces impede water managers' adaptation to improved seasonal climate forecasts. A national research network would have the capacity not only to test and synthesize hypotheses already

developed in the water management literature, but also to incorporate findings from other areas of behavioral research to develop new understandings of human behavior and decision making.

[19] At the level of policies and institutions, the puzzle of the Chesapeake Bay highlights the potential for disconnection between research on hydrologic processes and comprehensive action plans to solve environmental problems. Very large public investments have been made for more than three decades in an effort to understand, model, and intervene in the nutrient pollution processes that have degraded the Bay and its once-productive fisheries [*Ernst*, 2003]. While knowledge gaps concerning the sources and fates of contaminants are factors in the Bay's continuing degradation, a fundamental problem is the limited success in implementing policies to reduce stresses, especially nonpoint sources of nutrients and sediment [*Obama*, 2009]. Agriculture is of particular concern as the leading but largely unregulated source of nutrients and sediments entering the Bay [*Boesch et al.*, 2001, 2009]. In the Bay watershed, as elsewhere in the U.S., water quality protection from agricultural sources has largely been pursued through voluntary, technology-based strategies [*Ribaudo*, 2001]. The limited success of this approach has induced social science research into the adoption of water quality protection practices [*Prokopy et al.*, 2008] and the design of incentive mechanisms [*Shortle and Horan*, 2001; *Cason and Gangadharan*, 2005]. Applications of this science, enriched by additional laboratory and field experiments in different farming and social contexts, could transform policies addressing agricultural practices and land uses in the Bay and other watersheds [*Shortle and Horan*, 2008].

[20] Our understanding of human behavior and institutional performance in relation to the environment is meager [*Berger et al.*, 2001; *Scholz and Stiftel*, 2005; *Ostrom et al.*, 2007]. With respect to water, numerous institutional puzzles need to be solved. For example, adjacent states facing similar climate conditions and economic pressures often have completely different histories of water information collection, regulation, and market development [*Saliba and Bush*, 1987; *National Research Council*, 2002]. We have only the beginnings of a theory to explain this diversity in institutional responses to water management needs [*Saleth and Dinar*, 2004; *Ostrom*, 2007]. Systematic research on the forces that shape institutional responses and that drive interactions among water institutions would shed light on fundamental issues of institutional development and adaptation.

3.2. Complexity and Uncertainty

[21] The third reason why human dimensions of water science are critical is that climate change is increasingly recognized as a problem of complexity and "deep uncertainty" [*Kandlikar et al.*, 2005; *Roe and Baker*, 2007]. The uncertainty is in time, place, and magnitude, all of which represent aspects of complexity. Deep uncertainty occurs where there is fundamental disagreement about the driving forces that will shape the future, the probability distributions used to represent uncertainty and key variables, and how to value alternative outcomes [*Lempert et al.*, 2003]. Deep uncertainty fosters "wicked problems" confounded by disagreement on the basic scientific questions to be addressed [*Rittel and Webber*, 1973]. In an era of climate change, planning for water resources is fraught with deep uncertainties. As such, it requires a reorientation of water science away from forecasting and risk analysis and toward decision making under uncertainty.

[22] Rarely will all the uncertainties about climate change and other relevant stressors be resolved before decisions must be made about the construction of new water infrastructure and the design and creation of more sustainable cities. Water decision makers will need to consider future scenarios that range outside historical experience. In addition to extreme climate realizations, future water infrastructure will need to adapt to new human demands and technologies. Future water planning thus will require not only the monitoring of multiple components and interactions of the water cycle, but also of interactions and feedbacks with land use, population movements, family and community relations, and the institutions that govern water pricing and allocation.

[23] For purposes of addressing these deep uncertainties, agent-based modeling and Bayesian networks are promising tools for representing social systems in dynamic and socially and spatially explicit ways that are integrated with counterparts from the physical sciences and engineering [*Bankes*, 2002; *Korb and Nicholson*, 2004; *Miller and Page*, 2007]. However, an often cited challenge of creating such models is their information requirements about the attributes, preferences, behavior, and decision making processes of individual actors, and of the system-level characteristics they aim to explain [*Janssen and Ostrom*, 2006; *Fagiolo et al.*, 2007; *Robinson et al.*, 2007; *Dawid and Fagiolo*, 2008]. Systematic social science observation as part of a water observing system could greatly improve the capacity to parameterize these models. Below we propose fundamental questions that would drive the social science research as it is coupled to water cycle processes and prediction.

4. Transforming Social Sciences

[24] In addition to its importance for understanding water resources and human-environment interactions, a system of coordinated multiscale observation offers the potential to advance basic science in the hydrologic sciences, environmental engineering, and social sciences. Factors usually considered exogenous to one field are opened to examination, and new relationships can be explored [*Axelrod and Cohen*, 2001]. From the perspective of social sciences, the following examples illustrate how inquiry into decision making, institutional design, performance, evolution, and economics can be enriched by coordinated observation of the water environment.

4.1. Decision Making

[25] A fundamental science question concerning human decision making is: How do information, incentives, and social influences affect the way people and institutions arrive at decisions? Research shows that attitudes and behavior are influenced by concerns about what other people think [*Stevens and Fiske*, 1995; *Cialdini and Goldstein*, 2004; *Nolan et al.*, 2008] and that the nature of this influence differs for males and females [*Eagly*, 1987; *Werner et al.*, 2008]. These concerns are evident in private behavior, such as using lawn irrigation and chemicals to

beautify and maintain our homes and yards even when water is scarce [*Nassauer et al.*, 2009]. Reducing the use of water or chemicals may be the best option for protecting water resources, but the scientific understanding is piecemeal on how best to motivate behavioral responses to environmental problems [*Gardner and Stern*, 2002]. For instance, if people are more responsive to peer approval than to use and cost considerations, then campaigns designed to reinforce social norms among neighbors might be more influential in changing behavior (e.g., lawn watering amounts or chemical applications and disposal) than information about personal cost savings, traditional advertising, or messages from ''outside'' authorities [*Schultz et al.*, 2007]. Alternatively, if norms and economics operate interactively on individual behavior, then coordination of mechanisms is important to their success. However, the context or range of a community's experience can alter the relative influence of various behavioral pressures, magnifying the challenge of building a general understanding of human behavioral factors without a comprehensive, multidisciplinary observing network.

[26] Because of the difficulty of obtaining independent observations at the parcel or household level, where the behavior of individuals are manifest, the existing studies of peer effects usually rely on self-reported behavior and preferences [*Werner*, 2003]. Stronger evidence depends on coupling interventions (e.g., information or peer benchmarking) with the ability to measure water or chemical use or discharge at the household level. General insights can be gained by replication across hydroclimatic conditions (e.g., different landscaping norms) and across natural and planned experiments at specific locations.

4.2. Governance

[27] A fundamental science question concerning governance is: How do institutions respond to changes in natural systems and influence how humans use these systems? One paramount role of government is ensuring the safety and security of its citizens. Preparedness for and efficient response to events in nature, such as floods, droughts, and earthquakes, is an important barometer of governmental performance, as is the assurance of dependable water supply and sanitation services. Through systematic examination across natural conditions, we can learn whether and how governance structures, both formal and informal, reflect changes in the natural systems with which they interact [*Ostrom*, 1990; *Axelrod and Cohen*, 2001; *Lansing*, 2006]. These basic science insights would contribute to the understanding and implementation of adaptive management.

[28] An ongoing research problem in political science is to understand the implications of tradeoffs made in different governance arrangements between the efficiency with which services are provided, the power to make decisions, and the expertise to make wise decisions [*Ostrom et al.*, 1993; *Hamilton*, 2004]. A compelling example of a highly fragmented governance structure for water is in the Phoenix metropolitan region. Some 50 municipal and private providers make decisions about water in Phoenix and the surrounding area [*Gober*, 2007, 2009]. Each provider has a unique portfolio of supplies, faces fundamentally different demand conditions, sets its own prices, and runs its own conservation campaigns. As a result, climate change may affect the supplies of one provider differently from a neighboring jurisdiction. Without mechanisms to share under shortage conditions, it is possible, indeed probable, for one jurisdiction to have water aplenty while residents in a neighboring district face severe rationing. Even cities in water-abundant areas, such as the Great Lakes region [*Annin*, 2006], are served by fragmented water systems. Systematic observation across network nodes and over time will permit analysis of alternative solutions to the problem of local supply differentials and why particular solutions emerge in different contexts.

[29] As another example, it is commonly argued that the development of a watershed-wide collaborative partnership to coordinate policies of disparate water authorities will provide more sustainable water policies than the traditional hierarchical model or newer market-based models [*Leach et al.*, 2002; *Sabatier et al.*, 2005; *Koontz and Thomas*, 2006]. However, such a generalization may not be valid across different hydroclimatic zones or areas of varying human pressures on or experiences with water. Furthermore, professional organizations and networks may have greater influence on these nonregulatory partnerships. Water measurements systematically linked to institutional differences across space and time would be required to actually test the proposition that these partnerships make a difference, and these have not been available.

[30] A *National Research Council* [2002] committee found that, nationwide, there are large differences in state regulatory and information collection programs for water. Their report also advocated the use of stratified random sampling to collect data that would assist in the study of both water-using behavior and institutional arrangements. A water observing network offers the promise of assembling the requisite data sets through stratified sampling over sufficient geographic and temporal scales to identify the efficacy and adaptability of alternative institutional structures at local and state levels.

4.3. Value of Ecosystem Services

[31] A fundamental science question concerning economics is: What is the value of the ecosystem services provided by surface and groundwater? The ''diamond-water paradox'' has long fascinated economists and philosophers: Why does an absolutely essential good like water have such a low market price while diamonds, used mainly for unessential luxury purposes, have such a high price? This question perplexed Adam Smith [*Smith*, 1904], and its resolution compelled fundamental developments in the theory of consumer preferences, i.e., decreasing marginal utility [*van Böhm-Bawerk*, 1891]. These historical inquiries focused on the value of water in direct human use. However, increasing awareness of water's nonmarket importance, e.g., for cultural (aesthetic) ecosystem services [*Millenium Ecosystem Assessment*, 2005], raises new fundamental questions about the valuation of water and how those values can be rationalized in or with the marketplace [*Daily*, 1997; *National Research Council*, 1997; *Young*, 2005; *Egan et al.*, 2009].

[32] Measuring numerous water quality and quantity parameters, while also collecting geospatially coincident data on real estate values and recreation activities, would enable researchers to analyze and model factors that determine the values of the services that water provides and how those values evolve over time and space as the relative

qualities and quantities of in situ water change. Such research would better identify the role of ecosystem services in human choices, for example, of residential locations and land uses, as compared to the pursuit of employment or "conventional" economic opportunities [*Walsh*, 2007; *Clark et al.*, 2009; *Geoghegan*, 2002; *Wu and Irwin*, 2007]. These insights would further our understanding of the causes of sprawl and exurban or summer home development, with implications for future levels of anthropogenic influences on water quality, and consumption demands [*Alberti et al.*, 2007].

5. Social Science Observational Infrastructure

[33] This section focuses on, first, the types of social science data that would be most valuable along with the infrastructure required to collect them and, second, how we believe social science infrastructure should be viewed in the context of national research initiatives. For the USA, these initiatives have been carried out by the National Science Foundation whose primary vehicle for investments in large-scale research infrastructure is the Major Research Equipment and Facilities Construction account. We focus on USA/NSF MREFC because this is the prospective funding source for the three major environmental research networks: NEON, OOI, and WATERS Network. However, the same arguments apply to other models for research funding where human activities are fundamental to the science and significant infrastructure investments are required.

[34] Four forms of social observation offer promise for transformative research: geodemographic maps and protocols for data access and assembly, a national survey on the environment, computer-assisted decision environments, and a network-scale institutional review board.

5.1. Geodemographic Maps and Protocols for Data Access and Assembly

[35] The first type of infrastructure combines baseline social maps with systems for ongoing capture and assembly of social data for map updating [*Goodchild*, 2008; *Longley and Goodchild*, 2008]. Social phenomena would be mapped at multiple scales, with more granular observation around network nodes where intensive field observations on water quality and quantity are underway. Census block groups could be the basic building block for the social data. The U.S. Census locates each block group in space and provides extensive descriptive data on the households within each group. In the vicinity of each node in the observing network, the baseline maps would spatially articulate block groups to water supply and sewerage systems (from which pricing and flow data might also be collected), surface water catchments, floodplains, aquifers, rain gauges, land cover maps, air sheds, political jurisdictions, zoning districts, property assessment units, tax rates, watershed or environmental organization registries, news content analyses, and so forth. The goal would be to track these variables through time and correlate them spatially and temporally with the water flow, flux, and quality measurements collected with physical sensors.

[36] In order to produce time-evolving maps, the system would require durable data bridges to primary collectors, such as local, state, and federal agencies, for routine transfer of data streams and data. Beyond obtaining the data, cyberinfrastructure would need to be designed to ensure data integrity over time as well as to facilitate investigator access to the data. A pilot effort focusing on hydrologic data is already underway through the NSF-supported Hydrologic Information System (http://his.cuahsi.org/community.html). This effort could be expanded to capture important sociologic information such as spatially distributed water use data.

5.2. A National Survey Suite on the Water Environment

[37] The second class of social science infrastructure will enable the production of entirely new data on individuals and households and the social systems in which they are embedded. This infrastructure consists of a new suite of national-scale survey instruments focusing on humans in relation to the water environment. With a few exceptions that focus on recreation (the National Survey on Recreation and the Environment (http://www.srs.fs.usda.gov/trends/Nsre/nsre2.html), the National Park Service comprehensive survey of the American public [*Social Science Research Laboratory*, 2002], and the National Survey of Fishing, Hunting, and Wildlife-Associated Recreation [*U.S. Fish and Wildlife Service*, 2006], and the periodic administration of the "New Environmental Paradigm" attitudinal scale [*McCright and Dunlap*, 2008]) there appear to be no ongoing, national-scale surveys of human attitudes and behavior in relation to the environment, much less the water environment. The dearth of microscale data on humans and the environment contrasts with the well-established public survey data collection concerning national elections (http://www.icpsr.umich.edu/cocoon/ICPSR/SERIES/00003.xml), health and retirement (http://hrsonline.isr.umich.edu), and income dynamics (http://psidonline.isr.umich.edu/). A national-scale survey joined with field observations of the water environment would provide an important new platform for research addressing the coupling of human and natural systems.

[38] A nested suite of surveys could collect information from multiple strata of the human networks surrounding water: individuals, households, managers, and policy officials. For example, systematic surveys of targeted populations will help to understand decentralized management, the social networks through which information travels between individual decision makers, managers, and public officials, and responses to information campaigns [*Thurston et al.*, 2003; *Fullerton and Wolverton*, 2005]. These data would be placed into demographic, institutional, and environmental context with the geodemographic maps described above.

[39] Survey development requires a substantial up-front investment in building and pretesting survey instruments and developing representative, adaptable sampling strategies stratified to articulate with the hydrologic and built-system data collection. In addition, the creation of survey panels to the point of informed consent, preliminary to data acquisition, by itself represents a major investment in research capacity. The technology required to administer, collect, analyze, and efficiently disseminate the survey instruments and findings must also be built. Depending on the precise design of the survey process, the infrastructure may also require mobile data acquisition units and telemetry. The cyberinfrastructure created for the geodemographic mapping may also prompt, assemble, process, and archive the survey data in relationship to geophysical and engineering data sets. This latter connection links the survey

responses to the physical and institutional data collected with other observational tools.

5.3. Computer-Assisted Decision Environments

[40] An observing system that recognizes the central role of human decision making in influencing water quality and quantity, and one that leverages relationships between water scientists and water decision makers, will benefit from infrastructure that enables innovative controlled experiments that address visualization, decision-making experimentation, modeling of complex physical, engineered and social systems, and study of scientist-stakeholder interactions. One approach is to build on the data and modeling capacity provided by the geospatial mapping and modeling infrastructure to include visualization caves and theaters as spaces for scientists to observe their results and evaluate simulation experiments. This infrastructure would enable scientists to observe decision makers responding to "what if" scenarios of the future, and allow scientists and decision makers to build collaboratively more decision-relevant models of future water conditions. An existing network of NSF-sponsored decision centers (National Science Foundation, Climate change a focus of new NSF-supported research on how decisions are made in a world of uncertainty, press release 04-132, 2004, available at http://www.nsf.gov/news/news_summ.jsp?cntn_id=100447) provides a platform on which specialized modeling or visualization infrastructure might be added. These centers might also be connected to hydrologic or engineering experimental facilities where research subjects could gain direct exposure to pilot-scale technologies and simulations of environmental phenomena of interest.

5.4. A Network-Scale Institutional Review Board

[41] In addition to the three types of observational facilities noted above, the pervasive need in social science research to engage with human subjects or identifiable microdata raises the need for a fourth type of infrastructure. An institutional review board would arrange complex human subjects research, data sharing capacity, and data access. It would provide human subject protections efficiently while also facilitating access to suitably protected data on individuals. All federal granting agencies and universities require third-party review in advance of implementation of research protocols involving human subjects. Institutional review boards conduct these reviews [*Gunsalus et al.*, 2006, 2007]. Projects involving many institutions, as would be the case for a national-scale observing network, have typically required separate research protocol reviews for each university, thereby requiring redundant applications and reviews even where the protocol is identical across institutions.

[42] The types of research that are especially susceptible to redundancy and delays include: multisite research or clinical trials; studies responding to national priorities or time-sensitive situations, such as disaster response, in which coordinated, agile responses are essential; and collaborations among unaffiliated institutions (Association of American Medical Colleges, National Conference on Alternative IRB Models: Optimizing human subject protection, 53 pp., 2006, available at http://www.aamc.org/research/irbreview/irbconf06rpt.pdf; Department of Health and Human Services, Alternative models of IRB review: Workshop summary report, 7 pp., 2006, available at http://www.hhs.gov/ohrp/sachrp/documents/AltModIRB.pdf). All of these characteristics describe a water observing system that includes national and coordinated local surveys or multisite experimental research, making a compelling case for coordinated institutional review.

[43] In addition to its role in ensuring protections of human subjects in empirical studies, a system-based review facility could help address issues of privacy associated with access to data sets that contain potentially identifiable observations at the individual, household, or enterprise levels. The facility would establish agreements with entities that collect particular data streams, the Census Bureau, property assessors, water utilities, or survey researchers, and then establish guidelines for allowing investigator access to these possibly sensitive data. It would cooperate with other agencies that have established procedures for researcher access to privileged data, such as the U.S. Census Bureau (http://www.ces.census.gov/index.php/ces/1.00/researchprogram) and the U.S. Department of Agriculture (http://www.ers.usda.gov/Data/ARMS/).

6. Funding Integrated Research Infrastructure

[44] To this point, we have argued that: (1) research on water that couples physical, engineering, and social dimensions will have far broader impacts than research that isolates these dimensions; (2) water problems provide a rich setting for the study of fundamental questions of behavior, decision-making, and social organization; and (3) dynamic geodemographic maps, nested population surveys, decision laboratories, and national-scale institutional review for human subjects would potentially transform social sciences. We now turn to our final point—that social science research infrastructure is necessary to understand and manage natural and engineered water systems and that such research infrastructure should be included as part of large-scale investments in environmental observing systems such as USA/NSF's Major Research Equipment and Facilities Construction account (National Science Foundation, Guidelines for planning and managing the Major Research Equipment and Facilities Construction (MREFC) account, http://www.nsf.gov/bfa/docs/mrefcguidelines06.pdf).

[45] Even though a water environment observing system would require an extensive and expensive network of "hard" facilities, the use of, e.g., MREFC funds for the creation of hard infrastructure for social science research would be a significant departure from past experience. The use of "equipment" and "facility" funds for "soft" research infrastructure, such as maps, surveys, cyberinfrastructure for data assembly and dissemination, and protocols for human subjects, suggests an even greater departure from tradition. Nevertheless, for social scientists, these elements are analogous in function, funding profile, and importance to the intensive instrumentation of a large watershed or a full-scale experimental treatment plant. They address significant impediments to scientific progress; they require a construction and commissioning phase of initial investment; they serve as centralized platforms enabling many researchers to address specific questions in separately funded research projects; they are available to a broad and diverse community of scientists as platforms for focused studies; and there are few alternative funding programs for these

endeavors. In short, they are major research facilities for the social sciences. By tightly coupling the social science observational infrastructure with geophysical and engineering observation facilities, transformational interdisciplinary science linking people and the environment will be possible as never before.

7. Conclusions

[46] A program of integrated observation of water resources, including a social science component, responds to grand challenges for environmental research identified by the *National Research Council* [2001] and offers the potential to motivate participating natural and social science disciplines to make new discoveries. It is critical, however, to stipulate that advancing the cause of integrated scientific enterprise will require a new understanding of what constitutes scientific infrastructure to include the support systems for social science research. Social scientific infrastructure includes both hard and soft elements. Unless social science questions, and the hard and soft infrastructure required to support them, are included in the design, implementation, and funding of a water observing system, the potential for that system to produce transformative research at the juncture of humans and natural systems will be compromised.

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