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Research article

An urban runoff model designed to inform stormwater management decisions

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ABSTRACT

We present an urban runoff model designed for stormwater managers to quantify runoff reduction benefits of mitigation actions that has lower input data and user expertise requirements than most commonly used models. The stormwater tool to estimate load reductions (TELR) employs a semi-distributed approach, where landscape characteristics and process representation are spatially-lumped within urban catchments on the order of 100 acres (40 ha). Hydrologic computations use a set of metrics that describe a 30-year rainfall distribution, combined with well-tested algorithms for rainfall-runoff transformation and routing to generate average annual runoff estimates for each catchment. User inputs include the locations and specifications for a range of structural best management practice (BMP) types. The model was tested in a set of urban catchments within the Lake Tahoe Basin of California, USA, where modeled annual flows matched that of the observed flows within 18% relative error for 5 of the 6 catchments and had good regional performance for a suite of performance metrics. Comparisons with continuous simulation models showed an average of 3% difference from TELR predicted runoff for a range of hypothetical urban catchments. The model usually identified the dominant BMP outflow components within 5% relative error of event-based measured flow data and simulated the correct proportionality between outflow components. TELR has been implemented as a web-based platform for use by municipal stormwater managers to inform prioritization, report program benefits and meet regulatory reporting requirements (www.swtelr.com).

1. Introduction

1.1. Modeling stormwater impacts and BMPs

Hydrologic impacts associated with urban development are well documented and include declines in downstream receiving water quality (Arnold and Gibbons, 1996; Holman-Dodds et al., 2003; USEPA, 2013). Higher peak flows and increased total stormwater runoff volumes result from the expansion of urban impervious cover that limits the infiltration of rainfall and enhances the entrainment and transport of sediment, nutrients, bacteria, metals, pesticides, and other pollutants (Grove et al., 2001; Tang et al., 2005; USEPA, 2013). As a result of the 1972 Clean Water Act (CWA), the National Pollutant Discharge Elimination System (NPDES) and associated municipal separate storm sewer system (MS4) permits require that stormwater management programs protect downstream surface water quality and reduce pollutant discharge to the maximum extent practicable (USEPA, 2014). Municipalities implement structural controls (or structural best management practices (BMPs)) to reduce runoff and associated non-point source urban pollutant loading to receiving waters through infiltration and treatment of stormwater. These include small-scale decentralized low impact development (LID) and green infrastructure BMPs such as infiltration or bio-retention features, as well as larger scale centralized BMPs such as dry basins or treatment vaults (Brander et al., 2004; Bedan and Clausen, 2009; Gilroy and McCuen, 2009; Ahiablame et al., 2012).

California municipalities and regulators lack a comprehensive approach to prioritize where BMP implementation may have the greatest receiving water benefits and to assess progress towards stormwater and pollutant load reduction goals. Prioritization requires a reliable and consistent way to represent the relevant urban drainage attributes that contribute to runoff production irrespective of natural variability. Water quality monitoring to quantify urban stormwater impacts on receiving waters and runoff

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reduction effectiveness is a common NPDES permit requirement across the United States (e.g., California State Water Quality Control Board, 2013; Maryland Department of the Environment, 2013; State of Washington Department of Ecology, 2013), but there are significant practical challenges to using monitoring data to define priorities or reliably quantify the effectiveness of conservation efforts (Tomer and Locke, 2011). Monitoring costs severely limit the spatial and temporal extent of measurements relative to management information needs for reporting to regulators and making resource allocation decisions (Maheepala et al., 2001). Monitoring designs commonly fail to maximize the ability to detect changes distinct from natural variations (Karr, 1999). One key problem is the lag time between the implementation of BMPs and a measurable response in the receiving waters that can be detected above the hydrologic variability present in a stormwater system (Meals et al., 2010). Since our ability to detect changes in stormwater systems due to management actions is generally poor (Harmel et al., 2006; Rode and Suhr, 2007; Dotto et al., 2014), immediate use of monitoring data to guide implementation decisions and stormwater program adjustments is very limited.

Modeling provides a means to estimate stormwater reduction benefits of structural and non-structural BMPs, and test heuristic management scenarios to inform both short-and long-term stormwater programmatic planning decisions (e.g., Elliot and Trowsdale, 2007; Zoppou, 2001; Lee et al., 2012; Rossman, 2013; Voskamp and Van de Ven, 2015). Estimating event-based loads and concentrations in urban landscapes is complex, with timing that depends on wash-off effects that can vary between storms and even throughout the same storm based on pollutant species and land use (Lee and Bang, 2000). Model representation of such effects via continuous simulation requires data to characterize and parameterize these processes, but these data are generally unavailable or require an expert user to fit the model to observed data.

One would expect that over the long term, effective management actions that minimize runoff volumes and restore natural hydrologic functioning to urban environments will also minimize entrainment and delivery of urban pollutants to receiving waters (e.g., Walsh et al., 2016). Storm flows have been suggested by the National Research Council as a cost effective way to estimate pollutant loading (NRC, 2009) and have been used as a surrogate for pollutant loads in the Eastern US states (EPA Region 3, 2003). Given strong empirical associations between long-term urban pollutant loading, precipitation factors and drainage areas (Brezonik and Stadelmann, 2002), a simple approach that adequately characterizes precipitation and urban drainage conditions can help municipalities to comply with the statutory requirements of the CWA.

1.2. Study setting and objectives

In this paper we present a practical stormwater runoff model, the Tool to Estimate Load Reductions (TELR) specifically designed to be used by stormwater managers to inform annual program decisions and estimate the effectiveness of stormwater management actions across a municipality year after year. We compared TELR outputs with measured data from continuously monitored urban catchments in Lake Tahoe, California, as well as SWMM-based continuous simulation models to assess its adequacy as a planning tool. Runoff from urban catchments are a key driver of clarity loss in Lake Tahoe which threatens the aesthetics of this large subalpine ultra-oligotrophic lake (Schuster and Grismer, 2004); and stormwater managers are tasked with demonstrating progress towards runoff and pollution reduction goals. While only the hydrologic basis of the model is presented here, it should have direct utility for estimating long-term urban catchment pollutant loads by coupling runoff outputs with a basic pollutant module (such as the Simple Method of Schueler, 1987). Our approach simplifies the details of event-based process representation to align with the data commonly available to stormwater managers (the intended model users) and avoids site specific calibration required with most empirical and numeric approaches which adds to modeling costs and often introduces additional uncertainty to runoff estimates.

We defined the first study objective in terms of annual runoff simulation performance: *1) Achieve adequate performance relative to measured catchment flows and produce comparable estimates to continuous simulation models.* Fit with the observed data was judged relative to a number of metrics that reflect different aspects of model performance. To reliably quantity stormwater reductions, modeled structural BMP flow components should exhibit significant responses to changes in BMP inputs that match our understanding of BMP function and observed measurements of infiltrated, treated, and bypassed flows. Thus, we defined the second study objective relative to BMP simulation: 2) *Assess the ability of TELR to quantify BMP performance* via *runoff sensitivity to BMP inputs and comparisons with observed BMP data.* Sensitivity was quantified by the significance of the regression slope coefficient between BMP inputs and runoff component outputs, and correspondence with the observed data were judged based on relative percent error.

1.3. Model alignment with management needs

The intended use of model outputs should ultimately guide model selection and the necessary degree of model complexity (Leavesley et al., 2002) and the least complex model that reliably meets the anticipated application is often preferable (Chandler, 1994; Rauch et al., 2002; Dotto et al., 2012). While detailed representation of physical hydrologic processes within continuous simulation models can improve simulation performance, this model performance comes at the expense of greater structural complexity, particularly in the case of spatially distributed models (Snowling and Kramer, 2001), without necessarily increasing the usefulness of outputs (Lindenschmidt, 2006). Inclusion of extraneous model components or parameters that do not result in a measurable output response may improve simulation performance, but can also make a model less useful for discerning hydrologic changes in a catchment over time (Beven, 2001; Nandakumar and Mein, 1997), or testing heuristic management scenarios (Freni et al., 2011). In relatively complex model alternatives, such as the widely used Storm Water Management Model (SWMM), there are numerous free parameters that usually require user calibration, while only a few input variables may contribute significantly to the outputs (Li et al., 2014). Over-parameterization results in a high degree of uncertainty in the model outputs due to subjective decisions required during the calibration process (Beven, 1989, 2001) of parameter values that may vary over time and space (Hossain and Imteaz, 2016). Even where good hydrological data are available, they are probably only sufficient to support reliable calibration of models of very limited complexity (Jakeman and Hornberger, 1993; Gaume et al., 1998).

Overly burdensome input data requirements for setup, calibration, and validation of models are a barrier for use by stormwater managers, who are often not modeling specialists. Most available stormwater modeling tools are either intended exclusively for expert users (e.g., Atchison et al., 2012), or do not provide an efficient method for modeling multiple catchments or generating spatial outputs (e.g., Rossman, 2013; Tetra Tech, 2011). Simpler approaches to hydrologic modeling may provide comparable performance to more complex ones for certain applications (e.g., Kokkonen and Jakeman, 2001; Perrin et al., 2001; Bormann and Diekkruger, 2003; Reed et al., 2004). Indeed, with the inclusion of