Predicting Ecological Effects of Watershed-Wide Rain Garden Implementation Using a Low-Cost Methodology

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Abstract: Stormwater control measures (SCMs) have been employed to mitigate peak flows and pollutants associated with watershed urbanization. Downstream ecological effects caused by the implementation of SCMs are largely unknown, especially at the watershed scale. Knowledge of these effects could help with setting goals for and targeting locations of local restoration efforts. Unfortunately, studies such as these typically require a high level of time and effort for the investigating party, of which resources are often limited. This study proposes a low-cost investigation method for the prediction of ecological effects on the watershed scale with the implementation of rain garden systems by using publicly available data and software. For demonstration purposes, a typical urban watershed was modeled using Storm Water Management Model (SWMM) 5.0. Forty-five models were developed in which the percent impervious area was varied 3 to 80%, and the fraction of rain gardens implemented with respect to the number of structures was varied from 0 to 100%. The river chub fish (*Nocomis micropogon*) and its congeners (*Nocomis spp.*) were chosen as ecological indicators, as they are considered to be keystone species through interspecific nesting association. Depth and velocity criteria for successful nest building locations of the river chub were determined; these criteria can then be applied to many other watersheds. In this study, both base flow conditions and a typical summer storm event (1.3 cm, 6 h duration) were evaluated. During the simulated storm, nest-building locations were not affected in the 3 and 5% impervious cover models. Nest destruction was found to occur in approximately 54% of the original nest building sites for the 9% and 10% impervious areas. Nearly all of the nest-building locations were uninhabitable for impervious areas 20% and greater. Rain garden implementation significantly improved river chub habitat in the simulation, with greatest marginal benefit at lower levels of implementation. **DOI: 10.1061/(ASCE)EE.1943-7870.0000896.** © *2014 American Society of Civil Engineers.*

Introduction

Waterways in urban areas worldwide face an increasing threat from the process of watershed degradation. A majority of the world's population growth in the future is projected to occur in urban areas (Bernhardt and Palmer 2007). Urbanization has been shown to have many negative impacts on urban waterways and the environmental functions they support (e.g., Walsh et al. 2005; Allan 2004). Consequently, many urban waterways and their watersheds are in a state of degradation and are impaired ecosystems. Although restoration of urban streams and watersheds faces many challenges, there are many compelling interdependent reasons that justify the cost and effort of urban stream restoration (Findlay and Taylor 2006). These reasons include provision of ecological services, economic value of restored streams, and direct social benefits. Unfortunately, recent reviews and studies have indicated that often the desired ecological goals of urban stream restoration are not met (Violin et al. 2011; Louhi et al. 2011; Sudduth et al. 2011). One possible reason for the disconnect between stream restoration projects and their expected ecological goals may be a lack of predictive understanding between watershed and waterway restoration activities and the physical and biological processes that they are meant

to improve (Bernhardt and Palmer 2011, 2007; Beechie et al. 2010). For this reason, it is imperative that approaches and techniques are developed that link specific watershed restoration activities with improvement to downstream ecosystem processes. Studies to this end will be crucial in the effort to mitigate urbanization effects on waterways, and will provide more accurate estimates of benefits relative to the cost of restoration.

The increased runoff produced by high amounts of impervious surface existing in urbanized watersheds is the chief cause of watershed degradation (Walters et al. 2009). As impervious area increases, stream biodiversity will generally decrease leading to a decline in the health of the aquatic ecosystem. Schueler et al. (2009) developed an impervious cover model (Table 1) that classifies urban stream ecological health based on the percent of impervious area in the watershed. In this system, sensitive streams are defined as streams that generally retain their hydrologic function and can support good to excellent aquatic diversity. Impacted streams show signs of declining stream health through channel instability and loss of species diversity. Non-supporting streams no longer support their natural uses and will be difficult to recover to pre-development conditions. Streams classified as urban drainage systems are so extensively modified that they function as a conduit for runoff. Transitional zones between each ecological classification category address the variability in study data (Schueler and Fraley-McNeal 2008; Schueler et al. 2009).

The capacity of storm water control measures (SCMs) to reduce or eliminate storm water runoff through volume reductions has been verified through various observations and research (e.g., Finnemore and Lynard 1982; Debo and Reese 2003; Davis et al. 2012). Rain gardens are one type of SCM that has seen increasing use as they can be employed on both commercial

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Table 1. Summary of Impervious Cover Model (Schueler and Fraley-McNeal 2008; Schueler et al. 2009)

Watershed impervious cover (%)	Stream quality/ aquatic diversity	Ecological classification	Transition zones
0	Good to excellent	—	—
3	Good to excellent	Sensitive	—
5	Fair to excellent	Sensitive	Transition from sensitive to impacted
10	Fair to excellent	Sensitive	
20	Fair to good	Impacted	Transition from impacted to non-supporting
25	Fair to good	Impacted	
60	Poor to fair	Non-supporting	Transition from non-supporting to urban drainage
70	Poor	Urban drainage	
80	Poor	Urban drainage	—
100	Poor	Urban drainage	—

and residential properties. Rain gardens, which are aesthetically pleasing and provide ecological benefits, rely on both infiltration and evapotranspiration to control storm water (e.g., Davis 2008; Emerson and Traver 2008; Davis et al. 2009; Gilbert Jenkins et al. 2010; Welker et al. 2013). Rain gardens are also the focus of several SCM initiatives whereby communities set a goal of planting a certain number of rain gardens. For example, Kansas City, Missouri has set of goal of 10,000 rain gardens, Madison, Wisconsin has set a goal of 1,000 rain gardens, and Ambler, Pennsylvania has set a goal of 100 rain gardens.

A number of studies (Table 2) have addressed volume reductions caused by the implementation of SCMs on a watershed scale. These studies have shown that certain SCMs offer a higher capacity to mitigate storm flows than others. Even if volume and peak flows are reduced, it is difficult to determine the beneficial effects on downstream areas without having an ecological perspective.

Unfortunately, an exhaustive evaluation of the ecological effects of SCM implementation is likely to be costly and impractical for many municipalities. This type of evaluation would involve surveying and mapping the watershed, monitoring stream flows for several months (if not monitored already), developing and calibrating a model, and performing macroinvertebrate sampling before SCM installation. This paper presents a methodology using publicly available Federal Emergency Management Association (FEMA) flood insurance studies and United States Geological Survey (USGS) StreamStats data with the public domain United States Environmental Protection Agency (US EPA) Storm Water Management Model (SWMM) to determine if flow velocity and stream depths are maintained within a range suitable for an ecological keystone species. Generally, flood insurance studies are available online, and can be easily found with the use of a search engine.

Background

SWMM

For this study, EPA's SWMM 5.0 software (U.S. EPA 2010) was used, as it is a widely accepted program within the industry, and contains a robust method of modeling low impact development (LID) practices. SWMM is a dynamic rainfall and runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. The important variables required for this model are subwatershed area, soil information, land use, Manning's roughness coefficients, stream geometry, and storm intensity (Rossman 2010).

River Chub

To gain an ecological perspective, the nest building behavior of an important ecological indicator, or keystone, species (the river chub *Nocomis micropogon*) was investigated and applied to the SWMM model results. Keystone species are generally defined as species that have an effect on their ecological communities that is disproportionate to their abundance (Power et al. 1996). The river chub and its close relatives can be considered to be a keystone species through wide interspecific use of their nests. River chub may be considered nest habitat specialists (Peoples et al. 2014) and in many cases may provide the only suitable habitat for other species that also require cleaned gravel for spawning (Lithophilic). The raised profile and cleaned gravel of the river chub pebble mound nest may positively affect spawning success because of improved circulation of oxygen and transport of waste, and cleaner interstitial spaces in the nest (Peoples et al. 2011). A number of regional species are known to spawn in river chub nests, including the common shiner (*Luxilus cornutus*), creek chub (*Semotilus atromaculatus*), longnose dace (*Rhinichthys cataractae*), and the rosyface shiner (*Notropis rubellus*) (Jenkins and Burkhead 1993). Common shiners often preferentially use river chub nests (Miller 1964). Vives (1990) reported that five different fish species in the cyprinid family were found to rely on the river chub nests, as their eggs were consistently found within river chub nests in the Allequash Creek in Wisconsin. Another investigation showed that a drastic decrease of chub species in an area may greatly affect other species of fish that exhibit narrow geographic distributions (Pendleton et al. 2012). Furthermore, the larva of the endangered fine-rayed pigtoe mussel (*Fusconaia cuneolus*) relies on fish such as the river chub as a protective host until reaching maturity (Bruenderman and Neves 1993). River chub therefore function as a keystone species through their many positive interactions with other species.

The river chub is a large minnow that resides in clear, medium to large creeks and rivers, and can often be found hiding in pockets of deep water behind boulders (Jenkins and Burkhead 1993). Common to many chub species, the male River chub will construct a large pebble mound nest from the river bottom gravel substrate

Table 2. Summary of Selected Studies Evaluating the Effect of SCMs on a Watershed Scale

Reference	SCM type	Model	Results
Emerson et al. (2003)	Detention pond	HEC-HMS	Little storm attenuation, increased peak flow in some storm events
Carter and Jackson (2007)	Vegetated roofs	StormNet Builder	Reduction in peak runoff rates for storms less than 2 year, 24 h
Milwaukee Metropolitan Sewer District (2007)	Rain garden and rain barrel	HSPF	38% storm volume reduction in residential areas compared to combined sewer system
Milwaukee Metropolitan Sewer District (2007)	Green parking lot	HSPF	76% storm volume reduction in commercial areas compared to combined sewer system
Ahiablame et al. (2013)	Rain barrels and pervious pavement	L-THIA	8% storm runoff reduction with 25% rain barrel and pervious pavement implementation

during the spring spawning season (McManamay et al. 2010). These nests can be as large as 25 to 33 cm in height and 33 to 120 cm in diameter (Jenkins and Burkhead 1993; Reighard 1943). During construction, it is estimated that the male chub will make up to 6,000 trips to transport about 40 kg of river stones, swimming a total distance of 25.7 km (Reighard 1943). Investigations of river chub nests conducted by the authors revealed that the average volume of river chub nests were 8 liters with about 13 kg of pebbles. Due to the structure of their nests, there are specific stream depth and velocity criteria that need to be fulfilled for successful nest building and survival.

River chub nests are vulnerable to high, flashy flows, which may be one contributing factor for their elimination from fish faunas of highly urbanized watersheds (Kemp 2014; Peoples et al. 2014; Pirhalla 2004; Miller 1964). Projecting the effects of storm water control improvements on stream ecology prior to restoration activities will greatly improve assessment of predicted success in meeting ecological goals.

Methods

SWMM

Forty-five SWMM models were based on the Mill Creek Watershed located in Montgomery County, Pennsylvania. Publicly available data was gathered to determine variables such as the subwatershed area, soil information, and land use. Manning's roughness coefficients, stream geometry, and storm intensity/duration were estimated based on available information, site visits, and engineering judgment.

The Mill Creek watershed is approximately 21.5 km^2 with 9% impervious cover. Mill Creek originates from a constructed storm water wetland on Villanova University's campus and confluences downstream with the Schuylkill River. Minor tributaries to Mill Creek also exist throughout the watershed. To model the creek, the watershed was broken up into 32 subwatersheds primarily based on tributary streams. Mill Creek and its tributaries were input into SWMM using a series of nodes and open channel conduit sections. Fig. 1 illustrates the Mill Creek watershed as input into the SWMM program. The 32 subwatersheds are designated "S" for tributaries feeding into Mill Creek, and "NT" for non-tributary areas. Each subwatershed is routed to Mill Creek, which is denoted by a dotted line. Mill Creek itself was defined as an open channel in SWMM, and is denoted by the solid black line. Individual conduit sections are defined by two nodes, which are represented by black circles along Mill Creek. The outfall of the model is defined by a triangle, which marks Mill Creek's confluence with the Schuylkill River.

Subwatershed geometries and land uses were found through the publicly available USGS StreamStats (USGS 2013) database. Manning's overland roughness coefficient was estimated based on these land uses. An overall curve number of 77 was used for the watershed; this value was estimated through the use of the Web Soil Survey online database developed by the United States Department of Agriculture (USDA 2012).

The channel of Mill Creek was broken into more manageable lengths by inputting a series of nodes and conduits in SWMM. A FEMA flood insurance study (FEMA 2010) was utilized to determine the channel bed slope at each node. In total, 22 nodes were created along with 21 conduits to model Mill Creek. Similarly, nine small tributaries were modeled along Mill Creek consisting of one conduit each. The channel geometry of Mill Creek and its associated tributaries was assumed to be trapezoidal for simplicity. The trapezoidal shape is commonly used as an approximation of the cross-sectional shape for natural channels (Barr 2012; Dingman 2009). Furthermore, a site visit in the summer of 2012 revealed
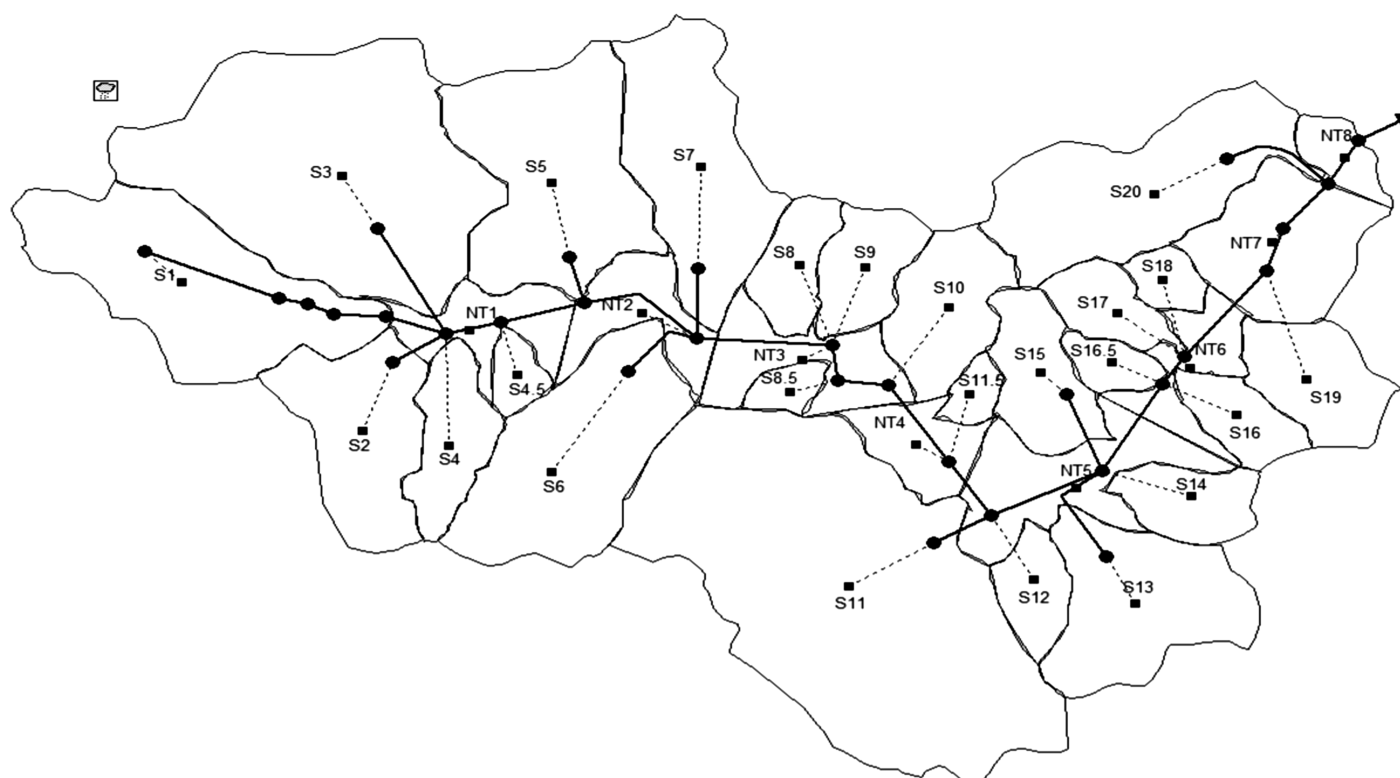

Fig. 1. Visual representation of Mill Creek watershed as input into SWMM

simple channel geometry characterized by one central deep point in the channel bed, and relatively symmetrical channel slopes. Manning's roughness coefficients for the channel reaches were estimated through site surveys and were set to 0.04 and 0.05 for the channel and overbanks, respectively. A base flow of 7.9 m³/s was set to flow through Mill Creek after site observations and utilization of the Manning's equation. For simplicity, base flow was defined by setting a flow at key nodes along the Mill Creek channel reach.

The model was calibrated to a 10 year, 24 h storm based on the FEMA (2010) flood insurance study. The maximum depth at each node for the design storm was compared to the flood insurance study. An initial average error of 33% called for changes to the hydrologic and hydraulic parameters within the model. Overland flow width and curve numbers in each subwatershed were altered, producing a range of curve numbers of 65–95. The channel and overbank Manning's roughness coefficients were altered and produced a range of 0.01 to 0.10. Table 3 displays the initial and calibrated water depths in the Mill Creek channel (nodes increase in the downstream direction). The furthest upstream and downstream nodes were difficult to calibrate because of model instability at the boundary conditions.

The 3, 5, 10, 20, 25, 60, 70, and 80% impervious area scenarios were developed by proportionally altering the impervious cover in each subwatershed. The 9% impervious area condition represents the existing conditions of the watershed and was used to develop the model. The impervious percentages chosen represent predevelopment and extremely urbanized scenarios. The increments chosen were based on the changes of stream health observed in Schueler's impervious cover model (Schueler 1994; Schueler and Fraley-McNeal 2008; Schueler et al. 2009).

The number of structures throughout the Mill Creek Watershed was determined by Google Earth aerial imagery. It was assumed that structures comprised one third of the total impervious area of the watershed (Schueller 1994; Nowak and Greenfield 2012). The predominant structure type was found to be residential. An average residential roof footprint was determined for each subwatershed of Mill Creek based on Google Earth and impervious cover information from USGS Stream Stats. Using design recommendations by

the Pennsylvania Department of Environmental Protection (PADEP 2006), a typical rain garden was designed to handle roof runoff from the residences within the Mill Creek Watershed. Four SWMM scenarios were created to describe levels of rain garden implementation: 25, 50, 75, and 100%. For example, in a 50% rain garden implementation scenario, half of all residential buildings within the Mill Creek watershed will be equipped with a typical rain garden to handle roof runoff. Although a 100% rain garden scenario is unlikely, a high percentage of rain gardens might be achieved through community awareness and involvement.

A typical summer storm event was developed to apply to the SWMM models using the Soil Conservation Survey (SCS) type II rainfall distribution. A 1.3 cm, 6 h storm was chosen based on the quick and powerful nature of summer thunderstorms often witnessed at this location. To develop the 0, 25, 50, and 100% rain garden scenario, a typical rain garden was designed to handle the roof runoff of the summer storm event. The rain garden area was found by applying the 5:1 drainage area to infiltration area recommended by the PADEP (2006) based on the average roof area measured within each subwatershed.

Velocity and depth criteria for successful nest building for the river chub were applied to the 45 SWMM models. The depth at each conduit was obtained by compiling results in SWMM. The minimum and maximum velocity component of each channel section was calculated from the average velocity output from SWMM. Assuming a logarithmic velocity distribution, the following series of equations were used to calculate the average maximum velocity for each conduit section:

$$\varepsilon = \frac{V_{\max}}{V_{\mathrm{avg}}} - 1 \tag{1}$$

$$\alpha = 1 + 3\varepsilon^2 - 2\varepsilon^3 \tag{2}$$

$$\beta = 1 + \varepsilon^2 \tag{3}$$

where V denotes velocity, α and β represent the geometry of the channel, and ε represents a factor based on channel geometry as well. The terms α and β were assumed to be 1.30 and 1.10, respectively, to describe the nonuniform alignment of natural streams (Thandaveswara 2009). The minimum velocity was found by back calculating from the equation

$$V_{\mathrm{avg}} = \frac{V_{\max} + V_{\min}}{2} \tag{4}$$

It can be assumed that the minimum velocity values will be experienced by the river chub on or near the bottom of the channel bed, thus the minimum velocity values were compared to the velocity criterion. Base flow conditions were evaluated within the SWMM models to determine feasible river chub nesting sites prior to looking at the effects of a typical summer storm.

River Chub

Appropriate velocity and depth criteria for suitable nesting locations of the river chub were developed to apply to the 45 SWMM models. As mentioned previously, the Mill Creek watershed was used as a basis for the development of the typical urban watershed in SWMM. The river chub species is not native to the Mill Creek watershed, but was selected to serve as an ecological indicator based on the species' vulnerability to high flows and sensitivity to urbanization. Table 4 summarizes the depth and velocity ranges and averages from studies on the river chub and closely related species.

Table 3. Water Surface Elevation Calibration

Node number	FEMA flood depth (m)	Uncalibrated model depth (m)	Percentage error	Calibrated model depth (m)	Percentage error
2	2.07	1.25 ± 0.50	40	1.16 ± 0.51	44
3	1.98	1.07 ± 0.49	46	1.56 ± 0.33	21
4	1.25	1.06 ± 0.16	15	0.91 ± 0.25	27
5	1.22	0.83 ± 0.17	32	1.02 ± 0.16	16
6	1.52	1.29 ± 0.21	16	1.44 ± 0.07	5
7	1.68	1.28 ± 0.31	24	1.62 ± 0.05	3
8	2.74	1.27 ± 0.69	54	2.12 ± 0.49	23
9	1.68	1.26 ± 0.32	25	1.52 ± 0.14	9
10	1.58	1.18 ± 0.31	26	1.50 ± 0.08	5
11	2.32	1.87 ± 0.36	19	2.35 ± 0.05	2
12	1.98	1.87 ± 0.11	6	2.02 ± 0.04	2
13	2.44	1.13 ± 0.61	54	2.59 ± 0.16	6
14	3.05	1.29 ± 0.75	58	2.23 ± 0.60	27
15	1.22	1.35 ± 0.15	−11	1.26 ± 0.04	3
16	1.07	1.35 ± 0.36	−27	1.71 ± 1.04	61
17	1.52	1.34 ± 0.16	12	1.50 ± 0.03	2
18	1.98	1.14 ± 0.46	42	2.21 ± 0.24	11
19	2.29	1.14 ± 0.57	50	2.03 ± 0.22	11
20	1.68	0.98 ± 0.40	41	1.68 ± 0.00	0
21	3.96	2.15 ± 0.99	46	3.73 ± 0.07	2
22	4.02	2.15 ± 0.99	46	2.47 ± 0.96	39

Table 4. Summary of Ranges and Averages for Water Depth and Velocity of Nests Constructed by River Chub and Closely Related Species (in Italics)

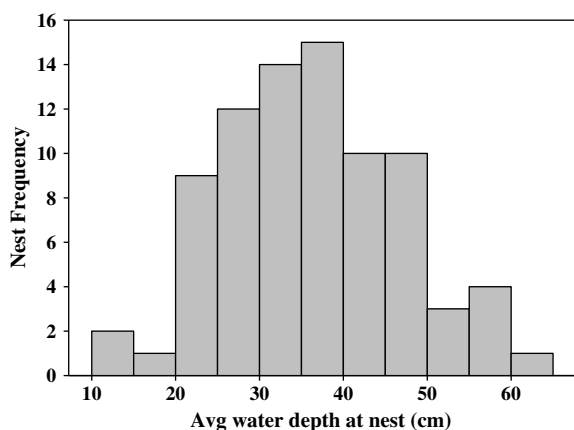| Depth range (cm)	Depth mean/average (cm)	Velocity range (cm/s)	Velocity mean/ average (cm/s)	Location	Source
Up to 91	46–60	NR	NR	Michigan	Reighard (1943)
20–43	36	NR	NR	New York	Miller (1964)
14–64	36	20–52	33	Maryland	Collected by authors
19–96	42	2–70	22	Virginia Appalachians	Peoples et al. (2014)
15–75	*38*	*7–69*	*38*	*West Virginia*	*Lobb and Orth (1988)[a]*
NR	21	NR	28	Virginia	Maurakis (1998)
NR	*51*	*NR*	*27*	*Virginia*	*Maurakis (1998)[b]*
NR	*52*	*NR*	*30*	*Virginia*	*Maurakis (1998)[a]*

Note: Location of study and source are also indicated. 'NR' indicates that quantity was not reported in this instance.

[a]Nocomis platyrhynchus.

[b]Nocomis raneyi.

Fig. 2 displays occurrences of river chub nests as a function of water depth in the Little Gunpowder Falls and Winters Run, Maryland (Kemp, unpublished data). Based on this study, Maryland river chubs prefer building nests in water depths ranging from 14 cm to 64 cm, with the maximum nest occurrences at 36 cm. Deeper and slower parts of the water column were used by river chub in a study by Peoples et al. (2014). Comparison with earlier published reports of nest depths suggests considerable variation in depths used. Peoples et al. (2014) suggest that river chub appear to use water velocity more than depth for nest site choice, with the rationale that there appears to be less variation in this criterion and that it is most important for determining nest stability. Comparison between Maryland and Virginia populations (Table 4) supports this generalization, although variation is apparent within and between populations.
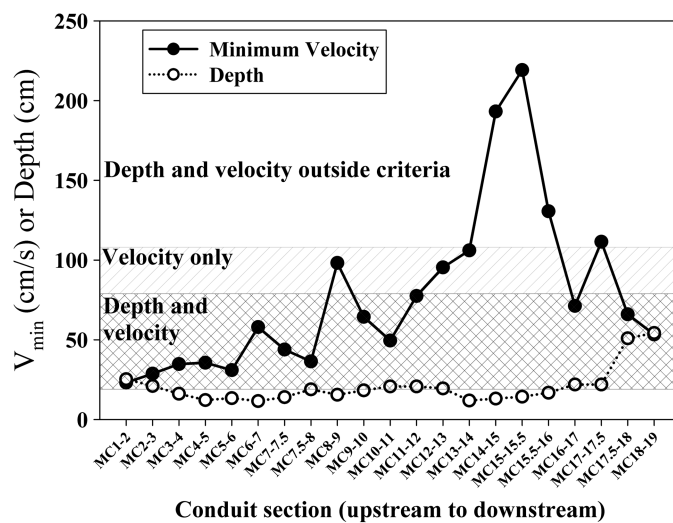
The depth and velocity observations were used to determine acceptable river chub nesting habitat criteria. A depth criterion of 20.4 to 76.2 cm was used along with a velocity criterion of 20.4 to 110.0 cm/s. These criteria were compared with results from the SWMM models to determine suitability of a particular stream section for river chub nest construction and survivability during high flows caused by storm events. As nests were found over a narrower range of velocities, this represents a liberal assessment of suitable nesting habitat. However, it is important to note that river chub are capable of finding suitable microhabitat for nest placement in high average base flow stream reaches using site choice and use of velocity shelters (Peoples et al. 2014). More importantly, assessment of the effectiveness of rain garden implementation is based on the ability of nests to survive high flows produced during storm events (Miller 1964). The exact stream velocity in which river chub nests can survive is unknown; however, there is some indication that they can temporarily survive some variation. For example, Peoples et al. (2014) found that river chub nests, while significantly reduced in height, were able to withstand high flows six times that of measured base flow. The upper boundary of 110 cm/s is therefore a reasonable limit to assume for spawning activity and nest viability during storm events. It is important to note that other key parameters for successful nesting sites were assumed to be favorable such as pebble size, temperature, and food sources.

Results

Fig. 3 displays the calculated minimum velocity and depth from upstream to downstream for the 21 conduit sections modeled. When comparing the base flow conditions to the nesting criteria, seven conduit sections of the main reach are suitable: MC1-2, MC2-3, MC10-11, MC11-12, MC16-17, MC17.5-18, and MC18-19. In total, the river chub have approximately 3,000 m of stream in which they can construct their nests during base flow conditions. With the nesting site availability

Fig. 2. Frequency distribution of water depths associated with river chub nests found in Little Gunpowder Falls and Winters Run, Maryland

Fig. 3. Suitability of stream reach baseflow conditions (depth and minimum velocity) for river chub nesting; cross-hatching indicates where both depth and velocity are acceptable, diagonal lines indicate where velocity is acceptable, and lack of pattern indicates where depth and velocity are not acceptable

Table 5. Number of SWMM Conduits Suitable for River Chub Nesting with Associated SWMM Conduit Length (m); and Indication of Velocity or Depth Criteria Exceedance, with Lower Limit

Percentage impervious area	Percentage rain garden implementation and criteria exceedance									
	0%	V/D	25%	V/D	50%	V/D	75%	V/D	100%	V/D
3	7 (3,061)	—	6 (2,988)	*V*	6 (2,988)	*V*	6 (2,988)	*V*	6 (2,988)	*V*
5	6 (2,070)	D	7 (3,061)	—	7 (3,061)	—	7 (3,061)	—	7 (3,061)	—
9	5 (1,399)	D	4 (1,326)	*V/D*	5 (2,317)	*V*	5 (2,317)	*V*	6 (2,988)	*V*
10	5 (1399)	D	4 (1326)	*V/D*	4 (1326)	*V/D*	5 (2317)	*V*	5 (2317)	*V*
20	2 (853)	V/D	2 (853)	V/D	2 (853)	V/D	3 (1067)	V/D	3 (1067)	V/D
25	1 (320)	V/D	1 (320)	V/D	2 (853)	V/D	2 (853)	V/D	2 (853)	V/D
60	0 (0)	V/D	0 (0)	V/D	0 (0)	V/D	0 (0)	V/D	0 (0)	V/D
70	0 (0)	V/D	0 (0)	V/D	0 (0)	V/D	0 (0)	V/D	0 (0)	V/D
80	0 (0)	V/D	0 (0)	V/D	0 (0)	V/D	0 (0)	V/D	0 (0)	V/D

Note: Exceedance denoted by italics font.

defined for the base flow conditions, nesting and nest survival during storm conditions can then be assessed.

The typical summer storm (1.3 cm-6 h) was evaluated for the 45 SWMM models to assess the relationship between river chub nest sites and percent impervious area and percent rain gardens. In each scenario, the velocities and depths were taken during the maximum flow of the storm hydrograph. The previously mentioned mathematical process was used to determine the minimum velocity at the channel bed during the peak flow of the storm event. Nest destruction during the storm event was assumed if a velocity greater than the criterion is reached during a storm event, as the pebbles of the nest would erode away. Depths outside of the depth criteria were assumed to produce adverse conditions for the development of juvenile river chub. Therefore, habitable locations refer to areas in which both criteria are met.

Table 5 displays the number of SWMM conduit sections (and length) meeting the nest building criteria for each scenario analyzed. The "V/D" column denotes if the depth criterion (D) or velocity criterion (V) were not met during the typical summer storm. Generally, the criteria were exceeded during the typical summer event. One upstream conduit, however, exceeded the criteria of the lower limit on several occasions. A shaded criteria exceedance box identifies this scenario. With no rain garden implementation and at impervious areas lower than 20%, the limiting criterion for successful spawning in some conduit sections was depth. The increases in impervious area generally lead to greater runoff and higher peak flows, thus exceeding both depth and velocity criterion as imperviousness of the watershed exceeded 20%. As the number of rain gardens handling roof runoff increased, only the velocity criterion was exceeded for impervious areas of less than 20%.

A percent impervious area ranging from 3 to 5% seems to be the ideal conditions for the river chub, as a typical summer storm will not reduce suitable sites for spawning. The ability to successfully spawn will be diminished in two to three of the seven total conduit sections during the typical summer storm for impervious areas of 9 to 10%. In the 20 to 25% impervious area scenarios, half of ideal spawning locations will be eliminated during the 1.3 cm-6 h storm. It is likely that the river chub will not be able to sustain itself as a species in the watershed with 60% or greater impervious area, as all ideal spawning locations are disrupted during the typical summer storm. The survival trend of the river chub based on percent impervious area closely resembles the revised impervious cover model (Schueler et al. 2009) where an impervious percentage between 10 and 25% is considered impacted and greater than 25% is considered ecologically non-supporting.

The river chub nesting regions are not affected by the typical summer storm event for the 3 and 5% impervious scenarios, and therefore an ecological improvement with the addition of storm water controls would not be seen. The 9, 10, 20, and 25% impervious cover scenarios show a decrease in nest habitat destruction by about one conduit per impervious area scenario as the rain garden percentage increases from 0 to 100%. With an impervious area of 60% and greater, no amount of rain gardens can produce favorable velocity and depth combinations to meet nest building criteria during a storm event.

Fig. 4 offers a visual representation of the percent of conduit sections that retain nesting function during the 1.3 cm-6 h storm. There is approximately a 10% increase in conduit sections meeting the depth and velocity criteria between the 0 and 100% rain garden implementation. Stream health ranges of sensitive, impacted, and non-supporting were defined as recommended by Schueler's impervious cover model (Schueler et al. 2009).

The 100% rain garden scenario initially shows a reduction in conduits retaining nesting function. This can be attributed to the special case noted in Table 4, where one upstream conduit experienced a drop in depth and velocity below the range of acceptable nesting criteria. The nesting function was not improved for the 10% impervious area watershed with the full addition of rain gardens. This anomaly may be attributed to model error within SWMM, or the effectiveness of rain garden implementation may experience a reduction during the transition between a sensitive and impacted stream. Nest function is sustained for 70 to 100% of the nest locations within the sensitive stream criteria (0 to 10% impervious area) for all SWMM runs analyzed. Impacted streams with watershed impervious areas between 10 and 25% showed nest functionality during the 1.3 cm-6 h storm of 15 to 70%.
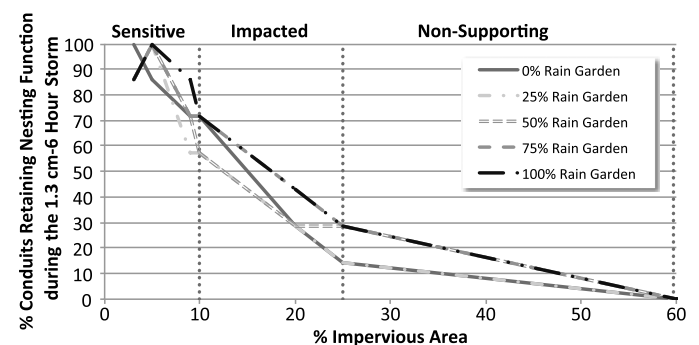
Fig. 4. Nesting function during the 1.3 cm-6 h storm simulation

Table 6. Results of Statistical Comparison (Wilcoxon Signed Ranks Test) of Average Minimum Velocities during Modeled Rain Storm Events at Different Levels of Rain Garden Implementation

Percentage rain garden levels	0–25%	25–50%	50–75%	75–100%
Z-statistic	−7.475	−6.337	−7.077	−7.356
P-value	<0.001	<0.001	<0.001	<0.001
Velocity reduction (cm/s)	6.1	2.8	3.7	4.0

Non-supporting streams with watershed impervious areas between 25 and 60% showed 0 to 30% river chub nest functionality. Generally, the implementation of 50% or more rain gardens to capture roof runoff restored about 15% of the river chub nesting function for watersheds with an impervious area of 10 to 35%, illustrating that stream functionality may be preserved if rain gardens are utilized when further urbanizing a watershed.

To examine the statistical significance of the reduction of minimum flows during storms by rain garden implementation, minimum flow during rain storm events were compared relative to proportion rain garden implementation. Data were arranged according to stream reach and impervious area so that a pairwise comparison of reduction of minimum flow was possible.

Data were found to deviate from normality, so a non-parametric test was used to compare between groups. A Wilcoxon signed ranks test (Sokal and Rohlf 1981) was conducted between groups of minimum velocities from different levels of rain garden implementation (0%, 25%, 50%, 75%, 100%), paired according to stream reach and percentage impervious area in model runs. Comparisons were done using data from numerically adjacent levels of rain garden implementation (0–25%, 25–50%, 50–75%, and 75–100%), to quantify the differences observed when increasing rain garden coverage by 25%. The results of these four comparisons are summarized in Table 6. Columns represent results of pairwise comparison of average minimum velocity at indicated levels of rain garden implementation. For each comparison, the test statistic (Z-Statistic), P-value, and the average minimum velocity reduction (cm/s) are provided. These tests show that rain garden implementation significantly reduced minimum in-stream velocity experienced during storm events, at all levels examined in this study. Average minimum velocity reductions ranged from 2.8 cm/s for the 25 to 50% change in rain garden coverage to 6.1 cm/s for the 0 to 25% change in rain garden coverage.

Conclusions

This paper represents an example of how the effects of implementation of SCMs can be evaluated using ecological criteria using the flexible SWMM framework, while drawing upon publicly available data in an effort to reduce costs. Expansion of this approach to include multiple species and various SCM strategies will greatly improve predictability of the effects of restoration on stream ecosystems. However, the depth and velocity criteria provided here may be applied to other watersheds. One benefit of this will be to provide a priori estimates of ecosystem benefits versus restoration costs. This allows for an accurate determination of the type and extent of restoration activities needed to meet ecological restoration goals, especially in light of limited financial resources. Future research will focus on analyzing the effect of multiple types of SCM being implemented.

Intuitively, as impervious area of the watershed increases, the survival rate of the river chub (and associated species) will decline.

River chub survival is not envisioned with an impervious area of 60% or greater, as a typical summer storm will destroy most, if not all, of the nest sites. Generally, the implementation of 100% rain gardens offers a 15% increase in nesting function during the 1.3 cm-6 h storm event for watersheds with impervious areas between 5 and 25%.

With the implementation of the maximum amount of rain gardens possible within the watershed, approximately one third of the total runoff from impervious areas is successfully captured prior to reaching Mill Creek. This watershed-wide capture of roof runoff has shown to be beneficial for the survival of the river chub, especially within the range of imperviousness comprising *impacted* stream quality. Rain gardens alone, however, cannot effectively counterbalance the stress placed on the ecology from the effects of urbanization. This study highlights the need for a comprehensive storm water control plan that addresses runoff from different types of impervious areas: roofs, parking lots, driveways, roads, etc. Community involvement could promote the implementation of rain gardens on private property on a watershed-wide scale, at minimal costs to the state or municipality. The construction of SCMs to handle street runoff would most likely require government funding, and may not be as feasible to implement on a large scale. Future work may include assessing the effects on habitat and hydrology when implementing a conglomerate of control measures to handle a greater amount of storm water runoff.

While improvement of ecosystem function is one of the most commonly stated goals of stream and watershed restoration, these goals are frequently not met in practice through stream restoration activities (Bernhardt and Palmer 2011). Challenges to effective ecological restoration of waterways include a lack of mechanistic understanding of the effects of restoration activities on downstream ecosystems and a failure to consider problems at the watershed scale (Beechie et al. 2010; Bernhardt and Palmer 2007). A large step in bridging the divide between restoration in practice and meeting ecological goals will be to incorporate specific and detailed habitat requirements into robust and flexible hydrological models of SCM benefits. While restoration of ecological function cannot be expected by improving habitat for a single species, identification and consideration of species that are exceptionally important to ecosystem function (*ecosystem engineers* or *keystone species*), such as the river chub, can be a logical starting point. Examples of species that are perceived to be critical to ecosystem function include the American oyster (*Crassostrea virginica*) and various species of submerged aquatic vegetation in the Chesapeake Bay (Kemp et al. 2005). Restoration of these species in particular is seen as essential to the overall Chesapeake Bay restoration effort, for example. For habitat improvement through stream restoration, one concern is that there is also a lack of relevant data concerning the habitat requirements of species available to implement this approach (Peoples et al. 2011). In the case of the river chub, there are surprisingly large gaps in the information available regarding specific habitat needs, particularly in the context of anthropogenic alteration (e.g., urbanization). However, recognition that these data are required in this modeling framework will hopefully foster research into acquiring these data. Notable attempts to model effects of watershed characteristics on habitat exist. However, without the incorporation of a quantitative understanding of the effects of SCMs and specific, relevant data on habitat requirements of species concerned, it will not be possible to accurately predict the impact of specific restoration activities on target species. Modeling frameworks, which join these considerations, as in the one presented here, will provide restoration practitioners with solid goals and will improve their chances for success in ecological restoration.

Acknowledgments

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