Hydrologic Futures: Using Scenario Analysis to Evaluate Impacts of Forecasted Land Use Change on Hydrologic Services

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Abstract

Land cover and land use changes can substantially alter hydrologic ecosystem services. Water availability and quality can change with modifications to the type or amount of surface vegetation, the permeability of soil and other surfaces, and the introduction of contaminants through human activities. Efforts to understand and predict the effects of land use decisions on hydrologic services—and to use this information in decision making—are challenged by the complexities of ecosystem functioning and by the need to translate scientific information into a form that decision makers can use. Hydrologic modeling coupled with scenario analysis can (1) elucidate hydrologic responses to anticipated changes in land use and (2) improve the utility of scientific information for decision making in a manner that facilitates stakeholder involvement. Using a combination of general concepts and concrete examples, this paper summarizes hydrologic consequences of land use changes and describes the use of modeling and scenario analysis to inform decision making. Two case studies integrate the concepts raised in the paper and illustrate how an approach employing modeling and scenario analysis offers a potentially powerful way to link research on hydrologic services with decision making.

Key words: Alternative futures; Automated Geospatial Watershed Assessment; ecosystem services; Generalized Watershed Loading Function; hydrologic modeling; Moodna Creek Watershed; scenario analysis; water quality; water quantity; water resources; watershed assessment; Willamette River Basin.

Introduction

Human modification of land cover—for agricultural production, urbanization, and the extraction of natural resources—results in sometimes profound, long-term impacts on ecosystems and the goods and services they provide (Millennium Ecosystem Assessment [MA] 2005a, b). The consequences of these changes for biological diversity, ecological resilience, and human well-being may rival those of climate change (Vitousek 1994, Chapin et al. 2002, DeFries and Eshleman 2004).

Changes in land use and land cover can substantially alter water availability or quality through changes in hydrologic processes and through the introduction of contaminants (Tong and Chen 2002, DeFries and Eshleman 2004, Foley et al. 2005, Brauman et al. 2007). Poorly planned land use changes can also create or exacerbate inequalities, such that poor or marginalized communities are sometimes affected more than affluent communities by water scarcity, low water quality, or flooding (Brauman et al. 2007, United Nations [U.N.] 2007, Rasul and Chowdhury 2010, Bunch et al. 2011, Tallis et al. 2011). The complexities of ecosystem functioning often confound efforts by scientists and decision makers to understand and predict the effects of land use decisions on hydrologic ecosystem services. Furthermore, decision makers often find that relevant scientific information is not available in a usable form (Liu et al. 2008a). Thus, decision makers often must make far-reaching decisions based on limited information about the potential unintended ecological and socioeconomic consequences—and they typically must do so quickly. The resulting decisions either (1) address current needs for water resources without adequately considering future needs or (2) address the needs of some stakeholders without considering the impacts on other stakeholders or the ecosystem itself (Power et al. 2005, Liu et al. 2008a).

Daily et al. (2009) challenged the scientific community and decision makers to integrate ecosystem services into everyday decision making. As part of this effort, they argue, scientists must, first, provide the knowledge and tools necessary to quantify and forecast ecosystem services and, second, help decision makers and stakeholders interpret and use this research in the design and implementation of policies and management actions (Daston and Galison 1992, Daily et al. 2009). The ultimate goal of meeting this challenge—the sustainable provision and use of ecosystem services—will address growing concerns about the unintended social, environmental, and economic consequences of rapid population growth, economic growth, and natural resource consumption (e.g., World Commission on Environment and Development 1987, National Research Council 2011). To contribute to the sustainable management of water resources in particular, scientists must more accurately describe and predict—at catchment, regional, continental, and global scales—how different land use decisions today might impact ecosystems and the human lives they will support tomorrow.

Modeling coupled with scenario analysis offers one way to meet Daily et al.'s (2009) challenge. Advances in remote-sensing, spatial analysis, and visualization tools provide valuable landscape information that can be integrated within hydrologic models to better forecast, detect, and monitor long-term ecosystem change (Kepner et al. 2000, 2002, Power et al. 2005). By taking advantage of these tools—often in conjunction with extensive stakeholder participation—

modeling and scenario analysis efforts can improve the utility of scientific information for decision making as well as the equity and transparency of the decision making process (Kepner et al. 2004, Liu et al. 2008a, Jacobs et al. 2010).

This paper demonstrates how modeling and scenario analysis can enhance scientific understanding and inform water resources–related decision making. It represents the culmination of selected discussions on the integration of scenario analysis with watershed modeling from the First Millennium Conference of the Ecological Society of America on Water–Ecosystem Services, Drought, and Environmental Justice in November 2009. In particular, we address three questions: (1) What do we currently know about the effects of land use change on hydrologic ecosystem services? (2) How can modeling and scenario analysis improve understanding of the tradeoffs and tensions between different land uses and the resulting impacts on hydrologic services? (3) How can scientists ensure that the interpretive information provided by such tools is useful for decision makers? To answer these questions, we briefly describe how land use change can affect water resources, provide an overview of modeling and scenario analysis approaches, and explore two case studies demonstrating the use of modeling and scenario analysis to predict and analyze the impacts of land use change on water resources.

Impacts of Land Use Change on Water Resources

Hydrologic ecosystem services—such as the availability of water for downstream uses, water quality, and the location and timing of water delivery—can change with increasing demands for surface or groundwater, alterations in the type or amount of surface vegetation, the permeability of soil and other surfaces, and the introduction of contaminants through human activities (DeFries and Eshleman 2004, DeFries et al. 2004, Foley et al. 2005, Brauman et al. 2007, Mark and Dickinson 2008).

Increases in local water demand to meet the needs of intensifying agricultural production or expanding urban and suburban development can contribute to water scarcity. In particular, diversions of surface water for agricultural and other uses can reduce streamflows and cause potentially serious alterations in habitat for fish and other aquatic organisms. And the extraction of groundwater for agricultural, industrial, and residential uses has reduced water tables and affected streamflows in many regions (Foley et al. 2005, Carlisle et al. 2010). Alterations in vegetation can also reduce water availability. In the southern hemisphere, for example, the replacement of native grasslands and shrublands with tree plantations—which is being driven by increasing demands for forest products and by policies and markets encouraging carbon sequestration—can reduce water yields (Farley et al. 2005, Mark and Dickinson 2008). Reduced water availability may cause or exacerbate local drought conditions, threaten municipal water supplies, diminish the functioning of hydropower plants, and degrade ecosystems (Brauman et al. 2007, Buytaert et al. 2007, Farley 2007, Harden et al. 2009).

Alterations in land use affect whether and to what degree contaminants reach surface and groundwater, posing potential risks to human health and biodiversity and increasing water treatment costs (where treatment is available). Human activities such as intensive agriculture, mining, or energy extraction can introduce nutrients, pesticides, industrial chemicals, heavy metals, and other contaminants to the landscape, with a variety of effects on hydrologic services.

For example, human-induced eutrophication, which is linked to activities such as annual row-crop agriculture and concentrated animal feeding operations (Smith et al. 1999, Dodds et al. 2009, Rothenberger et al. 2009), can result in a loss of diversity and richness of aquatic organisms, increased human health risks, and reduced property values (Schilling and Spooner 2006, Dodds et al. 2009).

Plants, soils, and microbes can help remove some pollutants from freshwater, but the removal or reduction of vegetation and the introduction of impermeable surfaces, such as concrete or asphalt, allow water to flow through the landscape relatively unimpeded, reducing opportunities for contaminant removal through filtration (Brauman et al. 2007). Soil erosion—which is exacerbated by some agricultural practices, mineral and timber extraction practices, and during large-scale urban and suburban development activities—can contribute to elevated sediment loads in streams and rivers and may reduce or degrade habitat for fish and other aquatic organisms, among other adverse effects (Bovee 1982, Gordon et al. 1992, Schueler 1997).

Changing ecosystem characteristics can also alter the location of water and the timing or predictability of its delivery, with potential consequences related to drought or water damage mitigation. For example, urbanization, and the associated expansion of impervious cover, increases the frequency and magnitude of storm flows and subsequent flooding (Brown 2000). Logging, grazing, and other land uses that compact soils can reduce the amount of surface water infiltrating the soil to become groundwater. And riparian vegetation buffers or upland wetlands can decrease the severity of both peak flows (flooding) and low flows (drought) by promoting the infiltration of surface water to groundwater (Brauman et al. 2007).

Mapping Possible Futures through Modeling and Scenario Analysis

To facilitate the consideration of ecosystem services and sustainability in decision making, scientists must elucidate hydrologic responses to anticipated changes in land use and other factors (e.g., social, economic, political, and climate variables). In addition, they should ensure that new information on these relationships is available in a timely manner and in a form that decision makers will be able to understand and use (Daston and Galison 1992, Liu et al. 2008a, Daily et al. 2009). For many decisions, collaboration among ecologists, hydrologists, social scientists, and decision makers will therefore be critical to achieving this goal. By enabling consideration of the potential future effects of management and policy decisions on water resources, we propose that hydrologic modeling coupled with scenario analysis can provide crucial support for long-term planning meant to ensure the sustainability of water resources (Liu et al. 2008a). Such efforts can be costly and time consuming, but by sharing information (e.g., guidelines and detailed examples of scenario analysis applied to hydrologic services) and open-source modeling software, the scientific community can help make the widespread use of this approach more feasible.

Hydrologic modeling

Models can provide a useful way to predict the effects of alternative management or policy actions. Integrated modeling approaches, in particular, offer a way to represent, within a single framework, the interactions within and between natural and human systems, capturing more of their inherent complexity than would be possible with simpler modeling approaches (Holling

1973, Costanza and Ruth 1998, Letcher et al. 2006, Gaber et al. 2008, Liu et al. 2008a). Integrated approaches to hydrologic modeling use information from multiple domains and disciplines. For example, Johnston et al. (2011) describe a modeling approach in which several process-based models were linked, allowing for (1) a comparison of different land use scenarios; (2) the elucidation of the connectivity of ecosystem processes by capturing interactions among the hydrosphere, atmosphere, and lithosphere; (3) improved understanding of the impacts of multiple stressors; and (4) a way to assess and communicate environmental uncertainties. Further, by employing different types and resolutions of models, integrated modeling can capture water resource issues occurring at various temporal and spatial scales (e.g., ranging from detailed vegetation and hydrologic characteristics to representations of socioeconomic and institutional features; Liu et al. 2008a).

Hydrologic and other environmental models can use data from a variety of sources—such as remote-sensing technologies or monitoring networks—as input variables used to characterize baseline conditions. The output of hydrologic models is in the form of key surface or groundwater hydrology endpoints (see Figure 1 for an example of model input and output data). Models vary in a number of respects, including the type of output, complexity, accuracy, flexibility, scale, resolution, assumptions, algorithms, data requirements, and ease of use. Depending on the objectives of the modeling exercise, the data available for the system of interest, and the knowledge of the stakeholders involved, one may use a given model alone or in combination with other models or modeling tools (e.g., linked hydrologic process and land use change models), scenario analysis, or visualization tools (Costanza and Ruth 1998, Gaber et al. 2008, Hernandez et al. 2010). Table 1 summarizes general information on several open-source hydrologic models and indicates how one may obtain and use them. In their review of watershed modeling and applications, Daniel et al. (2011) provide detailed discussions of commonly used watershed models and modeling systems available for watershed management at multiple scales.

Hydrologic models must be detailed and complex enough to be credible to scientists and decision makers and to enable realistic predictions about the impacts of alternative land use decisions. However, the results of such models also must be understandable to stakeholders and usable by decision makers (Daston and Galison 1992); this may require the development and communication of a clear conceptual model or the use of scenario analysis or visualization tools (Liu et al. 2008a).

Scenario analysis

Scenario analysis explores trajectories of change that diverge from present conditions, ultimately leading to alternative possible future states or events. In so doing, this technique provides a dynamic and flexible way to evaluate policy or management options. Scenarios are not predictions or forecasts; rather, they are "plausible and often simplified descriptions of how the future may develop based on a coherent and internally consistent set of assumptions about driving forces and key relationships" (Houghton et al. 2001:796). Scenario analysis enables an exploration of the potential impacts, risks, benefits, and management opportunities stemming from a variety of plausible future conditions. When used in conjunction with modeling, scenario analysis can help bridge the gap between science and decision making, illuminating how land use changes will affect hydrologic services across a range of spatial and temporal scales and allowing decision makers to effectively prepare for such changes (Swart et al. 2004, Liu et al. 2008a, b, Mahmoud et al. 2009, Hernandez et al. 2010).

Although one can conduct scenario analysis using input only from scientists (e.g., Santelmann et al. 2004), management plans (Kooistra et al. 2008), or models (Huisman et al. 2009), scenario analysis provides an excellent platform for stakeholder involvement. A participatory approach can require a significant investment of time and money to truly engage all stakeholders, but the benefits can include (1) improved communication among all participants, (2) scenarios that are more likely to be politically feasible, (3) a richer diversity of perspectives for consideration by decision makers, (4) a process that is viewed as more credible and transparent, and (5) an increased likelihood of decisions that adequately consider and balance tradeoffs among the demands of different human populations and between human and ecological needs (Liu et al. 2008b, Jacobs et al. 2010, Metcalf et al. 2010).

To provide guidance on the use of formal scenario analysis in environmental studies and decision making, Liu et al. (2008b) and Mahmoud et al. (2009) proposed a framework outlining an iterative process for scenario development (Figure 2). Mahmoud et al. (2011) describe an application that illustrates this framework in its entirety; other published scenario analyses provide useful examples of some of its individual phases. Below, we describe each phase in the context of decision making related to water resources.

In the first phase of this framework, *scenario definition*, researchers typically collaborate with experts, decision makers, and stakeholders to (1) identify the key factors driving the system under study and determine which of these driving forces to evaluate in the scenario analysis; (2) decide which environmental endpoints to assess (e.g., water quality, water quantity, and habitat); and (3) identify the characteristics that differentiate the scenarios, such as alternative land management options and the spatial and temporal scales of interest (Liu et al. 2008b; Figure 2). Stakeholders may participate in this and other phases of scenario development through a variety of means, such as interviews, focus group meetings, workshops, surveys, mailings and newspaper inserts, television and radio, and the internet (e.g., Hulse et al. 2004, MA 2005a). Scenarios initially should be developed as images or narratives (Leney et al. 2004) that clearly and convincingly describe either the end state of the scenario or the processes by which the end state could be achieved (Liu et al. 2008b). For example, a map could show the area of native vegetation to remain in a watershed 20 years from the baseline, or a narrative could describe policy changes expected to alter future patterns of agricultural and urban development.

Scenarios in environmental science and decision making typically span long time periods (20–50 years from the baseline) and use a wide range of spatial scales, from a single watershed (e.g., Giertz et al. 2006, Mutiga et al. 2010) to a continent (e.g., Schröter et al. 2005, Weiss et al. 2009) or the world (U.N. Environment Programme [UNEP] 2002, MA 2005a). Driving forces considered in scenario analyses related to hydrologic and other ecosystem services could include, for example, population growth rates, housing density, impervious cover, domestic and international migration, fertility rates, carbon emissions, anticipated climate changes, hydrologic features, environmental policies, and development plans (UNEP 2002, MA 2005a, Mahmoud et al. 2011). The incorporation of components such as water resource policies and local or state development plans are especially important for most scenario analyses related to hydrologic services; scenarios that reflect actual, proposed, or feasible policies and plans can more directly inform decision making (e.g., Kooistra et al. 2008).

In the second phase, *scenario construction*, scientists and stakeholders flesh out scenarios quantitatively or qualitatively (Liu et al. 2008b). Quantitative approaches can provide greater rigor, precision, and consistency and allow one to determine the effects of alternative strategies or changes in assumptions. Qualitative approaches, on the other hand, can capture aspects that cannot be quantified, such as human motivations, values, and behavior (UNEP 2002, MA 2005a, Liu et al. 2008b, Mahmoud et al. 2009). Water resources–related scenario analyses typically employ a quantitative modeling approach, representing scenarios as data sets that can be used as inputs into a combination of land use change and hydrologic process-based models (Kepner et al. 2008, Liu et al. 2008b). Quantitative approaches may be unnecessary if researchers and decision makers determine that simply drafting scenario narratives is sufficient (Liu et al. 2008b, Mahmoud et al. 2009). And in some cases, researchers may turn to a qualitative approach if decision makers or stakeholders find modeling results too complex to be useful (e.g., Bohensky et al. 2006), though one could also address such problems by using visualization tools. A combination of qualitative and quantitative approaches can allow one to capitalize on the advantages of both approaches (UNEP 2002, MA 2005a). Some watershed modeling systems, such as the Automated Geospatial Watershed Assessment (AGWA) tool (Miller et al. 2007, Daniel et al. 2011, Goodrich et al. 2011), provide the utility of generating quantified data at the subwatershed scale and spatially visualizing results for qualitative comparisons (Figure 1).

A modeling-based approach to scenario construction begins with the development of a conceptual model—an intuitive description or representation of what will be modeled and how, as well as the data requirements—to help ensure that decision makers, stakeholders, and researchers share a common understanding of the quantitative model (Liu et al. 2008a, b). Researchers proceed with scenario construction by selecting or developing models or other data generation procedures that can adequately represent the conceptual model, collecting and processing model input data, running the models for each scenario, and processing model output data (*scenario outcomes*; Liu et al. 2008b). In their application of this framework, Mahmoud et al. (2011) provide a particularly comprehensive description of the scenario construction phase.

In *scenario analysis*, researchers examine scenario outcomes and compare them to baseline conditions using statistical and other analytical techniques, inspect the data for consistency with scenarios, quantify uncertainties, and identify system conditions or behaviors, such as trends or triggers (Liu et al. 2008b). In particular, a full understanding of scenario implications requires consideration of the sources and magnitudes of uncertainties (see, e.g., Giertz et al. 2006, Kooistra et al. 2008, Huisman et al. 2009) and how best to communicate uncertainties to stakeholders and decision makers. Addressing uncertainties in scenario analysis can also help establish the transparency and credibility of the approach (Liu et al. 2008b, Mahmoud et al. 2009).

In *scenario assessment*, according to Liu et al. (2008b), researchers present the results of the scenario analysis phase to stakeholders and decision makers as narratives (e.g., Mahmoud et al. 2011) and in other forms, such as maps, tables, or graphs depicting patterns of change in various hydrologic or other endpoints for each scenario compared to the baseline (e.g., Hulse et al. 2004). Decision makers, stakeholders, and researchers then work together to identify risks, rewards, mitigation opportunities, and tradeoffs for each scenario and to devise plans for monitoring and auditing scenarios and the resulting management strategies or policy choices (Liu et al. 2008b).

Risk management, the fifth and final phase of this process, is generally the responsibility of decision makers, and sometimes stakeholders, who devise strategies, such as management or policy changes, for minimizing vulnerabilities to risk, increasing resiliency, and taking advantage of opportunities highlighted by the scenario analysis. A return to the scenario definition phase may be warranted if, for example, scenario outcomes and risk management efforts suggest that alternative management or policy options should be considered through further scenario analysis (Liu et al. 2008b).

In the monitoring and post-auditing process, which is conducted after completion of the scenario analysis, scenarios are compared with observations as the future unfolds to determine which scenarios are converging with or diverging from reality; this is essentially an adaptive management process (Liu et al. 2008a, Walker and Mostaghimi 2009). Through monitoring and post-audits, one can determine whether management plans or policies should be modified or whether new scenarios are needed. For example, monitoring may reveal how best to avoid risks or to take advantage of opportunities identified in a scenario that is converging with reality. Or, if none of the original scenarios appears to be a close match with the unfolding future, a scenario analysis team might choose to develop new scenarios (Liu et al. 2008b).

Case Studies: Using New Tools to Plan a Sustainable Future

Assessing alternative futures in the Willamette River Basin (Oregon, USA)

Over the past several years, a number of multidisciplinary teams have employed modeling and scenario analysis to evaluate the impact of future land use scenarios on a variety of outcomes—including surface water conditions, water consumption, habitat, and biodiversity—in the Willamette River Basin (WRB; Figure 3).

Situated in northwestern Oregon between the Cascade and Coast Range Mountains, the 29,728-km^2 WRB makes up only 12% of Oregon's land area, but is home to 68% of the state's population and Oregon's three largest cities (Portland, Salem, and Eugene–Springfield). The basin supports highly productive timber and agricultural lands as well as a rich diversity of native fish and several species of sensitive fish and wildlife. As of 1990, 69% of the basin was forested, predominantly in upland areas, with agricultural uses and urban development covering 19% and 5%, respectively, of the total area of the WRB (Baker et al. 2004, Kepner et al. 2008).

The expected doubling of the population in the WRB, from 2 million in 1990 to 3.9 million people in 2050, and the resulting increase in demands on land and water resources, prompted Governor John Kitzhaber in the mid-1990s to initiate efforts to produce an integrated, basin-wide strategy for development, conservation, and restoration. As part of this effort, Kitzhaber created two citizen stakeholder groups, the Willamette Valley Livability Forum (WVLF) and the Willamette Restoration Initiative (WRI), whose makeup was intended to be representative of the interests in the basin (Baker et al. 2004, Hulse et al. 2004). Each of these stakeholder groups played a key role in the definition of alternative futures used in the scenario analyses.

Scenario definition. Modeling and scenario analysis efforts in the basin began with work by the Pacific Northwest Ecosystem Research Consortium, a multi-stakeholder alliance among government agencies, nongovernmental organizations, and universities that continues today. For more than 30 months, this alliance worked with the WVLF, WRI, and other stakeholders to create, map, and refine scenarios concerning changes in land and water use and land cover in the WRB from 1990 to 2050. In addition to soliciting input from the WVLF, WRI, and the basin's entire population, researchers met frequently with a core group of stakeholders, the Possible Futures Working Group (PFWG). With support from technical experts, the PFWG helped define scenario families for three possible futures by answering, in a spatially detailed way, the questions of where, when, and in what patterns to accommodate the expected population increase. The PFWG and researchers developed a map legend with 65 land use and land cover categories that they used to develop scenario assumptions, which researchers then translated into mapped spatial patterns of land use and land cover using GIS-based models (Hulse et al. 2004).

Ultimately, the PFWG and researchers developed three scenario families, each of which reflected the same expected population increase for the basin, but with different approaches to future urban and rural development and conservation of natural resources (Hulse et al. 2002, 2004, Polasky et al. 2011): (1) *Plan Trend*: Assumes that existing comprehensive land use plans are implemented as written. (2) *Conservation*: Places greater priority on natural ecosystem protection and restoration, while still reflecting a plausible balance among ecological, social, and economic considerations as defined by citizen stakeholders. (3) *Development*: Assumes that current land use policies are relaxed and places a greater reliance on market-oriented approaches to land and water use.

Scenario construction and analysis. These three scenarios have now been evaluated by a number of research groups with respect to different endpoints. Among the first of these efforts, Baker et al. (2004) used a variety of modeling approaches to assess the likely effects of each scenario on endpoints such as stream condition and water availability. They found that, under the *Conservation* scenario, indicators of stream condition (e.g., a fish index of biotic integrity and a measure of vertebrate richness) increased 9%–24% relative to 1990 (a recovery of 20%–65% of the losses sustained since European American settlement of the area). The other two scenarios had negative, but minor, effects on aquatic life compared to 1990. They also found that water consumed for out-of-stream uses rose under all three scenarios by 43%–58%, resulting in decreased streamflow.

More recently, Nelson et al. (2009) used InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs), a spatially explicit modeling tool, to predict changes in ecosystem services, biodiversity conservation, and commodity production resulting from each scenario. Regarding ecosystem services, they found that storm peak mitigation scores declined (i.e., flood risk increased) slightly under all three scenarios, primarily in the developing areas on the basin floor. Declines were smallest under *Conservation* and greatest under *Development*. They found that *Plan Trend* and *Development* outperformed *Conservation* in the predicted market value of commodities produced in the basin. However, when they included a conservative estimate of the market value of carbon sequestration as part of the value of commodities, *Conservation* outperformed the other two scenarios, generating the most monetary value.

In another recent set of evaluations, Kepner et al. (2008) and Hernandez et al. (2010) used the AGWA tool (Miller et al. 2007, Daniel et al. 2011, Goodrich et al. 2011) in an integrated approach to predict, for each scenario, the impacts of urbanization and agricultural intensification on hydrologic services, including surface runoff, channel discharge, sediment concentration, nutrient loads, and percolation volume (i.e., groundwater recharge) at the subwatershed scale. They found that negative impacts are likely under all three scenarios (Table 2), though with considerable spatial variability (Figures 4 and 5). In general, *Development* had the greatest negative impact on surface hydrology and water quality, with greater simulated surface runoff, flow discharge, and sediment concentration than the other two scenarios as a result of the greater expansion of impervious cover. Most of the surface runoff and flow discharge impacts occurred in subwatersheds near the Portland area, where most future development is anticipated. Nitrate and phosphorus loadings increased under *Development* in subwatersheds close to the basin's outlet. Additionally, groundwater recharge reductions were greater under *Development* than under the *Plan Trend* and *Conservation* scenarios (Kepner et al. 2008, Hernandez et al. 2010).

Scenario assessment and risk management. Because these analyses were intended to facilitate community-based environmental planning in the WRB, researchers provided stakeholders and decision makers with data sets, maps, analyses, and comparisons of scenario results to aid the discussion of management options. In one of the immediate applications of the early results, the WRI developed a salmonid recovery plan, the terrestrial elements of which are based on the “conservation and restoration opportunities” component of the *Conservation 2050* map (Hulse et al. 2004). In addition, Baker et al. (2004) note that *Plan Trend 2050* generated a productive debate among stakeholders over whether it accurately reflects the future landscape in the absence of new policy. Many argued that the scenario is not accurate in this sense because it assumes that current policies are being (and will be) implemented exactly as written, which may not be the case. Hulse et al. (2004) indicate that other uses of project results are likely to include the management of factors affecting water supply and quality.

The scenario analysis process in the WRB has now evolved into Willamette Water 2100, a collaborative project managed by Oregon State University’s Institute for Water and Watersheds. This endeavor is designed to help public officials, water managers, and other stakeholders (1) evaluate how climate change, population growth, and economic growth will alter the future availability and use of water in the WRB and (2) incorporate this information into planning and decision processes (Bolte et al. 2006, Guzy et al 2008, *public communication* <http://water.oregonstate.edu/ww2100/project-overview>). The project has re-engaged stakeholders, decision makers, and researchers to consider scenarios throughout a longer timeline, to the year 2100.

At this point, it is still difficult to definitively tie specific policy or management changes to WRB scenario analyses. However, this effort has continued and evolved in large part because of the ongoing interest, commitment, and engagement of local decision makers and stakeholders.

Assessing alternative futures in the Moodna Creek Watershed (New York, USA)

An important tributary of the Hudson River, the 466-km^2 Moodna Creek Watershed (MCW) in Orange County, New York (Figure 6), provides water for 22 municipalities and many private residences. Further, the New York Department of State's Division of Coastal Resources has identified this watershed as valuable fish and wildlife habitat and an aesthetic landscape.

Currently, only 17% of the MCW has been converted to urban or suburban use. The remainder consists of forest, herbaceous vegetation, and shrub or scrub vegetation (47%); agricultural uses (20%); and wetlands and open water (16%). But its proximity to New York City has driven rapid urbanization and a corresponding loss of open space in the watershed over the last few decades. In addition to commercial and residential development, the watershed has been burdened by an increased frequency of both drought (i.e., low to nonexistent groundwater levels resulting in dry drinking water wells) and flooding. Residents and decision makers have expressed particular concern over certain subwatersheds, such as the Moodna East where development is occurring more rapidly than elsewhere in the watershed.

Concerns about drought, flooding, and the loss of open space have prompted the Orange County Water Authority (OCWA) and the Orange County Department of Planning (OCDP) to launch a number of initiatives, including the development of a conservation and management plan for the watershed (OCDP and OCWA 2010a) as well as a county open space plan (OCDP 2004) and water master plan (OCDP and OCWA 2010b), both of which are amendments to the county's comprehensive development plan (OCDP 2010). These plans will guide OCWA and local land use boards in determining where to allow development and where to focus the conservation of natural landscapes. The county's goal is to protect unfragmented open space and focus new development in existing urban areas (OCDP 2010).

Scenario definition. To conduct the scenario analysis, Ramsey et al. (2009) relied on extensive input from stakeholders and decision makers. Representatives from OCWA and OCDP, the director of the Moodna Watershed Coalition, and citizen stakeholders (including coalition members, land use zoning board members, and concerned citizens) participated in discussions with researchers regarding the potential impacts of land use change on areas of concern in the MCW. Ultimately, they agreed on five scenarios of land use change: (1) *Predevelopment*: No development; 100% open space. (2) *Current Land Use*: 17% of the watershed is developed; 47% open space. (3) *Urban Scenario 1*: Urban growth increases by 25% compared with the *Current Land Use* scenario. (4) *Urban Scenario 2*: Urban growth increases by 50% compared with the *Current Land Use* scenario. (5) *100% Development*: 0% open space. In these scenarios, *open space* is defined as forest (deciduous, evergreen, and mixed), shrub or scrub vegetation, and herbaceous vegetation, and *development* includes both low- and high-intensity development of open space. Other land uses include agricultural uses (hay pasture and cultivated crops) and wetlands (woody and emergent herbaceous); these land uses were treated as separate categories, distinct from open space and development, and were held constant in the *Current Land Use* scenario and in *Urban Scenarios 1 and 2. Urban Scenarios 1 and 2* represent the potential increase in development discussed in the county's comprehensive development plan (OCDP and OCWA 2010a and b). Citizen stakeholders were interested in comparing the hydrologic response under such increased development to the current land use as well as to the hypothetical scenarios of an undeveloped (*Predevelopment*) and fully developed (*100% Development*) watershed.

Scenario construction and analysis. Ramsey et al. (2009) used a simple watershed model, the Generalized Watershed Loading Function-XL (GWLFXL; see Table 1), to quantify the hydrologic services of the MCW's open space areas—including flood mitigation, maintenance of surface water baseflow conditions, adequate recharge of groundwater storage, and reduced runoff of sediment and nutrients—and how these services compared among the five different land use scenarios of interest. GWLFXL is an Excel/Visual Basic for Applications–based version of GWLF that estimates water balance and nutrient and sediment runoff based on land use or land cover, slope, and soil properties; it has been used to simulate runoff generation and nutrient fluxes for several watersheds in the United States and elsewhere (Lee et al. 2000, Lee et al. 2001, Schneiderman et al. 2002, Smedberg et al. 2006, Morth et al. 2007, Hong et al. 2012).

Researchers ran the model for 10 iterations (or 10 "pseudo water-years") using weather data (from 1990–2006 weather records) collected by a weather station located within the watershed. They considered each scenario at the level of the watershed as a whole and for individual subwatersheds, such as the heavily developed Silver Spring subwatershed. This case study presents results from the first stage of this ongoing project—subwatershed-level hydrologic responses (potential flooding, as indicated by simulated streamflow and runoff, and potential drought, as indicated by simulated groundwater) to increased development and loss of open space—for three subwatersheds of interest. Two of the subwatersheds, Moodna East (63% open space currently) and Silver Spring (28% open space) are moderately to heavily developed, respectively, and are among the "priority growth areas" (OCDP 2010) in which most future development is likely to occur. The third subwatershed, Mineral Springs Brook (92% open space), is a heavily forested subwatershed; Ramsey et al. (2009) included it in the analysis to contrast the hydrologic response of the more urbanized versus more forested areas of the MCW.

Model simulations of MCW subwatersheds showed two trends, which are illustrated by the simulated hydrologic responses of the three highlighted subwatersheds. First, continued urbanization and loss of open space are likely to result in an elevated frequency of both extreme low groundwater and high runoff, with a resulting increase in the potential for drought and flooding, respectively (Figures 7 and 8). Second, as open space declined (from the *Current Land Use* scenario to *Urban Scenarios 1 and 2*), subwatersheds with a relatively high initial percentage of open space appeared to experience less hydrologic alteration than other subwatersheds (Table 3).

Specifically, Ramsey et al. (2009) found that simulated average monthly groundwater flow (recharge to streams from the shallow surface layer, or uppermost layer of groundwater) declined in all three subwatersheds as the percentage of open space decreased from the *Current Land Use* scenario to *Urban Scenarios 1 and 2* (Table 3). However, the greatest percentage decrease with urbanization (50.8%) occurred in the subwatershed with the lowest initial percentage of open space, Silver Spring; the decrease was much less pronounced (2.89%) in the Mineral Springs subwatershed. The highest average monthly groundwater flow rates occurred less frequently with each increase in development (and subsequent loss of open space), from the *Current Land Use* scenario to *Urban Scenarios 1 and 2*, for the more developed Moodna East and Silver Spring subwatersheds, but not for the less developed Mineral Springs subwatershed (Figure 7).

As shown in Figure 8, the highest simulated runoff rates (greater than 25 cm·month^{-1}) in the Silver Spring subwatershed were most frequent—and thus the potential for flooding was greatest—under *Urban Scenario 2* (aside from the *100% Development* scenario, in which the model treats all precipitation as runoff). Simulated runoff flows in the Silver Spring and Moodna East subwatersheds increased by 41.9% and 42.6%, respectively, in *Urban Scenario 2* compared with the *Current Land Use* scenario (Table 3). In the Mineral Springs subwatershed, in contrast, simulated runoff flows increased by 11.8% in *Urban Scenario 2*. The increased intensity of average monthly runoff flows suggests the potential for higher daily streamflows representative of flooding conditions in the Silver Spring subwatershed.

Scenario assessment and risk management. For the MCW, the use of a simple watershed model has helped to quantify the loss of ecosystem services with projected decreases in open space and compare the delivery of these services among subwatersheds. As a bridge between abstract ideas about how the environment functions and how community decisions and activities affect land and water resources, the results of this modeling and scenario analysis project could be a valuable tool for the ongoing planning and outreach efforts of OCDP, OCWA, and the newly created Moodna Watershed Intermunicipal Council (on which representatives of both OCDP and OCWA serve). The county's goal for future development is to protect unfragmented open space areas and to more efficiently concentrate development in already-developed areas (OCDP 2010 and 2004). Modeling and scenario analysis work by Ramsey et al. (2009) could facilitate the county's planning efforts by (1) identifying key areas for conservation, (2) highlighting the potential usefulness of development techniques that reduce runoff and increase flow to groundwater, and (3) educating the public about the hydrologic services provided by the MCW's open spaces and the effects of further development on flooding rates and groundwater conditions.

As part of its implementation of the conservation and management plan, the council will reach out to landowners, planning boards, municipal boards, conservation advisory councils, and other decision makers and stakeholders to explain the relationship between land use and hydrologic services. OCDP, OCWA, and other council members have shown interest in using modeled scenario outcomes in these outreach and education efforts.

The relatively simple GWLFXL model is not a spatially distributed model; it provides estimates of hydrologic endpoints only at the watershed or subwatershed scale. Subwatershed-scale information can help county land planners to (1) better understand how much urbanization or development can occur in a subwatershed without causing impacts to hydrologic services or (2) identify the subwatersheds most vulnerable to a loss of hydrologic services as a result of urbanization. Ideally, however, one should be able to use modeled scenario outcomes to inform land use decisions at the scale most commonly used in local land use management—the parcel level. Ramsey et al. (2009) were not able to calibrate the model with site-specific surface and groundwater data because, when the initial scenario analysis was completed, no U.S. Geological Survey surface or groundwater gages had been established in the watershed. This limitation in model accuracy and predictive power, which is relatively common in modeling projects, has been a source of some frustration for MCW decision makers. But, by exposing the disconnect between the resolution of available monitoring data and the resolution needed for effective decision making, this modeling and scenario analysis project highlighted the need for surface and groundwater gages in the MCW. In 2011, a stream gage network was established in the MCW with funds from the New York State Department of Environmental Conservation's Hudson Estuary Program. Therefore, in the next steps of this ongoing project, researchers will be able to calibrate GWLFXL using site-specific surface and groundwater data and quantify the uncertainty in model parameters. These gages will also provide the data necessary for the use of more complex, spatially distributed, process-based hydrologic models; this will aid decision makers with parcel-scale land use decisions, helping them achieve the conservation and management plan's goals of better understanding vulnerabilities in the water supply and identifying key riparian areas for conservation under the open space plan (OCDP 2004, OCDP and OCWA 2010a). Planned modeling and scenario analysis work regarding the effect of open space areas on water quality (nutrient and sediment loads) will also provide useful information to county decision makers.

Conclusions

Alterations to land use and land cover impact hydrologic processes in a number of ways. Although many land use changes are necessary to meet increasing demands for resources, they may nevertheless have unintended consequences, such as a reduction in the resilience of ecosystems and in their capacity to provide valuable goods and services now and in the future. Efforts to understand and predict the effects of land use decisions on hydrologic services—and to enable the use of this information in decision making—are challenged by the complexities of ecosystem functioning and by the need to translate scientific information into a form that decision makers can use. Scenario analysis coupled with hydrologic modeling, an approach that is transferable to geographies and watersheds throughout the world, offers one way to facilitate communication with stakeholders and decision makers and to improve the utility of scientific information.

In both case studies examined here, hydrologic services were most negatively affected by scenarios that maximized urbanization and the extent of impervious cover. Perhaps more importantly, the case studies also illustrate (1) the importance of involving stakeholders and decision makers and of incorporating their input, (2) how to integrate hydrologic process models with a scenario analysis, (3) the potential for significant spatial variability in the hydrologic effects of land use change, (4) the ways in which decision makers may use scenario outcomes, and (5) the collaborative and iterative nature of the scenario analysis process. The central role of stakeholder and decision maker participation, in particular, has been crucial to the definition and construction of realistic, politically feasible scenarios addressing issues with relevance for the people and ecosystems of each basin. And, despite the complex, quantitative approach to scenario analysis employed in these case studies, stakeholders and decision makers generally found both the process and the results understandable.

Looking forward, we offer a number of recommendations for successfully using scenario analysis to evaluate the effects of land use decisions on hydrologic ecosystem services and for ensuring that the information provided by such tools is useful to decision makers. First, scientists must be responsive to the needs of decision makers—in terms of the specific questions that must be answered and the time frame and spatial scale for decision making—to ensure that we provide usable information and tools and that we do so in a timely manner. Second, modeling and scenario analysis should be conducted by multidisciplinary teams, including experts in the natural and social sciences, land and water managers and other decision makers, and a comprehensive group of stakeholders representing all affected communities and interests. Third, all participants should strive for consensus, in advance, on the goals of the project—whether, for example, to build capacity for improved decision making over the long term or to decide on particular management or policy options in the short term. Fourth, modeling and formal scenario analysis requires careful consideration of the time and cost requirements, especially for efforts that will involve stakeholder participation; in some cases, time and resource limitations may require other approaches, at least in the short term. Finally, the scientific community can facilitate scenario analysis more broadly by (1) developing, refining, and sharing tools, such as land use and water quality data sets, modeling and visualization software, and remote-sensing and monitoring technologies; (2) applying the scenario development and analysis framework for problem solving at a variety of locations, with varying levels of stakeholder involvement, and for multiple socially relevant endpoints; and (3) incorporating scenario analysis into university ecology and interdisciplinary curricula.

To help integrate ecosystem services and sustainability into decision making, the scientific community must develop usable scientific information on issues relevant to affected stakeholders (World Commission on Environment and Development 1987, DeFries et al. 2004, Liu et al. 2008a, Daily et al. 2009). Here, we propose that an approach employing hydrologic modeling and scenario analysis offers a potentially powerful way to link ecosystem services research with decision making. By better quantifying, visualizing, and evaluating the anticipated effects of land use changes on hydrologic services, scientists can arm decision makers and stakeholders with the information they need to develop and implement sustainable water resources management.

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Tables

Table 1. Selected open-source hydrologic models and tools.

Model	**Description**	**Download Information and Sources**
AGWA	Automated Geospatial Watershed Assessment tool. A GIS interface tool that can be used to automate the use of SWAT, KINEROS2, and RHEM. Inputs include GIS data layers and nationally available land cover/use data. Outputs include runoff (volumes and peaks), sediment yield, nitrogen, and phosphorus. Useful in scenario analysis.	Sources: Miller et al. 2007, Daniel et al. 2011, Goodrich et al. 2011 Available free of charge from EPA or USDA/ARS: http://www.epa.gov/esd/land-sci/agwa/index.htm http://www.tucson.ars.ag.gov/agwa/ Also see: http://cfpub.epa.gov/crem/knowledge_base/crem_report.cfm?deid=75821
BASINS	Better Assessment Science Integrating Point and Nonpoint Sources. A multipurpose environmental analysis system integrating GIS, national watershed data, and environmental assessment and modeling tools (including QUAL2E, TOXIROUTE, a nonpoint source model, and output visualization tools). Useful in watershed and water quality–based studies.	Source: EPA 1998 Available free of charge from EPA: http://water.epa.gov/scitech/datait/models/basins/index.cfm
GWLFXL	Excel/Visual Basic for Applications–based version of the Generalized Watershed Loading Function. A combined distributed and lumped-parameter watershed loading model developed to assess nonpoint source flow and sediment and nutrient loading from watersheds. Can also	Source: Hong and Swaney 2007, Magnus et al. 2007 Available free of charge from Dr. Bonghhi Hong, Cornell University:

	calculate septic system loads and allows for the inclusion of point source discharge data. Useful for comparing simulated pollutant loads and pollution mitigation strategies in multiple watersheds.	http://www.eeb.cornell.edu/biogeo/usgswri/GWLFXL/gwlfxl%20v1.2.1.zip
HSPF	Hydrologic Simulation Program–Fortran. A comprehensive, basin-scale modeling framework for the integrated simulation of watershed hydrology (including rainfall, runoff, and evapotranspiration) and water quality (related to both conventional and toxic organic pollutants). Outputs include time histories of runoff flow rate, sediment load, and nutrient and pesticide concentrations as well as a time history of water quantity and quality at any point in a watershed.	Available free of charge from EPA: http://www.epa.gov/ceampubl/swater/hspf/
KINEROS2	Kinematic Runoff and Erosion. An event-oriented, physically based distributed model to determine the effects of artificial features, such as urban development, on flood hydrographs and sediment yield. Outputs include interception, infiltration, surface runoff, and erosion from small watersheds.	Available free of charge from USDA: http://www.tucson.ars.ag.gov/kineros/
RHEM	Rangeland Hydrology and Erosion Model. A single-storm, hillslope-scale model designed for rangeland systems. Inputs include storm characteristics, hillslope shape and slope, dominant plant type, soil cover characteristics, and soil texture. Outputs include runoff, erosion by water, and sediment delivery rates.	Available free of charge from USDA: http://apps.tucson.ars.ag.gov/rhem/
SWAT	Soil and Water Assessment Tool. A basin-scale model to quantify the impact of land management decisions on water, sediment, nutrient, and pesticide yields in large,	Available free of charge from USDA: http://swatmodel.tamu.edu/

	complex watersheds. Components include surface runoff, percolation, evapotranspiration, pond and reservoir storage, crop growth and irrigation, groundwater flow, and nutrient and pesticide loads.	
WEAP	Water Evaluation And Planning system. A user-friendly, GIS-based, integrated water resources planning tool that facilitates the engagement of diverse stakeholders in an open process. Outputs include water demand, supply, runoff, infiltration, crop requirements, flows, storage, pollution generation, treatment, discharge, and instream water quality.	Available in multiple languages, after free registration in the WEAP forum, from the Stockholm Environment Institute: http://www.weap21.org/
WLS	WETLANDSCAPE. A climate-driven, process-based, deterministic simulation model. Inputs include daily precipitation and temperature data, wetland basin bathymetry and a watershed digital elevation model, and initial water levels. Outputs include interbasin flows, surface water depth and volume, depth to groundwater, and an index of the speed of the vegetation cover cycle for a wetland complex (a mixture of semi-permanent, seasonal, and temporary wetlands).	Sources: Johnson et al. 2010, W. C. Johnson, *personal communication* A user manual has not yet been developed for WLS; those wishing to use WLS should contact Dr. W. Carter Johnson, Department of Natural Resource Management, South Dakota State University.

Notes: ARS, Agricultural Research Service; EPA, U.S. Environmental Protection Agency; QUAL2E, Enhanced Stream Water Quality Model; USDA, U.S. Department of Agriculture.

Table 2. Simulated average annual sediment yield, surface runoff, percolation, nitrate, and phosphorus for the 1990 baseline and predicted change (relative to the baseline) for each of three development scenarios at the watershed outlet, Willamette River Basin, Oregon, USA.

Water Balance Component	**Baseline (1990)**	**Simulated Relative Change 1990–2050**		
		Conservation	***Development***	***Plan Trend***
Sediment Yield, t/ha (% change)	36.69	32.22 (−12.18)	33.70 (−8.15)	36.42 (−0.74)
Surface Runoff, mm (% change)	330.98	327.59 (−1.02)	334.81 (+1.16)	334.18 (+0.97)
Percolation, mm (% change)	655.12	656.27 (+0.18)	650.28 (−0.74)	653.04 (−0.32)
Nitrate, kg/ha (% change)	0.785	0.772 (−1.66)	0.788 (+0.38)	0.789 (+0.51)
Soluble Phosphorus, kg/ha (% change)	0.025	0.025 (0.0)	0.026 (+4.00)	0.025 (0.0)

Table 3. Simulated average monthly groundwater, streamflow, and runoff in three subwatersheds for each land use scenario and the predicted change relative to the *Current Land Use* scenario, Moodna Creek Watershed, New York, USA.

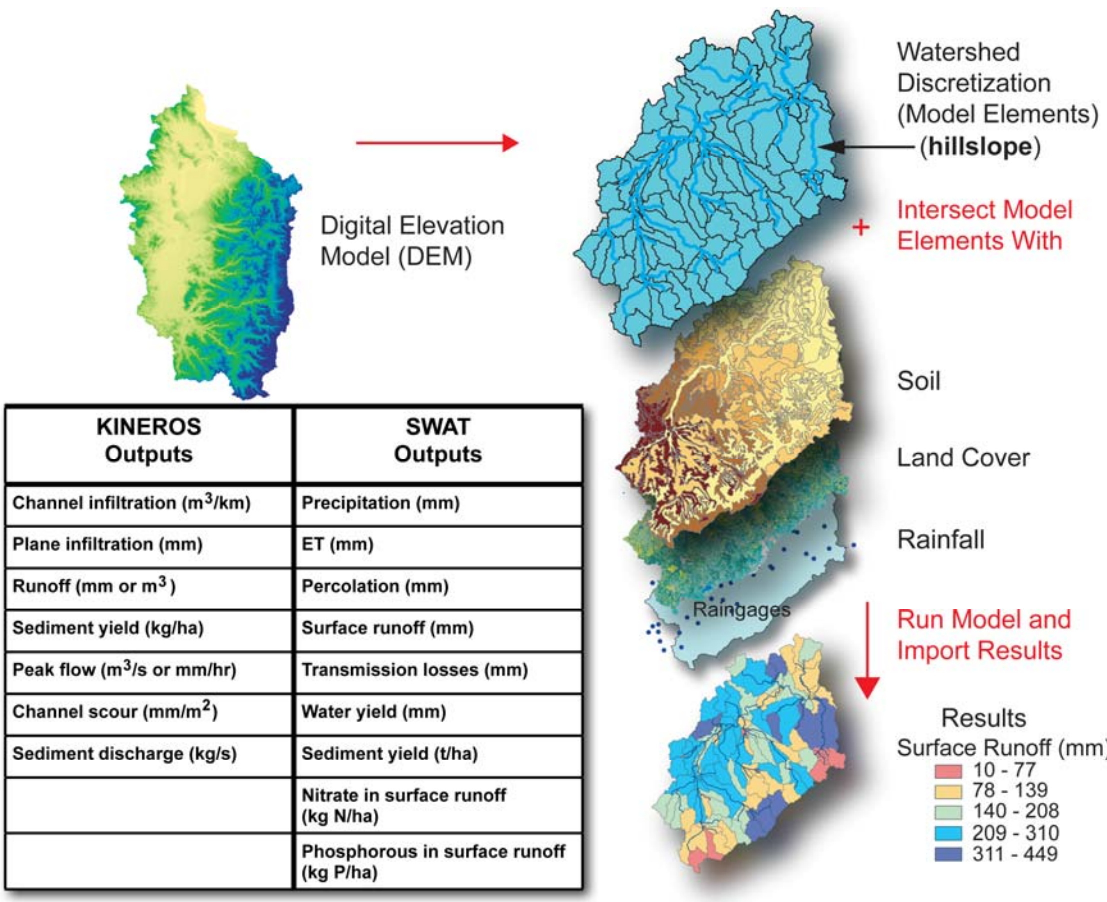
Endpoints	**Scenarios**				
	Predevelopment	***Current Land Use***	***Urban Scenario 1***	***Urban Scenario 2***	***100% Development***
Moodna East Subwatershed					
Runoff, cm (% change)	1.38 (–34.0)	2.09	2.54 (+21.5)	2.98 (+42.6)	7.33 (+251)
Streamflow, cm (% change)	6.64 (+0.302)	6.62	6.61 (–0.151)	6.59 (–0.453)	7.33 (+10.7)
Groundwater, cm (% change)	5.25 (+15.6)	4.54	4.07 (–10.4)	3.61 (–20.5)	0 (–100)
Silver Spring Subwatershed					
Runoff, cm (% change)	1.90 (–46.6)	3.56	4.32 (+21.3)	5.05 (+41.9)	7.44 (+109)
Streamflow, cm (% change)	6.63 (+0.91)	6.57	6.55 (–0.30)	6.52 (–0.76)	7.44 (+13.2)
Groundwater, cm (% change)	4.73 (+58.2)	2.99	2.23 (–25.4)	1.47 (–50.8)	0 (–100)
Mineral Springs Subwatershed					
Runoff, cm (% change)	0.93 (–15.5)	1.10	1.17 (+6.36)	1.23 (+11.8)	7.34 (+567)
Streamflow, cm	6.64	6.64	6.64	6.64	7.34

(% change)	(0)		(0)	(0)	(+10.5)
Groundwater, cm (% change)	5.71 (+3.07)	5.54	5.47 (–1.26)	5.38 (–2.89)	0 (–100)

Notes: All subwatersheds had an average of 0 cm·month^{-1} groundwater contribution to streamflow in the *100% Development* scenario. This is an artifact of the model algorithms: with all land use set as high-intensity development, the corresponding runoff curve number of 98 means that no precipitation infiltrates and all is transported as runoff to the stream.

Figure Captions

Figure 1. AGWA input and output variables. Using the AGWA tool as an example, this figure shows the types of data that can be used as model inputs and the types of outputs one could generate using such a system for the Willamette River Basin, Oregon, USA. AGWA divides a watershed into individual model elements (subwatersheds) using a digital elevation model. These subwatersheds are then intersected with soils and land cover data layers as well as rainfall/precipitation data to generate output regarding hydrologic endpoints. One of the models associated with AGWA (KINEROS2 or SWAT) is then run, and the quantified results are imported back into AGWA for visual display. ET, evapotranspiration; KINEROS2, Kinematic Runoff and Erosion; SWAT, Soil and Water Assessment Tool.



KINEROS Outputs	SWAT Outputs
Channel infiltration (m^3/km)	Precipitation (mm)
Plane infiltration (mm)	ET (mm)
Runoff (mm or m^3)	Percolation (mm)
Sediment yield (kg/ha)	Surface runoff (mm)
Peak flow (m^3/s or mm/hr)	Transmission losses (mm)
Channel scour (mm/m^2)	Water yield (mm)
Sediment discharge (kg/s)	Sediment yield (t/ha)
	Nitrate in surface runoff (kg N/ha)
	Phosphorous in surface runoff (kg P/ha)

Figure 2. The five phases of scenario development outlined by Liu et al. (2008b), showing the involvement of scientists and stakeholders and applied to studies of hydrologic ecosystem services. Adapted from Liu et al. (2008b).

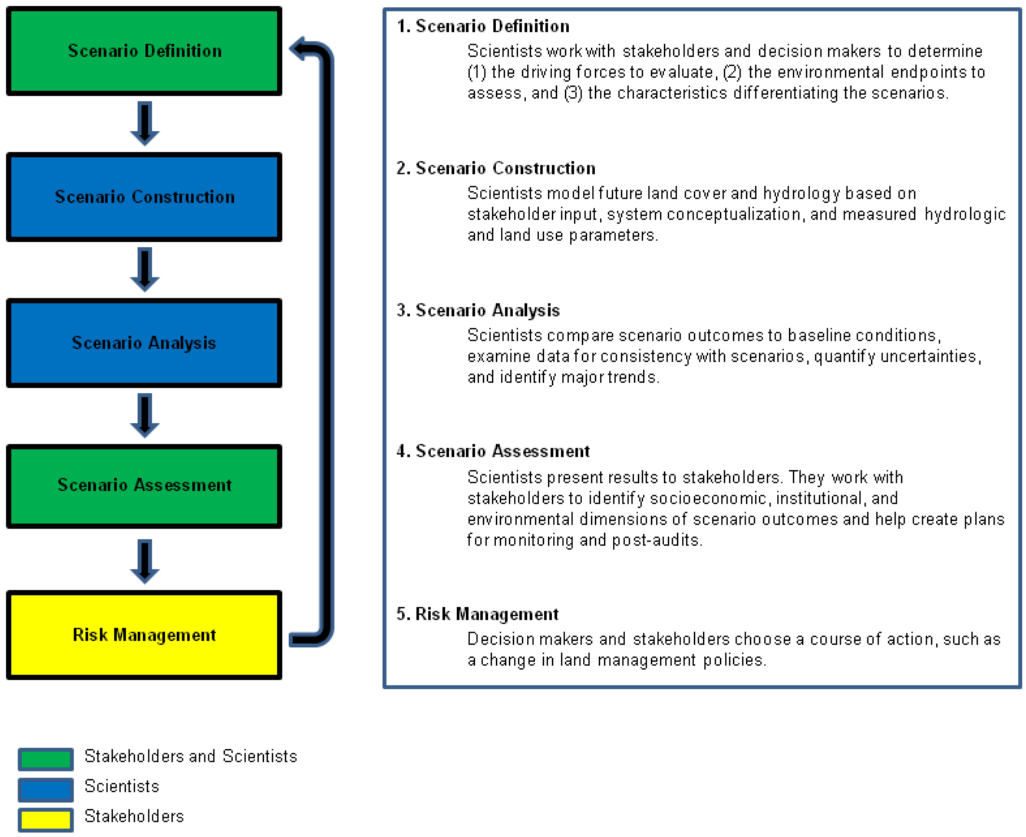


Figure 3. The Willamette River Basin, Oregon, USA (29,738-km^2 drainage area).

Figure 4. Percentage change in average annual (A) surface runoff, (B) channel discharge, (C) sediment yield, and (D) percolation for each scenario, 1990–2050, Willamette River Basin, Oregon, USA. Adapted from Kepner et al. (2008).

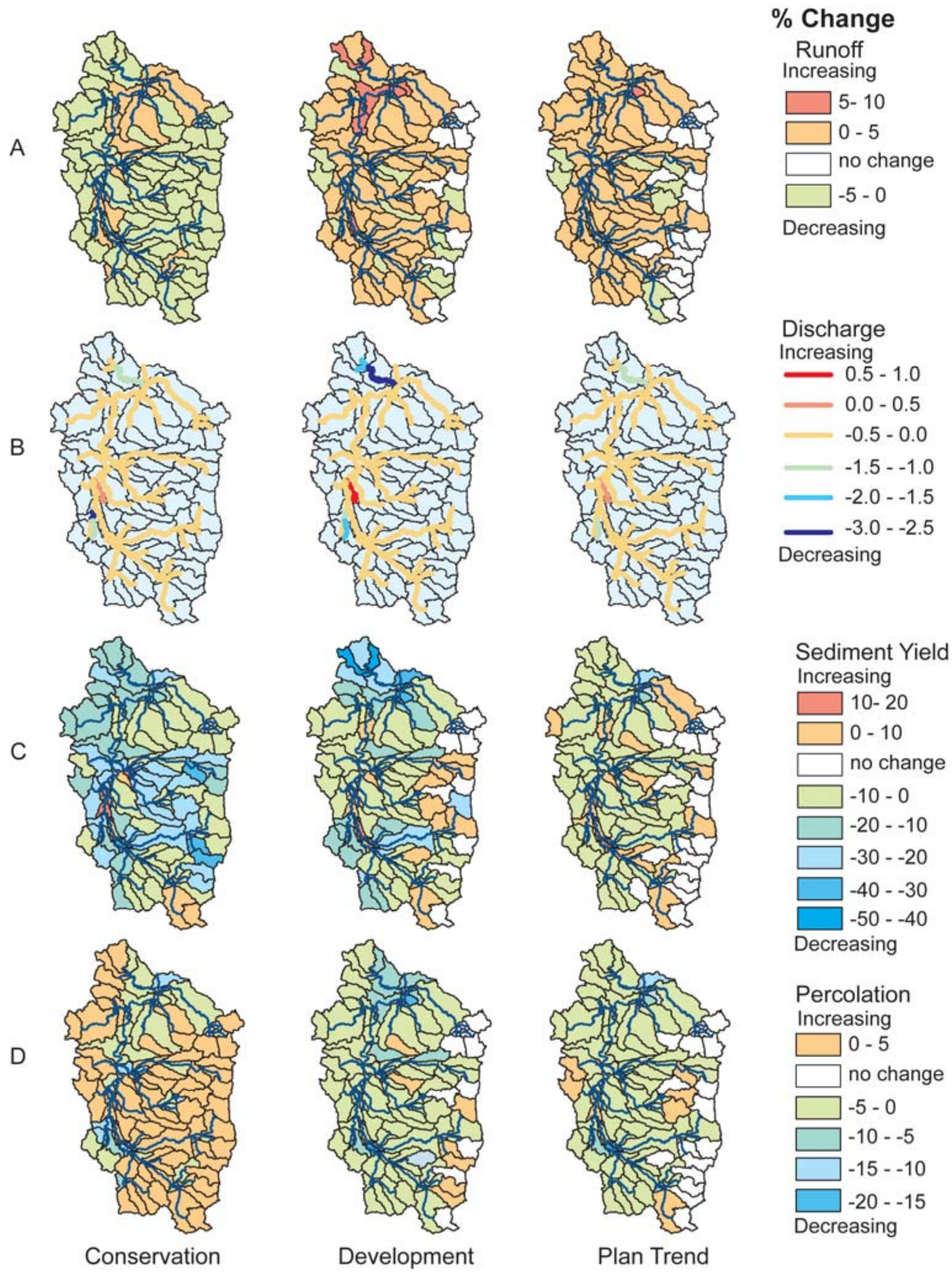


Figure 5. Percentage change in average annual nitrate and phosphorus transported with surface runoff under each scenario, 1990–2050, Willamette River Basin, Oregon, USA. Adapted from Hernandez et al. (2010).

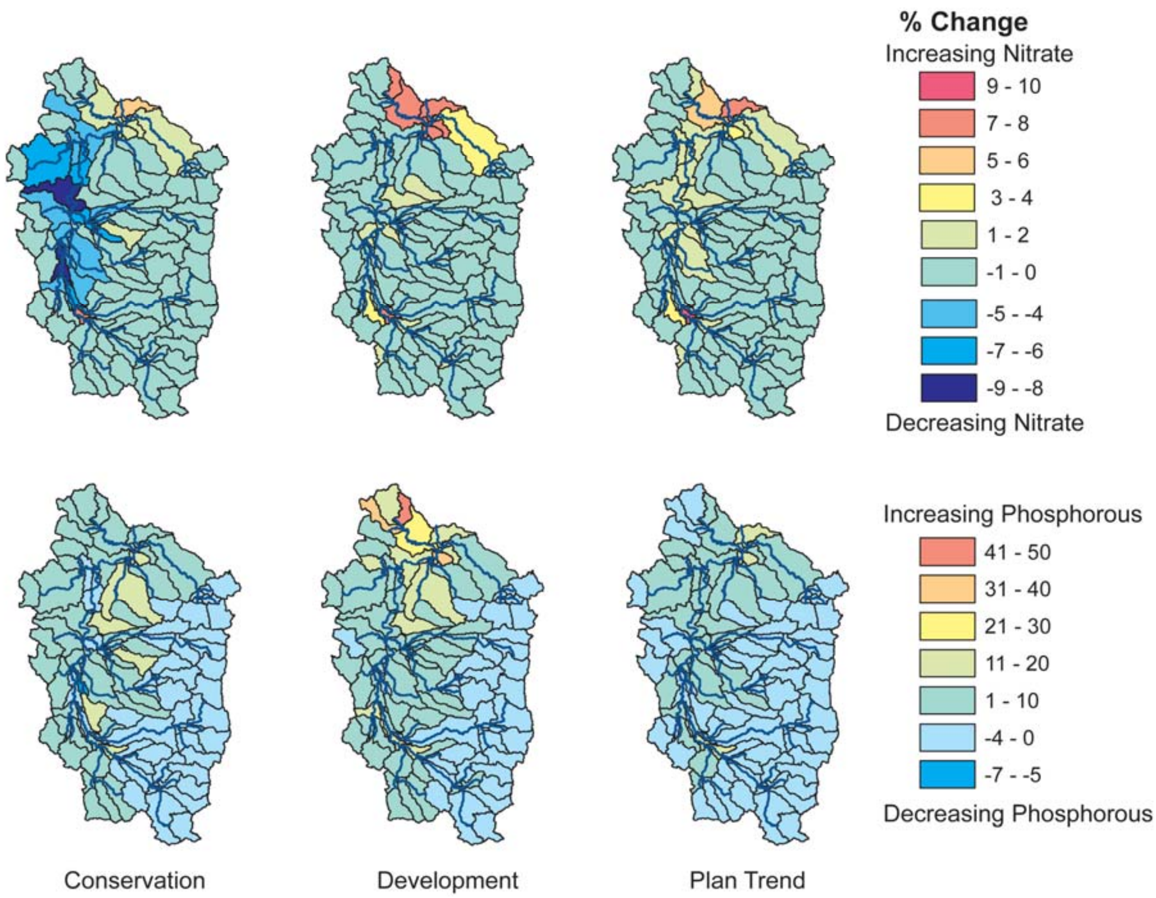


Figure 6. The Moodna Creek Watershed, a 466-km^2 watershed within the Hudson River Drainage Basin, New York, USA. The Moodna East, Mineral Springs, and Silver Spring subwatersheds are identified. Map created using the Multi-Resolution Land Characteristics Consortium's 2001 National Land Cover Data.

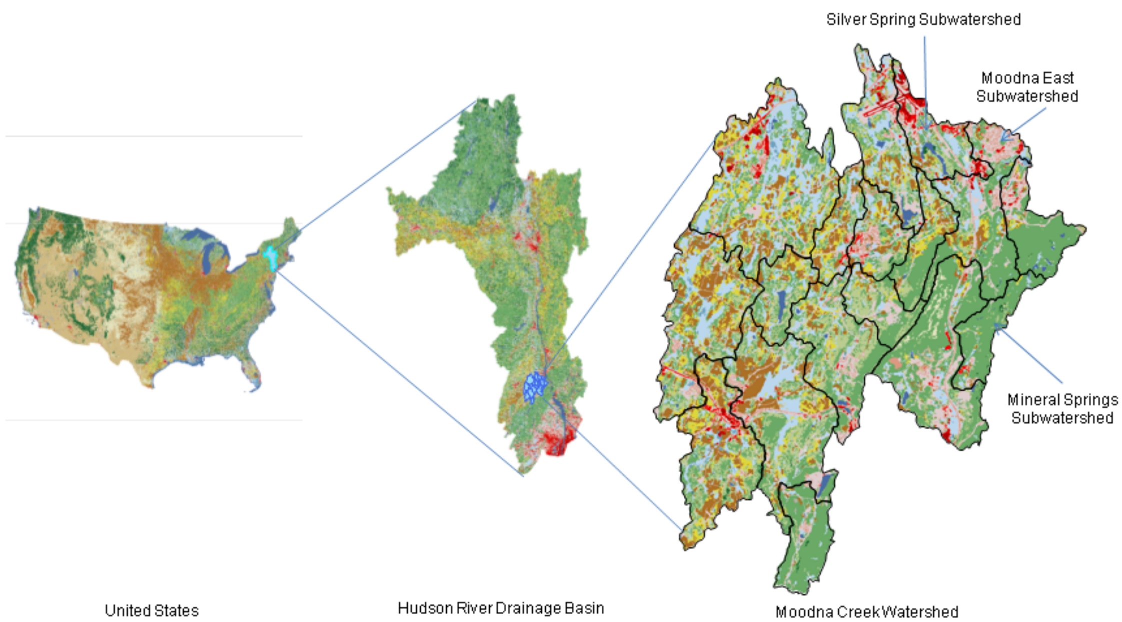
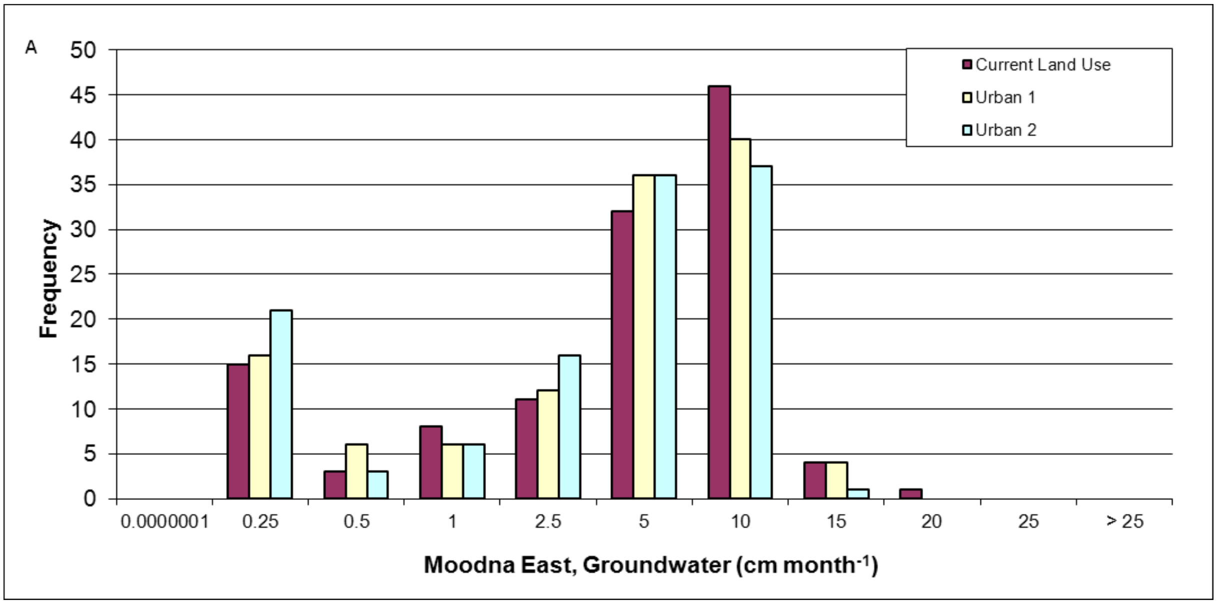


Figure 7. Frequency of simulated average monthly groundwater flow for the *Current Land Use*, *Urban 1*, and *Urban 2* scenarios in the (A) Moodna East, (B) Silver Spring, and (C) Mineral Springs subwatersheds. To allow for a clearer comparison of the three scenarios of greatest interest, the two hypothetical land use scenarios, *Predevelopment* and *100% Development*, are not shown.


A
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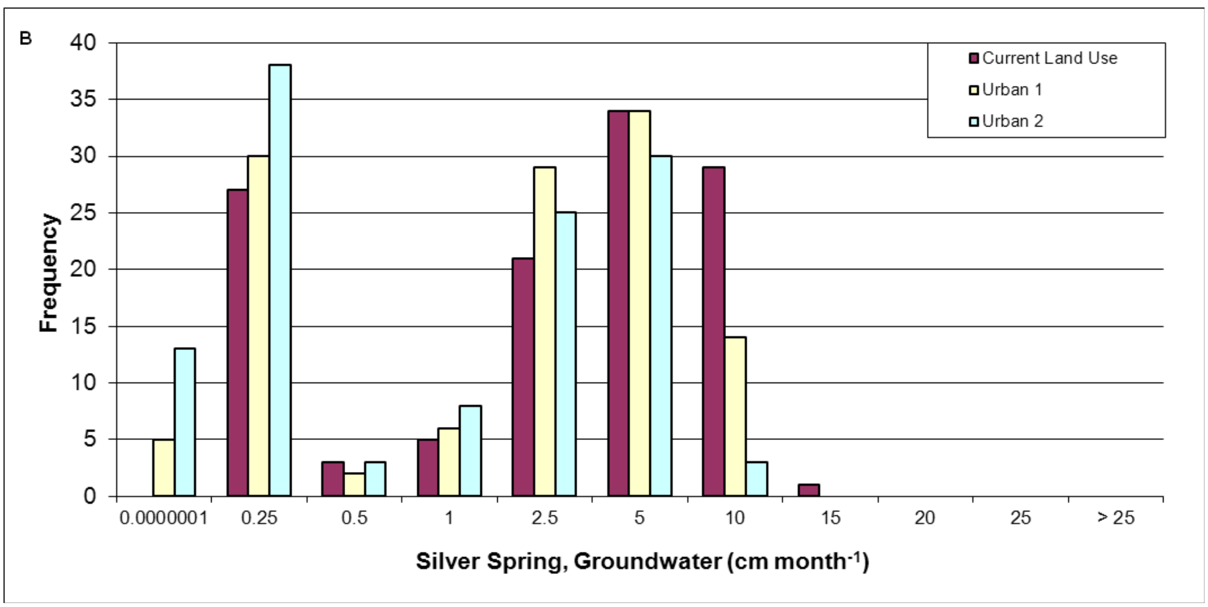
45
40
35
30
25
20
15
10
5
0
Frequency
Current Land Use
Urban 1
Urban 2
0.0000001
0.25
0.5
1
2.5
5
10
15
20
25
> 25
Moodna East, Groundwater (cm month-1)


B
40
35
30
25
20
15
10
5
0
Frequency
Current Land Use
Urban 1
Urban 2
0.0000001
0.25
0.5
1
2.5
5
10
15
20
25
> 25
Silver Spring, Groundwater (cm month-1)

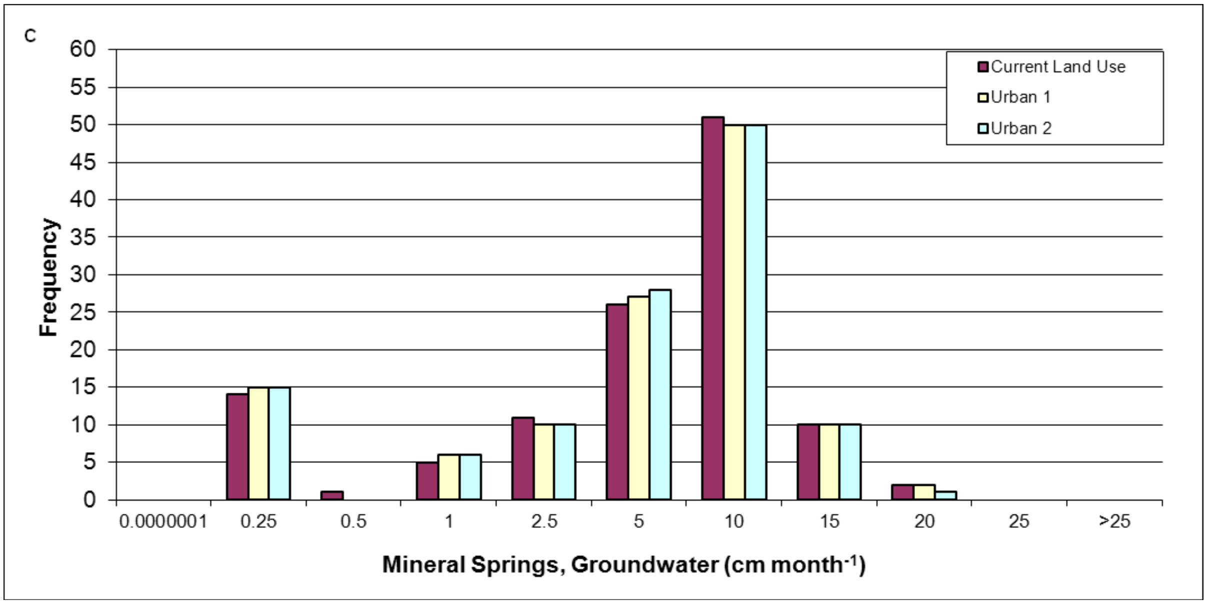
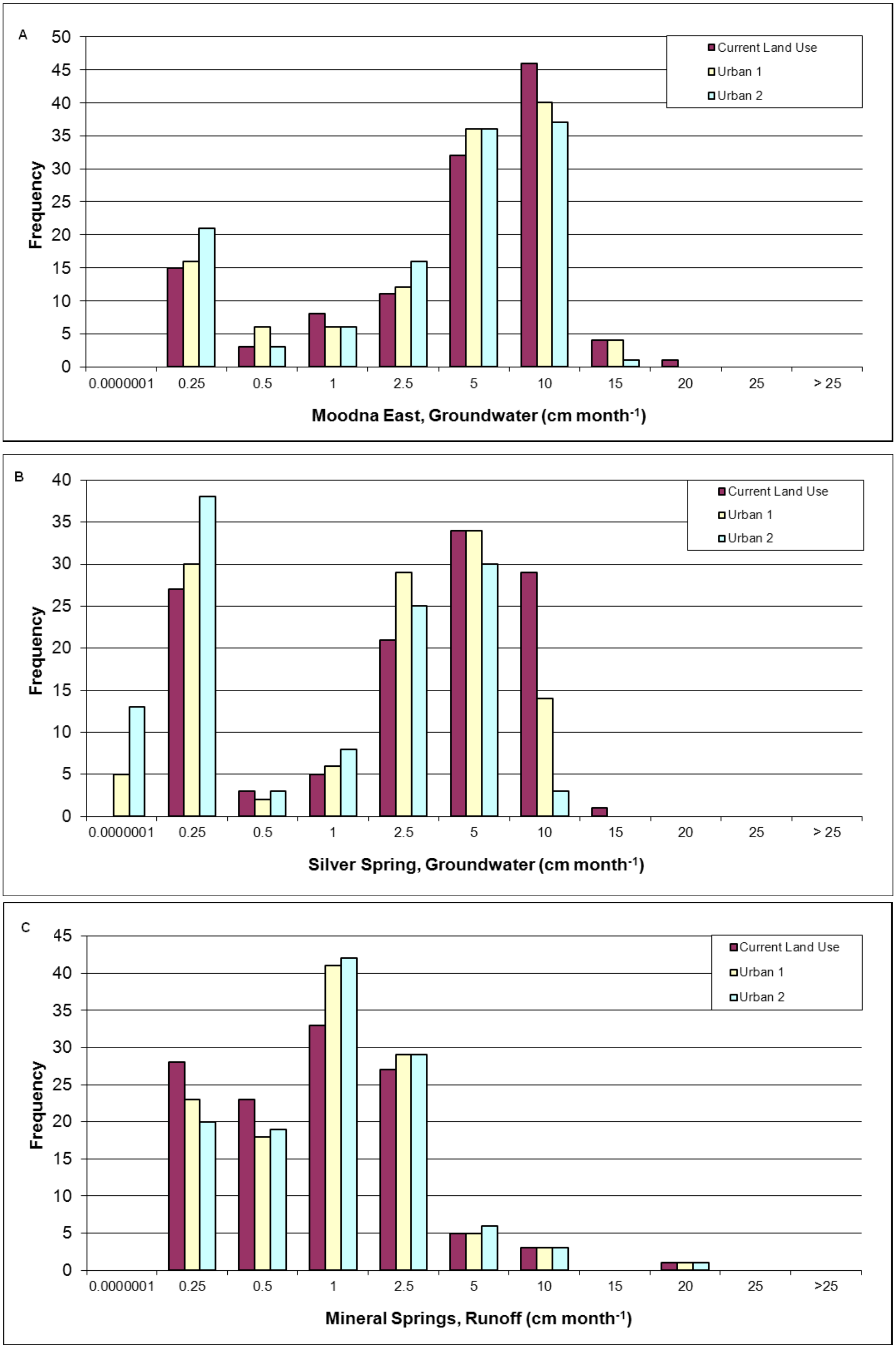


Figure 8. Frequency of simulated average monthly runoff for the *Current Land Use*, *Urban 1*, and *Urban 2* scenarios in the (A) Moodna East, (B) Silver Spring, and (C) Mineral Springs subwatersheds. To allow for a clearer comparison of the three scenarios of greatest interest, the two hypothetical land use scenarios, *Predevelopment* and *100% Development*, are not shown.


A
Frequency
Current Land Use
Urban 1
Urban 2
0.0000001
0.25
0.5
1
2.5
5
10
15
20
25
> 25
Moodna East, Groundwater (cm month-1)
B
Frequency
Current Land Use
Urban 1
Urban 2
Silver Spring, Groundwater (cm month-1)
C
Frequency
Current Land Use
Urban 1
Urban 2
>25
Mineral Springs, Runoff (cm month-1)