Measuring Environmental Sustainability of Water in Watersheds

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Measuring Environmental Sustainability of Water in Watersheds

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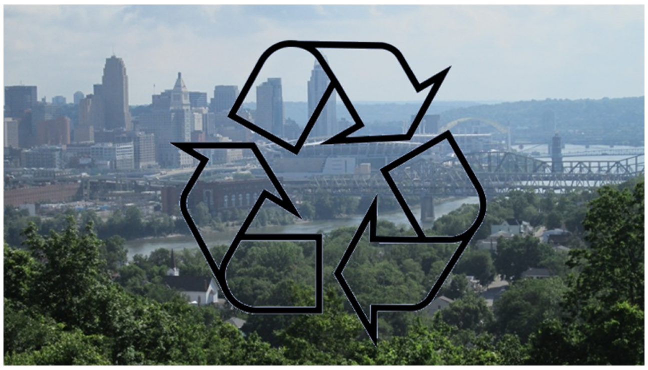

Environmental sustainability assessment is a rapidly growing field where measures of sustainability are used within an assessment framework to evaluate and compare alternative actions. Here we argue for the importance of evaluating environmental sustainability of water at the watershed scale. We review existing frameworks in brief before reviewing watershed-relevant measures in more detail. While existing measures are diverse, overlapping, and interdependent, certain attributes that are important for watersheds are poorly represented, including spatial explicitness and the effect of natural watershed components, such as rivers. Most studies focus on one or a few measures, but a complete assessment will require use of many existing measures, as well as, perhaps, new ones. Increased awareness of the broad dimensions of environmental sustainability as applied to water management should encourage integration of existing approaches into a unified assessment framework appropriate for watersheds.

The concept of environmental sustainability is decades old[1−4] but is increasingly loaded with diverse meanings for scientists, engineers, resource management agencies, and society.[5−7] A wide range of governmental and professional organizations publish information on the topic. The use of sustainability dashboards by organizations and sustainability consultants indicates growing interest. Investments in sustainability research are increasing, for example, the expanding Science, Engineering and Education for Sustainability (SEES) program at the National Science Foundation. In the midst of this exciting but confusing evolution, it is important to critically evaluate how environmental sustainability is measured.

Environmental sustainability exists within a broader sustainability context that includes social and economic sectors.[5,8,9] All sectors or subsystems must ultimately be addressed simultaneously for sustainability to be achieved (Figure 1). In this Feature, we focus on the environmental subsystem, consistent with the focus of *Environmental Science & Technology*, including direct effects of humans on ecosystems and indirect effects of humans on other humans via the environment. For the management of water in watersheds, this entails human activities impacting water quantity or quality that subsequently affects ecosystems and humans. We exclude people affecting each other directly through processes such as financial transactions (economic subsystem) or developing laws (social subsystem) (Figure 1). This constrains our discussion to a coherent and manageable subset of the wide range of measures currently in use. In this article we use the term "measure" to refer to any metric that quantifies some aspect of environmental sustainability. The term "indicator" is also used in the literature,[8,10−12] but not universally,[13,14] and is rarely defined. Thus, in this article we use "measure" as a more encompassing and generic term.

Sustainability assessment is a rapidly growing field where one or more measures are used within an assessment framework to evaluate and compare alternative actions.[10] Although the rigor of the assessment process depends upon a defensible quantification of sustainability, a broad suite of environmental sustainability measures and assessment frameworks is being used with little agreement or standards.[5,15−18] Most existing measures for evaluating water-related environmental sustainability focus on water use at the national level (e.g., ref 19) or impacts on water from product manufacturing or transport (e.g., ref 15). A smaller number of applications have focused on infrastructure such as wastewater treatment plants (e.g., ref 20). Yet the watershed is one of the most fundamental units of analysis for water resources, and we argue that sustainability must be quantified at that level to be useful in decision-making processes that occur at similar scales, such as urban planning. The importance of the watershed scale to sustainability assessment has been acknowledged in only a few recent studies (e.g., refs 11, 21, and 22), and no papers have reviewed the available measures.

In this Feature, we summarize the applicable measures currently in use, categorize them in ways that emphasize their diversity and interdependence, and discuss their relevance to watersheds. Although the diversity of available measures is impressive, indicating that much conceptual work has been done, a concluding goal of this article is to encourage the integration of existing measures into a unified framework for assessing environmental sustainability at the watershed level.

■ ENVIRONMENTAL SUSTAINABILITY ASSESSMENT FRAMEWORKS

Although our focus is on measures of environmental sustainability in watersheds, such measures are generally organized within the context of an assessment framework. We therefore briefly review the existing sustainability assessment frameworks in this section to provide context for reviewing measures in the Environmental Sustainability

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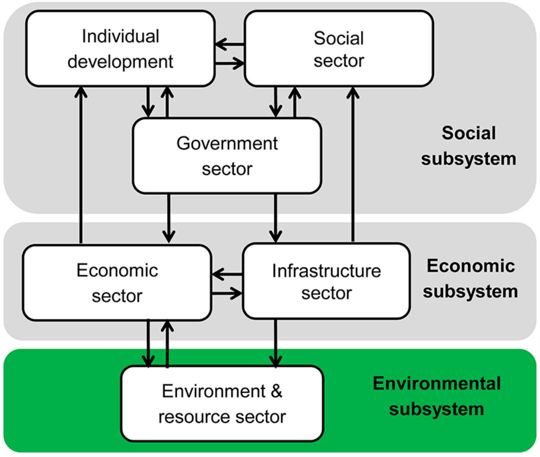

Figure 1. Six sectors of a societal system, and their major interrelationships, with aggregation into the three classic subsystems of sustainability (after ref 8). The focus of this paper, the environmental subsystem, is highlighted in green.

Measures section. The frameworks are not mutually exclusive but overlap in various ways. *Ecological footprint* is a simple accounting tool that measures how much land and water area a human population requires to produce the resources it consumes and to absorb its wastes and compares this to the carrying capacity of the earth.[23] Ecological footprints of activities within a watershed could be compared to the spatial extent of the watershed itself. Ecological footprint is conceptually simple enough that it could also be considered a measure. *Environmental impact assessment* (EIA) evaluates possible environmental impacts of a project or policy.[24] EIA is widely used to incorporate environmental impacts into decisions about proposed projects, and social and economic considerations are frequently included. Many types of impacts (or measures) are typically incorporated, including flooding, hazardous chemicals, and habitat destruction.

Process life-cycle assessment (LCA) evaluates the environmental impact of an activity, typically the manufacture, distribution, and consumption of goods or the provision of services.[15,25] LCA assesses impacts in a cradle-to-grave manner, is widely used, expandable and flexible, and can be comprehensive. The four main stages of LCA include (a) definition of goal and scope to set the system boundary and level of detail, (b) inventory analysis, which compiles detailed input and output data for the system, (c) impact assessment (LCIA) in which environmental significance is assessed, and (d) interpretation in which results are summarized for use in decision making.[26] The LCIA stage typically evaluates a range of impact categories each of which includes one or more indicators or measures of sustainability. LCA generally relates environmental impacts to a process or service rather than studying a geographic area. LCAs have focused on components of a watershed such as drinking water treatment plants (WTPs), wastewater treatment plants (WWTPs), and water reuse schemes (see Non-integrated Measures section and Figure 2). The watershed is also sometimes the unit used to analyze impacts in regional LCIA methods for ecotoxicology, eutrophication or water use.[22,27−29]

Material flow analysis (MFA) typically tracks steady-state flows of a material as it moves through the processes in a system.[30] A typical water-related example involves flows and fates of contaminants that are tracked within industrial or environmental compartments.[31,32] The flows (e.g., pollutant flux) calculated by MFA are measures as discussed further in Environmental Sustainability Measures section. MFA is simpler than LCA and tends to be less complete, often focusing on only a few contaminants and neglecting impacts outside the region

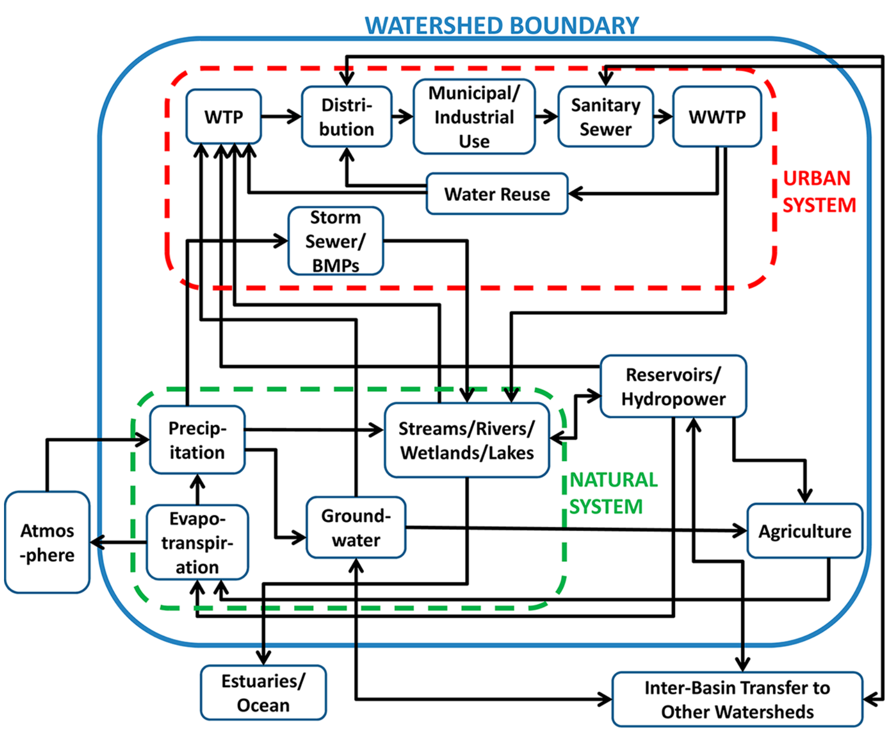

Figure 2. Example components of watershed hydrologic cycle for environmental sustainability assessment. Only major components and connections are shown. WTP = water treatment plant; WWTP = wastewater treatment plant; BMPs = best management practices.

studied. Material budgets for certain compounds (e.g., carbon, nutrients) have been applied to watersheds for decades,[33,34] although not always in the context of sustainability.

Input–output (IO) economic models track flows of goods and services through an economy, together with their unit prices.[35] Basic IO models assume that facilities producing all the products in an economy can be aggregated into a number of industrial sectors, based on standard industrial classification (SIC) codes, and that input–output flows among all sectors are linearly related. These simplifications enable governments to produce IO tables for their economies. If the flows of goods and services are expressed instead as flows of material and energy, and if data on resource requirements and environmental impacts are appended to the IO table, the resulting *economic input–output life cycle assessment* (EIO-LCA) models (http://www.eiolca.net) can be used to make economy-wide life-cycle assessments for any of the goods and services.[36] Similar to process LCA, EIO-LCA typically evaluates several impact categories each of which includes one or more indicators or measures of sustainability. A growing number of IO studies of water withdrawals for human activities have been carried out for the global economy, individual countries, and subregions of countries (e.g., refs 37–39).

System dynamics is very flexible and explicitly represents time and space,[40] capturing elements of dynamic complexity[41] such as feedbacks, time delays, accumulations, and nonlinearities.[42] The generic and readily understandable nature of the influence diagrams enables system dynamics to span disciplinary and organizational boundaries.[43] System dynamics models can simulate highly complex processes[44,45] including social and economic subsystems, provided that appropriate equations and input data to quantify relevant processes are available. Bossel[8] proposed basic orientors for each of the six sectors in Figure 1 that must be satisfied for a system to be sustainable. Various measures are then used to establish whether each of these orientors is satisfied.

ENVIRONMENTAL SUSTAINABILITY MEASURES

In this section we present a range of example measures that could quantify some aspect of environmental sustainability of water management in a watershed, as well as overlapping categories into which the measures can be sorted. We call these categories "dimensions" along which each measure can be arrayed. Our objectives are to emphasize the diversity of measures already in use, create a conceptual organization within which to understand their diversity, and highlight their strengths and weaknesses in the context of watershed management. Most of these measures could be adapted to work within most of the frameworks previously discussed.

Non-integrated Measures. Non-integrated measures quantify some aspect[10] of a watershed. We organize non-integrated measures in terms of several dimensions. For each dimension, we give example measures and cite case studies. We do not focus on issues of practicality, although these obviously need to be addressed. Examples of such practical considerations include measurability, data availability,[11] ease of comprehension by lay audiences,[40] changes in societal values needed to implement them,[40] usability for policy makers,[46] and how explicitly uncertainty is included in assessment.[47]

Components of the Human-Impacted Watershed Hydrologic Cycle. One of the key developments needed to assess environmental sustainability at the watershed level is recognition of, and accounting for, the many components of the hydrologic cycle within a human-impacted watershed (Figure 2). This is important because environmentally harmful human activities may occur in one part of a watershed, while the resulting environmental impact may occur in another. For example, domestic wastewater is generated by humans in homes, schools, and businesses. While the treatment process occurs first and foremost in WWTPs, and also in soils and streams, the effects of this mitigation are felt in downstream water bodies, such as reservoirs and estuaries. Components that have most frequently been assessed for environmental sustainability include urban water infrastructure (e.g., water treatment and water reuse[20,48,49]) and agriculture.[50] Assessing all components will be necessary for a complete assessment of sustainability of a watershed.

Physical, Chemical, and Biological Measures. Most measures relating to water can be categorized as physical, chemical, or biological in nature. Energy, a fourth category, is discussed below under integrated measures. The most commonly used *physical* measure is water use for specific human activities (e.g., product manufacturing, transportation, or mineral extraction;[15,51]) or by groups of people (e.g., geopolitical units or organizations). Water use is typically measured as a volume, and can include water consumed (i.e., lost to easy reuse via evaporation or incorporation into products) and water polluted (i.e., "gray" water).[52,53] Water use is also referred to as "water footprint",[54–56] although the term is nonspatial in contrast to ecological footprint. Water use at the national level includes internal (use of the nation's own water) and virtual (use of another nation's water when their products are imported)[19,57] uses. A related set of physical measures quantify the effect of water use on availability of water for people or ecosystems. For example, reduction of water availability is termed water scarcity.[27]

There are a wide range of water quality (often *chemical*) criteria created by governments (e.g., United States Environmental Protection Agency and European Union) for various pollutants. Many have existed for decades, have driven environmental remediation, and are typically in units of concentration. Pollutant levels can also be summed for a watershed as a total maximum daily load (TMDL) which is an allowable pollutant flux rate.[58] Example compounds include organics, heavy metals, pharmaceuticals, pesticides, and excess nutrients. Some compounds have secondary effects such as acidification by heavy metals and nitrogen oxides.[59] Thermal impacts to water bodies include effects on average temperature, temperature range, and peak temperatures.[60–62]

Biological (or ecological) aspects have many levels of abstraction, all of which can be impacted by humans.[63] Many of the water quality or thermal criteria mentioned earlier are derived from ecotoxicity or mortality studies of individual organisms or populations of organisms (e.g., refs 64 and 65). Many measures exist at the community level, including biodiversity, integrity indices, and indicator species.[66–68] Measures at the ecosystem level include direct effects on primary productivity or biomass (e.g., deforestation effects on detritus loading to streams[69]), as well as indirect effects such as the effect of excess nutrients on biological oxygen demand, dissolved oxygen concentrations, and eutrophication.[50,70] Only a few papers explicitly link these biological measures to sustainability.[71]

The impacts of climate change span physical, chemical, and biological aspects. The most common measure is mass of carbon emitted,[72] which is often called carbon footprint, another nonspatial use of the term footprint. Other measures include changes in atmospheric carbon levels, temperature, sea level, and precipitation.[73] Ultimately physical, chemical, and biological measures must all be included for a complete assessment of environmental sustainability of water in watersheds.

Midpoint versus Endpoint Measures. The terms "midpoint" and "endpoint" come from the LCA lexicon,[26,74] but the concepts are important to any sustainability assessment. Endpoints quantify human impacts on the ultimate concern itself, such as human health impacts, changes in biodiversity, or crop damage. In contrast, midpoints quantify intermediate steps within the environmental cause-effect chain between human actions and the endpoints, and are often focused on emissions of pollutants or extraction of minerals. Common examples of midpoints include global warming potential and eutrophication.[70,74−76] Endpoints have higher relevance than midpoints because they directly quantify human concerns, but they also have lower certainty and more subjectivity.[75,76] Midpoints are more commonly used than endpoints because of better data availability and therefore lower uncertainty. Physical and chemical measures are often midpoints, while biological measures are often endpoints. Environmental risk assessment is one way in which endpoints are calculated (see Integrated Measures section). We recommend moving toward endpoints as available data and methods improve.

Spatially Explicit Measures. A watershed is fundamentally a spatial concept. As a result, the most fundamental requirement of adapting environmental sustainability measures to a watershed is a spatially explicit viewpoint. Yet environmental sustainability assessments are rarely spatially explicit, with the notable exceptions of ecological footprints and national level indicators. Many nonspatial measures, such as pollutant concentration or mass of greenhouse gas emitted, could be made spatial by specifying the location or distribution of two things. First, the location of entities causing impacts can be specified (e.g., location of people that use resources or location of product manufacturing). National level indicators do this at a national spatial scale,[10] although calls have been made for global and individual person/family scales.[40] TMDLs are also spatially explicit because they identify the location of various pollutant sources within the watershed. Second, the location of impacts themselves can be specified, for example the location of pollutants migrating through a watershed or the location of ecological damage in rivers or lakes. TMDLs are spatially explicit in this way as well, because the watershed outlet is defined as the location of concern. A key question for sustainability of watersheds is which of these aspects should be included? For example, should the assessment of a watershed include all the people that live in the watershed? What about the impacts that occur in the watershed because of people living outside the watershed? Regardless of the answer, more comprehensive treatment of the spatial dimension is required for watersheds.

Temporally Explicit Measures. Many watershed processes such as precipitation or streamflow are highly variable in time. Time is also required for water to move through a watershed. Measures of environmental sustainability in this context must therefore account for temporal scales. Most measures can take a static "snapshot" of conditions or processes in past, current (e.g., national level indicators), or future timeframes (e.g., within LCA).[10] In this way, multiple applications of particular measures can determine trends in how human actions change with time and how those changes impact temporal aspects of the environment.

Directional changes to human impacts are consistent trends in one direction, with corresponding trends in environmental sustainability measures. An example is increased use of fertilizer exacerbating downstream eutrophication. Pulse changes are human impacts which are short, intense, and then dissipate. An example is a pulse of nutrients entering a river, which causes the population of an endangered fish species to crash. A third approach examines an increment of a directional change or pulse. Consider a directional change where increases in population lead to increases in flow rate through a WWTP, which lead to increases in energy use. In LCA, one way to quantify the impact of that trend is greenhouse gases emitted per increment of increased flow, in addition to total greenhouse gases emitted for the total flow.

There are important aspects of watershed dynamics that cannot be captured with a series of steady-state "snapshots," for example feedback loops where environmental changes spur changes in human actions.[47] Similarly, human actions not only affect the environment over time but can also affect the temporal characteristics of the environment. For example, humans can impact flows in streams and rivers (environmental flows) in terms of lowest, highest, and average flow; durations of flow; and rate and frequency of changes in flow.[77] All of these measures are relevant to water quality and biota,[78] and generally the closer flows are to their natural state (natural flow regime) the better for the biota.[79]

An important concept relevant to temporal trends is resilience.[17,80,81] Resilience is the ability of a system to recover from change, either directional or pulse, and is also thought of as a measure of sustainability. If resilience is high, then the system will recover, with little change in long-term sustainability. If resilience is low, a permanent decrease in sustainability may result.

Absolute versus Relative Measures. Most of the measures discussed above are absolute without reference to what is considered a sustainable level. Example units of absolute measures are kilograms of greenhouse gases emitted, milligrams per liter of pollutant concentration, and megaliters of water used.[13,16,51] Absolute measures can be used to compare sustainability among planning or engineering alternatives but cannot evaluate how close to sustainability a product or process or region is. To accomplish the latter, absolute measures must be compared to targets, where the target is a sustainable level or value of that measure. This can be expressed as a deviation from a target, which is called a sustainability gap.[5] Targets are less common than absolute measures, because of the difficulty of objectively determining a sustainable level for a given measure. Yet sustainable targets are clearly the preferred approach because targets not only indicate which direction to go to approach sustainability but also how far to go.[40]

Well-established targets include water quality goals (e.g., maximum contaminant levels for water quality in the USA) and biological indices that quantify impairment (or deviation) from sustainable reference conditions (e.g., ref 66). Newer ideas include comparison to available resource levels, for example water use or withdrawal relative to water availability.[15] Ecological footprints similarly compare requirements to available space, for example, the area of forest needed to offset carbon emissions. A final example is water use as a fraction of rainfall.[21]

Integrated Measures. Integrated measures combine different non-integrated measures (Non-integrated Measures section)[10] for a more complete accounting of sustainability. Integration requires adding or comparing measures with different units or scales, thus requiring a "common currency". Non-integrated measures are simpler and easier to use, yet a holistic view of sustainability can only be achieved with integrated measures. Example integrated measures include the Environmental Performance Index,[82] Environmental Sustainability Index, and Canadian Water Sustainability Index.[83,84] In this section we list the major common currencies in use.

Monetary valuation estimates the cash value of goods and services that are not normally priced in the marketplace, including processes, such as natural pollutant removal in wetlands, or entities, such as an endangered species. Measures include contingent valuation, travel cost, hedonic pricing, factor income, avoided cost, and replacement cost.[85]

Energy, needed for all human activities, is a measure of resource extraction and consumption[86] and is typically measured in joules or kilowatt-hours. Examples include energy used for water distribution or treatment [87] or other urban infrastructure.[14] Exergy is the fraction of energy available for useful work, while emergy is the amount of exergy used to produce a product.[88,89] The direct externalities of energy production can also be measured, such as mass of greenhouse gas or carbon emitted.[87,90] *Mass* of materials other than greenhouse gases is encountered more rarely but can be used to integrate impacts in LCA.[91]

Risk is the probability of a negative event. Environmental risk is the probability that death or disease will occur, averaged across a population. Such risks are calculated for exposure of humans or other organisms to chemicals at certain locations, compared among contaminants, and summed to a cumulative risk as part of an environmental risk assessment (ERA).[49,74] Although ERA is a common application of risk integration, risk is a generic concept that can be calculated for any environmental impact, compared among impacts or activities, and summed.

Integration in LCA is partly achieved by endpoint modeling to compare impacts for the same area of protection (human health, ecosystem quality, or resources).[92] Further integration is called normalization or weighting.[26,74] Indicator values are integrated, either within an impact category (e.g., different greenhouse gases are converted to kilograms of CO_2-equivalent) or across impact categories, generally by calculating per capita impact (i.e., person-equivalents).[12,76,93] Weighting factors can be included to express priority among different indicators or impact categories.

MEASURING ENVIRONMENTAL SUSTAINABILITY OF WATER IN WATERSHEDS

Although environmental sustainability assessments have generally not focused on watersheds, the relevant measures are diverse, collectively addressing a variety of important dimensions (Figure 3). Nevertheless, some key attributes necessary for a rigorous assessment of environmental sustainability of water management are not well-represented among existing measures. For example, spatial explicitness is relatively rare, with common measures, such as water footprint often entailing a simple volume of water used. Temporal explicitness is also relatively uncommon, with notable exceptions in the areas of environmental flow regimes. Finally, inclusion of all important watershed components in an environmental sustainability assessment has not occurred, with the effects of processes occurring in natural waterways (e.g., pollutant attenuation functions of streams) among those most frequently omitted.

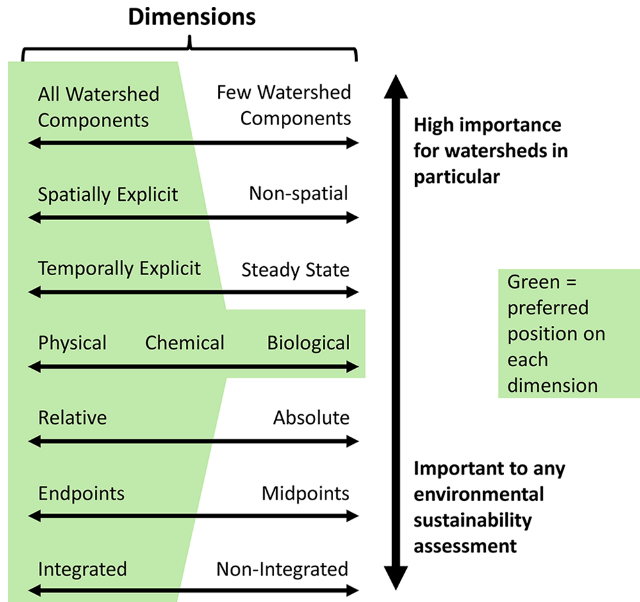

Figure 3. Conceptual diagram showing relative importance of the various dimensions of environmental sustainability measures in the context of watershed water management. Horizontal arrows represent dimensions of measures discussed in the Environmental Sustainability Measures section. Green area indicates position along each dimension that is required or preferred for application to watersheds.

We note that most of the papers cited here suggest that the particular measures they use quantify at least an important part of environmental sustainability (e.g., water use, energy use, pollutants emitted, biodiversity lost). Yet if many authors believe they are quantifying important aspects of environmental sustainability but are in fact measuring different things, the individual measures must be incomplete. We believe that most of the proposed measures quantify important aspects of sustainability, but are interdependent and complementary. A complete assessment of environmental sustainability will therefore require the simultaneous use of many existing measures, in turn requiring integration of measures using "common currencies". New measures may need to be devised, particularly those relative to sustainable endpoints. All measures must ultimately be related to and fully address the more fundamental orientors of sustainability, such as those proposed by Bossel.[8]

Determining whether a particular measure is valid for objectively evaluating a given subsector of the environment also requires assessing all six sectors of a societal system (Figure 1). In other words, a full view of the "forest" of measures is needed before the validity of an individual measure or "tree" can be established. A critical area for research is therefore integrating and further developing existing approaches into a unified and comprehensive approach.

We hope to foster growing awareness of the importance of assessing environmental sustainability questions at the watershed scale. The California Regional Water Quality Control Boards already divide their territory geographically based on watersheds, and this approach could be extended to other states, as well as other environmentally related regulatory arenas (e.g., dam regulation, power generation, and fish and game). Increased awareness of the broad range of interdependent measures of environmental sustainability may encourage crafting of more comprehensive guidance for sustainability assessment. This would clarify important knowledge gaps for researchers in terms of feedbacks between human activities and environmental, social, and economic aspects of sustainability.

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Notes

The authors declare no competing financial interest.

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Dr. John Little is Charles Edward Via, Jr. Professor in the Department of Civil and Environmental Engineering at Virginia Tech. His primary interests are cross-media mass transfer and process dynamics in environmental systems, with emerging areas of interest including interdisciplinary and sustainable systems research. Dr. Little serves as Chair of the International Water Association Specialist Group on Lake and Reservoir Management and teaches a new course titled "Engineering Solutions for Environmental Sustainability".

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■ REFERENCES

(1) Goodland, R. The concept of environmental sustainability. *Annu. Rev. Ecol. Syst.* **1995**, *26*, 1−24.

(2) Tilman, D. Global environmental impacts of agricultural expansion: The need for sustainable and efficient practices. *Proc. Natl. Acad. Sci. U.S.A.* **1999**, *96* (11), 5995−6000.

(3) Foy, G. Economic sustainability and the preservation of environemental assets. *Environ. Manage.* **1990**, *14* (6), 771−778.

(4) Vanpelt, M. J. F.; Kuyvenhoven, A.; Nijkamp, P. Environmental sustainability—Issues of definition and measurement. *Int. J. Environ. Pollut.* **1995**, *5* (2−3), 204−223.

(5) Moldan, B.; Janouskova, S.; Hak, T. How to understand and measure environmental sustainability: Indicators and targets. *Ecol. Indic.* **2012**, *17*, 4−13.

(6) Xu, M.; Weissburg, M.; Newell, J. P.; Crittenden, J. C. Developing a science of infrastructure ecology for sustainable urban systems. *Environ. Sci. Technol.* **2012**, *46* (15), 7928−7929.

(7) Grant, S. B.; Saphores, J. D.; Feldman, D. L.; Hamilton, A. J.; Fletcher, T. D.; Cook, P. L. M.; Stewardson, M.; Sanders, B. F.; Levin, L. A.; Ambrose, R. F.; Deletic, A.; Brown, R.; Jiang, S. C.; Rosso, D.; Cooper, W. J.; Marusic, I. Taking the "waste" out of "wastewater" for human water security and ecosystem sustainability. *Science* **2012**, *337* (6095), 681−686.

(8) Bossel, H. *Systems and Models: Complexity, Dynamics, Evolution, Sustainability*; Books on Demand: Norderstedt, Germany. 2007.

(9) Andre, E. Beyond hydrology in the sustainability assessment of dams: A planners perspective—The Sarawak experience. *J. Hydrol.* **2012**, *412*, 246−255.

(10) Ness, B.; Urbel-Piirsalu, E.; Anderberg, S.; Olsson, L. Categorising tools for sustainability assessment. *Ecol. Econ.* **2007**, *60* (3), 498−508.

(11) Kang, M. G.; Lee, G. M. Multicriteria evaluation of water resources sustainability in the context of watershed management. *J. Am. Water Resour. Assoc.* **2011**, *47* (4), 813−827.

(12) Owens, J. W. Water resources in life-cycle impact assessment: considerations in choosing category indicators. *J. Ind. Ecol.* **2001**, *5* (2), 37−54.

(13) Kaufman, S. M.; Krishnan, N.; Themelis, N. J. A screening life cycle metric to benchmark the environmental sustainability of waste management systems. *Environ. Sci. Technol.* **2010**, *44* (15), 5949−5955.

(14) Spatari, S.; Yu, Z. W.; Montalto, F. A. Life cycle implications of urban green infrastructure. *Environ. Pollut.* **2011**, *159* (8−9), 2174−2179.

(15) Berger, M.; Finkbeiner, M. Water footprinting: How to address water use in life cycle assessment? *Sustainability* **2010**, *2*, 919−944.

(16) Williams, P. R. D.; Inman, D.; Aden, A.; Heath, G. A. Environmental and sustainability factors associated with next-generation biofuels in the U.S.: What do we really know? *Environ. Sci. Technol.* **2009**, *43* (13), 4763−4775.

(17) Sarang, A.; Vahedi, A.; Shamsai, A. How to quantify sustainable development: A risk-based approach to water quality management. *Environ. Manage.* **2008**, *41* (2), 200−220.

(18) Tabone, M. D.; Cregg, J. J.; Beckman, E. J.; Landis, A. E. Sustainability metrics: Life cycle assessment and green design in polymers. *Environ. Sci. Technol.* **2010**, *44* (21), 8264−8269.

(19) Carr, J.; D'Odorico, P. Inequalities in the networks of virtual water flow. *EOS, Trans. Am. Geophys. Union* **2012**, *93* (32), 309−310.

(20) Munoz, I.; Rodriguez, A.; Rosal, R.; Fernandez-Alba, A. R. Life cycle assessment of urban wastewater reuse with ozonation as tertiary treatment: A focus on toxicity-related impacts. *Sci. Total Environ.* **2009**, *407* (4), 1245−1256.

(21) Mencio, A.; Folch, A.; Mas-Pla, J. Analyzing hydrological sustainability through water balance. *Environ. Manage.* **2010**, *45* (5), 1175−1190.

(22) Pfister, S.; Koehler, A.; Hellweg, S. Assessing the environmental impacts of freshwater consumption in LCA. *Environ. Sci. Technol.* **2009**, *43* (11), 4098−4104.

(23) Wackernagel, M.; Rees, W. *Our Ecological Footprint: Reducing Human Impact on the Earth*; New Society Publishers: Stony Creek, CT, 1996.

(24) Anjaneyulu, Y.; Manickam, V. *Environmental Impact Assessment Methodologies*, 2nd ed.; CRC Press: Boca Raton, FL, 2011.

(25) Graedel, T. E.; Allenby, B. R. *Industrial Ecology and Sustainable Engineering*; Prentice Hall: Upper Saddle River, NJ, 2010.

(26) ISO. *Environmental Management—Life Cycle Assessment—Principles and Framework*; International Standard 14040, 2nd ed., 2006-07-01; International Standards Organization: Geneva, Switzerland, 2006.

(27) Boulay, A. M.; Bulle, C.; Bayart, J. B.; Deschenes, L.; Margni, M. Regional characterization of freshwater use in LCA: Modeling direct impacts on human health. *Environ. Sci. Technol.* **2011**, *45* (20), 8948−8957.

(28) Helmes, R. J. K.; Huijbregts, M. A. J.; Henderson, A. D.; Jolliet, O. Spatially explicit fate factors of phosphorous emissions to freshwater at the global scale. *Int. J. Life Cycle Assess.* **2012**, *17* (5), 646−654.

(29) Humbert, S.; Manneh, R.; Shaked, S.; Wannaz, C.; Horvath, A.; Deschenes, L.; Jolliet, O.; Margni, M. Assessing regional intake fractions in North America. *Sci. Total Environ.* **2009**, *407* (17), 4812−4820.

(30) Rechberger, H. *Practical Handbook of Material Flow Analysis*; Lewis Publishers: Boca Raton, FL, 2007.
(31) Montangero, A.; Belevi, H. An approach to optimize nutrient management in environmental sanitation systems despite limited data. *J. Environ. Manage.* **2008**, *88* (4), 1538−1551.
(32) Lindqvist, A.; von Malmborg, F. What can we learn from local substance flow analyses? - The review of cadmium flows in Swedish municipalities. *J. Cleaner Prod.* **2004**, *12* (8−10), 909−918.
(33) Fisher, S. G.; Likens, G. E. Energy flow in Bear Brook, New Hampshire: An integrative approach to ecoystem metabolism. *Ecol. Monogr.* **1973**, *43*, 421−439.
(34) Bormann, F. H.; Likens, G. E.; Siccama, T. G.; Pierce, R. S.; Eaton, J. S. The export of nutrients and recovery of stable conditions following deforestation at Hubbard Brook. *Ecol.Monogr.* **1974**, *44*, 255−277.
(35) Duchin, F. Input−output economics and material flows. In *Handbook of Input−Output Economics in Industrial Ecology*; Suh, S., Ed.; Springer Science+Business Media B.V: Dordrecht, the Netherlands, 2009.
(36) Hendrickson, C. T.; Lave, L. B.; Matthews, H. S. *Environmental Life Cycle Assessment of Goods and Services—An Input−Output Approach*; Resources for the Future: Washington, DC, 2006.
(37) Lopez-Morales, C.; Duchin, F. Policies and technologies for a sustainable use of water in Mexico: A scenario analysis. *Econ. Syst. Res.* **2011**, *23* (4), 387−407.
(38) Hubacek, K.; Sun, L. X. Economic and societal changes in China and their effects on water use—A scenario analysis. *J. Ind. Ecol.* **2005**, *9* (1−2), 187−200.
(39) Lenzen, M.; Foran, B. An input−output analysis of Australian water use. *Water Policy* **2001**, *3*, 321−340.
(40) Dahl, A. L. Achievements and gaps in indicators for sustainability. *Ecol. Indic.* **2012**, *17*, 14−19.
(41) Meadows, D. H. *Thinking in Systems—A Primer*; Wright, D., Ed. ; Sustainability Institute, Chelsea Green Publishing Company: White River Junction, VT, U.S.A., 2008.
(42) Sterman, J. D. *Business Dynamics: Systems Thinking and Modeling for a Complex World*; Irwin McGraw Hill: Boston, MA, U.S.A., 2000.
(43) Sterman, J. D. Sustaining Sustainability: Creating a Systems Science in a Fragmented Academy and Polarized World. In *Sustainability Science: The Emerging Paradigm and the Urban Environment*; Weinstein, M., Turner, R. E., Eds.; Springer: New York, 2012.
(44) Sterman, J.; Fiddaman, T.; Franck, T.; Jones, A.; McCauley, S.; Rice, P.; Sawin, E.; Siegel, L. Climate interactive: the C-ROADS climate policy model. *Syst. Dyn. Rev.* **2012**, *28* (3), 295−305.
(45) Fiddaman, T.; Siegel, L.; Sawin, E.; Jones, A. P.; Sterman, J. C-ROADS Simulator Reference Guide, 2012. http://www.climateinteractive.org/simulations/C-ROADS/technical/technical-reference/C-ROADS%20simulation%20reference%20guide%20.
(46) Bauler, T. An analytical framework to discuss the usability of (environmental) indicators for policy. *Ecol. Indic.* **2012**, *17*, 38−45.
(47) McKone, T. E.; Nazaroff, W. W.; Berck, P.; Auffhammer, M.; Lipman, T.; Torn, M. S.; Masanet, E.; Lobscheid, A.; Santero, N.; Mishra, U.; Barrett, A.; Bomberg, M.; Fingerman, K.; Scown, C.; Strogen, B.; Horvath, A. Grand challenges for life-cycle assessment of biofuels. *Environ. Sci. Technol.* **2011**, *45* (5), 1751−1756.
(48) Godskesen, B.; Zambrano, K. C.; Trautner, A.; Johansen, N. B.; Thiesson, L.; Andersen, L.; Clauson-Kaas, J.; Neidel, T. L.; Rygaard, M.; Kloverpris, N. H.; Albrechtsen, H. J. Life cycle assessment of three water systems in Copenhagen-a management tool of the future. *Water Sci. Technol.* **2011**, *63* (3), 565−572.
(49) Chen, Z.; Ngo, H. H.; Guo, W. S. A critical review on sustainability assessment of recycled water schemes. *Sci. Total Environ.* **2012**, *426*, 13−31.
(50) Bartl, K.; Verones, F.; Hellweg, S. Life cycle assessment based evaluation of regional impacts from agricultural production at the Peruvian coast. *Environ. Sci. Technol.* **2012**, *46* (18), 9872−9880.
(51) Mudd, G. M. Global trends in gold mining: Towards quantifying environmental and resource sustainability? *Resour. Policy* **2007**, *32* (1−2), 42−56.
(52) Koehler, A. Water use in LCA: managing the planet's freshwater resources. *International Journal of Life Cycle Assessment* **2008**, *13* (6), 451−455.
(53) Mekonnen, M. M.; Hoekstra, A. Y. The green, blue and grey water footprint of crops and derived crop products. *Hydrol. Earth Syst. Sci.* **2011**, *15* (5), 1577−1600.
(54) Hoekstra, A. Y. *Water Neutral: Reducing and Offsetting the Impacts of Water Footprints*, Value of Water Research Report Series No. 28; UNESCO-IHE: Delft, the Netherlands, 2008.
(55) Cucek, L.; Klemes, J. J.; Kravanja, Z. A review of footprint analysis tools for monitoring impacts on sustainability. *J. Cleaner Prod.* **2012**, *34*, 9−20.
(56) Yu, Y.; Hubacek, K.; Feng, K. S.; Guan, D. B. Assessing regional and global water footprints for the U.K. *Ecol. Econ.* **2010**, *69* (5), 1140−1147.
(57) Allan, J. A. Virtual water: A strategic resource global solutions to regional deficits. *Ground Water* **1998**, *36* (4), 545−546.
(58) U.S. EPA. Impaired Waters and Total Maximum Daily Loads. United States Environmental Protection Website. http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/index.cfm (accessed January 3, 2013).
(59) Miller, G. T. *Living in the Environment: Principles, Connections, and Solutions*, 15th ed.; Brookes/Cole: Belmont, CA, 2007.
(60) Verones, F.; Hanafiah, M. M.; Pfister, S.; Huijbregts, M. A. J.; Pelletier, G. J.; Koehler, A. Characterization factors for thermal pollution in freshwater aquatic environments. *Environ. Sci. Technol.* **2010**, *44* (24), 9364−9369.
(61) Hester, E. T.; Doyle, M. W. Human impacts to river temperature and their effects on biological processes: a quantitative synthesis. *J. Am. Water Resour. Assoc.* **2011**, *47* (3), 571−587.
(62) Hester, E. T.; Bauman, K. Stream and retention pond thermal response to heated summer runoff from urban impervious surfaces. *J. Am. Water Resour. Assoc.* **2013**, *49* (2), 328−342.
(63) Death, R. G.; Dewson, Z. S.; James, A. B. W. Is structure or function a better measure of the effects of water abstraction on ecosystem integrity? *Freshwater Biol.* **2009**, *54* (10), 2037−2050.
(64) Ferrari, B.; Paxeus, N.; Lo Giudice, R.; Pollio, A.; Garric, J. Ecotoxicological impact of pharmaceuticals found in treated wastewaters: study of carbamazepine, clofibric acid, and diclofenac. *Ecotoxicol. Environ. Saf.* **2003**, *55* (3), 359−370.
(65) Hokanson, K. E. F.; Kleiner, C. F.; Thorslund, T. W. Effects of constant temperatures and Diel temperature-fluctuations on specific growth and mortality-rates and yield of juvenile rainbow-trout, Salmo-Gairdneri. *J. Fish. Res. Board Can.* **1977**, *34* (5), 639−648.
(66) U.S. EPA. *Rapid Bioassessment Protocols for Use in Wadeable Streams and Rivers*, EPA 841-B-99-002; U.S. Environmental Protection Agency, Office of Water: Washington, DC, 1999.
(67) Fausch, K. D.; Karr, J. R.; Yant, P. R. Regional application of an index of biotic integrity based on stream fish communities. *Trans. Am. Fish. Soc.* **1984**, *113* (1), 39−55.
(68) Kerans, B. L.; Karr, J. R. A benthic index of biotic integrity (B-IBI) for rivers of the Tennessee Valley. *Ecol. Appl.* **1994**, *4* (4), 768−785.
(69) Benstead, J. P.; Douglas, M. M.; Pringle, C. M. Relationships of stream invertebrate communities to deforestation in eastern Madagascar. *Ecol. Appl.* **2003**, *13* (5), 1473−1490.
(70) Struijs, J.; Beusen, A.; de Zwart, D.; Huijbregts, M. Characterization factors for inland water eutrophication at the damage level in life cycle impact assessment. *Int. J. Life Cycle Assess.* **2011**, *16* (1), 59−64.
(71) Doran, J. W.; Zeiss, M. R. Soil health and sustainability: managing the biotic component of soil quality. *Appl. Soil Ecol.* **2000**, *15* (1), 3−11.
(72) Hertwich, E. G.; Peters, G. P. Carbon footprint of nations: A global, trade-linked analysis. *Environ. Sci. Technol.* **2009**, *43* (16), 6414−6420.
(73) Solomon, S.; Plattner, G. K.; Knutti, R.; Friedlingstein, P. Irreversible climate change due to carbon dioxide emissions. *Proc. Natl. Acad. Sci. U.S.A.* **2009**, *106* (6), 1704−1709.

(74) U.S. EPA. *Life Cycle Assessment: Principles and Practice*, EPA/600/R-06/060; National Risk Management Research Laboratroy, Office of Research and Development. U.S. Environmental Protection Agency; Cincinnati, OH, 2006.
(75) Bare, J. C.; Hofstetter, P.; Pennington, D. W.; Haes, H. Midpoints versus endpoints: The sacrifices and benefits. *Int. J. Life Cycle Assess.* **2000**, *5* (6), 319−326.
(76) Guinée, J. B. *Life Cycle Assessment: An Operational Guide to the ISO Standards*, Final Report, May 2001; ISO: Geneva, Switzerland, 2001.
(77) Richter, B. D.; Baumgartner, J. V.; Powell, J.; Braun, D. P. A method for assessing hydrologic alteration within ecosystems. *Conserv. Biol.* **1996**, *10* (4), 1163−1174.
(78) Doyle, M. W. Incorporating hydrologic variability into nutrient spiraling. *J. Geophys. Res.: Biogeosci.* **2005**, *110*, G1.
(79) Poff, N. L.; Allan, J. D.; Bain, M. B.; Karr, J. R.; Prestegaard, K. L.; Richter, B. D.; Sparks, R. E.; Stromberg, J. C. The natural flow regime. *Bioscience* **1997**, *47* (11), 769−784.
(80) Loucks, D. P. Quantifying trends in system sustainability. *Hydrol. Sci. J.* **1997**, *42* (4), 513−530.
(81) Chapin, F. S.; Zavaleta, E. S.; Eviner, V. T.; Naylor, R. L.; Vitousek, P. M.; Reynolds, H. L.; Hooper, D. U.; Lavorel, S.; Sala, O. E.; Hobbie, S. E.; Mack, M. C.; Diaz, S. Consequences of changing biodiversity. *Nature* **2000**, *405* (6783), 234−242.
(82) Emerson, J. *Environmental Performance Index*; Yale Center for Environmental Law and Policy: New Haven, CT, 2010.
(83) Esty, D. C.; Levy, M.; Srebotnjak, T.; de Sherbinin, A. *2005 Environmental Sustainability Index: Benchmarking National Environmental Stewardship*; Yale Center for Environmental Law & Policy: New Haven, CT, 2005.
(84) GC PRI. *Canadian Water Sustainability Index (CWSI): Project Report*; Government of Canada, Policy Research Initiative (GC PRI): Ottawa, Canada, 2007.
(85) Pearce, D.; Turner, K.; Bateman, I. *Environmental Economics*; Harvester Weatsheaf: London, 1994.
(86) Bakshi, B. R.; Gutowski, T. G.; Sekulic, D. P. *Thermodynamics and the Destruction of Resources*; Cambridge University Press: New York, NY, 2011.
(87) Sahely, H. R.; Kennedy, C. A. Water use model for quantifying environmental and economic sustainability indicators. *J. Water Resour. Plan. Manage.* **2007**, *133* (6), 550−559.
(88) Yi, H. S.; Hau, J. L.; Ukidwe, N. U.; Bakshi, B. R. Hierarchical thermodynamic metrics for evaluating the environmental sustainability of industrial processes. *Environ. Prog.* **2004**, *23* (4), 302−314.
(89) Rugani, B.; Benetto, E. Improvements to energy evaluations by using life cycle assessment. *Environ. Sci. Technol.* **2012**, *46* (9), 4701−4712.
(90) Laurent, A.; Olsen, S. I.; Hauschild, M. Z. Limitations of Carbon Footprint as Indicator of Environmental Sustainability. *Environ. Sci. Technol.* **2012**, *46* (7), 4100−4108.
(91) The Ohio State University Center for Resilience, ECO-LCA Frequently Asked Questions. 2009. http://resilience.eng.ohio-state.edu/eco-lca/faq.htm (accessed 10−09−2012).
(92) Jolliet, O.; Muller-Wenk, R.; Bare, J.; Brent, A.; Goedkoop, M.; Heijungs, R.; Itsubo, N.; Pena, C.; Pennington, D.; Potting, J.; Rebitzer, G.; Stewart, M.; de Haes, H. U.; Weidema, B. The LCIA midpoint-damage framework of the UNEP/SETAC life cycle initiative. *Int. J. Life Cycle Assess.* **2004**, *9* (6), 394−404.
(93) Sleeswijk, A. W.; van Oers, L.; Guinee, J. B.; Struijs, J.; Huijbregts, M. A. J. Normalisation in product life cycle assessment: An LCA of the global and European economic systems in the year 2000. *Sci. Total Environ.* **2008**, *390* (1), 227−240.