Hydrologic and Water Quality Performance of Porous Pavers on Easy Street in Ann Arbor, Michigan

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Introduction

In 2007 as part of a novel project for the City of Ann Arbor, Michigan, 3 to 3.5-feet of the outer edges of existing asphalt on a half mile of residential street were replaced with porous pavers. Five rain gardens vegetated with Michigan native species were constructed in the road right of way adjacent to the pavers. The hydrologic and water quality benefits of the pavers and swales were assessed with wet weather flow and water quality monitoring and hydrologic/hydraulic (H/H) modeling. The monitoring included pre- and post-construction flow and water quality data collected about three years apart at the same locations. The US Environmental Protection Agency (EPA) Storm Water Management Model (SWMM) was used to simulate measured flows and forecast flows following installation of the proposed improvements.

Easy Street is located in southeast Ann Arbor adjacent to Buhr Park, a 40-acre multi-use city park. The park's storm sewer drains to the storm sewer in the project area on Easy Street (see **Figure 1** below). Before reconstruction most of Easy Street was asphalt pavement, had no curb and gutter, nor sidewalks and had not had a major re-surfacing in more than ten years. Due to a concerted grassroots effort from the residents of Easy Street, what originally started out as a road re-surfacing project become a new kind of street design for Ann Arbor.

The street has a standard crown in the middle with a 1% cross-slope. The entire street and most of the adjacent 28 homes and driveways drain to the street. The porous pavers on both sides of the street are underlain by an aggregate bedding layer, a deep (~2-feet) layer of larger aggregate with underdrain beneath that (see **Figure 2** below). The underdrain drops into existing storm sewer in the street.

Monitoring and Modeling

Preconstruction flow and water quality data were collected for two weeks in November, 2005 and again during a three-month period in Spring, 2006. Twenty events were captured with total event volumes between 0.07 and 1.84 inches and a maximum hourly intensity for all events of 0.59 inches. Project construction was completed in Fall, 2007. The post-construction monitoring was conducted from May to July, 2009 and captured fifteen events between 0.11 and 1.84 inches, with a peak hourly intensity of 0.81 inches. The field data were collected using continuous recording pressure transducers and automatic, timed grab sampling during wet weather events. The pressure data was converted to flow using SWMM-estimated depth to flow relationships for the monitoring sites. Event mean concentrations (EMCs) for total suspended solids (TSS), total phosphorus (TP), orthophosphate (OP), total copper (Cu) and total zinc (Zn) were developed using EPA protocol for developing flow-weighted composite water quality samples.

The data was collected at the furthest downstream, southerly end of storm sewer on Easy Street before it empties into the storm sewer main on Packard Street (refer to **Figure 1**). The portion of existing storm sewer in the project area is almost perfectly bisected by the storm sewer outlet from Buhr Park. During project planning, the team felt it would be better to monitor the entire half-mile of the Easy Street project rather than a quarter-mile and use a second flow monitor and a model of the system to tease out the Buhr Park contribution to flows in Easy Street.

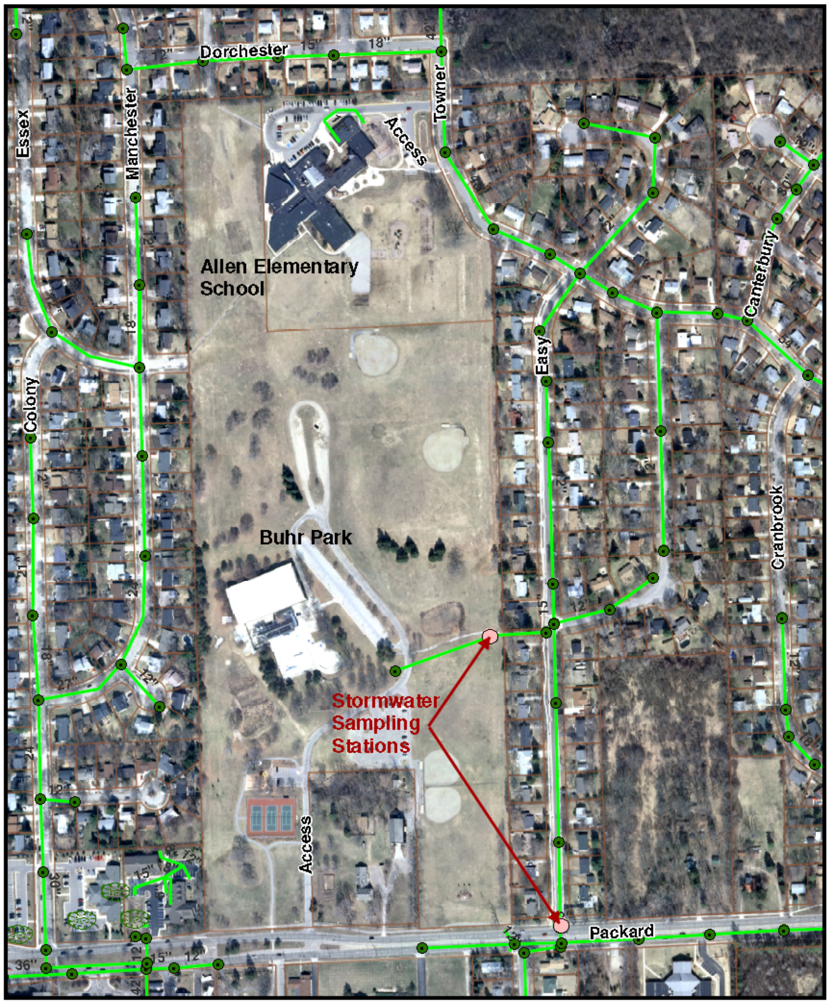

Figure 1. Easy Street and Buhr Park Stormwater Monitoring Locations

Water quality samples were retrieved immediately following rain events that were large enough to trigger timed sample collection. Samples grabbed by the auto sampler were stored in individual bottles. The individual grab samples were used to create a composite sample in a single bottle using a flow-proportioning method. In this manner, more weight (volumetrically speaking) was given to the concentrations occurring during high flow rather than at low flow. This assures that the *mass* of pollutant in each grab is fairly represented in the composite. The composite represents the flow-weighted average concentration taken over the whole event. The result is referred to as the event mean concentration (EMC) and is the recommended concentration unit for analysis by the ASCE/EPA joint project on urban stormwater BMP performance analysis (GeoSyntec, and EPA, 2002).

Figure 2. Easy Street re-constructed, October 2009, approximately two years after construction was completed

The H/H model of Easy Street had to account for flows directly to the storm sewer, street flow and flow that infiltrates through the pavers, bedding and aggregate and exfiltrates into underdrain that drains to existing storm sewer. The area simulated for this project is small enough that the modeling approach has to pay attention to a set of details that are typically “abstracted out” in wet weather modeling. SWMM is a lumped parameter model where spatial characteristics are averaged out at different scales and then assigned to specific points or areas in order to emulate spatial variability. With large watersheds, for instance, on the scale of hundreds or thousands of acres, all the small, unique runoff signals contributing to the combined signal at the watershed mouth start to average out. The Easy Street model; however, demanded a fine resolution modeling approach.

Preconstruction SWMM Model

The total watershed area of Easy Street and Buhr Park is 12 acres and 40 acres respectively. The Easy Street watershed is about 33% impervious area, while Buhr Park is about 10% impervious. For the preconstruction hydraulic model, the street was modeled as a long, flat rectangular channel. Each street subwatershed is connected to the storm sewer via a bottom orifice. The opening of the orifice is approximately the same area as the square inlet grates in the street. Often times in larger urban models, where curb and gutters are not significantly limiting runoff into the storm sewer, they do not have to be simulated explicitly. Impacts can be implicitly simulated by manipulating parameters that affect travel time. In this case, we realized, the rate at which water gets through the catch basin inlets is one of the key determinants of peak flow rates in the storm sewer in Easy Street. We found that the rate at which water gets into Buhr Park (for monitored events) is not limited by the storm sewer inlets. Buhr Park was modeled in the same fashion as large urban watersheds without explicit simulation of curb and gutter.

Post-Construction SWMM Model

For the post-construction model we located a subwatershed divide down the middle of the street. Each half of the street and associated drainage area is subdivided into 1) residential lot area draining to the street, 2) the portion of the street that is asphalt and 3) the porous pavers.

We took a hybrid approach to simulating the pavers and swales to try and capture the range of expected underdrain flow rates. For the first estimation technique we used the RUNOFF routine to route any runoff from the individual lots and pavers via infiltration through the pavers to the underdrain. We used SWMM's aquifer and underdrain exfiltration technique to route groundwater into the system. This technique tracks the changing groundwater elevation as infiltrating water accumulates. Once the groundwater elevation exceeds the underdrain invert elevation, exfiltration (outflow) is initiated. This technique gave us a reasonable relationship between event size and underdrain peak flows, but did not produce the expected tailing of flows.

For the street we routed runoff into composite paver/swale storage areas. For these areas, infiltration was routed to the underdrain via a "pump" workaround that operated under a head/flow relationship based on depth, porosity and infiltration rate of the composite storages. These composite storage basins allow standing water to accumulate over the pavers and continue to infiltrate. The crown of the road acts as the top of a "control weir"---- when water over the pavers is higher than three inches, the height of the road crown, this water floods down the street. Because the swale storage volume is proportionately so small, we lumped the proposed swale areas in with the porous paver storages. This technique provided the expected long, tailing outflows for several days after events.

The infiltration pump allows the user explicit control of the infiltration process. In the proposed conditions model the pump curve is set up so the pump outflow rate varies with the depth of water standing over the porous pavers. The outflow is determined by multiplying the area of inundated paver bottom by the infiltration rate and converting the answer into a volumetric flow rate with units of cubic feet per second-----the pump rate. The "pump curve" is the relationship between the changing paver inundation area, i.e., infiltration volume, and the pump rate.

Findings

Some data collection and SWMM model shortcomings complicate the results and interpretation. For instance, during the preconstruction modeling we realized that the street flooding residents had described was a key to a successful calibration. Initially, we did not simulate the street inlets; however, after many runs systematically over-predicted peak flows, we added the street inlet control. This control initiated flooding for rain events with intensities exceeding a 0.5-inch/hour. Floodwater often sat in yards for days after an event. We believe these flood volumes were not necessarily recorded during preconstruction flow monitoring. We speculate that this underestimation of preconstruction total event volumes, led to an underestimation of total volume control between pre- and post-construction conditions. We added model estimates of street flood volumes to total preconstruction storm volumes to create an upper bound for total preconstruction event volumes.

Another significant data collection issue was the reconstruction of the monitoring manhole for Buhr Park between the pre- and post-construction monitoring periods. The reconstructed manhole lost almost 2-feet in depth and due to this change the sampler sat more directly in the flow path than it had been during the pre-construction assessment. This change resulted in depths in the catch basin, particularly for large events, that far exceeded model estimates. At the same time, flows in Easy Street approximated the model estimates in a much more consistent fashion. We concluded that the Buhr Park post-construction flow data was biased and did not use it in the post-construction evaluation.

SWMM's shortcoming highlighted by this project is its simplified representation of groundwater and exfiltration into the underdrains. The model's surface water and groundwater equations are not explicitly linked and the groundwater routine does not close the mass balance. One result is the groundwater routine can send more water into the underdrains than input into the model. Because the underdrains are now the primary route for runoff to get into the Easy Street storm sewer, this shortcoming is important. In this evaluation we tried to bound the uncertainty so that we can have confidence that actual system performance falls within our upper and lower performance estimates.

The correspondence of the model results with collected flow data was generally good; but it was slightly better for the pre-construction model than it was for the post-construction model. Comparisons of model predictions and data were made by linear regressions of peak and total flows, direct comparison of peak and total flows and by visual inspection of overlays of model and data hydrographs. Slopes on the linear regressions (where a slope of 1.0 equals perfect correspondence between model and data) for Easy Street pre-construction and post-construction peak flow comparisons were 1.08 (r^2=0.83) and 0.76 (r^2=0.87), respectively. Regression slopes for the pre-construction and post-construction volume comparisons at Easy Street were 1.04 (r^2=0.81) and 1.21 (r^2=0.67), respectively.

For most of the pre-construction calibration events for both Buhr Park and Easy Street predicted and measured peak and total flows were within ±25% of each other for both the Buhr Park and Easy Street sampling sites. Note that we compared all discernible peaks for events, both the event maximum as well as local maxima. There was better agreement between the post-construction model and data for smaller events (<0.7 inches total) than for larger ones. One consistent finding for the calibration and design events was that street flooding was virtually eliminated for proposed conditions. Street flooding was completely eliminated for events up to and including the two-year design event and reduced 86% for the 100-year design event.

Pre-construction monitoring showed that Buhr Park and Easy Street contribute roughly the same volume of flow to the Easy Street outlet. Post-construction monitoring and modeling showed that frequently the proportion of flow from Buhr Park at the Easy Street monitoring location could be as much as 90%. By using the model to hypothetically eliminate Buhr Park flows, peak flow reductions in Easy Street were estimated to range between 49% and 90% and total event volume reductions were as high as 80%. Performance differences between pre- and post-construction peak and total flow reductions were greatest for the smaller, more frequently occurring events (<0.7 inches total rainfall or < 0.3 inches/hour rainfall intensity). This event threshold represents more than 95% of the average annual events that occur in Ann Arbor. As events got larger they tended to diminish the differences between pre- and post-construction conditions.

The pollutant EMCs were very much in line with EMCs developed for other regional monitoring programs (Cave, et.al., 1996) and for most constituents did not change between pre- and post-construction conditions. However, the TP and OP EMCs were substantially reduced at the Easy Street outlet for post-construction conditions. Average TSS, TP, OP, Cu, and Zn EMCs were 35 mg/L, 125 ug/L pre-/55 ug/L post-, 55 ug/L pre-/35 ug/L post, 5 ug/L, and 45 ug/L, respectively. Total pollutant loads were substantially reduced between 20%-90% for all constituents for comparably sized events between pre- and post-construction conditions.

For almost every statistical measure for TP and OP ----maximum, minimum and average---- the pattern of measured concentrations between Buhr (upstream) and Easy Street (downstream) is flipped for pre- and post-conditions. For pre-construction the Easy Street TP and OP averages and maximums are all significantly higher than at Buhr Park. For post-construction conditions, all maximums, minimums and averages at Easy Street are lower than at Buhr Park.

During this period, the City passed a phosphorus fertilizer ban; however, the TP and OP concentrations from Burh Park either did not change or increased while they did for Easy Street. It is not clear that the fertilizer ban can explain these results. We think filtering the runoff through an aggregate base helps adsorb infiltrating phosphorus. While this base holds only a finite number of spots for adsorption, we believe the adsorption capacity will be good for years and the root growth of natives in the swales will provide a sustainable phosphorus uptake and adsorption media for decades.

REFERENCES

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