USE OF SMALL SCALE PHYSICAL MODELS FOR CONDUCTING TRANSPORT AND DECONTAMINATION EXPERIMENTS

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Background

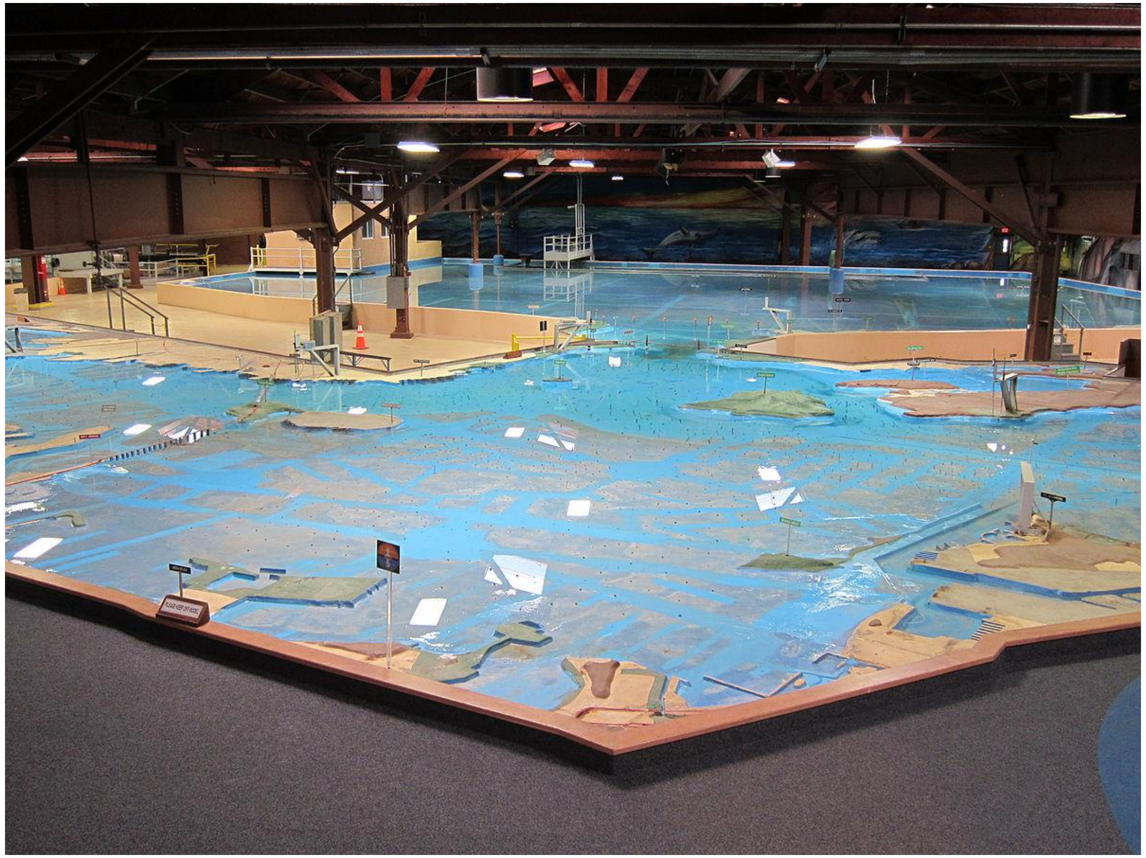
- Focus on fate and transport of radiological contaminants and biological agents in urban settings
- Challenges to the use of actual contaminants or even analogs (simulants) in field conditions
- Computer modeling of transport is typically applied, but limited real-world data available for calibration
- Small scale physical models may provide additional insight on mechanisms and help to improve models

Source: Prasanna and Goonetilleke, 2006

- This work presents practical and theoretical considerations related to the development of experimental small-scale models for contaminant transport

Scale Modeling (1)

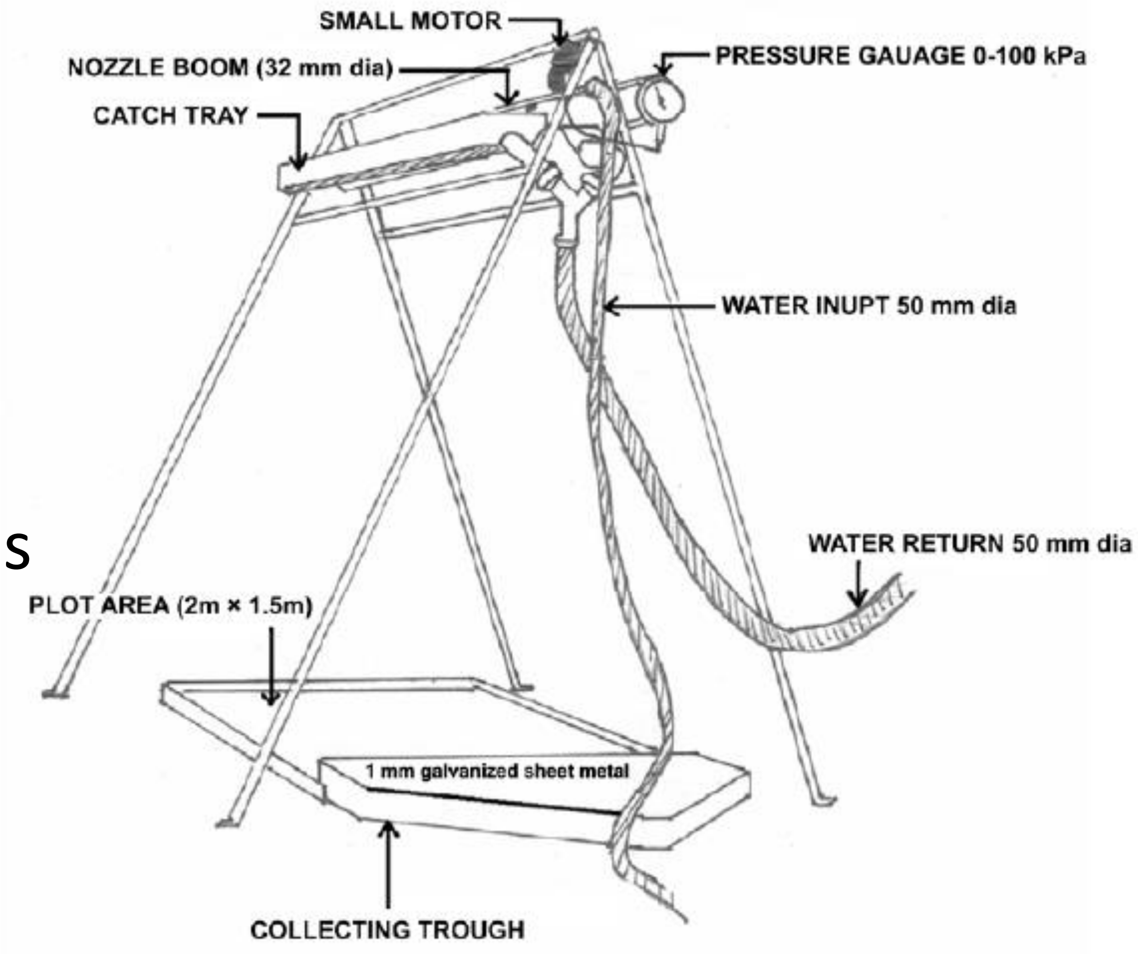
- Long history of application in fluid mechanics related work, such as for channel flow, turbines, aircraft wings, etc.
- Scale models used as an alternative to computer models



San Francisco Bay Model, Sausalito, California

Scale Modeling (2)

- Somewhat limited application in the urban stormwater realm, although some examples exist with simple surfaces
- Used to estimate washoff of chemicals from different surfaces



Source: Miguntanna et al., 2010

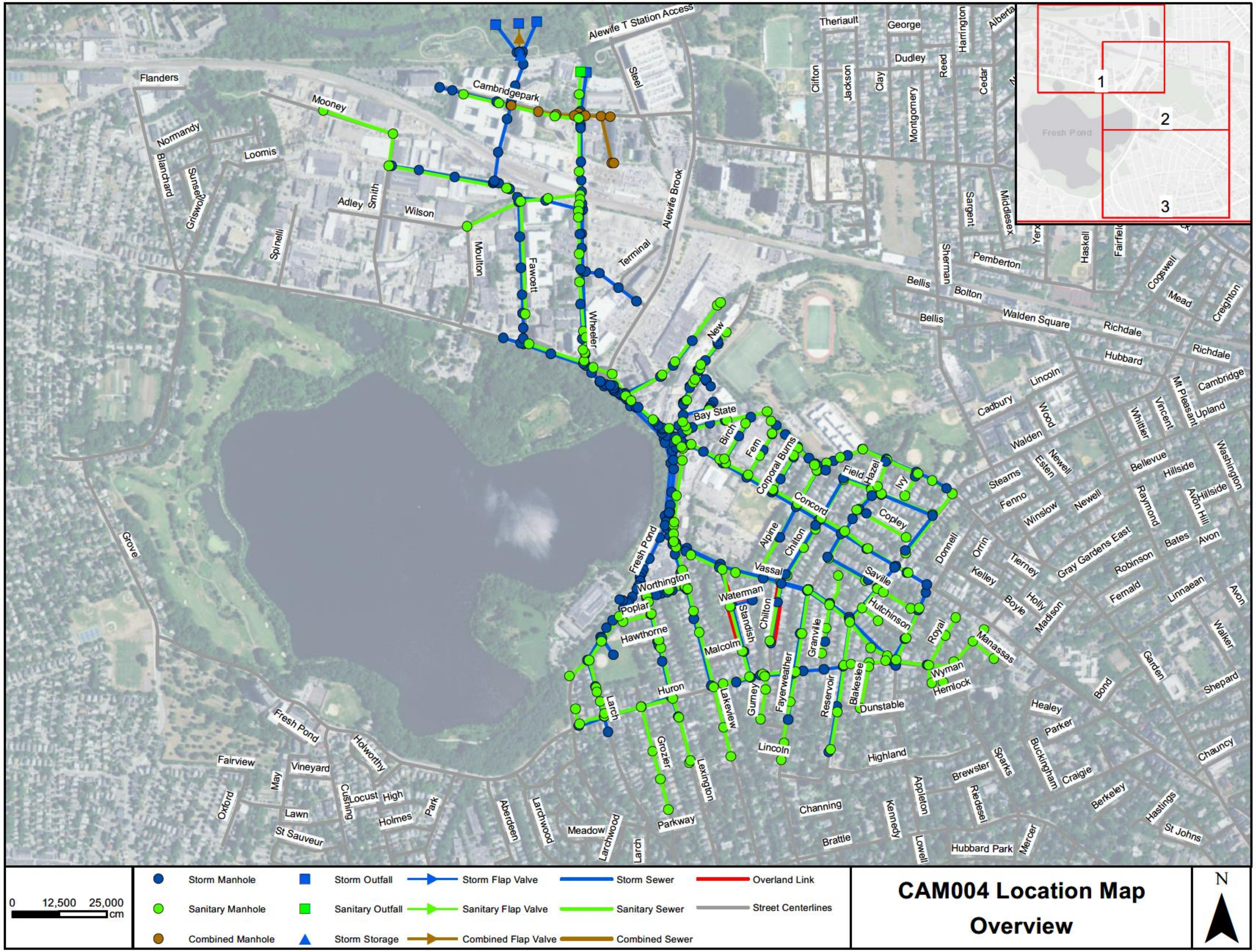
Objectives

- Develop a scale model of a cityscape to conduct experiments on contaminant fate and transport
- Work on a region with existing data/models:
  - Stormwater model
  - LiDAR elevation data
- Develop protocol for constructing prototype and scale model (in progress)
- Evaluate theoretical consideration for experimental design, such as flow rates and surface/simulant properties

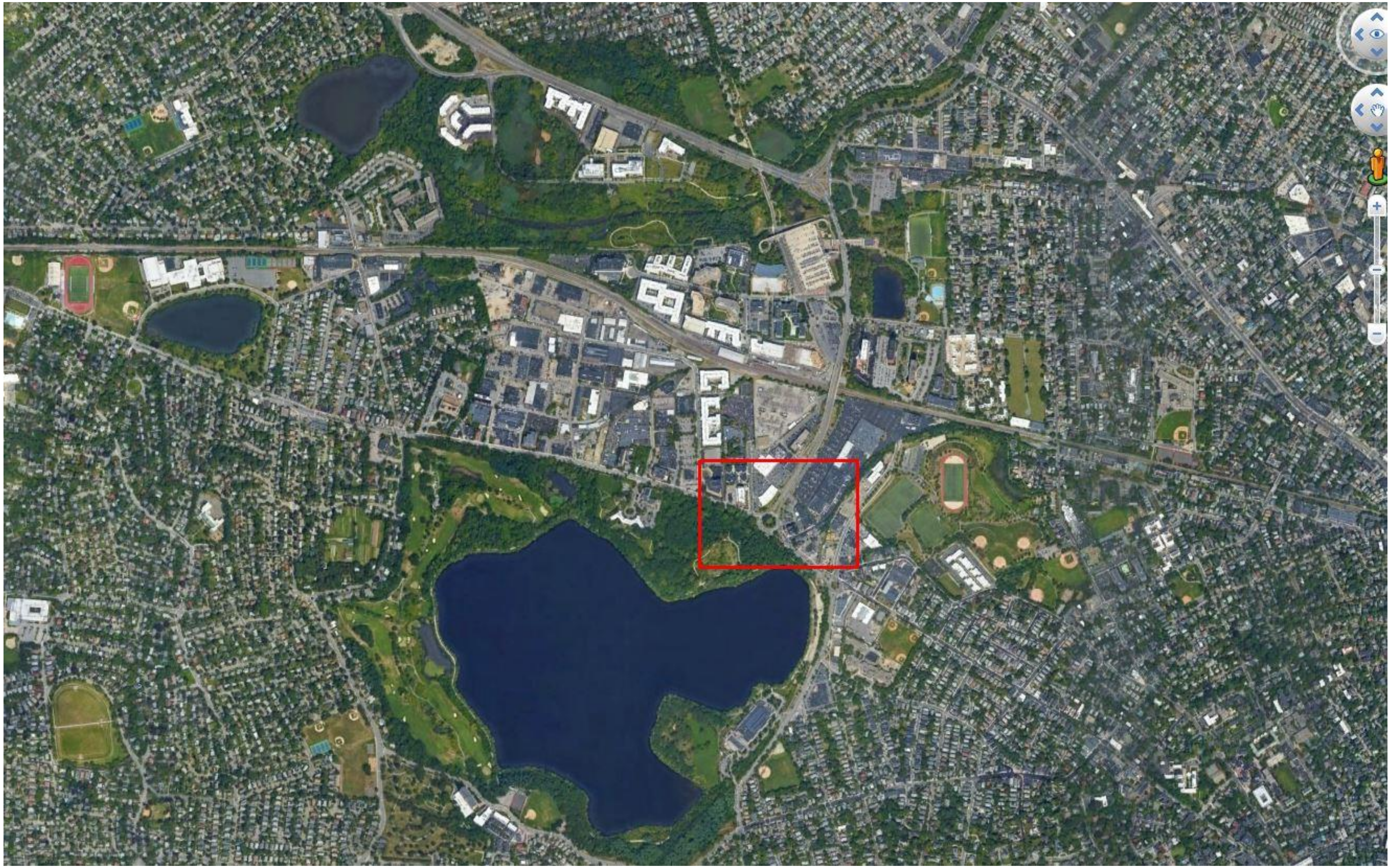
Cambridge (Massachusetts) Selected as Case Study

Stormwater model information provided by City of Cambridge and Stantec; Model developed in InfoWorks, an interface for EPA SWMM model.

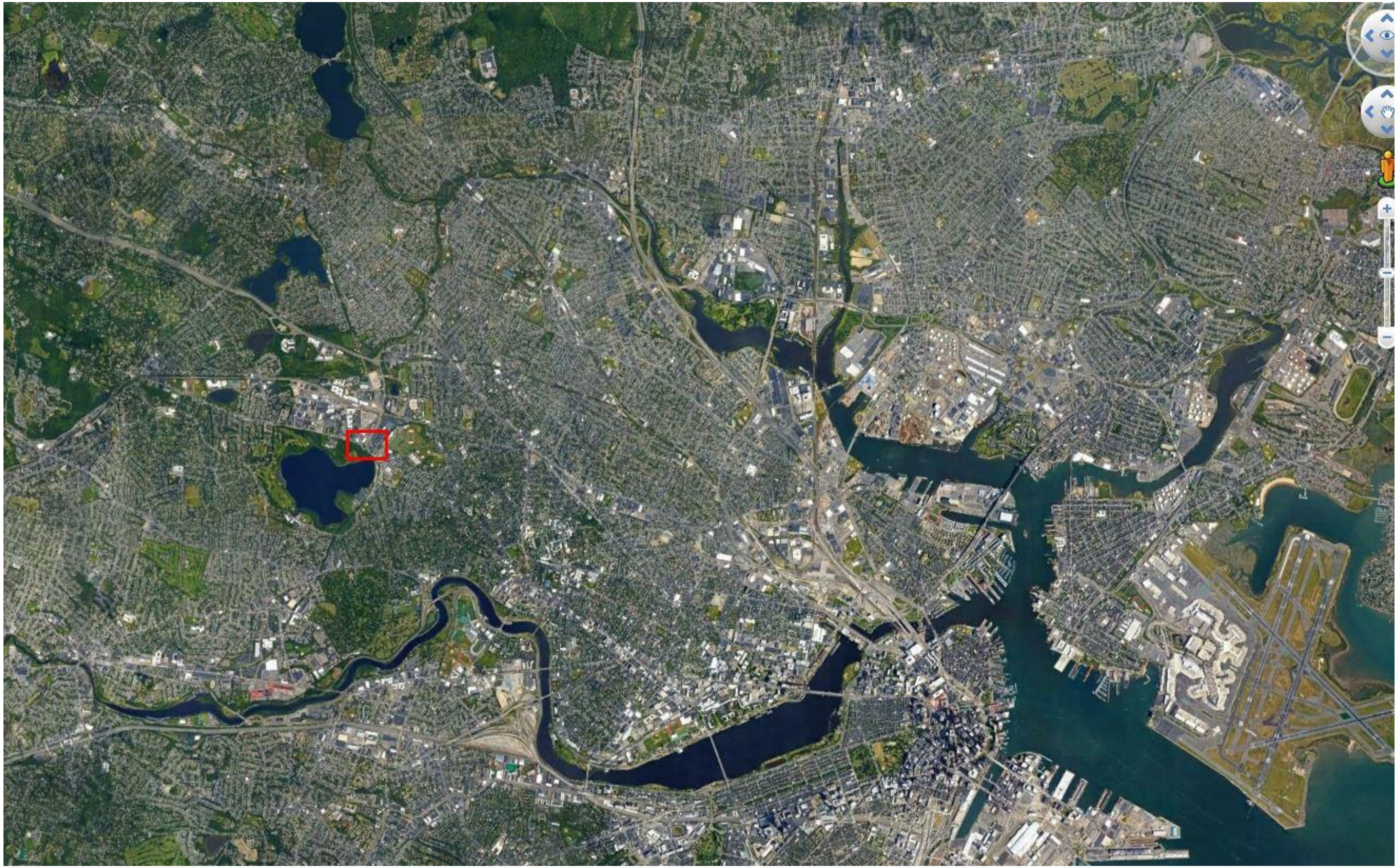
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community



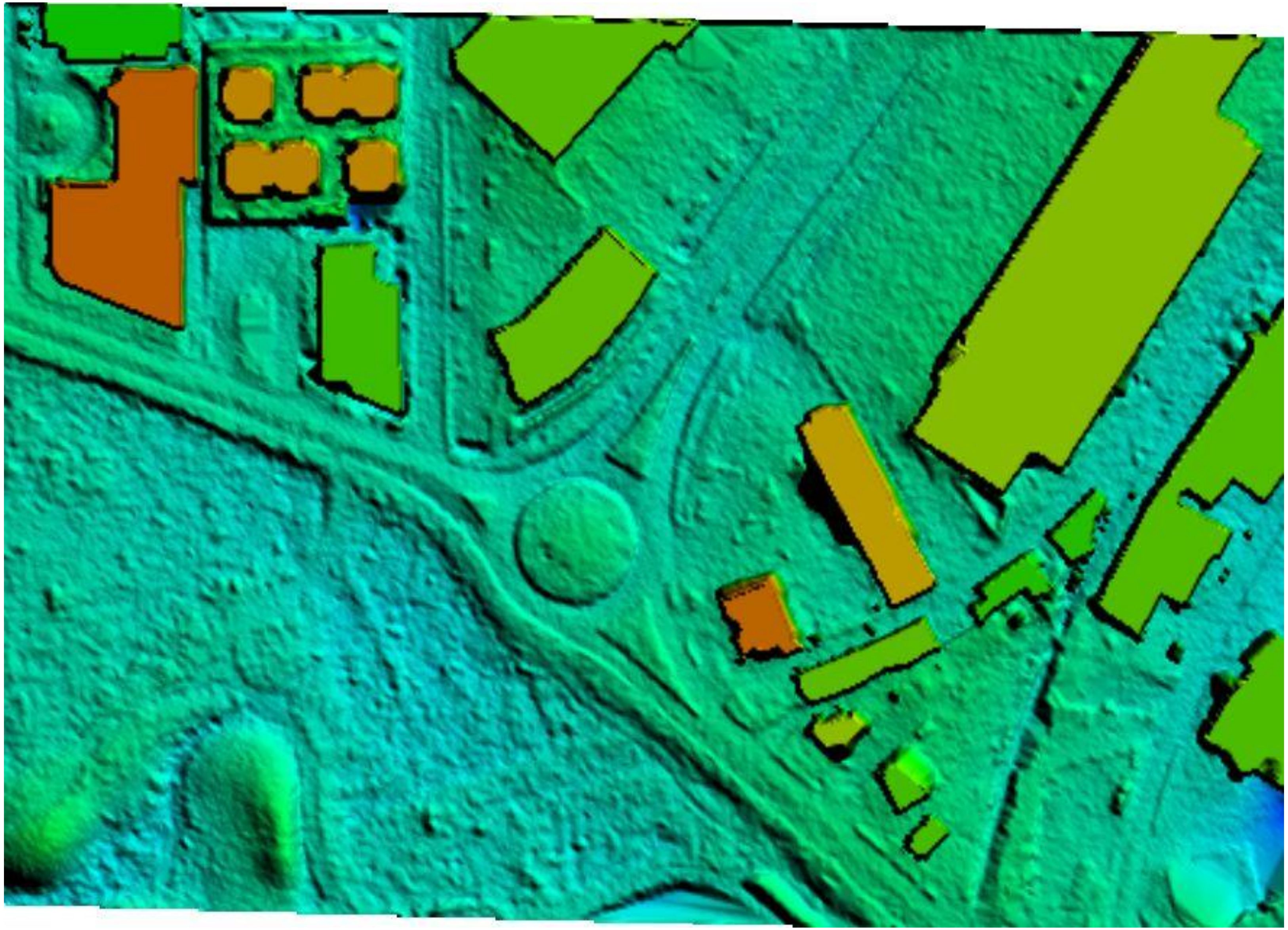
Prototype Area



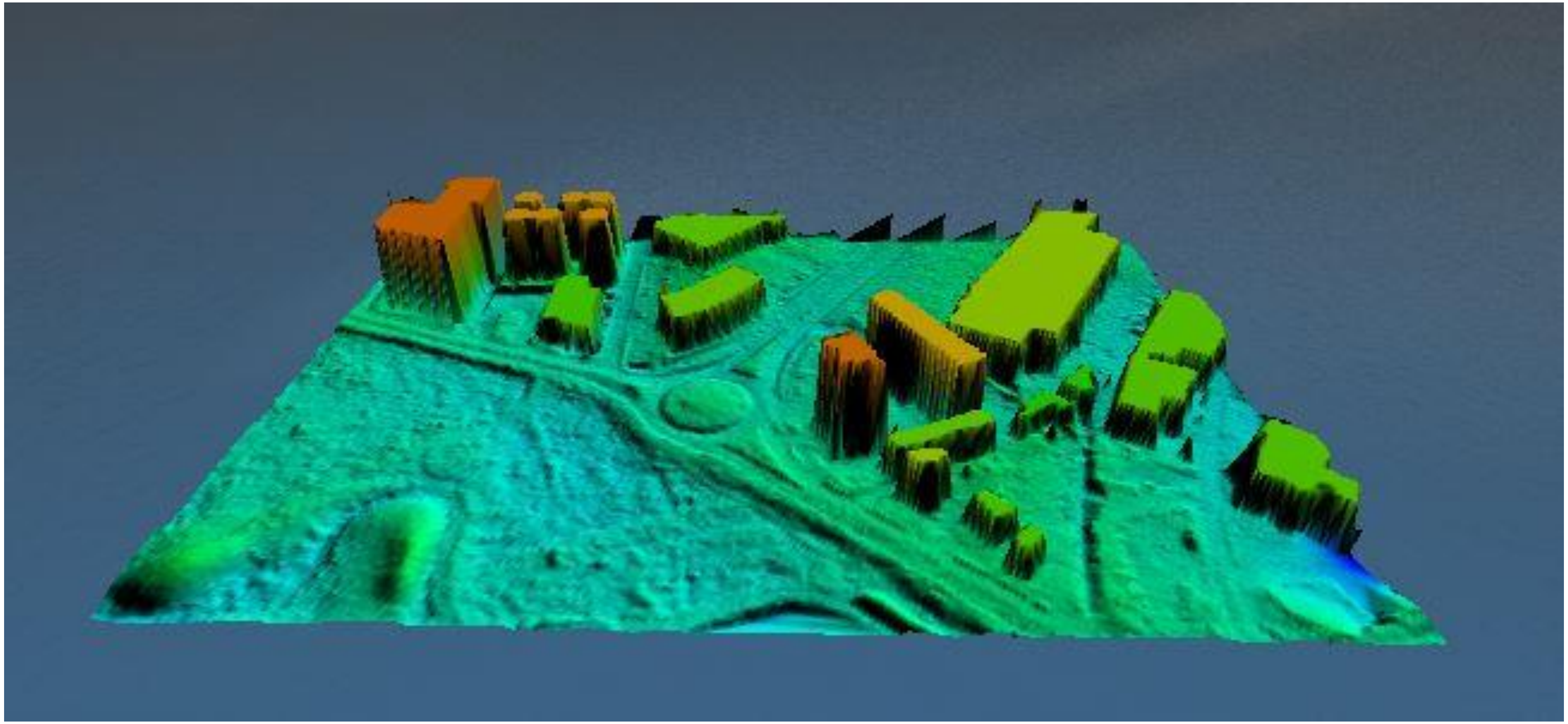
Prototype Area in Region



Subset of Area for 3-D Printing (LiDAR Point Cloud)



Vertically Exaggerated 3-D View

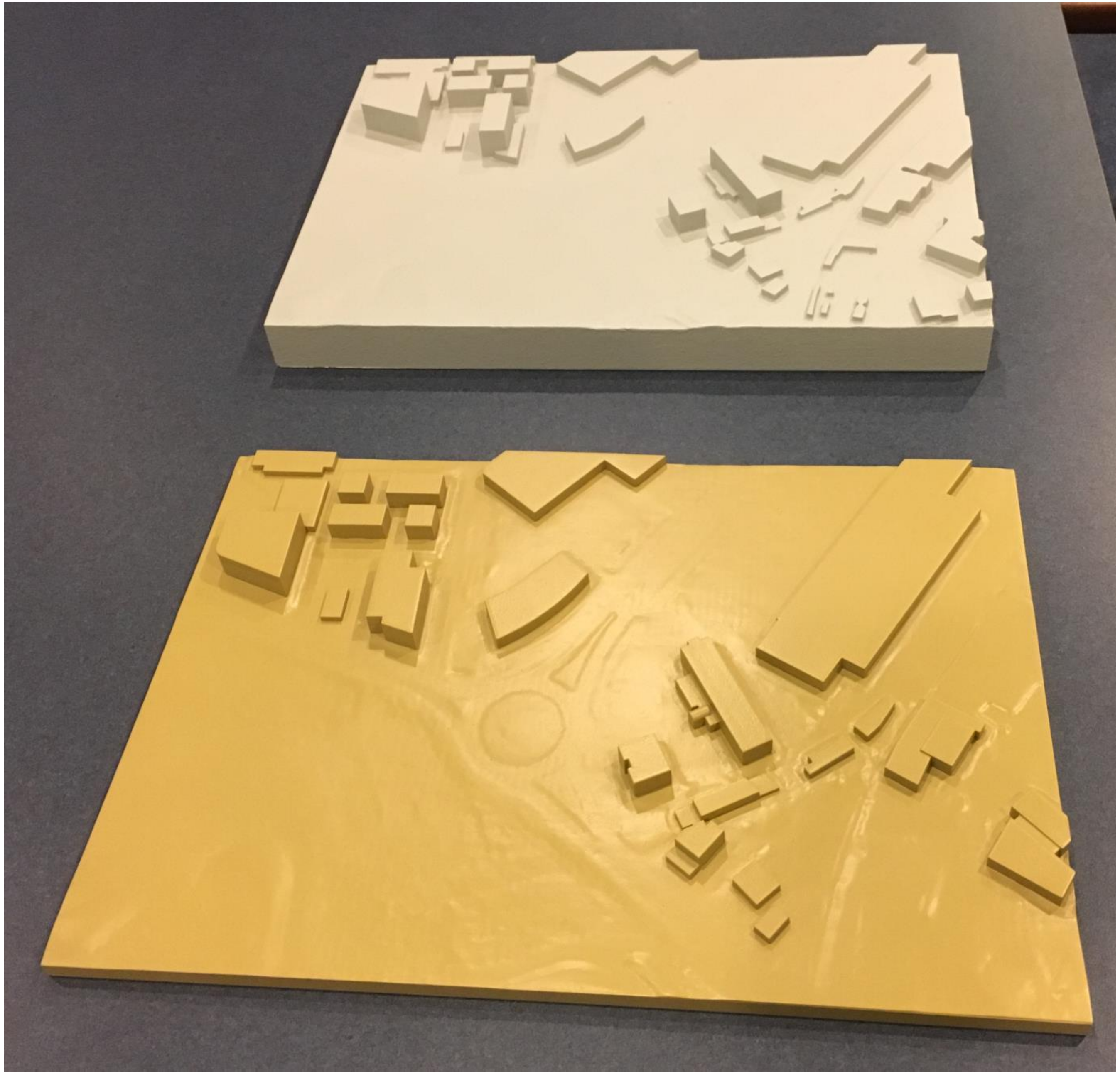


Physical Prototypes Developed

- Geospatial transfer of data entirely automated; used GlobalMapper software (developer BlueMarble Geographics*)
- 12 inches by 16 inches (1 inch = 100 feet); no vertical exaggeration
- Prepared using combination of 3-D printing and CNC milling
- Surface painted over

**Other options:*

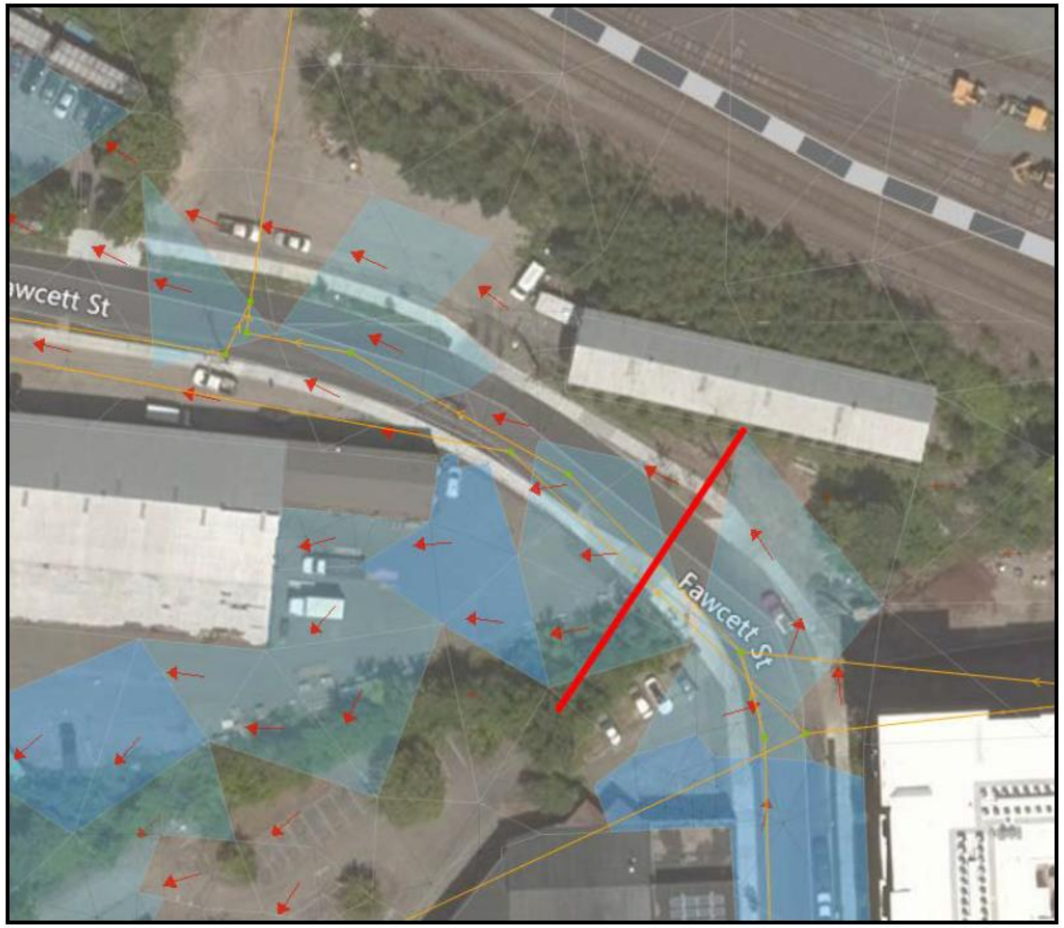
- *Terrascan and Terramodeler (from Terrasolid, Finland, distributed in the US by GeoCue, GA)*
- *LP360 (by GeoCue)*

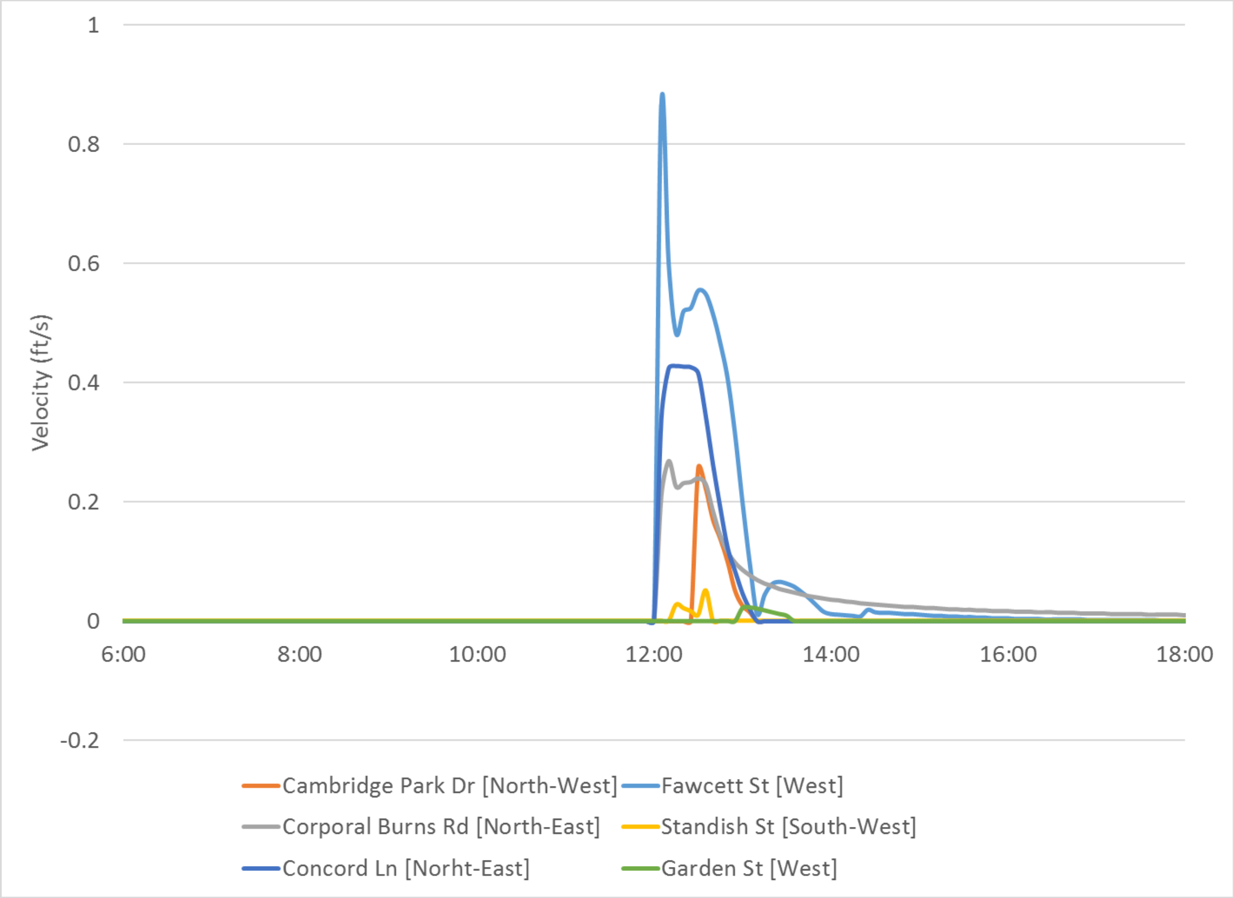


Theoretical Considerations

- Develop estimates of rainfall and flow rate to achieve similar fluid forces as might occur in the real-world system
- Consider surface chemical properties of model surface and simulant, to represent real-world interactions

Stormwater Model used to Generate Velocity Estimates for Characteristic Storms





Source: Bedoya, 2018

Key Dimensionless Parameters

Froude number Fr	**Ratio of flow inertia to the effect of gravitational action. Fr > 1 is called supercritical (rapid flow) and Fr < 1 is called subcritical (tranquil flow).**
Reynolds number Re	Relative importance of inertial force compared to viscous force. As Re increases, the greater the influence of inertial effects compared to viscous effects. Low Re flow is dominated by laminar, sheet like flow. High Re flow is dominated by turbulence and eddy currents. Transition occurs at Re = 500-2000 for overland surface flow.
Weber number We	Represents relative importance of inertia versus surface tension forces. The smaller We becomes, the larger the influence of molecular attraction along a solid/air contact zone. Inertia dominates when We>1 (approximately).

Calculation of Dimensionless Parameters

Parameter	Symbol	Mathematical Expression
Froude Number	Fr	$F_{r(exit)} = \sqrt{\dfrac{V_{water}^2}{g\, y_{exit}}}$
Discharge rate	Q (ft^3/sec)	$Q_{model} = C_{ro}\, L_{model}\, Cos\, \phi_{model}\, W_{model}\, I_{rain}$
Reynolds Number	Re	$R_e = \dfrac{V\, L\, \rho_{fluid}}{\mu_{fluid}}$
Discharge velocity	V (ft/sec)	$V_{water} = \dfrac{k_c}{n_{model}} \sqrt{Tan\, \phi_{model}}\; y_{exit}^{\frac{2}{3}}$
Weber Number	We	$W_{e(exit)} = \dfrac{V_{water}^2\, y_{exit}\, \rho_{fluid}}{\sigma_{fluid}} \dfrac{1}{32.2\left(\dfrac{ft}{sec}\dfrac{lb_m}{lb_f}\right)}$
Flow depth	y (ft)	$y_{exit} = \left(\dfrac{Q_{model}}{W_{model}} \dfrac{n_{model}}{k_c \sqrt{Tan\, \phi_{model}}}\right)^{\frac{3}{5}}$

Scaled Model Values for Single Street

Length (ft)	10	Runoff coeff.	1
Width (ft)	0.5	Fluid density (Lb_m/ft^3)	62.3
Slope (degrees)	2	Dynamic viscosity (Lb_f sec)/ft^2	2.03×10^{-5}
Rain intensity* (in/hour)	20	Surface tension of fluid with air (Lb_f/ft)	5.03×10^{-3}
Manning's roughness coeff.	0.013		

- ***Rain is only applied directly over the street itself.**
- **Relationship between pounds of force (Lb_f) and pounds of mass (Lb_m): $Lb_f = Lb_m \times (32.17\ ft/sec^2)$**

Summary of Results Evaluated at End of Street/Model Section

System	Width to length ratio	Discharge rate	Flow depth	Discharge velocity	Froude Number	Reynolds Number	Weber Number
	W/L	Q (ft^3/sec)	y (inch)	V (ft/sec)	Fr	Re	We
Street	1/20	8.3	0.88	3.8	2.5	26,500	400
Model	1/20	0.0023	0.076	0.73	1.6	440	1.3

Rain Droplet Parameters

Ohnesorge number, Oh	Relates tendency for a droplet to either stay together or fly apart during its descent. There is no specific threshold for this.
K parameter K	Measures the relative importance of droplet surface and kinetic energy versus the viscous dissipation of such energy at the point of impact with a fluid surface. K < 2100 indicates a splash-regime in which droplet remains relatively intact during impact and rebound. K > 2100 indicates a splash-regime in which droplet impact with a fluid surface will produce a corona or sheet of liquid that subsequently breaks up into secondary droplets.

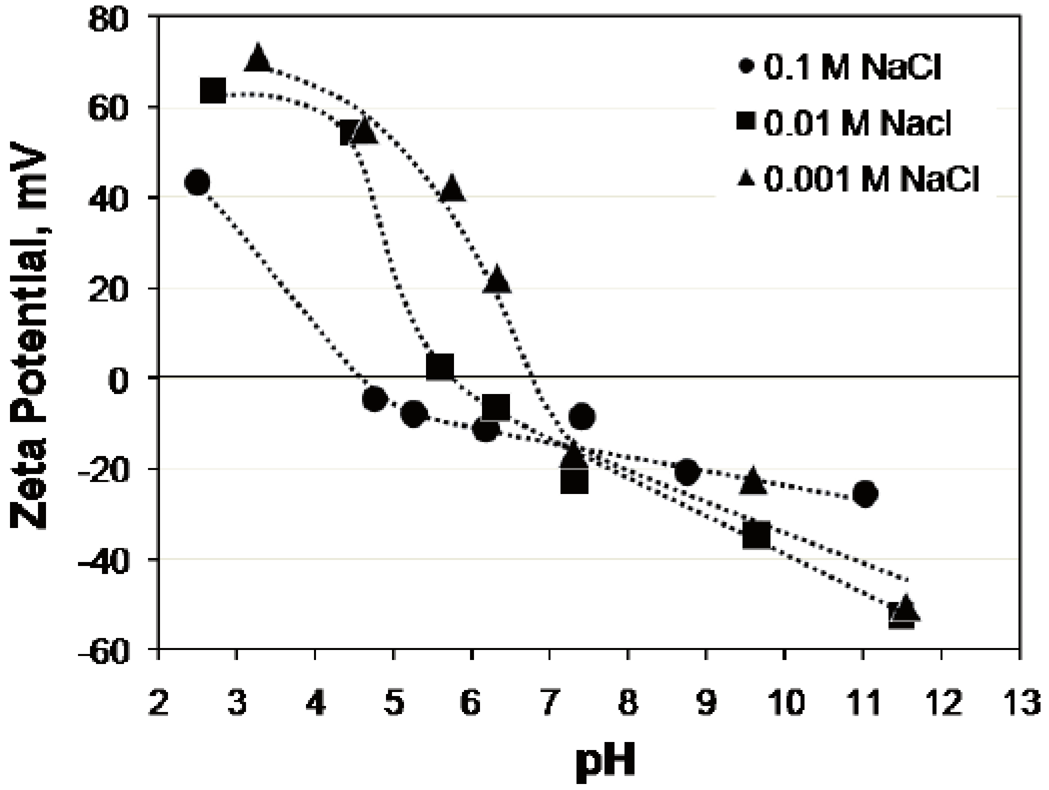
Summary of Droplet and Splash Parameters

Parameter	Symbol	Value	Comment
Rain droplet diameter	D_0	0.5 (mm)	Range of natural rain drops 0.2-0.5 mm (Yoxall, 1983).
Droplet's terminal velocity	U_0	~3-5 (ft/sec)	Terminal velocity if droplet is able to fall at least 5 ft.
Weber number for falling droplet	$We_{(droplet)}$	15.8	We < 1 surface tension dominates droplet behavior We > 1 inertial forces dominate droplet behavior
Reynolds number for falling droplet	$Re_{(droplet)}$	782	Splash behavior depends on the combined effects of the Weber and Reynolds numbers (see Oh)
Ohnesorge number	$Oh_{(droplet)}$	0.00508	
K splash parameter	$K_{(droplet)}$	131	K < 2100, non-splash regime. Droplet remains relatively intact during impact and rebound.

Yoxall, William. 1983. Dynamic Models in Earth-Science Instruction. Cambridge Univ Press.

Surface Properties

- Surface charge (sign and density) determine interactions between simulants and street surfaces
- Zeta potential is a typical estimate of this property
- Zeta potential can be a function of pH and ionic strength, and may be adjusted to represent natural conditions



FeO particles, Diaz Alloro et al., 2010

Summary and Next Steps

- Widely adopted geospatial tools, and prevalence of LiDAR data in major cities, allow development of input data for 3-D modeling using automated procedures
- A basic 3-D model of desired scale (10 feet by 4 feet) can be developed using commercially available tools
- Calculations of fluid flows suggest that a laboratory scale design for rain and stormwater flow can be readily developed
- Additional work is needed to characterize the surface reactive properties of contaminants and simulants for refinement of overall experimental design

Disclaimer

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