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Source: Environmental Health Insights, 9(s2)

Published By: SAGE Publishing

URL: https://doi.org/10.1177/EHI.S19586

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Sustainable Watersheds: Integrating Ecosystem Services and Public Health

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Supplementary Issue: Ecosystem Services and Environmental Health

ABSTRACT: Sustainable management of aquatic ecosystems is a worldwide priority; the integrity of these systems depends, in turn, on the integrity of the watersheds (catchments) in which they are embedded. In this article, we present the concepts, background, and scientific foundations for assessing, both nationally and at finer scales, the relationships between ecosystem services, human health, and socioeconomic values in the context of water quality, water quantity, landscapes, the condition of watersheds, and the connectivity of waters, from headwaters to estuaries and the coastal ocean. These assessments will be a foundation for what we have termed "watershed epidemiology," through which the connections between ecosystems and human health can be explored over broad spatial and temporal scales. Understanding and communicating these relationships should lead to greater awareness of the roles watersheds play in human well-being, and hence to better management and stewardship of water resources. The U.S. Environmental Protection Agency is developing the research, models, and planning tools to support operational national assessments of watershed sustainability, building upon ongoing assessments of aquatic resources in streams, rivers, lakes, wetlands and estuaries.

KEYWORDS: sustainability, water resources, human-ecological systems, aquatic life

SUPPLEMENT: Ecosystem Services and Environmental Health

CITATION: Jordan and Benson. Sustainable Watersheds: Integrating Ecosystem Services and Public Health. *Environmental Health Insights* 2015:9(S2) 1–7 doi: 10.4137/EHI.S19586.

RECEIVED: January 23, 2015. **RESUBMITTED:** March 16, 2015. **ACCEPTED FOR PUBLICATION:** March 18, 2015.

ACADEMIC EDITOR: Timothy Kelley, Editor in Chief

TYPE: Review

FUNDING: This study was funded in part by the U.S. Environmental Protection Agency. The authors confirm that the funder had no influence over the study design, content of this article, or selection of this journal.

COMPETING INTERESTS: Authors disclose no potential conflicts of interest.

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Introduction

The goal of sustainability, as stated in the National Environmental Policy Act[1] (NEPA), and recently (2011) reiterated by the National Research Council[2] is "to create and maintain conditions, under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generations." "Productive harmony" between humans and nature depends on the integrity of ecosystems in terms of structure, function, and their capacity to produce goods and services that humans require,[3] including clean and plentiful water. To achieve the NEPA goal, it is essential to sustain adequate, accessible supplies of clean water for the support of human health, ecosystems, and their attendant social and economic benefits. Indeed, sustainable management of aquatic ecosystems is a worldwide priority.[4]

Groundwater, wetlands, lakes and reservoirs, upland streams, great rivers, estuaries, and coastal oceans are all valuable water resources, and all are embedded in or – in the case of most coastal systems – strongly connected to watersheds. The quality of water and the quantities available depend to a great extent on the properties of watersheds: geology, topography, climate, land cover, and human uses. Many watersheds are dominated by human uses, including mining, oil and gas extraction, urban development, and agriculture (Fig. 1); this dominance can be expected to increase in concert with human population growth and urbanization.

Urban watersheds, many of which exhibit impervious land cover in high proportions, combined sewer overflows (CSOs), polluted runoff, and contaminated effluents, present major challenges to the integrity and sustainability of water resources. These conditions have been shown to cause severe impairment of aquatic ecosystems.[5,6] In epidemiological studies, watersheds with CSOs have been associated with higher rates of human illness.[7,8] In agricultural watersheds, water quality and quantity can be altered by irrigation and degraded by runoff of sediment, nutrients, pesticides, and herbicides, along with microbes, antibiotics, and hormones associated with livestock operations.[9,10] These stressors pose risks to aquatic life, recreation, and drinking water sources. In many watersheds not affected by urbanization or agriculture, various anthropogenic disturbances such as mining, drilling, timber

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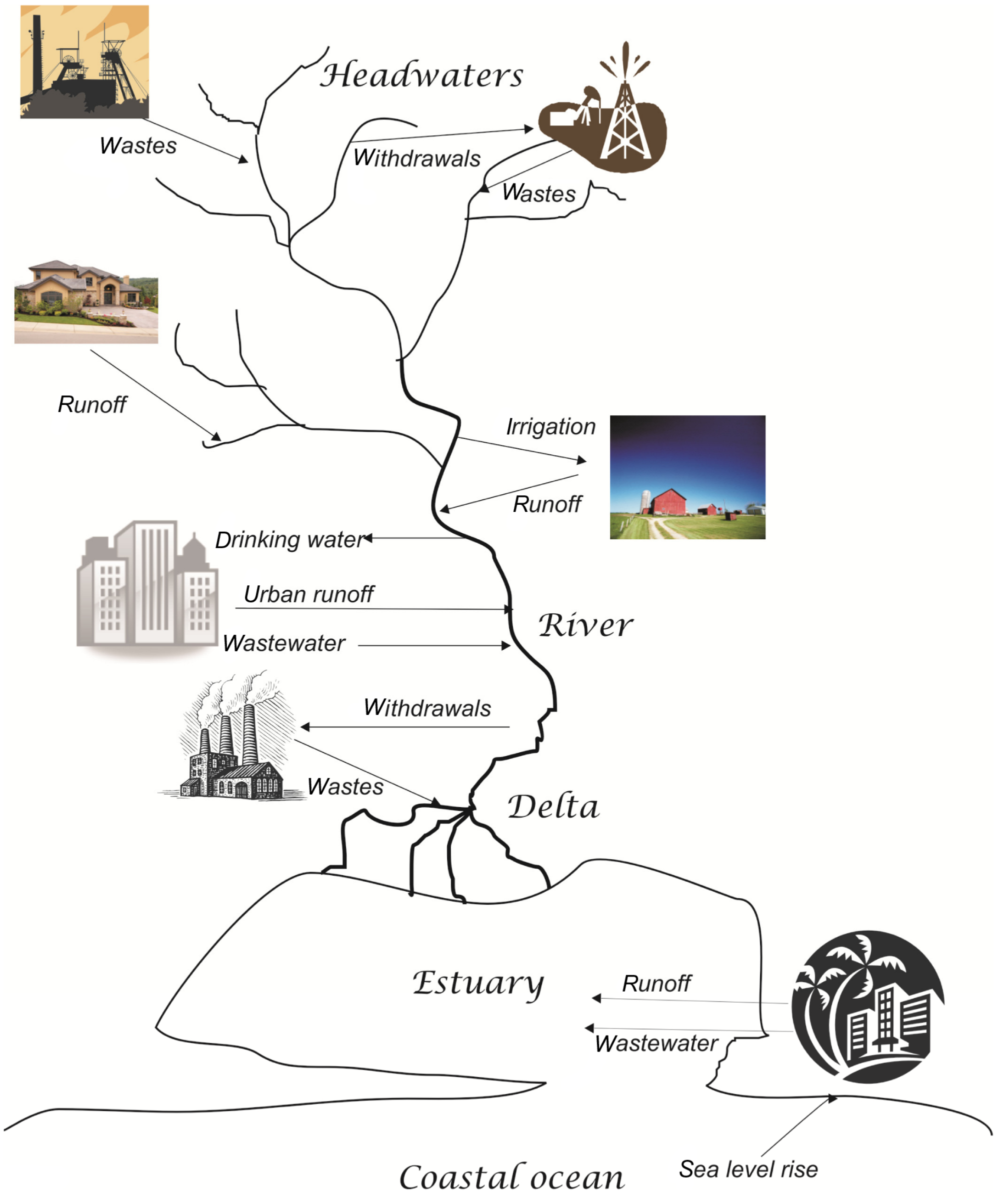

Figure 1. Schematic view of a watershed, showing sources of stressors and connectivity from headwaters to the coastal zone.

harvest, and some recreational uses can degrade water quality and aquatic habitats. It is important to note that these effects are not always local; altered water flow and pollutant loads can have effects far downstream, stretching from headwaters to estuaries and coastal waters.[11] Cornwell et al.[12] provide a comprehensive account of the occurrence and effects of multiple stressors (chemicals, microbes, invasive species, etc) on humans and ecosystems in the USA–Canada Great Lakes and their watersheds.

In cases where waters are wholly or relatively unimpaired, new and expanding human uses of watersheds threaten the integrity and sustainability of water supplies and aquatic ecosystems. Population growth requires development of land and infrastructure for residential, commercial, transportation, and supporting uses. Rapid expansion of oil and gas extraction by means of deep drilling and hydraulic fracturing is putting increasing demands on water resources and the capacity of watersheds to sustain water quantity and quality. Climate change and extreme events (eg, major floods and droughts), whether natural or forced by climate change, also threaten watershed integrity and sustainability. A recent study (2015) shows that water temperatures in watersheds of the US mid-Atlantic region are rising significantly, with many implications for aquatic life and human uses, including losses of cold water fisheries, increases in pathogens and invasive species, and greater fluxes of nutrients that contribute to eutrophication and harmful algae blooms.[13] In the interest of sustainability, watersheds that presently supply plentiful clean water and fully support aquatic life need to be identified, cataloged and targeted for enhanced protection.[14]

In this article, we consider the advantages of assessing the relationships between ecosystem services, human health,

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and socioeconomic values in the context of water quality, water quantity, landscapes, the condition of watersheds, and the connectivity of waters from highlands to oceans. Fuller understanding and communication of these relationships is essential if watersheds and water resources are to be managed comprehensively and sustainably. First, we present a few examples of how human activities on land can be translated through water resources to impacts on human health and welfare. Next, we present in conceptual form how this knowledge of watershed sustainability can be developed, while addressing some of the inherent difficulties: complexity, uncertainty, causal inference, an array of geographic and temporal scales, and data incompatibilities (eg, matching human health data with environmental data). Finally, we discuss the benefits of assessing, predicting, and communicating the qualities and values of watersheds as human-ecological systems.

Linkages between Humans and Ecosystems

Modern history demonstrates that the introduction of new technologies can have significant unanticipated consequences for both human health and ecological integrity. For example, in the pre-1970s, the environmental persistence, bioaccumulation, and toxicity of industrial chemicals were largely uncharacterized. Our lack of understanding and attention unequivocally contributed to environmental and human health injuries, which proved costly to correct in terms of both time and financial resources.[15] Although the mechanistic linkages between human health and ecosystems are complex and poorly understood, it is important to understand these linkages if we are to resolve many of the most significant ecological public health challenges to sustainable watersheds. Whereas larger scale crises could be developing, such as the effects of global climate change or encroachment of new landscapes, dramatic localized environmental disasters capture public attention and are immediately disruptive to daily life. A few examples follow.

As reported by Luoma et al.[16], the headwater drainage basin of the Clark Fork River (Butte, MO, USA) was a site of copper and zinc ore mining, and smelting beginning in the nineteenth century; more than 1 billion (1×10^9) metric tons of ore and waste rock were produced before the smelter closed in 1980.[17] The currently impaired condition of the Clark Fork River appears to be a legacy from historic waste inputs, which persist in the system as contaminated sediments, water, and biota.[18,19] The river's trout fishery remains far less productive than expected for a Montana stream.[20] Losses of environmental goods and services have been described as unambiguous, with the most extreme effects found in Butte and Deer Lodge Valley. Metals associated with the mines contaminate waters hundreds of kilometers downstream.[16] It has been shown recently (2014) that even very low densities of mines in a watershed can affect fish assemblages negatively in connected streams at the regional scale, well beyond the stream reaches in proximity to the mines.[21]

The environmental debate raised by reduced diversity of the benthic community and histopathological lesions in trout also raised concerns about potential effects on human health. Health effects in the area were a problem historically; Miranda et al.[15] speculated that human exposure to cadmium (linked to cardiorenal disease), arsenic, and radon (both linked to cancers) associated with mining provided plausible links to the observed high rates of these diseases. The loss of environmental goods and services was directly linked to changes in human well-being,[16] including higher than expected cancer rates.[22] This example is a cautionary tale: in hindsight, if care had been taken all along to sustain the Clark Fork River ecosystem and its services, much social and economic harm could have been prevented.

More recent (2014) examples of great scope and consequence in the US include (1) a spill of industrial chemicals into the Elk River, West Virginia, which contaminated a major public water supply, restricting water use for ~300,000 residents, fueling hundreds of complaints of illness and discomfort and leading to several hospitalizations,[23] and (2) loss of drinking water supplies to about 500,000 residents in the Toledo, Ohio area, because of toxic algae blooms (primarily related to phosphorus pollution) in Lake Erie.[24] Although in both cases the immediate effects on human health were less than catastrophic, the economic and social (well-being) effects were enormous (on the order of $100 million and approximately 800,000 people temporarily deprived of safe water), while the long-term effects on river and lake ecosystems have yet to be reported. The potential ecological effects, in turn, may reverberate in the economic and social spheres for years or decades if, for example, the ecosystems that support fisheries have been damaged by the pollution.

The goal of preventing contamination of water resources, if attained, would preclude such events. Nevertheless, responses to and outcomes of these watershed-related disasters could have been improved by such means as more rapid detection of spills and the presence of harmful contaminants, improved knowledge of health and ecological effects, and prediction of adverse events. In support of these ends, technologies are now available for monitoring site-specific water quality continuously and remotely, synoptic monitoring of surface water quality and algae blooms over large areas of coastal and inland waters using satellite imaging, and detecting and quantifying minute concentrations of thousands of contaminants in water. Advances in molecular technology have led to the documentation of full genomic sequences of several multicellular organisms, ranging from nematodes to humans. The related molecular fields of proteomics and metabolomics are beginning to advance rapidly as well. In addition, advances in bioinformatics and mathematical modeling provide powerful approaches for elucidating patterns of biological response embedded in the massive datasets produced during genomics research. Thus, changes or differences in the expression patterns of entire genomes at the level of the mRNA, protein,

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and metabolism can be assessed rapidly. Collectively, these emerging approaches may greatly enhance the ability to detect and predict problems, as well as establish causal mechanisms, thereby addressing major challenges to understanding the integration of ecosystem services and public health.

Many of the responses to various stressors are evolutionarily conserved, so that there are correspondences between indicators of human health and ecological health. For example, consider how animal, some plant, and microbial species respond to stressors, including emerging contaminants (both synthetic and natural), or parasites. It may be that the growing knowledge of comparative genomics between terrestrial and aquatic vertebrate, invertebrate, and plant species will substantially improve our ability to extrapolate effects currently derived in mammals to aquatic phyla in the future.[25] In the opposite direction, we have the example of Zebra fish (*Danio rerio*) embryos as model organisms for screening chemicals for human toxicology.[26] Creatures that spend all or most of their lives in water, with long-term, immersive exposures to aquatic stressors, can be sensitive sentinels for risks to human health.[27]

Watershed Epidemiology: Connecting Ecosystem Services to Human Health and Well-Being

By "watershed epidemiology" we mean adapting some of the precepts and methods of human epidemiology to the geographic scales of watersheds in order to gain a more complete understanding of connections between the environment, water resources, and the health and well-being of human populations. Kolok et al.[28] made a strong case for watersheds as natural boundaries in epidemiological evaluations of human effects of waterborne agricultural chemicals, especially endocrine-disrupting (hormone-like) compounds. The concept is illustrated schematically in Figure 2. Monitoring, assessment, and diagnosis of impairments in watersheds traditionally have been focused on ecological condition, based on various physical, chemical, and biological indicators. These types of indicators, although they can be informative, or even comprehensive from an ecological perspective, are insufficient if we are to consider watersheds within an evolving ecological public health paradigm.[29] Clearly, humans have altered and will continue to alter watersheds while concomitantly remaining intimately dependent upon the goods and services provided by these ecological systems. These alterations, or impacts, result from combinations of biological, physical, and socioeconomic phenomena. Until recently, evaluating and managing the effects of human activities on ecosystems, or managing the impacts of environmental goods and services on public health, have been undertaken as separate activities and treated as fundamentally distinct phenomena. It is clear that our concept of an ecological public health paradigm is emerging. The nature and science of the new paradigm are beginning to be explored, as are the consequences of decision making that jointly affects ecosystem services and public health.

Despite the challenges of measuring and communicating watershed sustainability, we quote Norström et al.[30] in reference to global sustainable development goals: ". recent social-ecological systems-based approaches for measuring multiple ecosystem services and human wellbeing [sic] provide hopeful avenues for developing integrated and scalable indicators." Coutts et al.[29] present a discussion of the growing understanding of the critical dynamic relationships between ecosystems and human health, with a suite of conceptual models that illustrate how this understanding has evolved historically. Further, a comprehensive information tool, the Eco-Health Relationship Browser,[31] has been made available by the US Environmental Protection Agency (EPA) for exploring and documenting ecosystem–public health connections. Here, we outline the development and application of a system of indicators and models, integrating the ecological condition and integrity of watersheds with economic values, social values, and human health outcomes, which will be scalable from small watersheds to regional and national assessments for the US (Fig. 2). When fully operational, this system will extend beyond conceptual and knowledge models into the spatial and temporal dimensions as a tool for planning and managing watersheds and water resources for sustainability.

The EPA, in cooperation with states, tribes, and other federal agencies, conducts periodic national assessments of lakes, rivers and streams, estuaries, and wetlands through its National Aquatic Resource Surveys.[32] Because the surveys are conducted with probabilistic designs, they are spatially unbiased and thus can be used to assess the overall condition of water resources at national, regional, and, in some cases, finer scales (eg, states). These data are supplemented and complemented by other comprehensive monitoring programs, including the National Water Quality Assessment Program, operated by the U.S. Geological Survey,[33] and those of the individual states. Currently, EPA is conducting research, building on the national assessments, to (1) develop predictive models of watershed integrity, (2) incorporate human health indicators into watershed assessments, and (3) estimate the economic values of the goods and services supplied by water and watershed ecosystems. Several complementary datasets are available at national scales; examples include land cover and other physical variables,[34] quality and quantity of surface and groundwater,[33] and a wide array of human health statistics, which can be explored online.[35] In Table 1, we list several types of data that, in combination with a variety of models, will be used to quantify the connections in Figure 2.

At the national scale, these types of data applied across thousands of watersheds (or millions depending on the scale of analysis) will provide substantial statistical power to elicit associations between the environment, ecosystems, and indicators of human health and welfare. Beyond the direct effects of poor water quality on human health caused by pathogens, harmful algae, and toxic contaminants, watershed epidemiology can be used to explore less direct associations between

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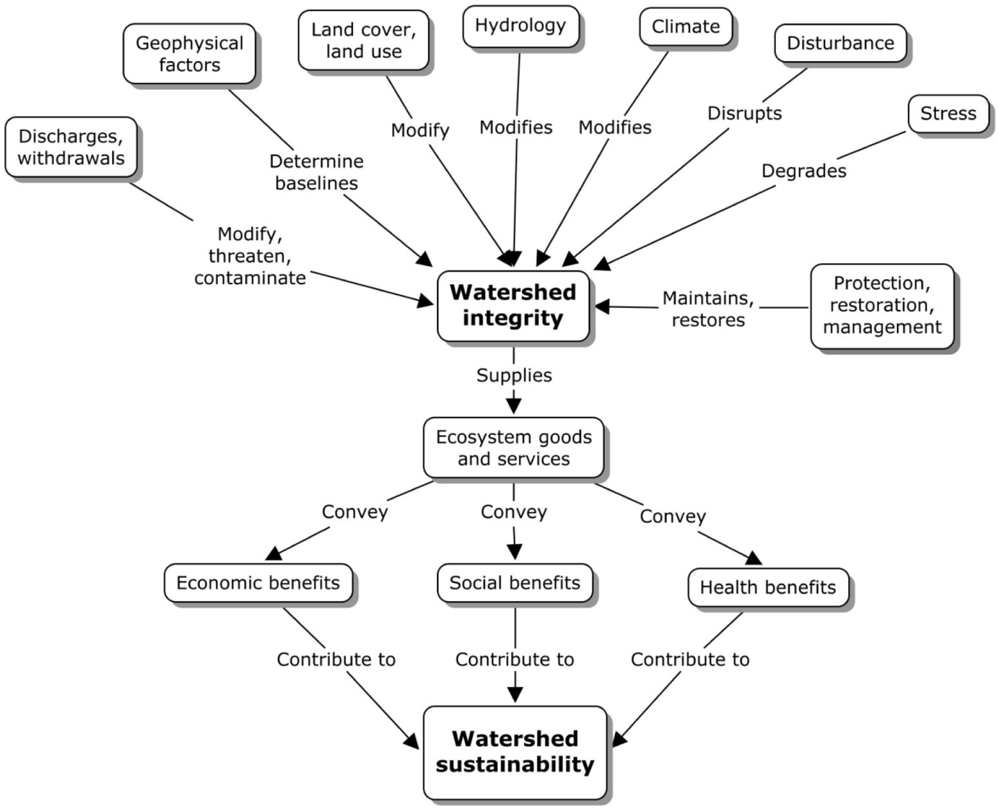

Figure 2. Conceptual model of watershed sustainability in the context of ecological public health. The diagram was constructed with Cmap tools, courtesy of the Florida Institute for Human & Machine Cognition (http://www.ihmc.us/cmaptools.php).

ecological integrity and human well-being: for example, we could explore correlations of health and economic data with the availability and quality of recreational, cultural, and esthetic experiences. It should be possible also to investigate demographic variability in associations across subpopulations, eg, by ethnicity, gender, and income level for considerations of environmental justice. Examples of statistical modeling of these relationships could include functional (regression) analysis of indicators as functions of stressors, multivariate classification and ordination of watersheds and human populations, and Bayesian network analysis. The results could be used to form hypotheses about the mechanisms and causes of associations, which could be tested with additional analysis or experimentally and incorporated into mechanistic models for predictive and diagnostic purposes. The conceptual model depicted in Figure 2 is being considered in planning these studies.

Uncertainty, Complexity, and Other Challenges

Many of the known linkages between human health and the condition of the environment are supported largely by correlational evidence. That is, higher rates of some diseases are observed in the presence of higher exposures to environmental stressors. An example is the epidemiological evidence for illnesses associated with water contact recreation, where exposures are estimated by water contact history, proximity of beaches to pollution sources, and the presence of indicator organisms as surrogates for the pathogens that cause illness.[40] Even when these associations are robust, ie, consistent over time and space, or observed mostly in exposed versus unexposed control groups, they are not fully probative of cause and effect and may be controversial or challenged in the regulatory realm. Therefore, it can be important to establish a greater standard of proof through experimentation and elucidation of causal mechanisms.

Integrating ecosystem services with public health in the context of sustainable watershed management implies that we can derive mechanistic understandings of the relationships between environmental factors and human health, thereby establishing cause and effect. For regulation and management of specific stressors or sources, such a reductionist approach may be both feasible and necessary. However, many environmental concerns, especially at the scale of entire watersheds – where there may be cumulative effects of multiple stressors from multiple sources[41] and a variety of conditions that modify stressor–response relationships – are laden with complexity and uncertainty. Scientific uncertainty about particular issues may result in controversy among scientists, and confusion among nonscientists – for example, the case of the harmful dinoflagellate *Pfiesteria* spp., which raised major concerns for human health and fisheries in Maryland in 1997. These disparities can delay, interfere with, or distort policy decisions.[16]

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Table 1. Examples of data to be integrated for watershed sustainability assessments.

DATA TYPE	EXAMPLE VARIABLES	SELECTED SOURCES OF NATIONAL DATA AND MODELS
Geophysical	Watershed boundaries, soils, geology, land cover, groundwater	USGS[33,34]
Atmosphere & climate	Air temperature, precipitation, air quality, climate change, atmospheric deposition to waters and watersheds	EPA-CMAQ[36]
Physicochemical (water)	Flow, groundwater discharge, temperature, conductivity/salinity, dissolved oxygen, pH, sediment (bedded and suspended), organic matter, contaminant concentrations	EPA,[32] USGS[33]
Pollutant sources	Watershed loads of nutrients, sediment, and toxic chemicals from point and non-point sources	EPA, USGS, USDA; various databases
Biota	Fish, invertebrate, and wildlife communities, contaminant body burdens, harmful algae, pathogens	EPA,[32] USGS[33]
Demographics	Population density; distributions of income, age, ethnicity, gender	US Census[37]
Human health	Cancer, fertility, birth defects, respiratory, gastrointestinal and psychiatric illnesses	CDCP[35]
Economics	Final ecosystem goods and services (production and values), human well-being index	EPA[38,39]

However, when watersheds are viewed as ecosystems, with feedbacks and emergent properties, full mechanistic understanding may be precluded, or less useful than a more holistic systems view.[42] The ecological human health and sustainability paradigms, in combination, should foster policy and management approaches to water resources and watersheds that are more flexible, adaptive, and effective than traditional rigid regulatory regimes, but also compatible with regulation.[43]

There is a need to better understand ecological and human exposures (ie, environmental concentrations and routes of exposure) to chemical and microbial contaminants as precursors to adverse effects.[44,45] Identifying geochemical conditions and other factors that affect contaminant bioavailability is one key question. For example, biological effects of some contaminants vary depending on the pH, alkalinity, hardness, and specific ion concentrations in water,[46] which in turn are determined by interactions of watershed geology and, often, human influences. Moreover, a particular exposure may differ in its effects on different species, individuals, and populations. Establishing relationships between exposures and effects requires weight-of-evidence postulates common to many fields of science.[47,48] Biological plausibility based on detailed mechanistic understanding is also critical in identifying causal relationships between exposures and effects.

The level of certainty that would be derived from defined exposures combined with defined effects and biological plausibility, while a notable goal, may be unrealistic given the uncertainties associated with the integration of ecosystem services and public health. In the real world, multiple exposures and multiple effects are ubiquitous. It is clear that, while the future lies in uncertainty, we must be ever more vigilant in developing sophisticated statistical insights to permit us to use effectively the ever-increasing availability of large data sets, particularly when things (watersheds in this case) have to be ranked or classified.[49]

Vast amounts of environmental, human health, and other relevant data are freely available and continue to accrue at an accelerating rate: for example, continuous remote water quality monitoring by automated sensors, and synoptic monitoring of lakes, reservoirs, and coastal waters by satellites are becoming routine. Nevertheless, integrating data for application to questions of watershed sustainability can be problematic. One important issue is that, although our targets are watersheds, most health and demographic data are classified by political jurisdictions (states, counties, census blocks), which virtually never correspond geographically with watersheds. Significant efforts in geographic analysis will be required to match datasets, eg, for watershed epidemiology investigations. Temporal lags between exposures and effects are another element of complexity; cancers, for example, can develop years or decades after exposures to environmental carcinogens. Further, we may find that some particular types of data strongly applicable to our questions may be sparse, unavailable, or of unsuitable quality. Some effort in primary data collection will be necessary, both to address specific questions and to validate model predictions.

Conclusion

Environmental data, health data, and related research are cumulative over time. We now have the tools (massive computing, geographical information systems) to work with big data, and to take advantage of these opportunities to greatly increase and integrate knowledge of relationships between ecosystems and human health. Understanding and communicating these relationships should lead eventually to greater awareness of the roles watersheds play in human well-being, and hence to better management and stewardship of watersheds and water resources. Watersheds, where human and ecological systems are inseparable, and which hierarchically span several orders of geographic magnitude, are suitable, perhaps ideal, units for applying the ecological public health paradigm.

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Acknowledgments

We thank John Stoddard, Tony Olsen, Steve Paulsen, and other colleagues for some of the concepts discussed in this article. Marty Chintala and Paul Sandifer made helpful comments on an early draft; four anonymous peer reviewers provided constructive comments. The views expressed in this article are those of the authors and do not necessarily reflect the views or policies of the EPA.

Author Contributions

Wrote the first draft of the manuscript: SJJ. Contributed to the writing of the manuscript: SJJ, WHB. Agree with manuscript results and conclusions: SJJ, WHB. Jointly developed the structure and arguments for the paper: SJJ, WHB. Made critical revisions and approved final version: SJJ. Both authors reviewed and approved the final manuscript.

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