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Case Study Article

Continuous Hydrologic Modeling of a Parking Lot and Related Best Management Practices with PCSWMM

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Abstract: Permeable pavements are a green infrastructure stormwater management practice that can serve as a functional component of the site design. However, previous field studies suggest high uncertainty in the parameters used for performing hydrologic calculations for permeable pavements. The Environmental Protection Agency (EPA) Storm Water Management Model (SWMM) within the PCSWMM software package was used to simulate the hydrologic dynamics of a parking lot that is 25% covered with permeable interlocking concrete pavers in Auburn, AL. The model was calibrated to field observations of water level at two points where the pavement system outflows to a bioretention basin and rainfall data from a nearby weather station. The use of the Curve Number (CN) method within SWMM resulted in good prediction of pavement outflow by the calibrated model, with R^2 and Nash-Sutcliffe model efficiency both greater than 0.8, except where issues with precipitation data coverage occurred. This demonstrates that permeable pavements can be modeled as a land cover type rather than as detention storage. The calibrated value of the runoff CN for permeable pavement was 60, much lower than what is recommended in many design guidelines for the underlying soil type at the research site, which is hydrologic soil group B. Based on evaluation of alternative model scenarios, the permeable pavement reduced runoff by 11-38% across contrasting rain events.

Keywords: *stormwater, permeable pavement, hydrologic modeling, model calibration, curve numbers*

Stormwater management is integral to mitigating the impacts of urban development on water resources. The sponsors of a development or redevelopment project that exceeds a certain size are typically required by local, state, or federal law to have a stormwater management plan to maintain or restore to the maximum extent technically feasible the pre-development hydrology of the property (US EPA 2009). This is achieved with stormwater best management practices (BMPs), which are structures and functional site components that store and treat stormwater before it is released from the watershed.

The conventional design of stormwater systems does not perform well in terms of reducing peak flows (NRCS 1986) and removing runoff contaminants (Roseen et al. 2006). Also, land uses with high levels of imperviousness are known for contributing to higher peak flows (NRCS 1986) and contaminant loadings (US EPA 1983). Permeable pavement is a stormwater BMP that also serves as a functional component of the site, such as a roadway or parking area, with the benefits of reducing peak flows by flattening flow-duration curves (Hood, Clausen, and Warner 2007), lowering contaminant loads (Dietz and Clausen 2008), and decreasing temperature in downstream water bodies (Van Dam et al. 2015). Examples of permeable pavements include interlocking pavers, pervious concrete, and porous asphalt; they have an open void structure that

Research Implications

- The Environmental Protection Agency (EPA) Stormwater Management Model (SWMM) is a useful tool for performing continuous hydrological modeling of permeable pavements in urban settings.
- Implementation of interlocking concrete pavers substantially reduced runoff volumes and this can be quantifiable through modeling.
- The curve numbers recommended for site design with permeable paver systems may be too high, resulting in overdesign of detention storage in systems that include both permeable paver systems and storage-based stormwater practices.

allows infiltration of water through the pavement and into an underlying drainage basin made of crushed stone or high permeability soil.

The rainfall-runoff dynamics of permeable pavements must be calculated as part of the site design process. The most common approach for rainfall-runoff calculations for stormwater management for small catchments is the Natural Resources Conservation Service (NRCS) Curve Number (CN) approach (NRCS 1986). Other infiltration calculation methods, including Horton, Modified Horton, Green-Ampt, and Modified Green-Ampt, are available in most modeling software but require field data that can be difficult to obtain. The advantage of the CN method is that it is based on a dimensionless parameter that is related to land use, hydrological soil group, and antecedent soil moisture. The CN method was developed for small agricultural watersheds (< 4 ha) and was originally developed as an event-based simulation approach. Within the Storm Water Management Model (SWMM), the CN method is implemented with time as a variable (continuous simulation) and the initial abstraction can be used as a calibration parameter. Due to the ease of calibration and simulation in SWMM and the minimal input data requirements, the CN method was chosen for this study.

To apply this approach to a catchment containing permeable pavements, a CN must be assigned to the permeable pavement surface so that runoff from each rainfall event can be calculated as it would be for a pervious or impervious land cover, such as grass or conventional pavement. However, simulation of unsaturated flow through permeable pavements suggests that runoff is only produced when the permeable pavement subgrade becomes fully saturated from below (Chai et al. 2012). Therefore, mass balance routing approaches that treat permeable pavements as detention storage rather than as a land cover type have been proposed as more appropriate than the CN approach, particularly for systems with underdrains (Martin and Kaye 2014; 2015).

One advantage of the CN approach is that the parameters can be readily obtained with the knowledge of hydrological soil group and land use type. Thus, it is widely used as a means to compute runoff abstractions in hydrological models such as the EPA SWMM. SWMM is a dynamic hydrologic-hydraulic model that is used to simulate runoff quantity and quality for single or continuous events. The model estimates the runoff generated by subcatchments, transporting it through collection systems and computing the flow rate, flow depth, and water quality in each component of the collection system (Rossman 2015). The implementation of CN into SWMM is relatively new. The original NRCS CN method was an event-based methodology, which was adapted for continuous simulation as outlined in Rossman and Huber (2016). Software packages such as PCSWMM, developed by Computational Hydraulics International (CHI, Guelph, ON, Canada), are often used for this type of modeling. The computational engine of the PCSWMM software package is SWMM. SWMM was selected for use in this study because it was designed for stormwater management in urban watersheds and simulates both hydrologic and hydraulic dynamics. Other models, such as the United States Department of Agriculture (USDA) Soil Water Assessment Tool (SWAT) (Arnold et al. 2012), are more appropriate for agriculture and forested watersheds, while models such as the U.S. Army Corps of Engineers Hydrologic Engineering Center's Hydrological Modeling System (HEC-HMS) (Feldman 2000) and River Analysis System (HEC-RAS) (Brunner 2010) are more appropriate

for focused hydrologic or hydraulic analysis, respectively.

Recent research has made progress in representing permeable pavements within SWMM. Zhang and Guo (2015) performed an initial investigation into permeable pavement modeling and provided recommendations for setting time steps and other model parameters for these systems. Later work found that SWMM produced representative hydrographs for permeable interlocking concrete paver systems using the porous paver module (Randall et al. 2020). Madrazo-Uribeetxebarria et al. (2023) linked porous pavers and CN, focusing on creating an equivalency between the CN model in SWMM and the approach based on green infrastructure practices (GIP).

A major challenge associated with using the CN approach for permeable pavements is the broad range of hydrologic behavior observed in the literature (Bean, Hunt, and Bidelspach 2007; Beisch and Foraste 2011; Eger, Chandler, and Driscoll 2017), which leads to uncertainty in the parameters of the calculation. The CN values recommended in many design manuals for permeable pavement surfaces are high. For example, a value of 85 is recommended by the City of Auburn, Alabama, which has relatively high permeability soils (primarily hydrologic soil group B) (e.g., City of Auburn 2019). However, the limited empirical studies on the topic have reported a wide range of values between 6 and 89 (Bean, Hunt, and Bidelspach 2007; Beisch and Foraste 2011), with much of the variability attributed to differences in design and underlying soil type. The use of a CN that is too large could result in an overly conservative design of downstream detention storage and higher construction costs (Ellis et al. 2022).

Few studies have combined field data collection with hydrologic modeling to evaluate the hydrologic behavior of permeable pavements. In this study, hydrologic monitoring data were collected for a municipal parking lot in Auburn, AL, that includes permeable interlocking concrete pavements (PICP) and these data were used to develop a calibrated model in SWMM. The following research objectives were addressed.

1. Determine the calibrated value of the runoff CN for PICP and compare it to recommended values for design.
2. Evaluate the ability of SWMM with its CN method to accurately model a small catchment with PICP for an extended period.
3. Use the calibrated model to assess how increasing or decreasing the area of PICP would affect runoff.

Methods

Study Site

This study was conducted at a municipal parking lot in Auburn, AL (32°36’32.06”N, 85°28’37.01”W). The climate is humid subtropical with mean annual precipitation of 1340 mm and mean annual temperature of 18°C. Soils are classified as well-drained loamy sands and sandy loams in hydrologic soil group B (NRCS 2020). The parking lot consists of a 0.29 ha paved area, of which 25% is PICP and 75% is impervious asphalt (Figure 1). The PICP are underlain by a 15 cm aggregate choker course (5 cm of #89 stone above 10 cm of #57 stone) and a 60 cm aggregate recharge bed consisting of #2 stone. The permeable pavement system drains to an onsite bioretention basin through an underdrain. There is also a grass channel to convey excess surface runoff from the asphalt and PICP area to the bioretention basin. In addition to the asphalt and PICP, 0.015 ha of greenspace drains to the bioretention basin, making the total catchment area 0.31 ha.

Field Data Collection

Field data were collected from April to July 2021, to allow for calibration of PCSWMM. Five-minute precipitation data recorded with a HOBO RX2100 tipping bucket rain gauge (Onset Computer Corporation, Bourne, MA) were obtained from the City of Auburn from a station that is 1.3 km from the research site, which introduced some uncertainty in the timing of rain events. Two HOBO U20L-04 (Onset Computer Corporation, Bourne, MA) water level loggers were used to measure water depth above the bioretention basin media at the entrance to and within the bioretention basin. The sensors have an accuracy of 0.6 mm and measured at a 5-minute interval. A third logger was installed outside of the bioretention basin to measure barometric pressure

for atmospheric compensation. The water level logger at the entrance of the bioretention basin was installed behind a two-stage hydraulic control to allow for the calculation of flow rate (Figure 2). The structure included a 75 mm diameter circular sharp-crest orifice to enable a depth-discharge relationship for low flow computations within SWMM, and a trapezoidal crest weir with a base of 1.6 m and 30-degree side slopes that was used for the discharge of large flows. The assessment of these control structures was made through a comparison between the observed depths and the modeled results.

SWMM Model Development

Because of the simple geometry of the system, each different land cover type could be explicitly represented as subcatchments in SWMM. Thirteen

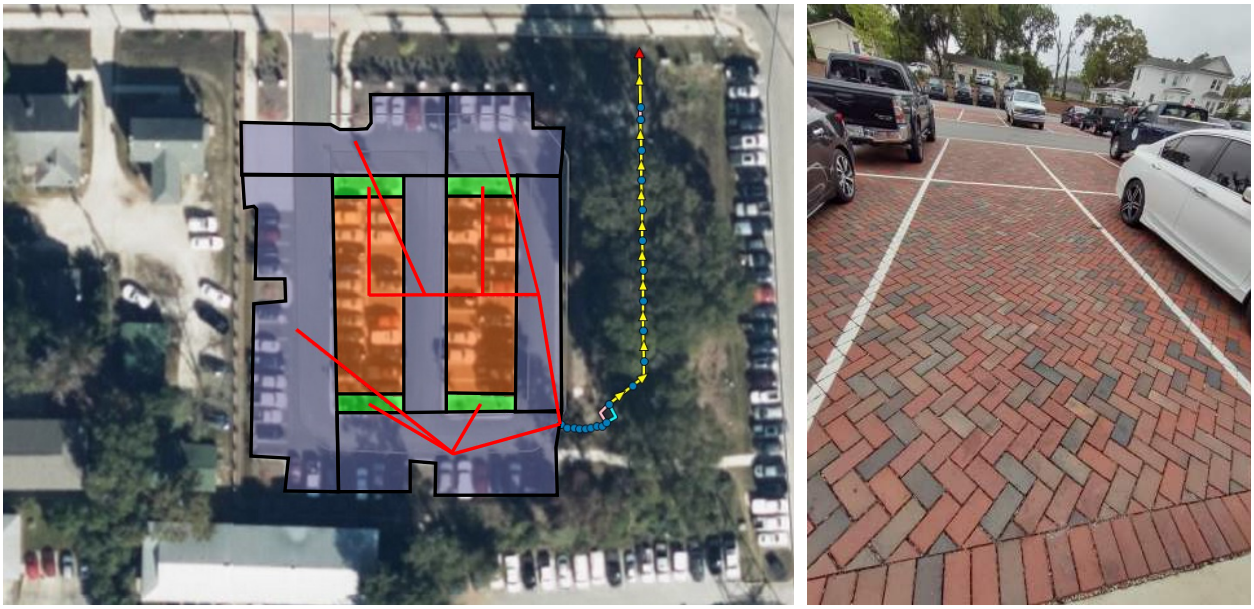

Figure 1. Left: Parking lot catchment draining to the bioretention basin on the east side of the parking lot including asphalt (purple), PICP (orange), and greenspace (green). The flow paths to the bioretention basin (blue dots) and through the bioretention basin (yellow arrows) are also shown. Right: PICP installed at the site.

Figure 2. Hydraulic structure at the entrance to the bioretention basin with an orifice for low-flow measurement and a weir for high-flow measurement.

subcatchments were represented, all draining to the channel that leads into the bioretention basin (Figure 3). The bioretention basin was represented as a trapezoidal channel with an outlet structure at the downstream end. The infiltration in the bioretention basin was represented by setting the property seepage loss rate for the channel reaches with values calibrated from measured water level data.

The groundwater/aquifer module in SWMM was not used to represent exfiltration in the model. The exfiltration was represented within the model as a seepage rate of 5 mm/hr in each link. Changes in vegetation growth, which would influence the surface roughness for flows in the bioretention basin and greenspace, were not considered in this study since SWMM does not consider this process in its calculations. Evaporation was represented using a daily evaporation rate based on temperature obtained through the Global Historical Climatology Network - Daily (GHCN-Daily). The CN value for dense graded asphalt pavement (98) was obtained from the NRCS TR-55 (NRCS 1986). The small areas of constructed greenspace within the parking lot are pine straw over a high-permeability soil draining to the permeable pavement recharge bed and were assigned a low CN value of 40. Model calibration was performed using the Sensitivity-based Radio Tuning Calibration (SRTC) tool in PCSWMM Version 5.1. The calibrated parameters were the following:

- CN value for PICP;
- Manning's roughness of overland flow for pervious subcatchments (PICP and greenspace);
- depression storage for each subcatchment;
- drying time parameter for each land cover type;
- Manning's roughness of the bioretention basin;
- seepage rate in the bioretention basin; and
- discharge coefficients for the weir and orifice.

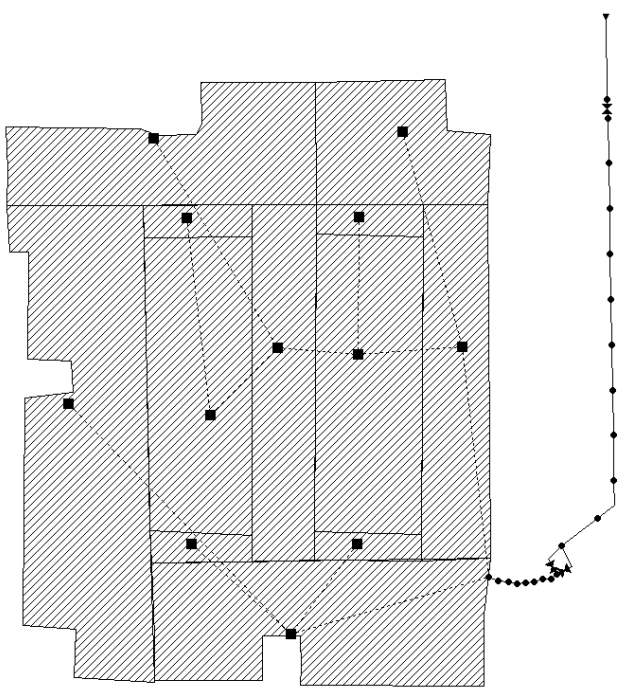

Figure 3. SWMM model representation of the parking lot. The subcatchments (hatched areas) converge to the bioretention basin, which is represented as a channel (dotted lines).

The model was run continuously at a sub-daily routing time step of 0.1 s from April to July of 2021, which included 15 rain events. The routing time step obeys the Courant-Friedrichs-Lewy (CFL) condition and a small routing time step was selected because of the unsteady characteristics of the system and the way that the bioretention was modeled. This period includes the period of active convective thunderstorms that typically represents the highest annual rainfall intensities in the study region. A select group of rain events that represent the range of outflows from the parking lot were used for model calibration and validation. The coefficient of determination (R^2) and Nash-Sutcliffe model efficiency (NSME) were used to evaluate model performance. There was some variation in model performance statistics across rain events, which is represented by the selected rain events. Additionally, a visual inspection of the rising and falling limbs of the hydrograph was used to determine which modeling conditions were most representative of the field measurements.

Scenario Analysis

Within the calibrated model, it was possible to create alternate scenarios to study the effect of permeable pavements on runoff. Two alternative scenarios were considered and the total runoff volume for the full simulation period (April to July 2021) was compared across the scenarios. First,

a scenario was considered in which the entire parking lot was constructed from impermeable dense graded asphalt pavement. Second, a scenario was considered in which the entire parking lot was constructed from PICP. These scenarios were developed to consider the full range of design possibilities for a parking lot built with a combination of impermeable pavement and PICP.

Results and Discussion

Model Calibration

Within the period of the hydrological modeling, four rain events in 2021 were selected for SWMM calibration that span the range of conditions observed in the study area (Figure 4).

1. April 10: Total depth 27 mm, duration 6 h.
2. April 24: Total depth 63 mm, duration 19 h.
3. May 3: Total depth 68 mm, duration 45 h.
4. June 19: Total depth 48 mm, duration 72 h.

The site-specific calibrated values of the model parameters are given in Table 1. All calibrated values were within the range typically found in the literature except for the discharge coefficients. The weir coefficient was lower than SWMM's traditional value of 1.8 (Brater et al. 1996), likely due to a lack of perfect horizontal alignment of the weir crest. The orifice coefficient was larger than SWMM's recommended value of 0.65. At this study site, there were frequent problems with debris, such as leaves and twigs, blocking discharge through the orifice. This reduced the area

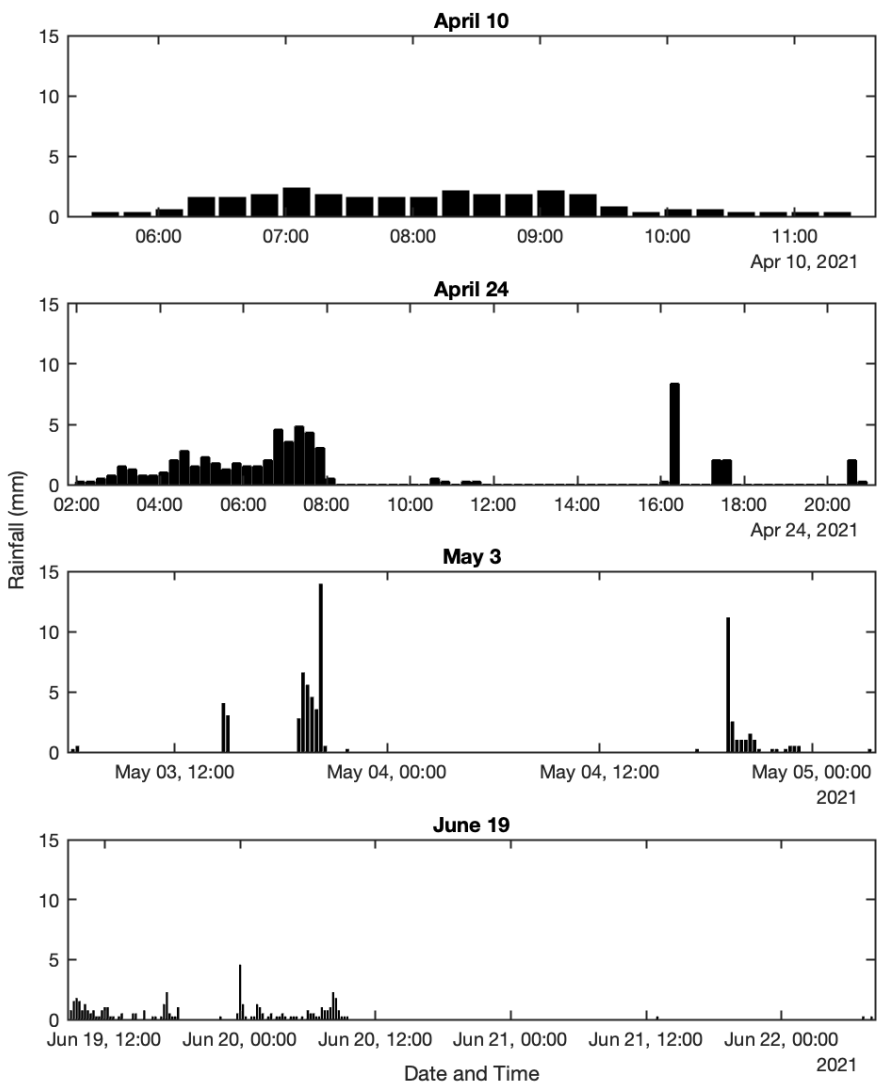

Figure 4. Fifteen-minute hyetographs of the four rain events selected for SWMM calibration. Note that the time range (x axis) is different for each subplot.

Table 1. Calibrated SWMM parameters. The range of values tested in the calibration procedure and the final calibrated value are shown.

Parameter	Range	Calibrated Value
PICP CN	40-80	60
Manning's Roughness (Overland Flow)	0.011-0.031	0.021
Depression Storage (mm)	0.6-2.4	1.2
Drying Time (days)	2.5-7.5	5.0
Bioretention Basin Seepage Rate (mm/h)	2.3-9.0	4.5
Manning's Roughness (Bioretention Basin)	0.022-0.090	0.045
Weir Discharge Coefficient	0.6-1.2	0.8
Orifice Discharge Coefficient	0.2-0.5	0.3

of flow through the orifice, leading the calibrated value of the discharge coefficient to be larger. In this case, it was easier to correct for this problem by calibrating the discharge coefficient to a larger value than to adjust the discharge area.

Observed and Modeled Water Depths

Figure 5 presents a comparison of the observed water depths with calibrated model results above the media in the bioretention basin and at the hydraulic structure. The response at the hydraulic structure was very flashy in response to rain, as it captures the surface drainage from the parking lot, a small and largely impervious catchment. The water depth in the bioretention basin rises quickly in response to the rain events, due to its small volume. However, the process of drainage through infiltration was much slower, taking at least four days.

Based on R^2 and NSE, the model predictions of bioretention basin water level were satisfactory, with values consistently above 0.8 for both statistics. The exception was the June rain event (Figure 5g-h), in which the observed onset of water level rise did not match the model. This may be because the rain gauge is not located immediately at the study site and rain may have started earlier at the rain gauge site. The calibrated model also performed reasonably well at representing the dynamics of runoff from the parking lot, though R^2 and NSE were lower for both the May (Figure 5e-f) and June (Figure 5g-h) rain events. In the May rain event, there was a small early spike in the observed data that is not captured in the model. It is likely that this is also due to issues with the rain gauge location. The amount of runoff in this early spike was not large enough to cause a change in the water level in the bioretention basin. The falling limb of the bioretention basin hydrograph was longer in the model simulation than in the observed data, which is likely due to an underestimation of infiltration rate. However, representing peak flows correctly was the primary goal, and these show good agreement.

Some studies have suggested that a modeling approach that treats permeable pavements as a detention reservoir rather than a catchment is more appropriate (Martin and Kaye 2015). The calibrated SWMM results demonstrated that the CN approach is adequate for modeling permeable pavements, though a very low depression storage value (> 2 mm) must be used. Further, the calibrated values of CN (60) indicated that the values recommended in many design guidance are too high. One important remark is the importance of the field data acquisition to ensure the calibration of the hydrological modeling. Finally, the ability to perform continuous hydrological modeling provides more confidence that previous rain events are properly incorporated in the predictions and that the CN values obtained here are representative for the test site.

Alternative Pavement Scenarios

For the alternative scenarios, a complete replacement of dense graded asphalt pavement by

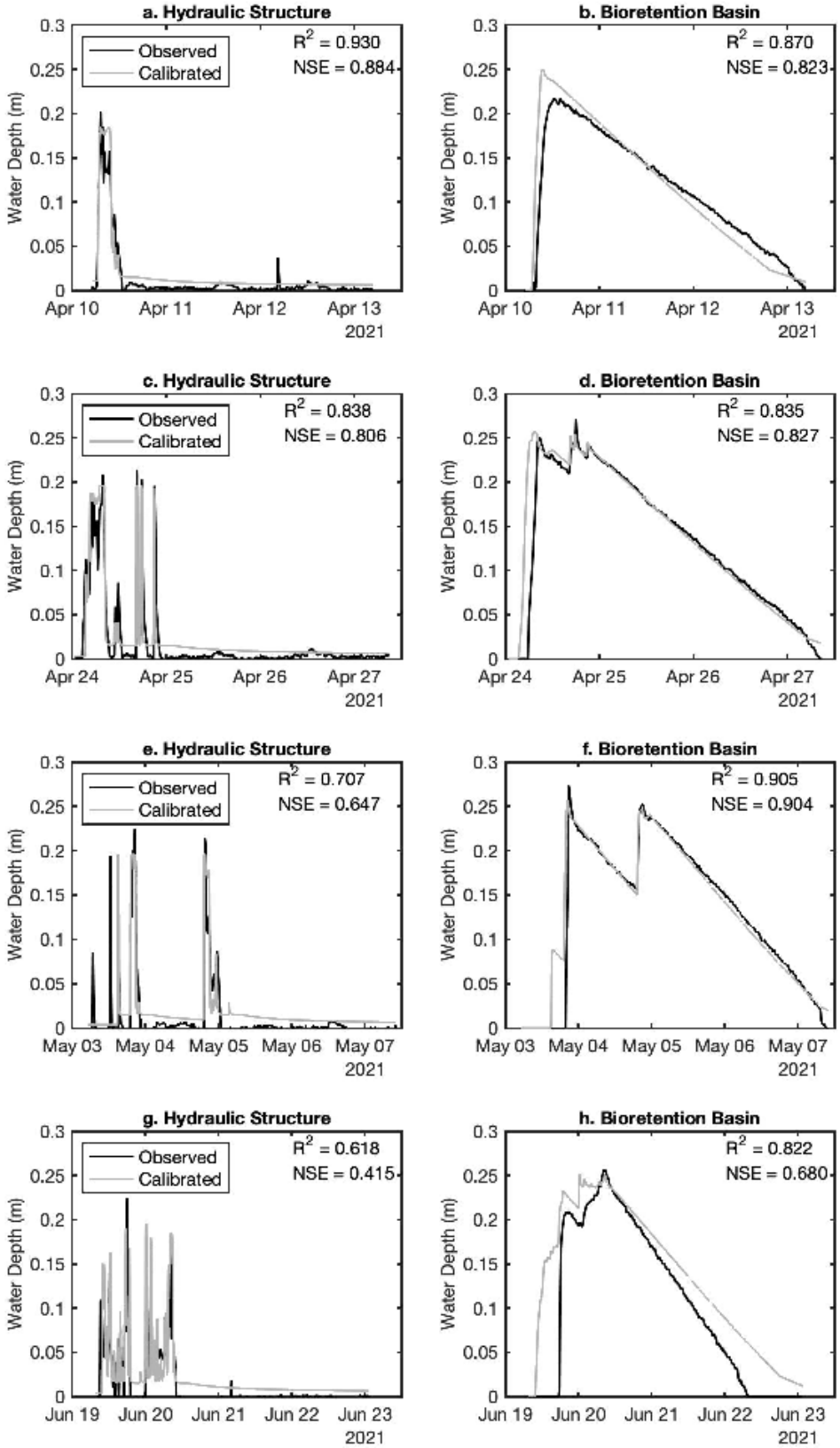

Figure 5. Observed (black line) and modeled (gray line) changes in water depth in (a, c, e, g) the hydraulic structure and (b, d, f, h) the bioretention basin for the rain event on (a-b) April 10, 2021, (c-d) April 24, 2021, (e-f) May 3, 2021, and (g-h) June 19, 2021.

PICP substantially reduced the runoff volume. The decrease in volume from the as-built design ranged from 86% for the smallest rain event to 60% for the largest rain event (Figure 6). The difference between the as-built design and a parking lot built entirely from impermeable dense graded asphalt pavement was much smaller, ranging from 11-38%. Expanding the area of PICP in the lot could reduce runoff volume, which reduces the required size and cost of detention storage (Ellis et al. 2022). However, this must be weighed against other considerations, such as the greater durability of impermeable pavement for high-traffic areas.

Conclusions

This work, consisting of continuous hydrologic modeling supported by field monitoring, concluded that a calibrated CN of 60 yielded a representative description of the parking lot hydrology. This is much lower than the value of 85 that is currently recommended by the City of Auburn stormwater design guidelines. While some parts of the city have less permeable soils and may require a more conservative CN, the value of 85 is likely too high for the large parts on the city with hydrologic soil group B. This finding indicates that using a lower CN for permeable pavements at this site will more accurately represent the hydrologic benefits of using this type of green infrastructure practice. Further studies of this nature at other sites could encourage wider application of permeable pavements in Auburn and across Alabama. The scenario analysis in this study demonstrated that PICP can reduce runoff volume from a parking lot by up to 86% depending on the percentage of area covered by PICP and the type of rain event.

The results also highlight the benefits of using SWMM as a tool for designing stormwater management for sites that include green infrastructure practices, as the predictions of the model showed good agreement with measured values following calibration. Within this model, and considering this parking lot, the modeling parameter depression storage (which is very important for computing hydrological abstractions) was found to be in the range of 1 to 2 mm. Future work should consider the application of extended-period SWMM to other types of green infrastructure practices to precisely quantify their benefits. Another possible future direction is to perform similar studies in other sites with permeable pavements but different hydrological characteristics, to understand how these can impact the values of CN for hydrological modeling.

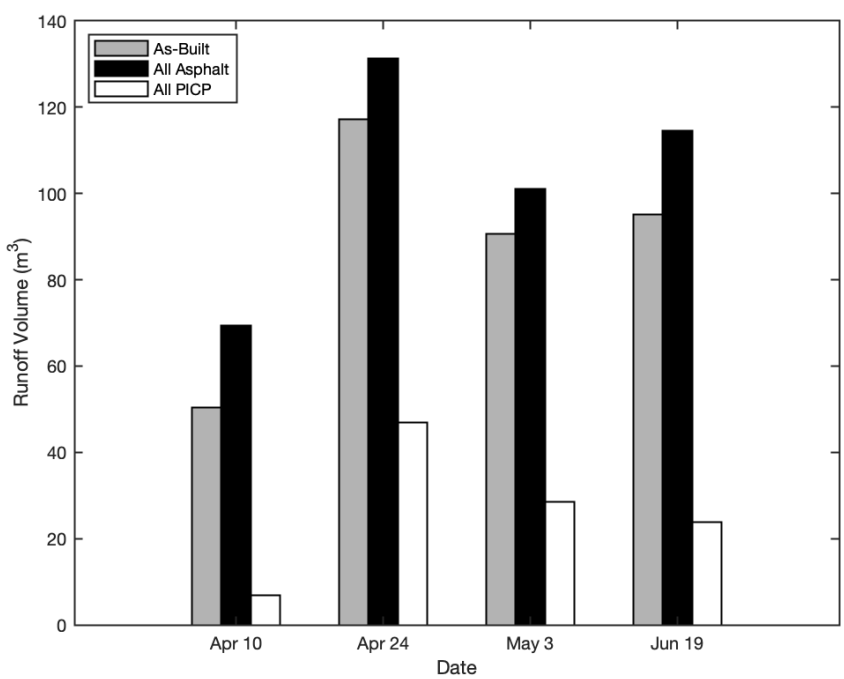

Figure 6. Total runoff volume generation for the as-built design and alternative scenarios where the parking lot is entirely impervious asphalt or entirely permeable pavement.

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