Modeling runoff response of pervious pavement systems at a catchment scale

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1. INTRODUCTION

The application potential of pervious pavements as an effective urban infiltration management tool presently exceeds its exploitation. While entirely eliminating urban Total Impervious Area (TIA) is not a feasible solution, pervious pavements operate as self-mitigating surface or source control, working cohesively with other Best Management Practices (BMPs) in the urban context to reduce runoff generation. Though their relatively recent development compared to older, more incumbent BMPs makes difficult any long-term or large-scale analysis, recent publications have been cautiously optimistic about not only permeable pavements' ability to efficiently manage runoff [1, 2], but also as treatment - with an observed improvement in discharge concentrations of Total Suspended Solids (TSS) and total Zinc[3]. Locally, the Flood Control District of Maricopa County (FCDMC) has passed First Flush regulation (policy 3.6.6[4]), establishing a minimum level of control for initial surface runoff associated with increased pollutant concentrations[5], which requires retaining or treating the first 12.7 mm of direct runoff. Pervious pavements stand to contribute to damping initial contaminant loading, runoff volumes and corresponding velocities associated with First Flush, which the study intends to quantify through runoff velocity and volume modeling in a 9.5 hectare urban catchment.

2. RESEARCH OBJECTIVES

Despite the modularity of pervious pavement systems, our understanding of the associated runoff dynamics at large spatial scales over variable land use and land cover lags significantly the scalability potential of the technology. Subsequently, the primary research objective is to quantify the net effect of pervious pavement systems on runoff dynamics at a catchment scale, accounting for variable traffic load and land use patterns.

3. METHODS

LAND USE - LAND COVER (LULC) CLASSIFICATION identified Pierce catchment as an area of mixed-use zoning (zoning boundaries – see Fig 8); predominantly residential, detached single-family home subdivision and light industrial, bordering Indian Bend Wash (IBW) in south Scottsdale, Arizona (Fig 1). LULC classification was carried out in ArcMap 9.3 (ESRI, 2011) according to land cover material and land use type for future analysis of traffic load and ensuing pavement potential (Fig 2). LULC data was used for identifying Total Impervious Area (Fig 3), to which sidewalks, main roads, and alleyways contributed 13,654.75 m^2, 31,410.20 m^2, and 3,368.91 m^2, respectively. Additionally, LULC parameterization contributed to TIN breaklines (Fig 6), and for MAHLERAN input file calculations (primarily in determining friction factors, ksat, pavement and vegetation cover, antecedent and saturated soil moisture conditions).

Fig 1 | Study Area: Pierce Catchment (dashed, red) and IBW (hatched, blue)

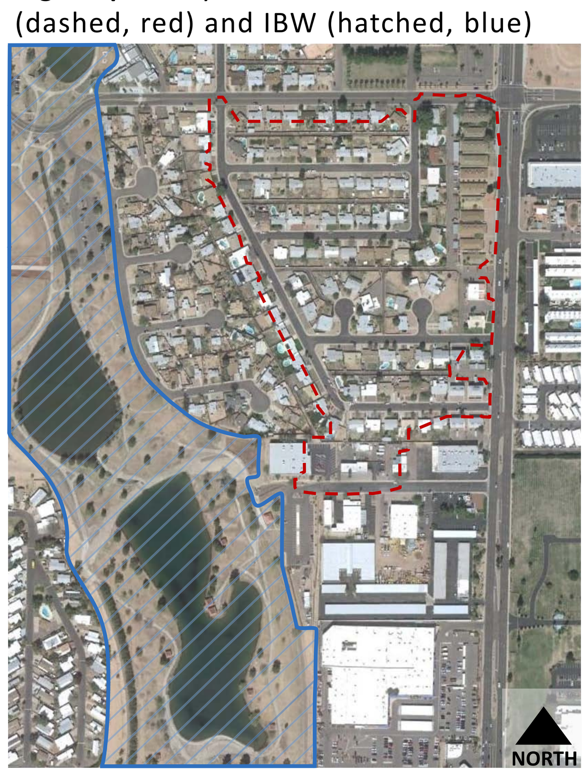


Fig 2 | LULC classification of Pierce catchment (in red) and surroundings

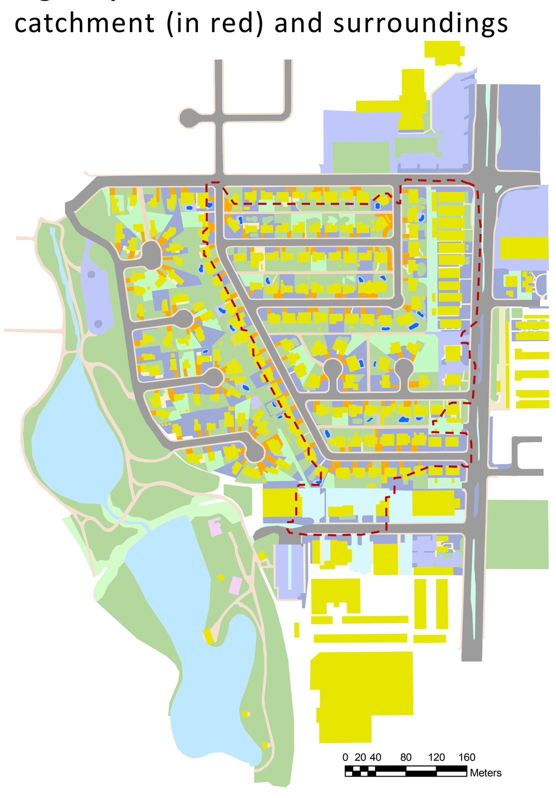
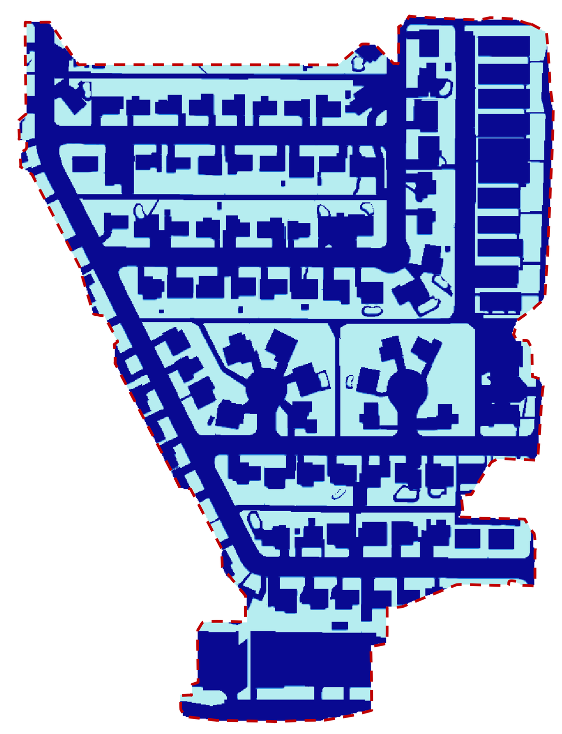


Fig 3 | TIA analysis for Pierce catchment (dark blue – impervious)



DIGITAL ELEVATION MODEL (DEM) of Pierce was originally extracted from the City of Scottsdale DEM. At a resolution of 10 m^2, the DEM was too coarse to accurately render elevation profiles for Pierce (95,168.50 m^2) and subsequently, unsuitable for fine (0.25 m^2) modeling. An alternate DEM was constructed using a Trimble handheld GPS unit to record elevations at key points (Fig 4). Using 3D Analyst in ArcMap, a preliminary TIN (Triangulated Irregular Network – Fig 5) was created, with forced surface break-lines (hard lines) added to model urban behavior (Fig 6). TINs maintain the precision and integrity of raw input data (Fig 4) and interpolate mesh values between known points (nodes), making them ideal for high-precision modeling of smaller areas[6]. The modified DEM (Fig 6) was converted to a raster (Fig 12). Through stormwater routing, flow, and accumulation analysis, the derived DEM resulted in new catchment boundary delineation (Fig 8).

Fig 4 | Raw Trimble GPS Data

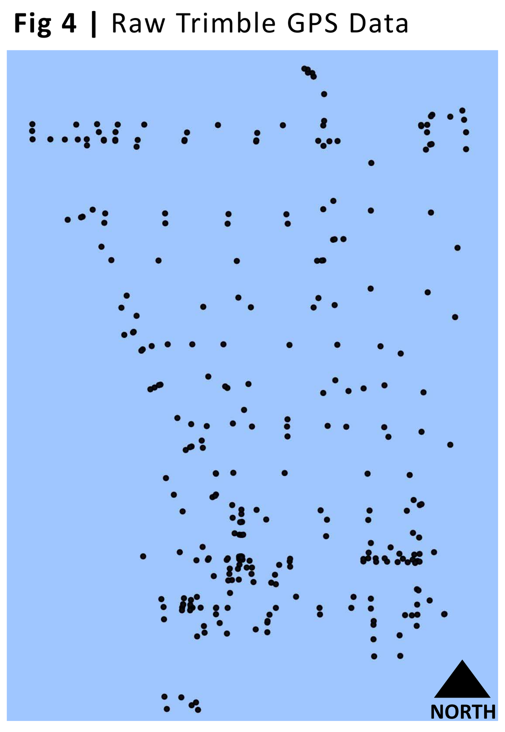


Fig 5 | Constructed TIN DEM

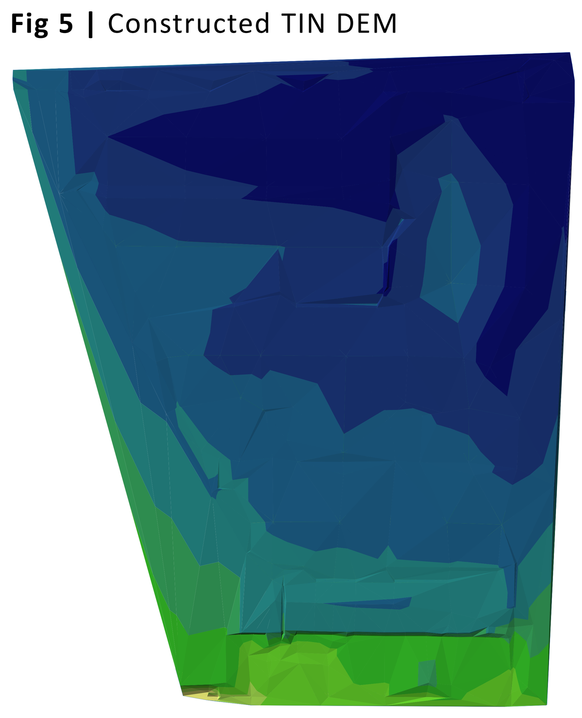
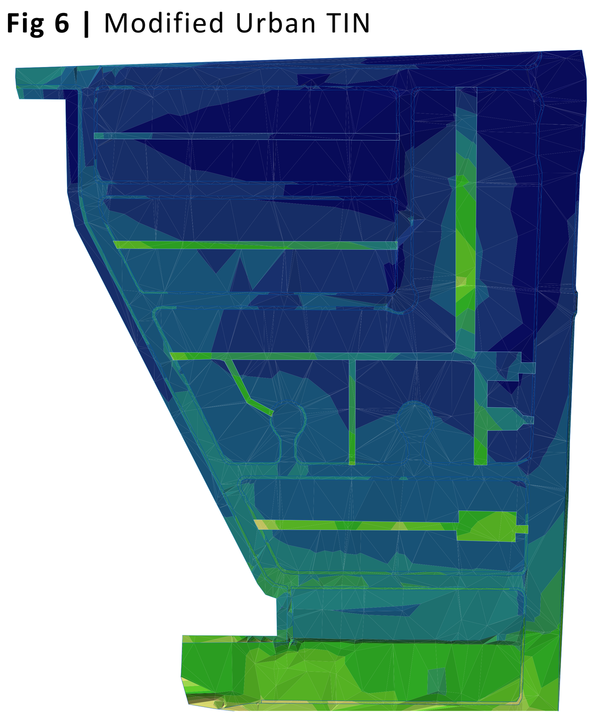


Fig 6 | Modified Urban TIN



HYDROLOGIC RESPONSE MODELING was carried out using MAHLERAN (Model for Assessing Hillslope-Landscape Erosion, Runoff and Nutrients)[7], a spatially explicit, event-based model, parameterized at a spatial resolution of 0.25 m^2. MAHLERAN's process representation of runoff dynamics relies on inputs of spatially explicit DEM, vegetation and pavement cover percentages, final infiltration rates (ksat), soil thickness (effective depth to wetting front), friction factors, wetting-front suction, drainage parameters, and initial and saturated soil moisture content in addition to a temporally explicit rainfall process-driver. Soil properties were obtained from the USDA NRCS Soil Report[8] in conjunction with LULC Classification, FCDMC Runoff Coefficients[9] and additional USDA Soil Conservation Service literature[10] (Tables 1,2). Rainfall data was obtained from a FCDMC 'tipping-bucket' precipitation gauge (ID #4600), located at Indian Bend Wash and McKellips Rd, 0.342 km SW of the CAP flow monitor at Pierce. Euler's simple backward difference method was used for computation of flow-routing, and Smith and Parlange's (1978) mechanistic model for computation of infiltration.

Table 1 | USDA - Natural Resources Conservation Service soils report for Pierce catchment[8]

Map Unit Symbol	Map Unit Name (Fig 7)	Area in Catchment	Percent of Catchment	Depth to Restrictive Feature	Hydraulic Conductivity at Natural Saturation (Ksat)	Available Water Capacity
Gm	Gilman loam	4,856.227 m^2	5.3%	> 2.032 m	0.004 - 0.014 mm/s	0.259 m
LaA	Laveen loam, 0 to 1% slopes	39,254.507 m^2	41.3%	> 2.032 m	0.004 - 0.014 mm/s	0.259 m
RiA	Rillito gravelly loam, 0-1% slopes	30,351.423 m^2	32.0%	> 2.032 m	0.004 - 0.014 mm/s	0.218 m
RiB	Rillito gravelly loam, 1-3% slopes	20,234.282 m^2	21.4%	> 2.032 m	0.004 - 0.014 mm/s	0.168 m

Spatially explicit soil properties have been parameterized from rough LULC-based calculations as a preliminary step to running MAHLERAN. The North Desert Village experiment and its datasets of monitored urban soil properties are expected to contribute to significantly more accurate parameterization of inputs contingent on ecohydrologic interactions in semiarid urban catchments.

Spatially-explicit infiltration rates for soils in Pierce catchment were obtained using the USDA NRCS Soil Survey, which identified four soils falling within the catchment area (Table 1). To represent the effects of urban land cover on natural soil ksat, LULC-dependent runoff coefficients were used to establish the percentage of rainfall available for infiltration (Runoff Percentage + Infiltration Availability = Total Precipitation), and multiplied by hydraulic conductivity at natural conditions to derive theoretical baselines for urban conditions.

Fig 7 (below)| NRCS Pierce Soils[8]

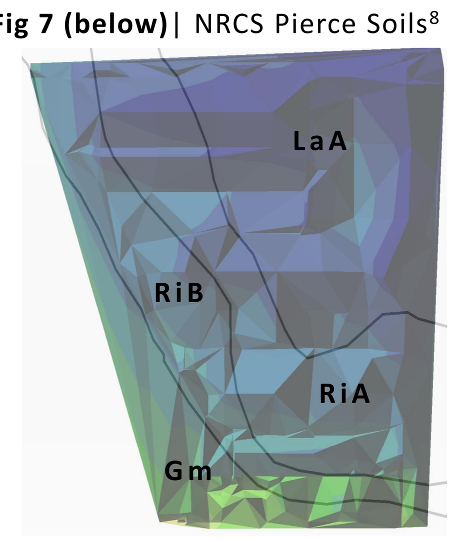


Table 2 | FCDMC 25 year flood[9] Ksat calculations by LULC class within Pierce catchment boundary

Pierce LULC Class	Land Cover Type	Runoff Coefficient		Infiltration Availability			Derived Urban Ksat (mm/s)		
		min	max	min	max	mean	min	max	mean
Rooftops	Rooftops	0.83	0.94	0.06	0.17	0.115	0.00024	0.00238	0.00104
Residential Driveways - Concrete	Drives/Walks	0.75	0.85	0.15	0.25	0.200	0.00060	0.00350	0.00180
Multi-house Parking - Asphalt	Streets - Asphaltic	0.83	0.94	0.06	0.17	0.115	0.00024	0.00238	0.00104
Alleyways	Streets - Gravel	0.66	0.77	0.23	0.34	0.285	0.00092	0.00476	0.00257
Landscaping - Grass	Lawns	0.18	0.33	0.67	0.82	0.745	0.00256	0.01148	0.00671
Landscaping - Gravel	Streets – Gravel*	0.10	0.20	0.80	0.90	0.850	0.00320	0.01260	0.00765
Pools	MAHLERAN based*	0.00	0.00	0.00	0.00	0.000	0.00000	0.00000	0.00000
Pool decks - Concrete	Drives/Walks	0.75	0.85	0.15	0.25	0.200	0.00060	0.00350	0.00180
Landscaping - Dirt	Undeveloped Desert	0.30	0.40	0.60	0.70	0.650	0.00240	0.0098	0.00585
City Sidewalk - Concrete	Drives/Walks	0.75	0.85	0.15	0.25	0.200	0.00060	0.00350	0.00180
Main Roadway - Asphalt	Streets - Asphaltic	0.83	0.94	0.06	0.17	0.115	0.00024	0.00238	0.00104
Residential Footpaths - Concrete	Drives/Walks	0.75	0.85	0.15	0.25	0.200	0.00060	0.00350	0.00180
Industrial Parking - Asphalt	Streets - Asphaltic	0.83	0.94	0.06	0.17	0.115	0.00024	0.00238	0.00104
Road Elements - Concrete	Streets - Concrete	0.83	0.94	0.06	0.17	0.115	0.00024	0.00238	0.00104
Misc. Parking - Asphalt	Streets - Asphaltic	0.83	0.94	0.06	0.17	0.115	0.00024	0.00238	0.00104

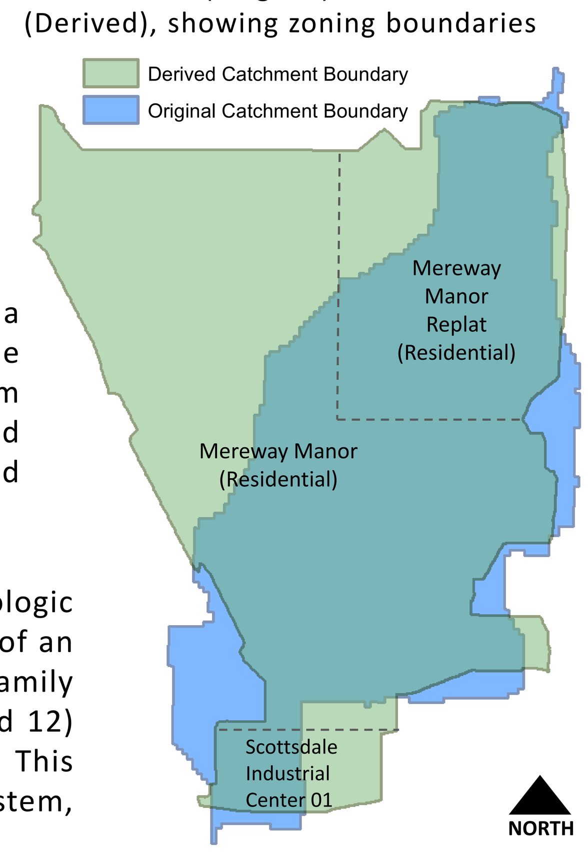
PAVEMENT DESIGN SCENARIOS for modeling pavement-runoff dynamics consist of five main designs:

1. Conventional pavement (control scenario); existing conditions based LULC classification.
2. Conventional pavement throughout catchment, permeable asphalt in Area 1 (Fig 10).
3. Permeable Friction Course (PFC) only; limited to city (public) main roads.
4. PFC on public roads, permeable asphalt in alleys, industrial and commercial parking.
5. PFC on public roads, permeable asphalt in alleys, pervious paver gutters, permeable concrete sidewalks.

4. RESULTS

DEM CONSTRUCTION identified significant differences between the original catchment delineation produced by the City of Scottsdale DEM, and the DEM constructed by field-based GPS measurements (Fig 8). The new derived catchment delineation added 30,145.70 m^2 to the previous area of 65,022.80 m^2, with a subsequent increase in runoff accumulation potential. Additionally, a refined DEM raster at 0.25 m^2 resolution accurately picked up several significant site characteristics: a 7.38 m elevation drop over the North-South length of the catchment, a 1.32 m elevation drop along the boundary line between residential lots in the North from industrial zoning in the South of the catchment (Fig 7), and a 35.37 m long canal (Area 2, Fig 11) which directs flow accumulating in the residential section of the catchment directly into an industrial lot, from where flow diverges around the building and arrives in the street and gutter, eventually reaching the monitoring sensor at 33°27'16.35"N and 111°54'41.96"W.

Fig 8 | City of Scottsdale Catchment Delineation (Original) vs. Field Based (Derived), showing zoning boundaries



RUNOFF CONTRIBUTION identified two areas of particular hydrologic significance (Fig 10). Area 1, in the NW corner of the catchment, consists of an asphaltic alleyway and on-street parking for detached single floor multi-family residential units. The area has a large depression (best seen in Figs 5 and 12) and collects run-on from neighboring lots in addition to local detention. This depression has neither runoff outlets nor connection to a storm drain system, and is subsequently prone to flooding.

Fig 9 (below) | Runoff contribution for Pierce catchment, with noted areas of hydrologic significance

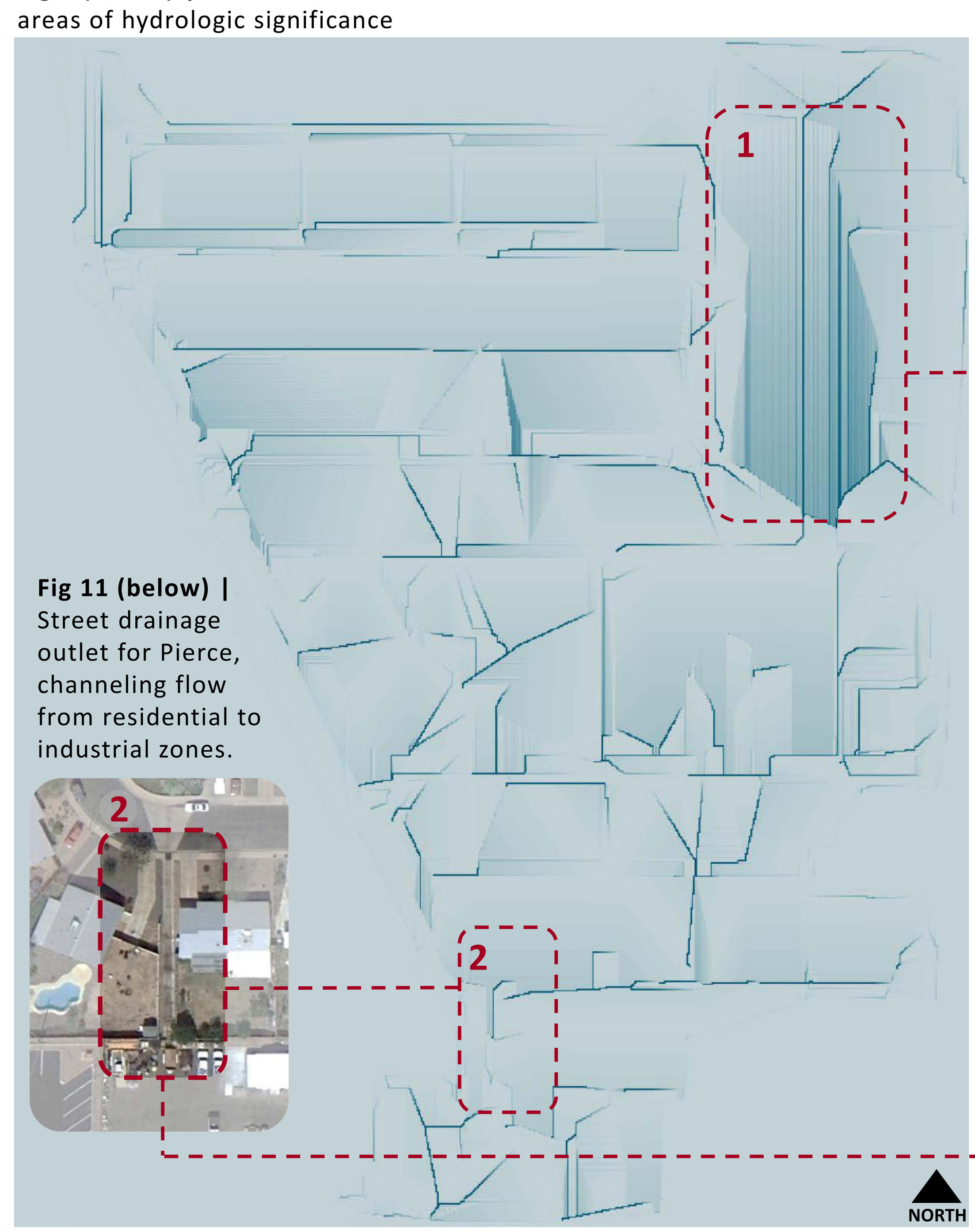
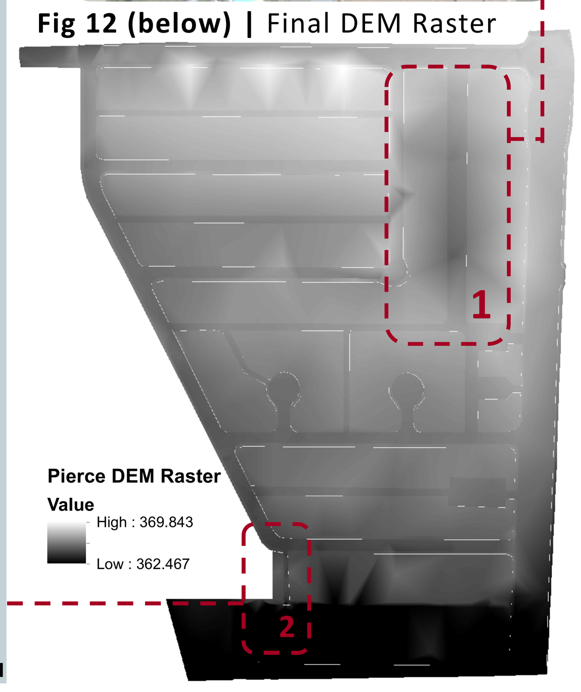


Fig 11 (below) | Street drainage outlet for Pierce, channeling flow from residential to industrial zones.

Fig 10 (below) | Multi-use Alleyway and residential parking

Fig 12 (below) | Final DEM Raster



5. SUMMARY | NEXT STEPS

SUMMARY: to date, final DEM raster accurately renders both local and catchment wide topography-driven patterns; channeling flow down streets and alleyways, following south-bound flow across catchment. Model-derived contributing area matches up with flow (runoff) contribution area, and matches field-observed topographic properties. The CAP monitoring station located in the SW corner of the catchment both displays the highest flow accumulation, and effectively intercepts the majority of the runoff from the north residential zones. This is consistent with field observations, previous assumptions, and reiterates that modeled flow is being routed correctly. Several zones of elevated hydrologic significance have been identified; the multi-use alleyway and multi-house residential parking area in the NE corner of the catchment would serve as an ideal location for localized pervious pavement application, consistent with design criteria identified in several previous case studies.[1,2,11] Preliminary modeled hydrographs currently show severe inconsistency between modeled and monitored discharge, both for winter convective (Fig 13) and summer monsoonal (Fig 14) storms.

NEXT STEPS involve refining parameterization of soil properties and attaining a significant level of confidence in model corroboration for CAP monitored events as well as FCDMC baseline 2-100 year design storms; later, parameterizing pervious pavement ksat rates from EPA studies[12], as well as determining parameters characteristic of soils underlying pervious pavements. Finally, the pervious pavement network performance will be tested for monitored and design storms, accounting for seasonally-driven precipitation variability. Analysis will quantify effectiveness of pavement change, in terms of volume, peak velocity, and potential First Flush damping.

Fig 13 (below)| Monitored discharge for winter convective storm

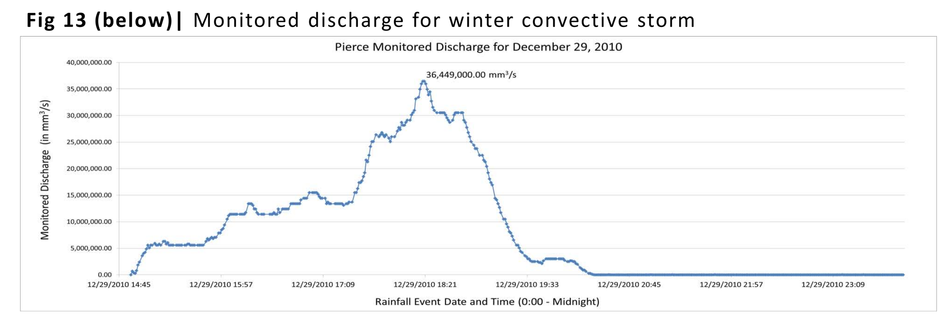
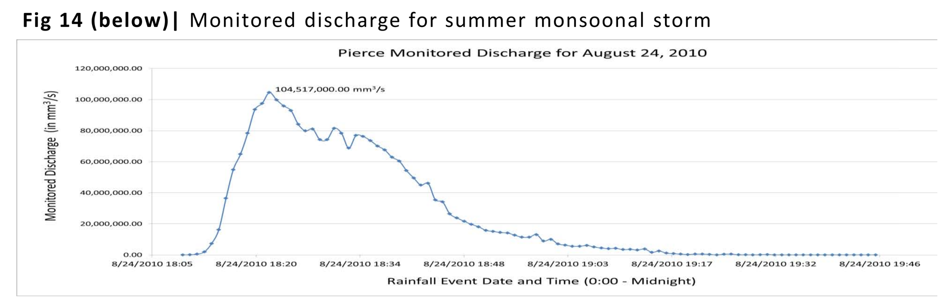


Fig 14 (below)| Monitored discharge for summer monsoonal storm



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