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Managing Uncertainty in Runoff Estimation with the U.S. Environmental Protection Agency National Stormwater Calculator†

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Abstract

The U.S. Environmental Protection Agency National Stormwater Calculator (NSWC) simplifies the task of estimating runoff through a straightforward simulation process based on the EPA Stormwater Management Model. The NSWC accesses localized climate and soil hydrology data, and options to experiment with low-impact development (LID) features for parcels up to 5 ha in size. We discuss how the NSWC treats the urban hydrologic cycle and focus on the estimation uncertainty in soil hydrology and its impact on runoff simulation by comparing field-measured soil hydrologic data from 12 cities to corresponding NSWC estimates in three case studies. The default NSWC hydraulic conductivity is 10.1 mm/h, which underestimates conductivity measurements for New Orleans, Louisiana (95 ± 27 mm/h) and overestimates that for Omaha, Nebraska (3.0 ± 1.0 mm/h). Across all cities, the NSWC prediction, on average, underestimated hydraulic conductivity by 10.5 mm/h compared to corresponding measured values. In evaluating how LID interact with soil hydrology and runoff response, we found direct hydrologic interaction with pre-existing soil shows high sensitivity in runoff prediction, whereas LID isolated from soils show less impact. Simulations with LID on higher permeability soils indicate that nearly all of pre-LID runoff is treated; while features interacting with less-permeable soils treat only 50%. We highlight the NSWC as a screening-level tool for site runoff dynamics and its suitability in stormwater management.

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Keywords

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Introduction

Urban landscapes present the ongoing challenge of dealing with stormwater runoff volume generated from impervious surfaces (Arnold and Gibbons, 1996; Lee and Heaney, 2003; Shuster *et al.*, 2005; Gilbert and Clausen, 2006; Chen *et al.*, 2017). The advent of green infrastructure (GI) for stormwater management marks a transition from centralized wastewater-stormwater collection systems that route runoff into gray infrastructure (Delleur, 2003; Cherrier *et al.*, 2016), to decentralized low-impact development (LID) and GI techniques that are placed to manage and detain runoff at the scale of a residential or commercial parcel (Parikh *et al.*, 2005; Jarden *et al.*, 2016; Shuster *et al.*, 2017). The overarching philosophy of GI and LID entails mitigating against runoff formation (as infiltration-excess, or saturation-excess mechanisms), and retaining runoff volume as close to its point of generation as possible. Some examples of LID and GI include: maintaining active arbors and vegetation to maximize evapotranspiration (ET) during the growing season; removing impervious surface and restoring infiltration opportunities; disconnecting directly connected impervious surface from the collection system with interspersed pervious areas; or a combination of any or all of these approaches (Green *et al.*, 2016; Lim, 2016; Schifman *et al.*, 2016; Fry and Maxwell, 2017; Schifman *et al.*, 2017). The overall objective of GI management is to keep excess stormwater runoff volume from entering the local wastewater collection system where surcharges can cause combined, septic, or both types of collection system overflows.

In particular, runoff from residential and commercial parcels and properties can constitute a considerable proportion of stormflow volume, yet holds much potential for management with LID and GI techniques applied to parcels, neighborhoods, and in right-of-way areas (Green *et al.*, 2012; Shuster and Rhea, 2013; Herrmann *et al.*, 2016; Jarden *et al.*, 2016; Schifman *et al.*, 2016; Shuster *et al.*, 2017). Any type of GI installation is a hydrologic intervention, and more often than not, requires hydrologic modeling to support the planning and design process. Beyond establishing a range of variability in runoff volume, accurately estimating the effect of GI-LID on even a small site is difficult without a model that is representative of the hydrological conditions within the area of interest. Approachable and easy-to-use hydrologic modeling tools may also promote a better understanding of runoff management issues by the public, and enhance the capacity of stakeholders to visualize the benefits of LID practices toward stormwater control. While such tools should not require specialized modeling skills (*e.g.*, those required to set up simulations in the U.S. Environmental Protection Agency (USEPA) Stormwater Management Model (SWMM) or similar), they provide opportunities for simplified LID screening approaches, and bridge the gap between a broad user community and a simulation that can estimate runoff volume (Table 1). These tools have been developed using a combination of different computational platforms and rainfall-runoff modeling approaches that generally rely on empirical methods

(*i.e.*, Rational Method, NRCS Curve Number) to generate runoff volume. Yet, none of these runoff estimation methods can be implemented to explicitly account for the rainfall forcing and soil hydrologic factors that regulate the production of urban stormwater runoff, much less in a standardized manner across the conterminous United States (U.S.) and Puerto Rico.

The National Stormwater Calculator (NSWC) was developed by the USEPA in response to requirements for a user-friendly, calculator-type, modeling tool that provides an authentic representation of the hydrologic processes which drive the formation of stormwater runoff volume, and visualizes options for runoff management. In this context, the NSWC is a consolidation of SWMM (Rossman, 2015). Multiple existing hydrologic models and tools were evaluated before choosing SWMM as the backend hydrologic model for the NSWC (*e.g.*, CNT Green Values Calculator, Virginia Runoff Method, TR-55-SCS Curve Number Method, Hydrological Simulation Program-Fortran, Western Washington Hydrology Model, L- Long Term Hydrologic Impact Analysis, and WERF Select). However, these other models either required calibration efforts beyond the scope of most applications the NSWC is intended for, were too simplistic for accurately estimating pre-development versus post-development runoff depth, or did not offer a comprehensive environment for visualizing LID-GI management. Since SWMM is commonly used at the sub-catchment scale to estimate surface runoff from small urban development sites, its core simulation environment was pared down to provide planning-level approximations of stormwater runoff, and integrate existing SWMM representations of LID and GI practices (Lee and Heaney, 2003).

The NSWC has four main objectives, which are to: (1) develop a user-friendly application with a “wizard”-type guided user interface, (2) balance sufficient detail and automation of parameter selection with usability among individuals with varying technical backgrounds; (3) bundle this application with actual maps (to locate the area of interest), and standardized data for site-specific rainfall, soil hydrology, and regional LID-GI cost data; and (4) to assist the EPA National Water Program in evaluating and activating the potential for post-construction or retrofit LID or GI to control stormwater runoff volume. In this paper, we describe the features and limitations of standardized data and NSWC functions as a screening-level hydrologic simulation tool. While rainfall record, ET, and soil hydrology parameters are particularly sensitive to poor estimation (Beven, 1989; Herbst *et al.*, 2006; Pataki *et al.*, 2011; Litvak *et al.*, 2017), we focus our efforts on identifying soil hydrology as a major influence on simulation skill and model uncertainty, and present a parcel-level case study that clarifies how SSURGO soil hydrologic parameters compare with actual measured estimates. We then conclude with an overview of new NSWC features that expand on its current utility.

How does the National Stormwater Calculator Work?

The NSWC is currently run as a downloadable desktop application (<https://www.epa.gov/water-research/national-stormwater-calculator>, accessed June 6, 2017) that can be used to estimate annualized depth and frequency of runoff flow for locations in the U.S., including Puerto Rico. The calculator starts with site selection, ideally for sites smaller than 5 ha. It then relates historic rainfall and potential ET data, and uses the primary drivers of land

cover, topography, and local soil hydrologic conditions to regulate the conversion of rainfall into runoff based on the Green-Ampt infiltration rate model (Rossman, 2013).

With its straightforward user interface, the abstraction of hydrologic processes simulated by the NSWC are geared to site developers, landscape architects, urban planners, and homeowners.

NSWC Parameterization, Background and Estimation

In this section, we expand on the NSWC user manual and discuss how different parts of the hydrologic cycle contribute to estimating runoff. We briefly explain the different functions of the model as implemented in SWMM, point out where processes have been adapted from another model (SWAT, Soil Water Assessment Tool) (Arnold *et al.*, 1994), and more specifically, identify limitations on how the NSWC handles the urban environment.

Rainfall Variability—The NSWC presents runoff depth and intensity estimates for storms with recurrence >5-years; higher frequency storms are presented as the estimated annual runoff volume and recurrence. In keeping with the objectives of reasonable detention capacities for LID and GI, emphasis is placed on the assessment of the most frequent storms with lower total depths. It is well-established that measurement accuracy for rainfall is affected by distance and density of gages, gage type and adherence to a calibration schedule, landscape topography, microclimate, among other influences on gage catch (Faures *et al.*, 1995; Wood *et al.*, 2004; Price *et al.*, 2014). The NSWC attempts to moderate bias due to spatial and temporal variability by accessing local data sources (*e.g.*, airports, wastewater treatment plants, *etc.*).

Losses by Evaporation, Transpiration—Since SWMM is limited to estimation of evaporation (only) losses, the Penman-Monteith approach as implemented in SWAT was directly adopted to estimate potential evapotranspiration (PET) in the NSWC (Neitsch *et al.*, 2011). Average daily PET values are referenced to the plant canopy resistance factor for alfalfa (*Medicago sativa*), implying an agricultural setting. It remains an open question as to whether a PET sub-model developed for agricultural contexts is suitable for urbanized landscapes where turf or other vegetation may be driving ET (Fisher *et al.*, 2017; Litvak *et al.*, 2017). Similarly, the role of ET in urban settings is likely most significant in semiarid and arid urban landscapes (Pataki *et al.*, 2011; Litvak *et al.*, 2017). Here, high evaporative demand is coincident with both impervious and pervious surfaces, and higher anticipated latent heat flux. On the other hand, transpiration losses between storms can deplete soil moisture and thereby refresh detention capacity, and are therefore relevant to the NSWC estimation procedure. Considering seasonal variation, growing season transpiration will be higher than senescent season transpiration, and therefore soil moisture removal as transpiration will be maximized when climate demand for moisture is also highest. To get a better estimate of ET in urban areas, specialized models such as i-Tree Hydro could be used to simulate ET, and direct field monitoring is also an option (*e.g.*, CSI ET107; Campbell Scientific, Logan, Utah). Yet, each of these approaches to improve ET accounting would require a new facility for accepting time series data, which is not currently available in the NSWC.

Impervious and Pervious Surface Hydrology—The NSWC simplifies classification of impervious surface with a lumped fraction total impervious surface (TIA). Unlike SWMM, the NSWC does not assess connectivity between impervious and pervious surfaces. Pervious surface hydrology is parameterized as soil hydrology via the USDA SSURGO database, which draws from largely agricultural, county-level soil surveys conducted at different times over the last century. Therefore, the SSURGO entries are incomplete for many urban locations, with most U.S. cities mapped as “Urban Land,” “Urban Land-complex,” “Made Land,” or more plainly, “Area Not Investigated.” The overall proportion of mapped U.S. urban soils is highly variable (Figure 1), where the extent of SSURGO data availability ranges from scarce to complete coverage. The data gap for urban soil hydrologic data, and the sensitivity of the NSWC hydrologic model to pervious surface hydraulic conductivity (compared to larger scale drivers, like rainfall data), suggest that this area of model function requires the most improvement, or at least a quantification of uncertainty that is introduced by different estimations of hydraulic conductivity. Further, hydraulic conductivity is highly impacted by urbanization processes like construction, (re)development, or demolition processes. Because this variation in soil hydrology can be introduced at a parcel-level scale, existing county soil surveys cannot not be expected to reflect these land-use dynamics.

The estimation of soil hydraulic conductivity for general hydrologic modeling is not standardized (Fuka *et al.*, 2016) besides the highly interpolated field data provided by SSURGO (Anderson *et al.*, 2006). Yet, the NSWC is set up to take full advantage of best-available, localized soil hydrologic data. The NSWC provides parameter options (Figure 2) as: a default hydraulic conductivity of 10.1 mm/h (0.4 in/h; option A); querying the SSURGO database to obtain best-known, local soil hydraulic data derived from county soil surveys (option B); and a user-supplied value for hydraulic conductivity (option C; *e.g.*, measured values).

Since many urban soils are not mapped, and the user is using option B for soil hydrology estimates for a site of interest, the NSWC will automatically extend the radial search area by 1,000 m intervals, up to 5,000 m. Even though this is well outside of 5 ha (the practical limits of the application), the NSWC will spatially aggregate and average available conductivity values within this search area for local variability among different soils.

Although subsurface hydrologic processes (*e.g.*, percolation, drainage) are not represented in the current NSWC code, SSURGO offers an estimated hydraulic conductivity of the least-conductive soil horizon. To ensure the best representation of the site of interest, users should perform initial site investigations to identify areas with poor drainage or shallow groundwater tables. These site conditions would require more specialized LID designs, such as rain gardens with sub-drains that facilitate faster drainage of soil moisture from the rooting and storage zones.

Case Study 1: Performance of NSWC with Different Sources of Soil Hydrology Data

We next illustrate how the NSWC simulation responds to common (*i.e.*, SSURGO) and unique data sources for urban soil hydrology. As part of a unique urban soil hydrologic assessment, the USEPA has assessed hydraulic conductivity in over 400 parcels within 12

cities in the contiguous U.S., Puerto Rico, and Majuro Atoll, Republic of the Marshall Islands. The objectives of the urban soil hydrologic assessments are twofold, quantifying urban soil hydrology to judge suitability for infiltration- or storage-type GI, and generating consistent hydraulic conductivity data that could be used to verify, validate, and potentially calibrate urban hydrologic models. This level of measurement effort spanned 2010-2015, entailed 1,929 infiltration measurements taken at 379 sites, with at least four conductivity measurements per site (vacant lots, parks), per city. Site selection was opportunistic, balancing geographic coverage with site access. We measured hydraulic conductivity at near-saturated conditions with tension infiltrometers set to -2 cm hydraulic head (DecagonDevices, 2016). This method reduces variability associated with flow into macropores (Shuster *et al.*, 2014), and results in a conservative measurement of hydraulic conductivity emphasizing the hydraulics of the surficial soil matrix.

We found that 131 of the EPA Urban Soil Assessment sites had corresponding, localized data in the NSWC (32% of total), and 86 sites in the SSURGO Web Soil Survey (21% of total). We used these sites as the basis for our comparisons. In terms of coverage between EPA Urban Soils Assessment and NSWC, SSURGO databases, the range of overlap among these measured and estimated data was from 0 to 100%, for each of the cities assessed (Table 2). Coverage was complete in Portland, Maine; Phoenix, Arizona; and New Orleans, Louisiana, and limited in, for example, Omaha, Nebraska and Cleveland, Ohio (Figure 1, Table 2).

The average hydraulic conductivity for each city compared differently with the NSWC default setting, and with values determined from NSWC databases. The default hydraulic conductivity value of the NSWC (10.1 mm/h) underestimates average measured hydraulic conductivity measurements made in Cleveland, Ohio where average surface soil hydraulic conductivity was 18 ± 2 mm/h in vacant lots with wide variety in surface vegetative cover (Shuster *et al.*, 2014). At the extremes of our assessments, vacant parcels in New Orleans, Louisiana exhibited an average hydraulic conductivity of 95 ± 27 mm/h, nearly 10 times greater than the default; whereas urban parks and vacant areas in Omaha, Nebraska registered values 3 times lower than the mean NSWC conductivity, averaging 3.0 ± 1.0 mm/h (Table 2, Figure 3). In the case of New Orleans, post-Katrina vacant lots were often found to be backfilled with a fine-sand fill from borrow pits outside of the city. This sandy fill was much more permeable than the clay-rich, pre-existing soil, resulting in higher infiltration rates. This change in soil hydrology is not captured by available soil survey data, and at least situationally, will contribute to uncertainty in NSWC simulation output.

Between-city comparisons further clarify the relative degree of deviation from predicted NSWC values for hydraulic conductivity compared to measured values (Figure 3). Differences in the number of measurements contributing to the average also affect the sample standard error of the mean, and its 95% confidence interval (Figure 3). Across all cities, we find that the NSWC underestimated hydraulic conductivity by an average of 10.5 mm/h compared to corresponding measured values (Figure 3). These discrepancies between estimated and measured data are attributed to lack of a baseline in the largely agricultural county soil surveys (as high estimation error), as well as differences between estimation and measurement protocols for hydraulic conductivity among SSURGO and recent USEPA

efforts. This underestimation of hydraulic conductivity may yield higher simulated runoff volumes in a generalized simulation with rainfall depth and all other parameters held. This can result in a more conservative LID design, which may also be oversized. This circumstance highlights the NSWC as a screening-level tool that should only be used as a start toward refinements in the LID selection and design process.

Case Study 2: How NSWC Soil Hydrology Influences Runoff Response

In contrast to the urban setting, we benchmarked a cross-comparison of soil hydrology estimation to a well-characterized rural ultisol (Cecil loam; Watkinsville Georgia). This was done to evaluate how hydraulic conductivity influences runoff estimation and impact of LID features in the NSWC. The NSWC predicted value for hydraulic conductivity was 1.3 mm/h at the site, the field measured average was 2.3 mm/h ($n = 6$), and SSURGO registered values of 15.6 mm/h (surface layer), and 5.9 mm/h (all layers averaged). For the Cecil loam, SSURGO has a complete suite of soil hydrologic data, including C and D hydrologic soil group (HSG) estimates of hydraulic conductivity (Figure 4). The NSWC estimate for hydraulic conductivity compared well to the field measured value, however, was still much less than the SSURGO value predicted for surface soils. Moderation of the NSWC estimate (compared to SSURGO) may be attributed the NSWC spatial averaging feature for soil hydrology.

Separate models were run for each hydraulic conductivity over a range of impervious cover (0-40% in 5% increments), with all other parameters (*i.e.*, rainfall record, ET, *etc.*) kept constant. Simulation outputs over a range of percent impervious cover shows that the NSWC produces similar amounts of runoff for hydraulic conductivities in the range 1.3-15.6 mm/h, with a nearly monotonic increase from zero to 40% impervious cover. Runoff production in this higher range of hydraulic conductivity is roughly convergent at 40% impervious surface. At an apparent threshold hydraulic conductivity of 1.3 mm/h, the soil acts more like impervious surface. At this low hydraulic conductivity, runoff production by infiltration excess is compounded by an increase in direct runoff attributed to increasing fraction of impervious surface. The NSWC shows unexpected sensitivity and separable trends in runoff production at these lower values of hydraulic conductivity, which are estimated from SSURGO (Figure 4A, S1). To illustrate the expanded output capacities of the NSWC, a complementary set of simulations were run from the perspective of estimated days with runoff, per year (Figure 4B). In this context, the NSWC shows a general trend of increased days with runoff tracking increased fraction impervious cover. Yet, pervious areas (*i.e.*, soils) classified as HSG A and B (hydraulic conductivity between 1.3 and 15.6 mm/h) behave similarly with fewer days of runoff per year for fraction impervious cover below 10% (Figure 4B). Separation among HSG C and D runoff frequency is maintained to an imperviousness of 15%. Any increase in imperviousness beyond the 15% level indicates that soil hydrology is not important. Above 15% fraction imperviousness, the different soil hydrologic conditions converge, with the annual number of days that produce runoff increasing monotonically with percent impervious surface (Figure 4B). Given the parameter constraints for this simulation and practical ranges in fraction impervious surface cover, the NSWC details the impacts and limits of site characteristics (*i.e.*, soil hydrology, imperviousness) on runoff production. Soil hydrologic condition may be improved through

management (revegetation, building soil structure, *etc.*), which may then better accommodate LID-GI practices (Pavao-Zuckerman and Sookhdeo, 2017). Impervious surfaces may be removed or otherwise treated via rooftop downspout disconnection. In any case, these simulations also point out that some LID options may be better than others, especially where these options involve infiltration (and therefore rely on soil hydrologic characteristics) to create detention capacity for excess stormwater runoff.

Case study 3: How LID features and soil hydrology interact in the NSWC

We assessed influences of each of the seven LID options on runoff reduction for a 10-acre (4 ha) exurban development site comprised of 70% lawn, 29% impervious cover, and 1% forest, situated on the same well-characterized ultisol used to benchmark our simulations (Figure S2). A range of representative hydraulic conductivity values was selected for each simulation, namely, an “A type” soil with a conductivity of 15.6 mm/h, a “B type” soil with 1.3 mm/h hydraulic conductivity, and a “D type” soil with a conductivity of 0.5 mm/h. The NSWC was run for each LID feature using the three different hydraulic conductivities with all other parameters held constant. The fraction impervious area converted to LID corresponded to appropriate scenarios for each individual LID, and based on available area for LID development (Figure S2). Individual models for each LID feature were compared to a baseline simulation that contained no LID feature (pre-development). Due to the large amount of impervious area present as parking lot and roadways, the simulated scenario using permeable pavement LID resulted in the greatest portion of impervious area conversion (80%), also resulting in the greatest reduction in runoff (49-80%, dependent on conductivity; Figure 5A). Similarly, the addition of street planters mitigated 50% of impervious area, and its relative impact on runoff reduction ranged from 17 to 47% and is attributed to its interaction with local, pre-existing soil hydrology (Figure 5A). In general, it was a combination of the hydraulic conductivity of the pre-existing, local soils and the LID features that influenced the potential for runoff reduction. For the LID features that do not interact with the surrounding soil (*e.g.*, green roofs and rain harvesting-storage), soil hydrology had predictably less impact on runoff reduction. Where LID features closely interact with local soils, simulations with higher hydraulic conductivity in HSG A or B soils show a nearly 1:1 relationship between reduction in runoff and impervious cover fraction that is converted to LID. Under these circumstances, nearly 100% of the runoff is treated, which would have otherwise been generated from pre-LID impervious surface. On the other hand, simulations with a less-permeable HSG D-type soil yield a 1:2 relationship between runoff reduction and the fraction impervious cover converted to LID, indicating that the soil is only half as efficient at abstracting runoff as the more permeable soils (Figure 5A).

The distinction between LID features that incorporate pre-existing soils becomes clearer when analyzing the largest rain events for which runoff was detained (Figure 5B). Here, the different detention capacities in permeable pavement, street planters, and disconnection-type LID were dependent on the hydraulic conductivity of the soil. By contrast, rain gardens and infiltration basins show minimal variation in runoff depth. This may be due to the assumption of higher permeability-engineered replacement soils, and reliance on how much impervious cover is actually converted to LID. Finally, LID features that have no interaction with the pre-existing soil (rain harvesting and green roofs), only respond to impervious

cover converted and, as anticipated, runoff generation is invariant under different soil hydrologic conditions (Figure 5B).

Uncertainty

The main goal of the NSWC is to account for the main drivers of runoff production in small parcels, and obtaining meaningful estimates of annual runoff volume. Yet, modeling a small urban parcel in the absence of any measured data is not unlike a small-scale version of the unaged, uncalibrated simulation of catchment hydrology (Seibert and Beven, 2009). The lack of calibration data hamper the simulation of confirming meaningful water balance estimates at all levels of hydrologic simulation. Ideally, the user takes into consideration localized field observations and measurements; and the model's parameters are calibrated by comparing modeled outputs to measured runoff data. As we illustrated here, the NSWC provides options for best parameterizing soil hydraulic conductivity. However, the user may want to create a coarse impression of uncertainty by, for example, changing rainfall pattern, while holding constant the other parameters. The NSWC manual guides users through a basic uncertainty assessment, which proposes using parameters that reflect the relevant extremes of site characteristics, *i.e.*, changing hydraulic conductivity or impervious area fractions. This creates an ensemble of outputs that can be at least qualitatively compared to understand the impact of different parameters on runoff depth. Each of these model outputs build toward a range of variability in model inputs such as percent of impervious surface, soil type and hydrology, and how sizing of LID-GI (larger-smaller, deeper-shallower) can affect runoff production and its management. In terms of reducing uncertainty on a more localized level, the NSWC is currently not configured to take advantage of more specific meteorological data.

For more accurate screening applications with reduced uncertainty, it would be beneficial to include more localized rainfall data. For example, municipal wastewater authorities often operate rain gage networks that cover their service area. Similarly, potential changes in rainfall pattern under a changing climate are quantified by the NSWC with the built-in USEPA Climate Resilience Evaluation and Awareness Tool (EPA, 2016), which allows the user to modulate simulations with forecasted change in precipitation and ET, for the nine climate regions as defined by NCDC. However, it bears mention that this estimation procedure adds another component of uncertainty, over and above the spatial and temporal variability inherent to any precipitation data (Wood *et al.*, 2004; Fowler *et al.*, 2007). To improve LID planning for future scenarios, the integration of an uncertainty estimate of the climate forecasting tool would be a valuable addition to the calculator. Similarly, field determination of soil hydrology, such as those from USEPA urban soil hydrologic assessments, could be integrated into NSWC-accessible databases to improve soil data coverage in the currently less-represented urban areas of the U.S. and Puerto Rico. However, this is currently not yet under development.

Next Steps, and Development of New Features

In response to stakeholder concerns about LID costs and return on investment, a cost estimation module was developed for the NSWC and released publicly in April 2017. This newly developed module provides localized, planning-level estimates of capital investment,

and average annual operation and maintenance costs of LID. The cost estimates for the calculator are regionalized, using the U.S. Bureau of Labor Statistics (BLS) datasets with information about the costs of typical services for constructing GI. At this time, BLS data are available for 23 major metropolitan areas in the U.S.; though parts of the Western U.S. are underrepresented. For areas without regional BLS costing data, the NSWC fills this gap using average national costing estimates. The costing module provides estimates based on various factors, including: type of development project (new or redevelopment); complexity of the site as influenced by existing utilities, soil hydrology (soil management or replacement affects cost); slope (categorized as simple, typical, complex); and the presence or absence of pre-treatment facilities (*e.g.*, swale, forebay filtration). However, the NSWC cost estimation module is not an estimator for lifecycle or construction costs.

Nevertheless, there are enhancements to make the NSWC more accessible and to facilitate the development needs tailored to the user community (see SI on uses of the NSWC). One enhancement for the NSWC is a recently released mobile web application (<https://swcweb.epa.gov/stormwatercalculator/index.html>). This version of the NSWC allows users, such as practitioners, homeowners, and communities, to utilize the calculator on any mobile device, including smartphone and tablets. This mobile web version of the NSWC is meant to assist users with further utilizing the tool while in the field. Furthermore, an open-source development approach may facilitate improvements to the NSWC by allowing the incorporation of more localized data as well as a response to the needs of cities and municipalities which could use the basic structure of this tool to further the development of the application. If such a move were to take place, a standard quality assurance procedure for integrating data would be an important part of the innovation process, though one that is not currently addressed in this conceptual model.

Conclusions

The NSWC is an example of a software calculator, which is implemented as a specialized version of SWMM. The general calculation features of SWMM become secondary to the primary objective of the calculator, which is the estimation of rainfall-runoff relationship based on localized and standardized input parameter sets that are not expected to be adjusted with regard to calibration data. The calculator therefore offers a basis for interaction with the user by providing well-defined operations that can be held constant or iteratively changed. As with any hydrologic simulation for stormwater management, there is a decision support context for these estimates of runoff production. Since this is a screening-level tool, the runoff estimates are useful to the extent that results are taken in context. Interpretation assumes the user has some basic knowledge of the drainage area, its tendency toward runoff production, and extenuating circumstances that may affect runoff and its management.

As it stands, the NSWC provides a simulation environment that fills a critical gap in communities of practice around stormwater management for effective screening-level simulation. An increased awareness of practical uses for the NSWC in planning and its ongoing development will serve to increase the usability and effectiveness of this tool.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1. Soil Mapping Coverage within SSURGO for the 12 Urban Areas that Have Been Investigated as Part of the EPA Urban Soils Assessment. Cities like Detroit, Michigan; Cleveland, Ohio; Tacoma, Washington; or Cincinnati, Ohio are mapped well in the outskirts of the urban areas; however, city centers are poorly mapped. Contrarily, Phoenix, Arizona; New Orleans, Louisiana; and Portland, Maine are well mapped, even in city centers.

Figure 2.

Screenshot of the Tabs for Selection of Soil Type (A) and Soil Drainage (B) in the National Stormwater Calculator (NSWC). Data in both tabs are obtained via the USDA SSURGO database. The user can parameterize the NSWC using data from these national datasets or data describing actual site conditions if available.

Figure 3.

Deviation between NSWC Predicted and Measured Hydraulic Conductivity for 10 U.S. Cities. Positive values indicate that the NSWC estimate of hydraulic conductivity is greater than that of the field measurement, whereas negative values indicate that the NSWC estimate is lower than the field-measured value. The center of the symbols is the average deviation between the NSWC predicted and measured conductivity. The size of the symbol (circles) represents the relative number of measurements for each city. The mean deviation and its 95% confidence intervals are listed to the right of the graph.

Figure 4. National Stormwater Calculator Output for (A) Depth of Runoff and (B) Number of Days with Runoff Generated per Year Are Illustrated for Different Percent Impervious Cover, and Over a Range of Hydraulic Conductivities for a 10-Acre Site in Watkinsville, Georgia without Low-Impact Development Stormwater Controls.

Figure 5.

Comparison of Runoff Reduction (A) and Largest Rain Event that Does Not Produce Runoff (B) Based on Different Low-Impact Development (LID) Practices, and as a Function of Soil Hydrology and Impervious Surface for a Conceptual, 10-Acre (4 ha) Suburban Site. LIDs that function independent of soil conditions (*i.e.*, rain harvesting and green roofs), or those that usually require modification of surface soils (*i.e.*, rain gardens or infiltration basins), show that soil hydrology has little effect on the runoff reduction.

Table 1.

Summary of a Selection of Other Stormwater Runoff Tools and Their Features

Tool	Capability	Reference
RECARGA	Downloadable application Site-scale Evaluates the performance of bioretention facilities, rain gardens, and infiltration basins Handles surface ponding, up to three different soil horizons, underdrains, user-specific precipitation and evaporation patterns Presents ponding zone, soil moisture, infiltration and recharge volume, underdrain flow, evapotranspiration	Atchison and Severson (2004)
i-Tree	Downloadable application City-wide scale Uses location, tree species, size and condition as input Quantifies environmental services of trees along with structure and risk Generates annual benefits of individual trees and their growth Presents benefits of trees in terms of carbon sequestration, air quality, stormwater management, accounting of emergy	USFS (2016)
WERF Select	MS Office Excel-based spreadsheet program Watershed-scale Uses long-term hourly rainfall as input Converts rainfall into runoff based on runoff coefficients Can handle a variety of common stormwater pollutants Presents annual pollutant loads and frequency curves with uncertainty, whole life BMP costs	Pomeroy and Rowney (2013)
CNT Green Values	Online tool Site-scale Uses annual or event precipitation, land use, soil type, runoff reduction goal and BMP feature as input Selects particular best management practices that meet a specific stormwater reduction goal to present costs, air quality improvements, carbon sequestration, groundwater recharge	CNT (2009)

Table 2.

Summary Statistics for the Investigated Sites in Several U.S. Cities

Location	Number of Sites	Mean Hydraulic Conductivity $\pm$ SE (mm/h)	Min (mm/h)	Max (mm/h)	% in NSWC	% in SSURGO
Atlanta, Georgia	12	17 $\pm$ 4	1	59	8	8
Camden, New Jersey	21	54 $\pm$ 20	2	445	10	10
Cincinnati, Ohio	40	6 $\pm$ 1	0	18	100	15
Cleveland, Ohio	109	17 $\pm$ 2	0	106	2	0
Detroit, Michigan	55	10 $\pm$ 3	0	136	16	0
New Orleans, Louisiana	20	95 $\pm$ 27	1	494	100	95
Majuro, Republic of the Marshall Islands	8	13 $\pm$ 3.2	2.6	26	0	0
Omaha, Nebraska	26	3 $\pm$ 1	0.3	9	0	65
Phoenix, Arizona	10	8 $\pm$ 1	4	17	100	100
Portland, Maine	20	8 $\pm$ 2	1	22	100	100
San Juan, Puerto Rico	20	7 $\pm$ 2	0	26	57	35
Tacoma, Washington	17	32 $\pm$ 9	2	156	12	0