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WATERSHED SCIENCE BULLETIN

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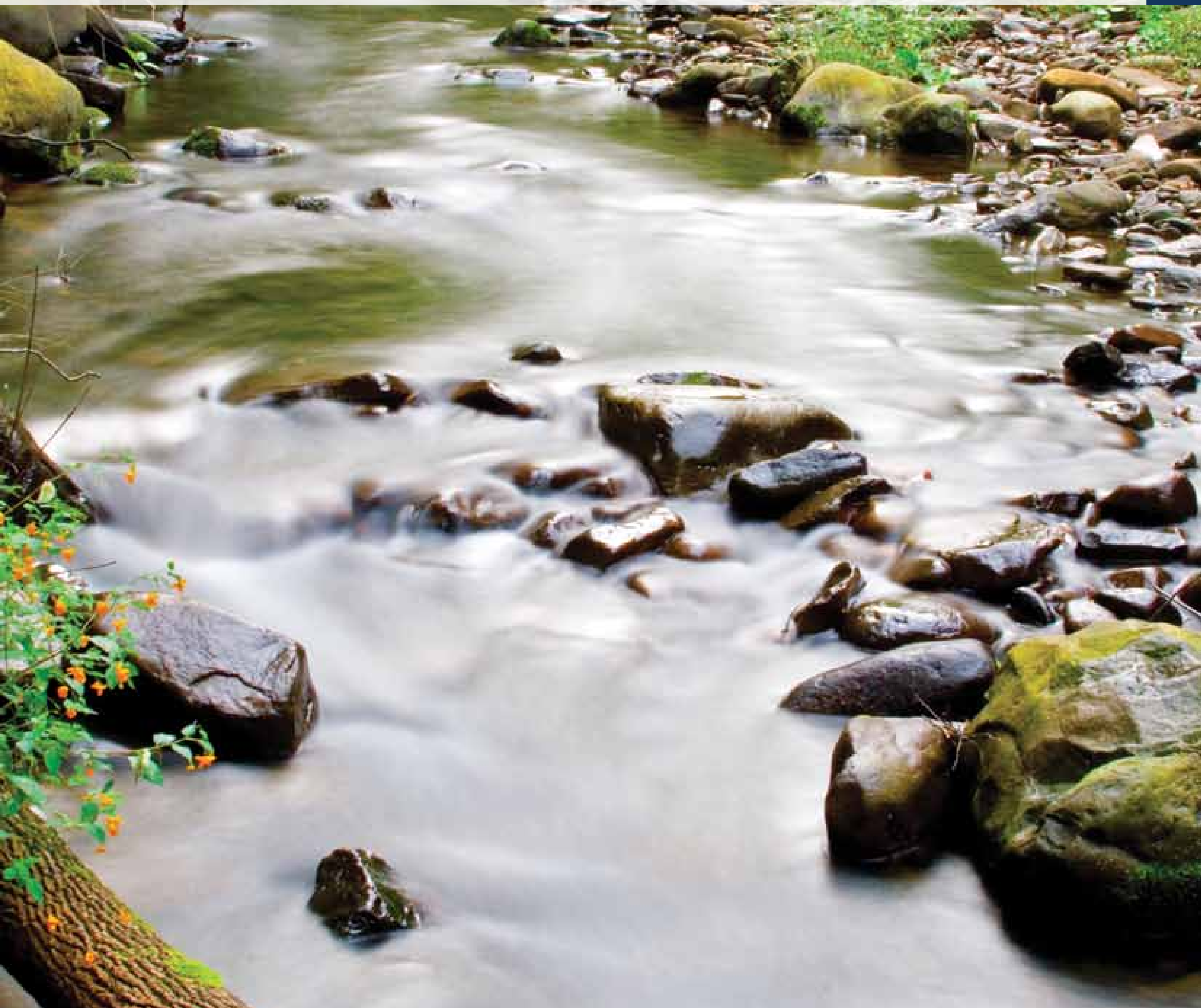
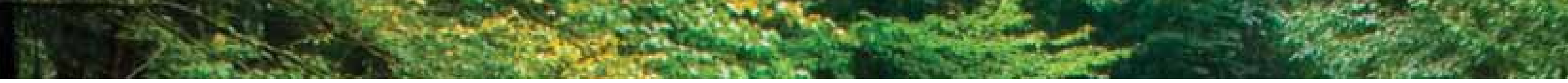


Total Maximum Daily Loads (TMDLs)

Innovations and Implementation



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Cover photo courtesy of Bryan Seipp (www.btseippphotography.com), Watershed Manager, Center for Watershed Protection
This photo was taken along Pocono Creek in Monroe County, PA, near Camelback Mountain. Like many streams in Pennsylvania, it is dominated by a forested watershed and provides critical habitat for trout populations. Some tributaries in the Pocono Creek watershed qualify for the highest level of water quality protection under Pennsylvania regulations. Population growth and the resulting urbanization and hydrologic changes are a threat to the health of the watershed.

TMDLs: Improving Stakeholder Acceptance with Science-Based Allocations

Jason A. Hubbart,[a] John Holmes,[b] and Georganne Bowman[c]*

Abstract

Although mitigating water quality impairment through total maximum daily load (TMDL) implementation can sustain natural resource commodities and development practices, it is challenging. Research-based land use planning can substantially reduce or eliminate error in TMDL decision-making processes while improving stakeholder acceptance. To address water quality issues in the central United States, the Hinkson Creek watershed was equipped with state-of-the-art monitoring instrumentation in 2008. Results from this and similar studies will support future urban development by validating engineering strategies that may overlook land use, topography, and site-specific development constraints.

Introduction

Pollution of streams, lakes, and other surface waters is a greater issue for society than ever before. The successful restoration of water quality in impaired watersheds requires an understanding of the interconnections between hydrology, climate, land use, water quality, ecology, and socioeconomics. Current understanding of these interactions is limited primarily by a lack of innovation, investment, and interdisciplinary collaboration. Pollution from diffuse sources is most often driven by meteorological events (i.e., precipitation). Pollutant loadings from a given watershed are correlated with rainfall volume, infiltration, runoff, and storage characteristics (Novotny and Olem 1994). Hydrologic modification resulting from development can increase or decrease diffuse pollution loads, illustrating the need to quantify the pollutant-transporting mechanism(s) and consider the various pathways by which contaminants may travel from source areas to receiving water bodies. In Missouri, more than 150 water bodies have been identified as impaired or limited for a variety of beneficial uses since 2000. This figure is 15% higher than the national average of 25% freshwater impairment in a given state. This is particularly important considering that Missouri is one of nine central US states that contribute more than 75% of upland nitrogen and phosphorus to the Gulf of Mexico (Alexander et al. 2008).

Given the complexity of climate stochasticity and landscape interactions, not surprisingly, meeting water quality goals such as total maximum daily loads (TMDLs) is a challenge, particularly in rapidly urbanizing watersheds where jurisdictions must also meet the US Environmental Protection Agency's (USEPA) National Pollutant Discharge Elimination System (NPDES) requirements. Often, the information necessary to accurately estimate and model rainfall and runoff relationships and to calculate accurate stormwater flow is not available, making it difficult for stormwater managers to make the best management decisions. Faced with the lack of information and the scope of NPDES program requirements, stormwater managers struggle to predict the effect of local ordinances on water quality and receiving water bodies. While scientifically validated TMDLs can energize a community, the opposite may be true in watersheds implementing mandated TMDLs that lack substantive information, data, and validation. Unfortunately, states under pressure from federal mandates and limited by staff expertise are instituting such incomplete TMDLs. With these complications in mind, this article supplies a possible avenue forward (i.e. science-based decision making) towards ameliorating complex contemporary TMDL allocations.

A common strategy for estimating TMDL allocations for urban watersheds is to use flow as a pollutant surrogate. One method used to calculate a flow-based TMDL, flow duration analysis, is generally intended to set stormwater volume reductions for the impaired stream by estimating predevelopment flow conditions (USEPA 2007a). Unfortunately, the method often fails to account for many local watershed process interactions among topography, soils, development, imperviousness, and legacy effects persisting from previous agriculture and/or development. Addressing such interactions is critical to the quantifiable validation of land use effects on runoff processes (Hibbert 1966; Stednick 1996; Hubbart et al. 2007). As a result of the disconnect, instead of working toward a common objective, state and federal regulators and municipalities vehemently debate the efficacy of volume reductions to achieve water quality standards, the cost of implementation, and the potential harm that single flow criteria could exact on watershed form and function. Recently, the Vermont Department of Environmental Conservation (VT-

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DEC) established a TMDL wasteload volume reduction requirement of 16% for high flows and an increase of 11.2% for base flow for Potash Brook, an 18.47-km^2 watershed in Vermont (VTDEC 2006). Current estimates to achieve a 16% and 11.2% flow alteration include extensive retrofits at a cost of $25.5 million (VTDEC 2010). Considering the amount of taxpayer investment in TMDL mandates such as Potash Brook, demand is increasing for the thorough evaluation and validation of TMDL estimates prior to implementation. A viable solution lies in formal research methods that result in accurate hydrographs that better reflect local watershed process interactions and thus produce more accurate flow duration estimates.

Hydrograph analysis is one of many methods for analyzing land use, surface runoff and flow relationships (Viessman and Lewis 2003). Methods of hydrograph estimation range from direct measurement (i.e., automated or manual streamflow measurements over time), to model-generated hydrographs (USEPA 2007b) and unit hydrograph methods (Sherman 1932), which synthesize hydrographs from rainfall. Seminal hydrograph work by Seaburn (1969) demonstrated dramatic alterations in urban settings, where runoff was as much as 4.6 times greater than runoff prior to urbanization. Deriving methodologies of hydrograph estimation and synthesis is beyond the scope of this article. However, it is worth noting that direct measurement will almost always result in the most accurate TMDL estimates. While direct measurement is expensive in terms of instrumentation and labor, if a study is designed correctly (e.g., nested-scale and paired watershed study designs; Clausen and Spooner 1993; Hewlett and Pienaar 1973), results are often scalable and transferrable. It is therefore critical to support properly designed regionally representative watershed studies and to avoid scattered investments in various landscapes (i.e., a "shotgun" approach), which can cost millions of taxpayer dollars but never supply the data sets necessary to estimate an accurate TMDL. Projected future increases in urbanization necessitate research investigations to better understand development impacts at the watershed scale (Nowak and Walton 2005; Wolf and Kruger 2010).

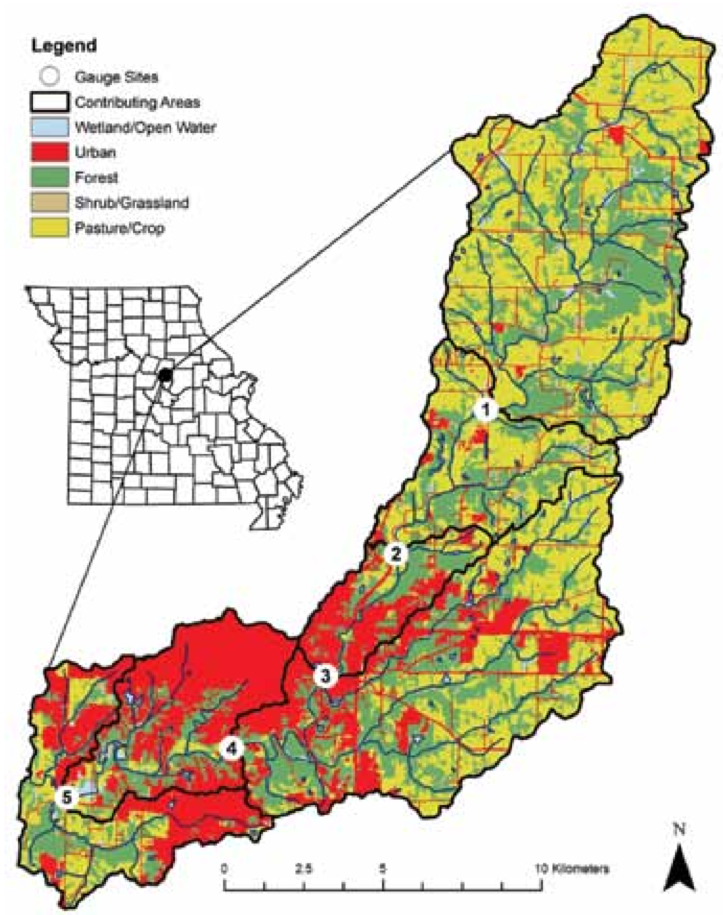

Figure 1. Locations of gauge sites (where #4 includes the USGS gauging station) in the Hinkson Creek watershed in central Missouri, USA. The 16 classes of 30-m resolution land use/land cover defined in the National Land Cover Database (NLCD) 2001 were combined to form the five generalized classes shown here. NLCD 2001 is based on Landsat Thematic Mapper imagery dating from 2001 and was produced by the Multi-Resolution Land Characteristics Consortium, a collaboration among multiple US federal agencies (NLCD 2001).

An Emerging Case Study: The Hinkson Creek Watershed

The Hinkson Creek watershed (HCW), located within the Lower Missouri–Moreau River basin (LMMRB) in central Missouri (Figure 1), encompasses approximately 231 km^2, ultimately draining to the Missouri River. Urban areas are primarily residential with progressive commercial expansion from the city of Columbia (population 90,000). Land use in the watershed is approximately 34% forest, 38% pasture or cropland, and 25% urban area. The remaining land area is wetland, open, or shrub/grassland areas (Table 1).

The Missouri Department of Natural Resources (MDNR) targeted a portion of the LMMRB as critical for controlling erosion and nonpoint source pollution in 1998 (MDNR 2006). Watershed restoration efforts in the LMMRB were accelerated by mandates of the Clean Water Act (CWA) and subsequent lawsuits. HCW is representative of the LMMRB with respect to hydrologic processes, water quality, climate, and land use and was one of the first water bodies in Missouri to be placed on the CWA 303(d) list. The impaired use for Hinkson Creek is "protection of warm water aquatic life" from unknown pollutants with the source attributed to urban runoff (MDNR 2006, 4). In such cases, it is not uncommon to calculate a reduction in stormwater runoff as a surrogate for any pollutants of concern. USEPA has approved this approach for many states, as supported by the federal rule for TMDL development, 40 CFR 130.2(i). Estimating a TMDL is therefore a reasonable goal in the HCW. However, translating pollutant loading to specific land uses to validate the assumption that reducing flow will reduce pollutants is a difficult task without understanding water and pollutant transport at multiple locations throughout the watershed (Tim and Jolly 1994; Frankenberger et al. 1999). Furthermore, relating aquatic biological health to pollutant loading adds an additional layer of complexity to the task of resolving potential water quality impairment.

To generate data that address these uncertainties while providing a scientific basis for developing the TMDL target, the watershed was equipped with state-of-the-art instrumentation in fall 2008. The project is designed to supply quantifiably validated scalable and transferrable results. Instrumentation is complemented by a US Geological Survey gauging station (USGS-06910230) that has collected data intermittently since 1966. Five fully equipped hydroclimate stations, including the USGS station, are co-located along Hinkson Creek following a nested-scale watershed study design (Figure 1). Each fully automated gauging station monitors water depth, suspended sediment (using laser-based, in situ particle analyzers), and a complete suite of climate variables. Water samples are collected for analyses of total nitrogen (nitrate, nitrite, and ammonia), phosphorus, chloride, pH, and many other constituents. The project, currently in its second successful year, will soon begin to generate the information necessary to produce validated TMDL estimates of the above-listed constituents. With as little as four years of data collection, it is anticipated that the project will generate the information necessary to quantify cumulative effects as well as comparisons of land use types. This information will be used by policy-makers to improve current and future TMDL efforts in the watershed.

Table 1. Cumulative contributing area and corresponding land use areas for each of five hydroclimate gauging sites located in the Hinkson Creek watershed in central Missouri, USA.

Component Sub-Watersheds	Total Area (km2)	Wetland/Open Water (% Area)	Urban (% Area)	Forest (% Area)	Shrub/Grassland (% Area)	Pasture/Crop (% Area)
Site 1	77	2	5	36	2	55
Site 2	101	2	6	36	2	54
Site 3	114	2	11	36	2	49
Site 4	180	2	16	36	1	44
Site 5	206	2	23	34	1	39
Entire HCW	231	2	25	34	1	38

Discussion

Volume-based approaches, a current trend of stormwater management and stream corridor protection, are encouraged by USEPA and the National Research Council (2008) for the mitigation of problems with water quality, instream biota, low flow, groundwater recharge, stream temperature, and channel stability. Volume-based approaches can be more effective than traditional peak flow–based detention because they do not create the extended durations of elevated flow that are typical with traditional detention. However, some of these problems can be exacerbated by poorly designed volume-based solutions. For example, if streamflow during moderately sized events is reduced by increased retention but pollutant loading is not, an increase in pollutant concentration could result. Likewise, if volume reductions are so successful that some stream reaches support flow only during large events, streams could become clogged with debris and sediment.

In a complex watershed such as the HCW, where significant fractions of the watershed have been influenced by agriculture for a century, urbanization for half a century, and ongoing development, it is difficult to predict the extent of stream system adaptations to previous impacts. Although indications of reductions in stream health in highly urbanized HCW subcatchments are clear (MDNR 2006, 2010), no mitigation strategy yet found is likely to restore the health of such streams (Booth et al. 2004). Previous studies indicate that it is not uncommon for streams to have adapted to urbanization that occurred more than 20 years ago (Finkenbine et al. 2000; Henshaw and Booth 2000). Thus, stream systems of the Midwest could have adapted to agricultural activities that have been ongoing for the past century. In that case, reversion of the hydrologic regime to predevelopment conditions could destabilize the stream. Whether this is a wise strategy in contemporary watersheds is worthy of substantial investigation.

In addition, it remains unclear whether a one-size-fits-all flow reduction solution is possible. Some authors (e.g., Brown 2010; McCuen and Davis 2010) have asserted recently that returning to predevelopment runoff conditions to meet TMDL objectives is not as simple as one might assume. Previous studies showed that much can be learned from replicated gauging sites with complementary long-term time series data about land use effects on the hydrologic regime (Hibbert 1966; Stednick 1996; Hubbart et al. 2007). Therefore, the establishment of an urban experimental watershed like the HCW, which encompasses the majority of land uses, will help us to better understand, quantifiably, how urban development is changing the flow regime.

A volume reduction target of approximately 50% was recently set for the HCW in the wasteload allocation (WLA; MDNR 2010). The WLA runoff reduction is required to come from existing urban and developed areas, and the load allocation must come from agricultural and open areas. Although the extent of agricultural and open areas in the basin is more than twice that of urban and developed areas, each type of area is required to contribute approximately half of the total reduction. This is not an unusual approach in developing urban watersheds. Given this scenario, if policies disallowed increased runoff from future development, municipalities would need to find a way to reduce runoff from the existing developed area by 50% to meet the WLA. Therefore, to meet the TMDL requirements, the municipality will need to encourage landowners to retrofit existing development to capture 50% of current runoff volumes. Notably, the 50% volume reduction target for the HCW was set using USGS data alone. The current study is collecting data at multiple sites simultaneously; researchers of the Interdisciplinary Hydrology Laboratory (IHL) of the University of Missouri will use these data to validate and refine the current TMDL target. Published study results will be used by MDNR, Boone County, and the City of Columbia to revise TMDL policy.

Current local (city and county) policies require that developed areas undergoing redevelopment must address stormwater quality and peak flow for newly added impervious area plus a proportion of existing impervious area. Design challenges in reducing runoff include stormwater storage space allocations (i.e., retention facility space), conveyance to treatment facilities, stormwater release rates and timing, maintenance, and design and regulation conflict resolution. These challenges exist both for newly developed sites and for retrofitted sites but are intensified on retrofit projects where constraints are generally more stringent. The National Research Council (2008) recently found that redevelopment primarily occurs in areas that are (a) already challenged by medium to high levels of imperviousness, (b) space limited, and (c) high-value properties. These complexities drive up the costs of stormwater runoff mitigation. It may therefore be argued that holding developers in high-development areas to standards equal to those of *greenfield* (i.e., previously undeveloped) developments is a financial disincentive for redevelopment. Ultimately, without careful planning, stormwater and volume-based reduction requirements may discourage redevelopment in areas where it should be occurring—in already developed urban areas.

…much can be learned from replicated gauging sites with complementary long-term time series data about land use effects on the hydrologic regime

Another design challenge is that not all development situations are appropriate for infiltration mitigation. For example, many of the soils in the HCW and in northern Missouri generally have a relatively strong shrink and swell potential, as shown through an analysis by the Boone County Soil Survey (US Department of Agriculture 1997) and the University of Missouri's Center for Applied Research and Environmental Systems (CARES) watershed evaluation tool (CARES n.d.) for the HCW (HU 1030010206). These sources indicate that 84% of the soils in the HCW are classified as moderate to very limited for use as building sites because of the shrink and swell potential. Therefore, it would be inappropriate to intentionally introduce water into these soils if they are serving as the base for pavement. Based on research reported by North Carolina State University (Hunt and Collins 2008), USEPA (n.d.) acknowledged the need to use an impermeable liner when placing permeable pavement on soils with shrink and swell potential. In general, soils with limited infiltration capacity or a need for impermeable liners could be problematic for flow reduction regulations that assume increased groundwater recharge with increased detention.

Ultimately, without careful planning, stormwater and volume-based reduction requirements may discourage redevelopment in areas where it should be occurring—in already developed urban areas.

Stormwater storage for later use is currently a preferred method for reducing runoff volume. Although this method can be effective, it presents other challenges that limit its applicability to existing development. Challenges include water conveyance to storage and reuse areas, space allocations, and management of the storage volume to maximize the availability of useable water while ensuring that the storage volume is available when a storm event occurs. The challenges are often not insurmountable but, at a policy-making level, the realities of accomplishing significant reductions in stormwater volume are often overlooked. For example, to store the excess stormwater runoff from a water quality design storm of 3.3 cm (1.3 in) for a typical 186-m^2 (2,000-ft^2) home in central Missouri, 22 standard 55-gallon rain barrels would be required. A more reasonable solution might be to use four rain barrels, one at each corner of the house; this setup would allow storage of the excess runoff from a 0.94-cm (0.37-in) storm. This is a worthwhile approach but would not come close to meeting a typical requirement to manage 90% of annual runoff. Ultimately, lacking incentive, relatively few homeowners are likely to install four rain barrels, the barrels may be partially full when storm events occur, and the distribution systems will be far from perfect. Regardless, policy-makers contend that rain barrels will make a significant contribution to achieving a volume-based TMDL. How this would be incentivized has not been resolved.

Problems such as those discussed here are not isolated to the HCW, Missouri, or the United States; instead, they speak to the general potential for excessive optimism regarding the applicability of volume-based flow reduction among policy-makers. Given difficulties in site assessments, development, and flow processes, it is conceivable that inadequately administered TMDLs could result in as many (or more) problems as those that they were created to solve. This further emphasizes the value of properly conducted studies leading to science-based TMDL allocations. The investment in such studies is easily justified by the potential to save millions of taxpayer dollars that might otherwise be wasted on misinformed, unevaluated, and thus ineffective management strategies.

Conclusions

Watershed studies, such as the HCW, using established study design protocols (i.e., nested-scale design) can provide validated data on the relationships between land use, runoff, and water quality to lend support for volume-based TMDLs. Through this and similar studies, state and federal agencies will justify the appropriateness of applying a single volume criterion to an entire watershed or of setting expectations for a return to predevelopment conditions. By means of extensive watershed-scale studies conducted in regionally representative watersheds, scientists can conclusively determine the appropriateness of volume-based approaches and true TMDL pollutant allocations. Because many watersheds have been extensively altered since pre-urban settlement, many urban water bodies have probably experienced a shift in the average magnitude and frequency of high-flow events and pollutant flushing, possibly achieving or approaching new flow and transport equilibria. In watersheds the size of Hinkson Creek, it is imperative that a comprehensive management approach be undertaken to examine not only the volume of water causing impairments, but also the variable-use landscape and the pollution load being transported. In the HCW, this work is timely given the legal mandate to provide quantifiable TMDLs in the watershed. Additional studies will be implemented in the HCW to investigate future management and climate change scenarios. The study is encouraging cooperation, trust, and innovation among watershed stakeholders to reach a common goal of improving and sustaining water quality. In this manner, the HCW serves as a model urban watershed for similar studies.

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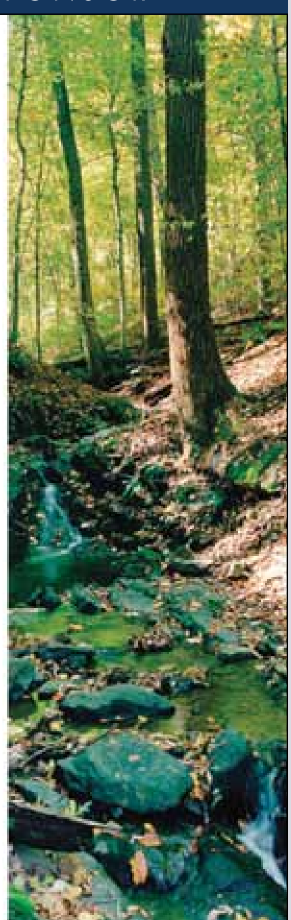

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