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Urbanization and watershed sustainability: Collaborative simulation modeling of future development states

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SUMMARY

Urbanization has a significant impact on water resources and requires a watershed-based approach to evaluate impacts of land use and urban development on watershed processes. This study uses a simulation with urban policy scenarios to model and strategize transferable recommendations for municipalities and cities to guide urban decisions using watershed ecohydrologic principles. The watershed simulation model is used to evaluation intensive (policy in existing built regions) and extensive (policy outside existing build regions) urban development scenarios with and without implementation of Best Management practices (BMPs). Water quantity and quality changes are simulated to assess effectiveness of five urban development scenarios. It is observed that optimal combination of intensive and extensive strategies can be used to sustain urban ecosystems. BMPs are found critical to reduce storm water and water quality impacts on urban development. Conservation zoning and incentives for voluntary adoption of BMPs can be used in sustaining urbanizing watersheds.

1. Introduction

With increasing population and urbanization, built environments continue to increase and change the nature of watershed systems. Urbanization affects watershed systems through changes in urban spatial patterns (form, density, grain, and connectivity) and alters water quantity and quality (sources, sinks, ecological support systems and impacts on human well-being) at the local, regional, and global scales (Alberti, 1999). Urbanizing watersheds have altered hydrologic and ecological processes that need a careful assessment and planning for achieving sustainability. This is also needed for addressing urban issues like assessment of total maximum daily loads of contaminants, development of master plans for optimal land use, and implementation of best management practices to restore ecological structure and functions of urban ecosystems. An ecosystem-based management and policy that balances achievement of multiple criteria through a collaborative process (Cardwell et al., 2011) can be used improve sustainability of urban watersheds. We use sustainability as defined in URBAN21 Conference as "Improving the quality of life in a city, including ecological, cultural, political, institutional, social, and economic components without leaving a burden on the future generations (Hall and Pfeiffer, 2000). This study develops such a watershed-based, collaborative approach to evaluate outcomes of alternate policy scenarios of built environment on watershed processes to sustain urban ecosystems.

2. Background

Water withdrawals, wastewater discharge, and impervious cover dominate urban landscapes with substantial impact on eco-hydrologic processes. These changes can result in a net loss or gain of water, potentially resulting in unintended consequences on flow regime, water quantity and quality, and ecosystem services. Pattern of impervious cover in an urban area is an influential factor in shaping the hydrologic response (Mejia and Moglen, 2010). Impervious cover contributes immensely to surface and groundwater contamination (Kauffman and Brant, 2007; Margerum, 1997; Perlman and Milder, 2005) and is often used as key indicator of impairment in water quality (EPA, 2007; Brabec et al., 2002; Tripathi et al., 2006) in urban watersheds.

Given increasing urban water issues like potable water, wastewater, and storm water, there is a need for integrated approach involving a systems framework using collaborative decision-making (Goldfarb, 1994) to achieve urban watershed sustainability. In urban water resource management, there is often

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a disconnection between science and policy (Wolosoff and Endreny, 2002), needing such systems approach to link the two. A watershed-based, systems approach is appropriate to integrate ecological and socioeconomic processes and ecohydrologic principles (Rodriguez-Iturbe, 2000) for urban policies and to promote comprehensive urban management.

In developing watershed-based approaches, collaborative modeling is useful in stakeholder participation in water resource management decisions (Michaud, 2013). The watershed approach is goal driven through use of collaboratively developed vision of desired future conditions. Sandoval-Solis et al. (2013) used collaborative modeling with stakeholders to evaluate water management scenarios in Rio Grande Basin. Langsdale et al. (2011) used collaborative modeling for decision support in water resources. Baker et al. (2004) uses stakeholder in alternative futures analysis in the Willamette River Basin in western Oregon. Randhir et al. (2001) used collaborative modeling to prioritize watershed land for water supply protection.

Despite the recognition of the watershed approach to urban resource management, it is not used prevalently in urban planning because of difficulties faced in practice (Douglas, 1992; Sukopp and Numata, 1995), that include disparity between watershed and administrative boundaries, low priority to ecosystem criteria in city planning process, or budgetary reasons. Municipal officials and city planners recognize the need for reconciling administrative jurisdiction and ecohydrologic boundaries like watersheds for achieving sustainability. Decisions that do not use watershed-based information can lead to disruptions in biotic and abiotic processes in watersheds, specifically stream morphology, aquatic habitat, biodiversity, water supplies, and water quality, thereby affecting the overall urban sustainability.

In addition, integrated approaches require watershed models to be integrated into planning frameworks. A spatial approach with systems modeling allows urban planner and water managers to integrate several types of information into the computation process. In addition, there is need for planning criteria and processes to be incorporated into an interdisciplinary framework for collaboration and institutional change for effective decision-making (Margerum, 1997).

This study is unique in developing water resource protection under future development pathways in urban watersheds. The use of a collaborative, watershed-modeling approach is also unique to study impacts of urban land use on water resources under various policy scenarios. It also provides a framework for water resource protection under future development options of urban ecosystems. A city-based, watershed model and analysis is a first step in guiding policy-making and decision-making in urban areas (Pickett et al., 2004), to achieve economic, environmental, and social sustainability (Pickett et al., 1997). The analysis aims to guide policy regulations and decision making into the near future, through five development scenarios involving changes in land use patterns, population density, lot size, and best management practices. The scenarios reflect innovative land use practices in built watersheds and are useful to assess watershed-scale effectiveness of various conservation practices for improving urban ecosystems.

The general objective of the study is to develop a watershed-based, collaborative sustainability framework for an urbanized region and to assess impacts of land use policy on the watershed system. Specific objectives of the study are: (i) to model hydrologic processes that affect water quantity and quality in a built environment; (ii) to evaluate watershed-scale impacts of BMPs in planning scenarios on watershed process; (iii) to identify strategies to protect urban watersheds using land use scenarios. We hypothesize (Alternate Hypothesis) that: (i) built environments can have significant impact on water quality and quality through substantial alteration of the hydrograph and pollutograph characteristics; (ii) BMPs can have significant impact on runoff and pollutant loads in urban watershed and (iii) there exist opportunities to reduce negative impacts of urban land uses using sustainable planning methods for urban ecosystems.

The watershed associated with the City of Northampton is used to model watershed process, especially water quantity and quality changes. We chose the City of Northampton (Massachusetts) based on several reasons: (i) Availability of monitoring data for modeling; interest of city planners in making it a sustainable city; (ii) water quality is impacted; (iii) water flow issues like flooding are a major problem in the city; and (iv) it is a relatively smaller city that allows reasonable scale for modeling. Using GIS for spatial data processing, a watershed simulation model (GWLF-Generalized Watershed Loading Functions) is used to simulate hydrologic flows. Data on topography, temperature, precipitation, land use, and soils are used to estimate water quantity (runoff, infiltration, evapotranspiration, groundwater storage, and streamflow), and water quality (soil loss, total suspended solid (TSS) total nitrogen and total phosphorus) under baseline and policy scenarios.

3. Methodology

3.1. Study area

The study area is the City of Northampton in Massachusetts, USA and located within the Mill River Watershed (Fig. 1). The city population is at 28,549, with 11,783 households (United States Census, 2010). The population density was at 834 people per square mile, with 12,405 housing units at an average density of 360 per square mile (US Census, 2010). In 2003, the City of Northampton was awarded funds provided by the Commonwealth's Massachusetts Executive Order (418 program) to develop an initial plan (Grow Smart Northampton) as part of the process for revising the Northampton Vision 2020 Comprehensive Plan. This plan provided a cursory water budget analysis for drinking water only. Furthermore, the Massachusetts Department of Environmental Protection (MA DEP) completed a Source Water Assessment Program (SWAP) report that included a review of the watershed lands and aquifer protection zones. The largest threats to the water supply identified in the report were from residential fuel storage and large scale commercial uses.

A conceptual model (Fig. 2) represents the data flows of the study. The watershed system is represented by abiotic (hydrology and soils) and biotic (plant cover) component that are influenced by land use practices. Conservation strategies are developed as scenarios to target specific land uses in order to reduce storm water flows and to reduce water quality impacts in the built environment.

The model is applied to the Mill River watershed, which has been experiencing northerly and westerly residential expansion along transportation corridors over the past 50 years, and because of this there is a strong interest in sustainable development (Arsenault et al., 2005). While the total population of the City of Northampton has remained constant since the 1950, number of households has increased by 16% since 1980 (Shaw et al., 2011).

Alternate scenarios (Table 2) are used to quantify various existing and proposed land use measures, best management practices (BMPs), and combinations of these. The current zoning map of the City is presented in Fig. 3. The scenarios simulated alternative future pathways that the urban watershed could take and their implications on water quantity and quality. The outcomes of each scenario are compared to baseline levels. In the baseline, water quality and quantity analysis of the Mill River Subbasin is determined based on present zoning and land use patterns and used as a reference point for quantifying effects of scenarios. All