Stormwater Modeling Response to a Wide Area Radiological Dispersal Device Incident

Background

After the Chernobyl nuclear disaster stormwater played a role in transport of radionuclides. High concentrations of ^{137}Cs were found around houses where rain transported radioactive materials from roofs, secondary contamination of sewage systems/sludge storage areas was caused by washoff from roads, and decontamination activities included watering streets to move radionuclides into the sewer system.[1] In some locations, stormwater runoff from streets was contaminated by ^{137}Cs for up to seven years.[2] After the Fukushima nuclear disaster, ^{137}Cs associated with soil particles were mobilized during periods of high rainfall and hydrogeological maps were used to assess mobilization pathways and recontamination routes when planning decontamination.[3] In addition to a nuclear power plant incident, a radiological dispersal device (RDD) can result in a widespread surface deposition plume that presents both an immediate exposure risk and a potential long-term risk mediated through processes such as storm-induced transport. Managing the response to an urban radiological terrorism incident requires advanced planning and rapid mobilization to minimize health risks to residents and mitigate long-term impacts to municipal infrastructure and the environment. A well-organized response is critical to effectively managing contaminant transport and exposure and reducing the spread of radiological contamination. Stormwater modeling may be used to support response actions and to explore the feasibility of different remediation and sampling options.

The U.S. Environmental Protection Agency (EPA), Office of Research and Development, Center for Environmental Solutions and Emergency Response has developed models of Detroit, Michigan and Buffalo, New York to track and quantify washoff of deposited Cesium (Cs)-137 following an RDD incident. The models identify transport and discharge pathways following rain events and are modifications to the cities' existing municipal stormwater management models (SWMM)[4], with the additional data and modeling steps as follows:

- Subcatchment updates spatially congruent to natural drainage boundaries (where needed).
- Creation of a high-resolution 2D mesh (HRM) that replaced the standard subcatchments intersecting the plume in and adjacent to the blast zone.
- Incorporation of a ground deposition plume of Cs-137.
- Assignment of midrange washoff rates to the subcatchments according to infrastructure components (i.e., buildings, roads, and open areas).
- Incorporation of high return frequency storms based on real storm events.

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[1] Environmental consequences of the Chernobyl accident and their remediation: twenty years of experience / report of the Chernobyl Forum Expert Group 'Environment'. — Vienna: International Atomic Energy Agency, 2006.
[2] U.S. EPA. Particle Transport of Radionuclides Following a Radiological Incident. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-15/113, 2015.
[3] JAEA Model project report (Remediation of Contaminated Areas in the Aftermath of the Accident at the Fukushima Daiichi Nuclear Power Plant: Overview, Analysis and Lessons Learned Volume 1: A Report on the "Decontamination Pilot Project" Fukushima Environmental Safety Center, Sector of Fukushima Research and Development Japan Atomic Energy Agency Sakae, Fukushima, Fukushima 960-8031, Japan)
[4] https://www.epa.gov/water-research/storm-water-management-model-swmm
[5] https://www.pcswmm.com/

This research was developed in collaboration with the Interagency Modeling and Atmospheric Assessment Center (IMAAC), the Great Lakes Water Authority (GLWA), and the University of Buffalo's Department of Civil, Structural and Environmental Engineering.

Model Elements and Data Sources

To develop the modified local models, EPA's Stormwater management model (SWMM) version 5.1.015 was implemented using a proprietary software package: PCSWMM (Computational Hydraulics International (CHI), Guelph, Ontario, Canada).[5] This proprietary software was selected because of its utility for generating the 2D mesh used in simulations of overland flow and its ability to interface with EPA's SWMM (the software used to create the local models).

Physical data integrated into the models included the municipal sewer model layers (provided by GLWA and the University of Buffalo), meteorological (precipitation) data, a ground deposition plume (provided by IMAAC), a digital elevation model (DEM), spatial land use data, and building footprints. In addition, washoff parameters for the contaminant derived from data available in research publications were incorporated in the models.

Constructing the High-Resolution Mesh

The HRM for each local model was developed in PCSWMM and consists of 2D cells, junctions, and conduits for modeling overland flow. The HRM was created using two data layers: one that represents features which obstruct free overland flow such as buildings or walls, and a DEM that provides ground surface elevations. For both local models, the DEM was created from LIDAR imagery with a resolution of 3 meters. A boundary layer for each model for incorporating the HRM was constructed by overlying the original SWMM subcatchments (Figure 1) that intersect the portion of the ground deposition plume in higher concentration areas.

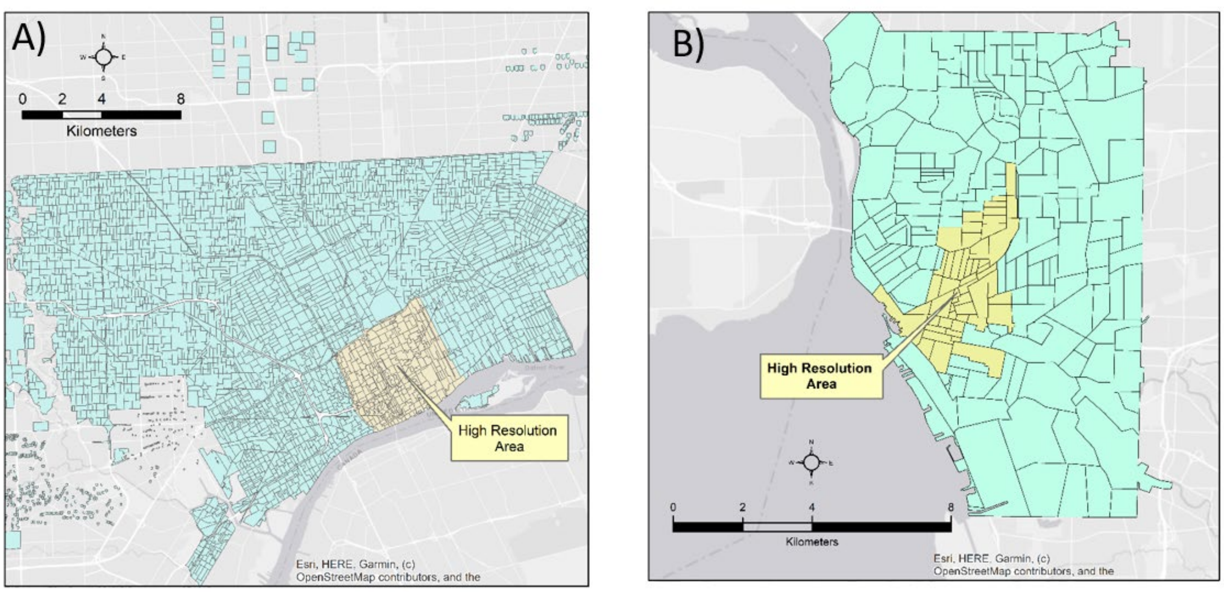

Figure 1. A) Detroit and B) Buffalo model subcatchment extents and high-resolution mesh areas.

Linear representations of roads within the boundary layer were necessary to enforce the rectangular geometry of the uniform grid. A very fine mesh size resolution (12 meters) was applied to roads within the boundary layer to allow simulated surface sampling at fine resolution. Areas outside of the road features were assigned hexagonal geometry with increasingly coarse resolutions (from 24 to 98 meters) outwards from the RDD detonation point to improve computational speed of the model simulations. Once the HRM was created in PCSWMM, the original SWMM subcatchments were replaced by the HRM cells and the building footprints. Attributes of the new HRM subcatchments were assigned using spatial joins to the original SWMM subcatchments and the National Land Cover Database’s impervious layer. The fine detail of the HRM subcatchments (Figure 2) better aligns with the shape of the plume and with the scale of subcatchments in the literature utilized to derive the washoff parameters for the models.

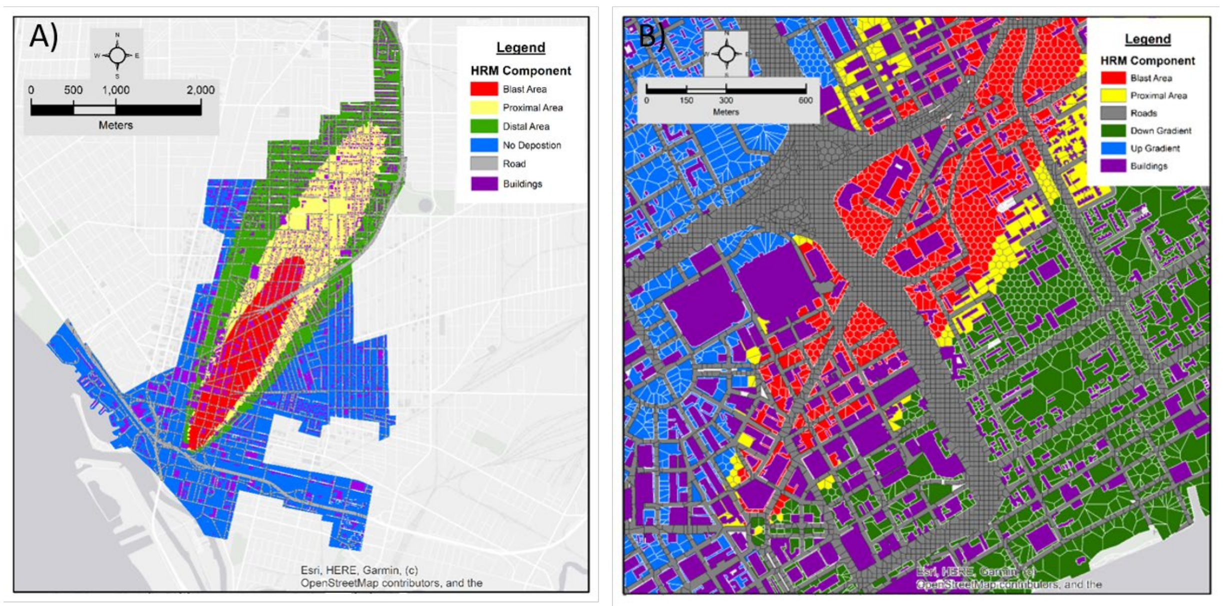

Figure 2. A) Buffalo entire HRM area and B) Detroit HRM zoomed in to see the rectangular, hexagonal, and building geometries.

The ground deposition plume as Cs-137 activity/area was imported to PCSWMM as a polygon shapefile and assigned to the subcatchments using the Area-Weighting tool in PCSWMM. Transport via overland flow was simulated in the HRM subcatchments using a network of 2D-conduits. These conduits were linked to the existing underground conduit network at the outlet nodes of the original SWMM subcatchments using the Connect 1D to 2D tool in PCSWMM and the bottom orifice option. Washoff from the HRM subcatchments was transported to these outlet nodes and from there to the existing stormwater infrastructure.

Land use and Contaminant Washoff Parameters

Three land use types were defined in the models: Urban, Road, and Building, to specify the subcatchment washoff properties. The scale of HRM subcatchments modeled were similar to those in literature experimental studies. Parameter values reported in exponential washoff models exhibit wide variability. Midrange values were used but may be modified in future studies. An exponential washoff curve was applied with coefficients derived from washoff behavior in urban environments. Transport modeling was based on the transport behavior of contaminant adsorbed to total suspended solids (TSS). Higher values of the washoff parameters were assigned to Building surface types to simulate rapid first flush effects, and lower values for Urban land use types to account for infiltration and greater retention in grassy areas. Values for parameterizing the Road land use were interpolated from Urban and Building land use values.

Running the Model

Because of the very fine resolution needed to incorporate the plume and define the overland flow component directed along roadways, the computational run time of the model can be very long. For this reason, three timeframes and representative rainfall events were used:

- A 3-hour rainfall event to examine the response to a short but high intensity event. (The highest intensity corresponded to a 2-year return, 1-hour peak rainfall frequency estimate)
- A 24-hour rainfall event to determine response to a sustained storm (2-year return frequency estimate, 24-hour rainfall), and
- An additional 48 hours following the 24-hour rainfall event to simulate transport of the residual contamination in the sewer system after the rainfall has stopped.

Typical simulation rates were about 2 to 4 simulation sections per second, corresponding to about 12 hours to complete the 24-hour simulation for the Detroit model and 10 hours to complete the 24-hour simulation for the Buffalo model.

Summary Results

Data outputs include the fraction of the original deposition lost from the subcatchment surfaces during the storm events, the conduit mass flux, the total contamination quantity discharged at each outlet, and the concentration at each outlet over the simulation time. The models can be run and the data displayed graphically on maps to aid emergency response teams in the following ways:

- Identify where the contaminant may have been transported,
- Locate the points of maximum discharge,
- Locate the most impacted portions of the infrastructure, and
- Inform decisions prioritizing cleanup and other response actions, and identify the best locations for monitoring and treatment, and where entry and duration of ingress should be restricted.

An example of the model results identifying the conduits and discharge points that represent the principal transport pathways and release points is shown in Figure 3. These models continue to be used for research studies, including in a comparison of mass transport values using the original municipal stormwater transport values using the original municipal stormwater models vs. the HRM-modified models. The models' washoff coefficients and rainfall events are easily modifiable for future training and/or table-top exercises.

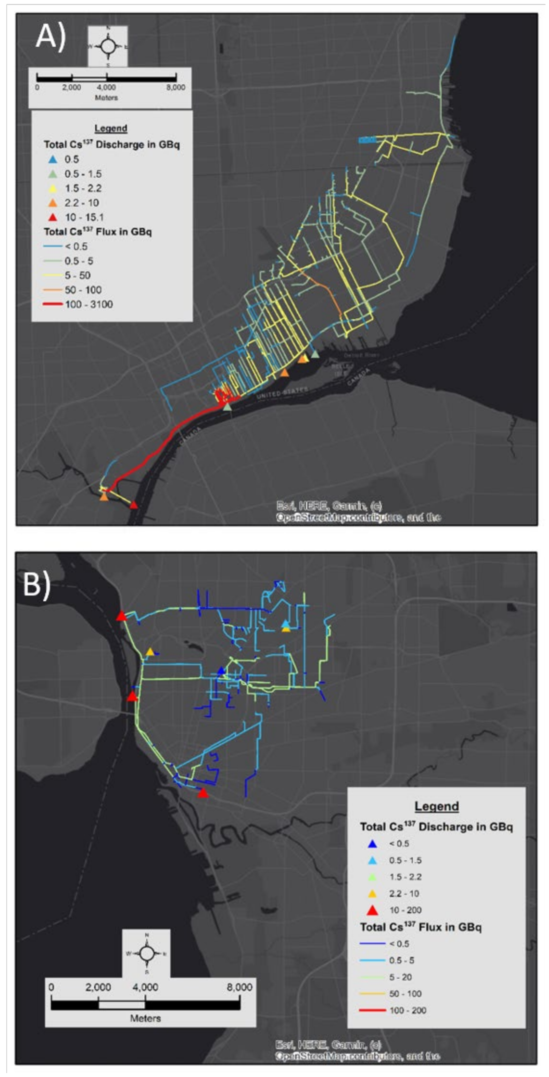

Figure 3. A) Detroit and B) Buffalo model results showing contaminant flux in SWMM conduits and discharge at outfalls.

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