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A model examining hierarchical wetland networks for watershed stormwater management

Matthew J. Cohen, Mark T. Brown*

Center for Environmental Policy, Department of Environmental Engineering Sciences, PO Box 116350, Gainesville, FL 32611-6350, United States

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ABSTRACT

There is increasing awareness that solutions to degraded quality and excessive quantity of stormwater and resulting impacts on downstream water bodies may require a watershed approach to management rather that the incremental approach that is now common. Examination of low-relief watersheds characteristic of the southeastern coastal plain reveals common hierarchical patterns of surface water convergence that may be emulated in developed watersheds to enhance the efficacy of peak-flow attenuation and pollutant removal. A dynamic systems model was developed to compare stormwater management using a hierarchical network of treatment wetlands with the standard incremental approach wherein treatment systems are designed considering only site-level effluent criteria. The model simulates watershed hydrology, suspended sediment transport and phosphorus removal and transformation. Results indicate that watershed planning of stormwater collection and treatment systems using hierarchical networks can greatly enhance overall effectiveness (annual retention improvements of 31% for flow, 36% for sediment and 27% for phosphorus) with respect to an equal area of uniformly sized wetlands. Further, network proportions can be adjusted to specific runoff characteristics. Distinct roles were observed for each wetland size class: small headwater wetlands effectively removed sediment, medium-sized mid-reach wetlands retained phosphorus, while large wetlands primarily stored and attenuated long-period hydrologic flows.

1. Introduction

Stormwater runoff is considered the major threat to aquatic ecosystem health in the United States (Olson, 1993; USEPA/USDA, 1998). Numerous techniques have been devised for attenuating hydrologic flows and removing contaminants from urban and agricultural runoff, but the major constraint continues to be diffuse delivery, which necessitates extensive regional infrastructure, large capital investments, and intensive management. This problem will increasingly require planning at the watershed scale in order to efficiently protect aquatic resources (Loucks, 1990; Mitsch, 1993; Black, 1997; Carle et al., 2005). This paper describes use of simulation modeling to explore conceptual patterns of stormwater treatment system design at the watershed scale.

Using wetlands – both natural and man-made – for capturing stormwater runoff and pollutants, has emerged from an understanding of the role wetlands naturally play in landscapes (Ewel and Odum, 1986; Mitsch and Gosselink, 1993; Leibowitz et al., 2000). Specifically, wetland stormwater treatment areas (WSTAs) can provide the services of water storage and peak-flow attenuation (Ogawa and Male, 1986; DeLaney,

* *Corresponding author at*: Forest Water Resources Laboratory, School of Forest Resources and Conservation, PO Box 110410, University of Florida, Gainesville, FL 32611-0410, United States. Tel.: +1 352 846 3490; fax: +1 352 846 1277.
E-mail address: mjc@ufl.edu (M.J. Cohen).

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1995), nutrient cycling and burial (Richardson, 1985; Reddy et al., 1993), metal sequestration (Thurston, 1999; Odum et al., 2000), sediment settling (Kadlec and Knight, 1996), and breakdown of organic compounds (Nix et al., 1994; Knight et al., 1999). Numerous authors have highlighted constraints, benefits, and design considerations for using wetlands to treat stormwater (Loucks, 1990; Stockdale, 1991; Rushton et al., 1997) and enhanced stormwater treatment basins exist where ecological and treatment objectives are simultaneously met (Knight, 1996; Otto et al., 2000).

Stormwater management is typically achieved incrementally (i.e., on a site-by-site basis—Emerson et al., 2005), with little attention paid to larger scale hydrologic organization that exists in all landscapes shaped by water. The common result is watersheds that lack the characteristic hierarchical hydrologic convergence found in undeveloped basins (Sullivan, 1986; Ogawa and Male, 1986; Loucks, 1990). Our hypothesis, after examining hydrologic convergence patterns found in undeveloped watersheds, is that stormwater management systems might be improved by emulating these patterns. Watershed scale planning (USEPA/USDA, 1998) warrants explicit attention to these larger scale patterns. In particular, siting and sizing stormwater treatment areas for regional management of runoff has garnered attention (Palmeri and Bendoricchio, 2002); recent work using spatial models to site treatment areas (Zhen et al., 2004; Newbold, 2005) could be used in concert with conceptual planning tools like the one we propose in this study to optimize watershed-scale runoff control system design.

Several authors have explored the role of wetland size and location on treatment. Loucks (1990) suggests small wetlands should be the focus of hydrologic restoration because they have been extensively removed from the landscape, further arguing that upstream erosion and flooding would be poorly addressed by large terminal treatment wetlands. Van der Valk and Jolly (1992) suggest that small headwater wetlands will most effectively intercept agricultural pollutants. Mitsch (1993) analyzed implementation costs of large, downstream wetlands versus small, headwater wetlands and concluded that smaller wetlands were more flexible and less expensive. In contrast, Ogawa and Male (1986) used simulation models to show that large downstream wetlands were most effective at attenuating peak basin outflow conditions, and that benefits of flow impedance were highly localized, with negligible effects observed a few miles downstream. We examine the synergistic effects of multiple size classes of WSTAs on watershed discharge.

Previous work (Tilley and Brown, 1998) focused on the role of three size classes of WSTAs separately. They suggest, based on area requirements for meeting target outflow criteria, that treatment function is scale-dependant: small wetlands sequester P, medium wetlands capture sediments and large wetlands attenuate water flows. Complementary roles suggest increased effectiveness if different sizes are used concurrently.

Wetland arrangement in a regional network can borrow from convergence characteristics observed in undisturbed basins. Sullivan (1986) analyzed low-relief watersheds in Florida and observed a hierarchical arrangement of wetlands (Fig. 1). Fig. 2A shows the distribution of wetland size in four low-relief watersheds in Florida. Fig. 2B shows mean location

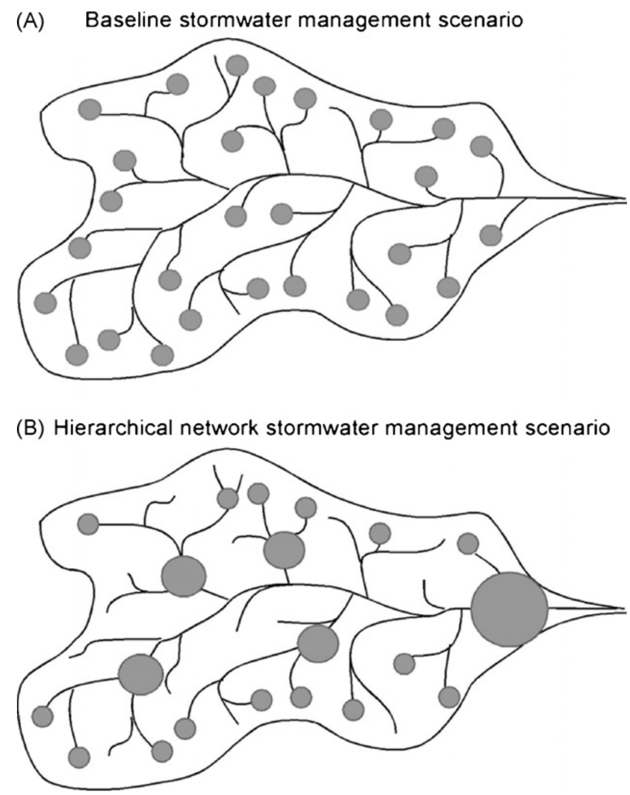

Fig. 1 – Schematic of landscapes arranged with (A) small wetlands only (baseline scenario) and (B) with hierarchical network of wetlands (network scenario).

and variance, measured as distance from watershed outlet, for each size class. Small wetlands are distributed throughout, but are the dominant size class in headwater regions. Medium wetlands (sloughs/riparian systems) were centrally located, converging flow to a few large wetlands in the lower reaches of watersheds (coastal wetlands and extensive bottomlands). Morphologically, small wetlands correspond to isolated wetlands, medium wetlands correspond to conveyance wetlands—riparian systems or sloughs, and large wetlands are regional receiving systems (coastal or bottomland).

While there is no direct evidence to suggest that wetlands are hierarchically organized in undisturbed landscapes to maximize pulse attenuation of water, nutrients or sediments, it is our hypothesis that emulating the observed spatial hierarchy for WSTAs will improve stormwater discharge properties in urbanizing watersheds in comparison with an incremental approach wherein hierarchical hydrologic convergence is ignored. We explore this hypothesis using a theoretical process-based systems simulation model.

2. Study site

Improving water quality entering Biscayne Bay from the low-relief watersheds on the Atlantic Coastal Ridge in Dade County, Florida (Fig. 3) was the focus of this work. Water management in the region is complex due to the network of canals and control structures, and the absence of topography