
Sustainable management of urban watersheds: a system-of-systems approach

La gestion durable des bassins versants : une approche 'systèmes de systèmes'

John C. Little, Erich T. Hester, and Adil Godrej

Environmental and Water Resources Engineering Program, Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, Virginia, USA
(jcl@vt.edu)

RÉSUMÉ

On reconnaît de plus en plus clairement la nécessité d'une approche systématisée dans l'évaluation de la durabilité. Cette prise de conscience est due au fait que l'on doit pouvoir intégrer ou associer un large éventail de systèmes, y compris, par exemple, l'eau, l'énergie, l'air, la terre, le climat, l'agriculture, la pêche, la sylviculture, l'exploitation minière et l'extraction des ressources, les transports, les milieux urbains, la santé des personnes, les écosystèmes naturels, mais aussi d'autres systèmes économiques et sociaux. Nous illustrons le développement du cadre commun proposé en utilisant le modèle du bassin versant d'Occoquan qui est le premier d'une série de modules, et en mettant en valeur certains aspects environnementaux de la durabilité. Nous nous concentrons sur les orientations et les indicateurs qui se rapportent à la quantité ou la qualité de l'eau, et sur leurs effets sur les systèmes humains et les écosystèmes. Les caractéristiques essentielles du modèle de bassin versant sont mesurées au niveau de systèmes où un ensemble d'orientations et d'indicateurs à une échelle adéquate sont employés pour évaluer et améliorer la durabilité environnementale. Le développement d'une approche uniforme permettant d'évaluer et d'améliorer la durabilité est un défi de taille, qui peut prendre des décennies, mais l'objectif même de parvenir à la durabilité se jouera peut-être dans des délais similaires, et l'on pourrait gagner énormément en travaillant à la mise en place d'un cadre interdisciplinaire commun.

ABSTRACT

There is growing recognition of the need for a systems approach when evaluating sustainability. This arises because of the need to integrate or couple a wide range of systems, including, for example, water, energy, air, land, climate, agriculture, fishing, forestry, mining and resource extraction, transportation, urban environment, human health, natural ecosystems, as well as other economic and social systems. We illustrate the development of the proposed common framework using the Occoquan watershed model as the first in a series of modules, and emphasizing environmental aspects of sustainability. We concentrate on orientors and indicators that relate to water quantity or quality, and their effects on human systems and ecosystems. The essential features of the process level watershed model are up-scaled to the systems level where an appropriately scaled set of orientors and indicators are used to assess and enhance environmental sustainability. The development of a unifying approach for assessing and enhancing sustainability is a daunting challenge that may take decades, but the goal of achieving sustainability will itself play out over similar timescales, and much could be gained by working toward a common interdisciplinary framework.

KEYWORDS

Catchment, Model, Sustainability, Systems, Watershed

1 INTRODUCTION AND OBJECTIVES

While sustainability is an essential concept to ensure the future of humanity and the integrity of the resources and ecosystems on which we depend, identifying a comprehensive yet realistic way to assess and enhance sustainability may be one of the most difficult challenges of our time. In recent decades, there have been numerous reviews focusing on sustainability and sustainable development, including those that analyze the development of sustainability science and those that evaluate the various frameworks, indicators, tools, approaches, methods and schemes (which we collectively refer to as approaches) used to assess sustainability. In a recent conceptual review [1] we evaluated these approaches, including adaptive management, eco-efficiency analysis, ecological footprint, economic input-output life-cycle assessment, green accounting, green chemistry, green engineering, indicators, industrial metabolism, input-output models, integrated assessment, integrated indicators, material flow analysis, orientors, process life-cycle assessment, planetary boundaries, rating systems, resilience, scenarios, and whole-system design. We also identified the collective limitations of the approaches, showing that there is not a consistent definition of sustainability, that the approaches are generally not comprehensive and are subject to unintended consequences, and that there is little to no connection between bottom-up and top-down approaches. To overcome these challenges, we propose a unified, system-of-systems approach that is causal, modular, tiered and scalable.

The development of a unifying approach for assessing and enhancing sustainability is a daunting challenge that may take decades, but the goal of achieving sustainability will itself play out over similar timescales, and much could be gained by working toward a common interdisciplinary framework [2]. In this paper, we propose a common framework for assessing and enhancing sustainability using a system-of-systems approach. We illustrate the framework using the Occoquan watershed model [3] as the first in a series of modules or systems, and emphasizing environmental aspects of sustainability.

2 APPROACH

There is growing recognition of the need for a systems approach when evaluating sustainability [4-6]. This arises because of the need to integrate or couple a wide range of systems, for example water, energy, air, land, ocean, climate, agriculture, fishing, forestry, mining and resource extraction, transportation, urban environment, human health, natural ecosystems, as well as other economic and social systems. Unfortunately, it is often the case that the complexity of the systems in which we are embedded overwhelms our ability to understand them [7]. Complex systems are constantly changing, tightly coupled, governed by feedbacks, nonlinear, history-dependent, self-organizing, adaptive and evolving, characterized by trade-offs, and counterintuitive [7]. As a result, many seemingly obvious solutions to problems fail or actually worsen the situation [7], causing unintended consequences. While mathematical models that are based on causal relationships may have substantial uncertainty, and may be subject to chaotic, nonlinear behavior, they represent our best hope when trying to understand complex systems. The coupling of many systems in a modular fashion (see Figure 1) would be greatly facilitated if there was a common, systems-level computational language which is sufficiently generic to represent and couple a wide range of processes at the systems level. System dynamics models [7] provide a good starting point as they are already being used extensively in evaluating the sustainability of natural, social and engineered systems [1], have no size restriction, and are essentially only limited by data availability and computational feasibility.

Although the Brundtland definition of sustainability [8] is widely accepted, it lacks specificity. In reality, the definition of sustainability is currently determined by the specific combination of assessment framework and/or indicators that are used, and these vary widely [1]. To allow sustainability to be assessed over a wide range of coupled systems, the definition of sustainability must be applied in a comprehensive fashion [9]. Bossel [10] proposed that the sustainability of autonomous, self-organizing systems (which include both ecosystems and human systems) is completely determined by several basic orientors, including existence, effectiveness, security, adaptability, coexistence, and in the case of human systems, freedom of action, and psychological needs. One advantage of this definition is that it treats human systems and natural systems in an equivalent fashion. The basic orientors are abstract, but are translated into more pragmatic operational orientors. Then, sustainability is assessed by comparing the operational orientors (which reflect the desired state of the system) to specific indicators or integrated indicators (which reflect the actual state of the system) and evaluating the extent of orientor satisfaction, with each orientor requiring a minimum level of satisfaction for the system to be considered sustainable.

A system-of-systems approach that couples a wide range of environmental, economic and social systems is needed to assess and enhance sustainability. Interestingly, a simplified systems approach is already being implemented by the climate change community, with integrated assessment models that include key features of human systems, such as demography, energy use, technology, the economy, agriculture, forestry and land use [11]. These models incorporate simplified representations of the climate system and are calibrated against more complex climate models. The models are used to develop emissions scenarios, simulate feedbacks, estimate the potential economic impacts of climate change, evaluate the costs and benefits of mitigation, and evaluate uncertainties [11]. The development of these integrated assessment models involve two conceptual steps – the first being the creation of reduced-order models from more complex ones, also known as “up-scaling,” and the second being the coupling of the “up-scaled” components using a common computational language. The required characteristics of this common language are not completely clear, but are coming into focus. For example, Kelly et al. [12] reviewed five approaches for modeling complex systems including system dynamics, Bayesian networks, coupled component models (which are assembled from a variety of different components), agent-based models and knowledge-based models (also known as expert systems) and mentioned the possibility of a hybrid approach [12].

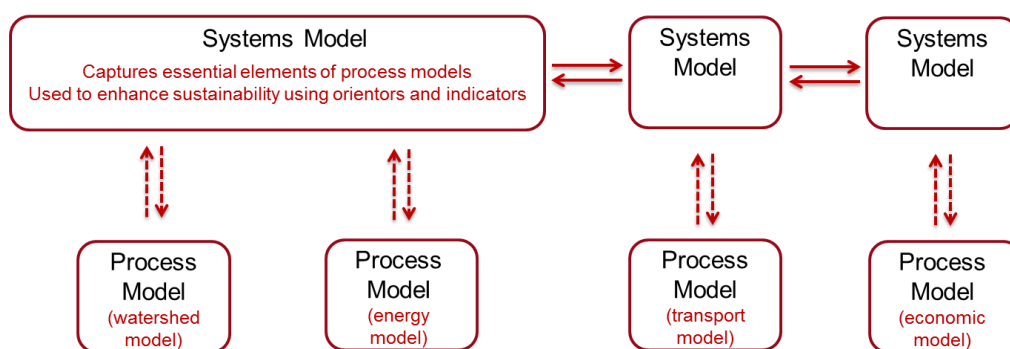


Figure 1. Tiered structure with process models up-scaled to the systems level, where they are coupled in a modular fashion and then used to assess and enhance sustainability.

We believe that system dynamics should be included in the hybrid computational language. As described by Kelly et al. [12] system dynamics models capture the causal relationships, feedback loops, delays, and decision rules that govern system behavior, and are conceptualized in terms of “stocks and flows.” The stocks represent the system state variables while the flows are the processes that influence change in the levels of the stocks [13]. System dynamics is flexible and can explicitly represent time and space, capturing elements of dynamic complexity such as feedbacks, time delays, accumulations, and nonlinearities [14]. The visual nature of the influence diagrams helps system dynamics to be understood across disciplinary and organizational boundaries [7]. System dynamics can simulate complex processes [15] including social and economic phenomena, provided that appropriate equations and input data to quantify the relevant phenomena are available.

The Occoquan watershed in northern Virginia is located in a temperate climate zone. The watershed has an area of 1,530 km² and a population of 478,000. A well-calibrated watershed-stream-reservoir modeling system already exists. The model uses seven applications of the Hydrological Simulation Procedure-Fortran (HSPF) software [16] for the overland, subsurface and stream components of the system; and two applications of CE-QUAL-W2 (W2) [17] for the two reservoirs. For the Occoquan watershed model, seven HSPF models (simulating seven sub-basins) and two W2 models (simulating the two reservoirs) are linked to form the overall model. Recent work has included a comparison of the PQUAL and AGCHEM modules of HSPF for agricultural Best Management Practice (BMP) assessment, of land segment size on predictive capabilities, and sensitivity analysis of the PQUAL and AGCHEM algorithms [18]. The model accounts for watershed runoff, shallow groundwater flow and interflow, stream processes related to parameters being simulated, full reservoir hydrodynamics and water quality with an emphasis on nutrients and algal growth. Atmospheric deposition is implicitly included in runoff from various land-use types.

A sophisticated wastewater reclamation facility that discharges to Occoquan waters has recently been modeled with iViewOps, and coupled with the Occoquan watershed model. The safe yield from the Occoquan reservoir is almost doubled due to the discharge of reclaimed water from UOSA. We are currently creating an iViewOps model for the water treatment plant that withdraws water from the

downstream end of the Occoquan reservoir. Thus, the loop from abstraction of water, to water treatment and distribution for consumption, to collection and treatment of wastewater, to augmentation of the source water with the reclaimed wastewater, will be complete, and we will be able to model the entire system.

We illustrate the development of the proposed common framework using the Occoquan watershed model as the first in a series of modules, and emphasizing environmental aspects of sustainability. We concentrate on orientors and indicators that relate to water quantity or quality, and their effects on human systems and ecosystems. The essential features of the process level watershed model are up-scaled to the systems level where an appropriately scaled set of orientors and indicators will be used to assess and enhance environmental sustainability. The project will assess baseline watershed sustainability, and then evaluate ways to enhance sustainability using a range of state-of-the-art watershed management scenarios.

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