A Revisit of Temporal and Spatial Variability and Resolution of Rainfall Measurements Relevant for Urban Hydrology

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Abstract

Localized and severe storms can cause citywide flooding, leading drainage systems to surcharge and overflow to nearby water courses. Urban catchments feature high degrees of imperviousness and heterogeneity, often resulting in highly nonlinear hydrologic responses with shorter time of concentration, lag times, and sharper peak flows. Additionally, due to population and economic growth, urban drainage systems have attempted to evolve to more efficiently drain surface waters and reduce vulnerabilities. A critical outcome of this evolution is the need for finer spatio-temporal resolution rainfall measurements and hydrological modeling. As the major driving mechanism, the spatio-temporal variability in rainfall is acknowledged as a key source of uncertainty for urban hydrological modeling. The objective of this research is to revisit the impact of the temporal and spatial resolution of rainfall measurements on urban hydrological applications. We first provide a quantitative analysis of the spatiotemporal structure and variability of rainfall using both a 9-member hourly rain gauge network spaced ~10 km apart and a single WSR-88D dual-polarimetric weather radar with precipitation resolved every 5 minutes at ~500 m. Precipitation data from each observing system extracted at different time steps is aggregated within urban catchments and compared for three typical intense storms over a set of urban catchments located in Chicago Metropolitan area. Then the rain-runoff dynamics for 9 geographically-diverse (relative to the underneath sewer system) and differently-sized catchments are examined utilizing MetroFlow – a coupled hydrologic and hydraulic modeling system. Finally, city-wide flooding risks are simulated by routing the predicted surface runoff through the as-built sewer system. Additional mitigating storage capacity is also considered by numerical modeling the deep tunnel and reservoir in construction. The sensitivity of urban flood variables (i.e., mean and peak depth as well as duration) to rainfall spatio-temporal resolution is analyzed. Our results complement and advance the limited literature attempting to resolve the ideal resolution of rainfall data relevant for urban hydrology and stormwater management.

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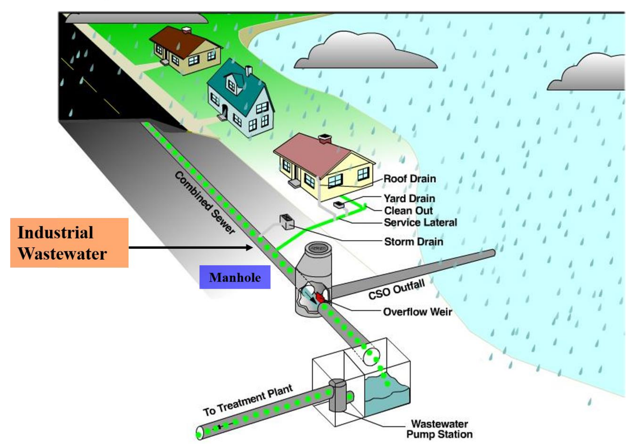
INTRODUCTION

➢ Urban drainage system

Major Elements

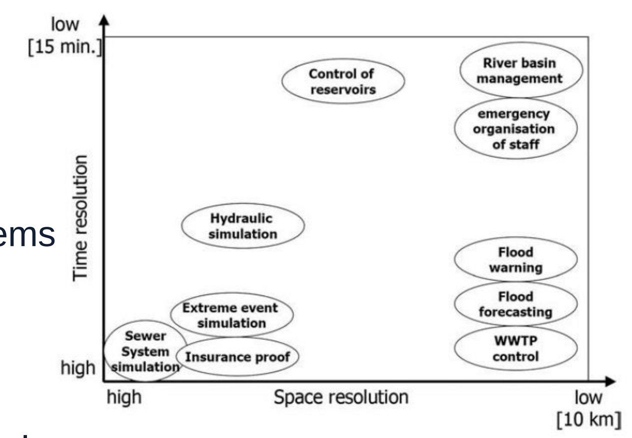


Major Characteristics

- highly impervious (residential, commercial and industrial)
- much shorter time and length scales (minutes and meters)
- high degree of heterogeneity and nonlinearity in response
- evolving due to economic and population growth, infrastructure rehabilitation, intervention or mitigation measures.

➢ Motivations

- Rainfall is the driving mechanism of urban runoff.
- Localized and severe flash storms can cause citywide flooding, leading drainage systems to surcharge and overflow to nearby water courses.
- The observed tempo-spatial variability of rainfall has a significant impact on hydrological systems and constitutes a major source of uncertainty for urban hydrologic modeling.
- The small space-time scales of urban catchments and complex underground drainage systems require rainfall data at the fine spatial-temporal resolutions.

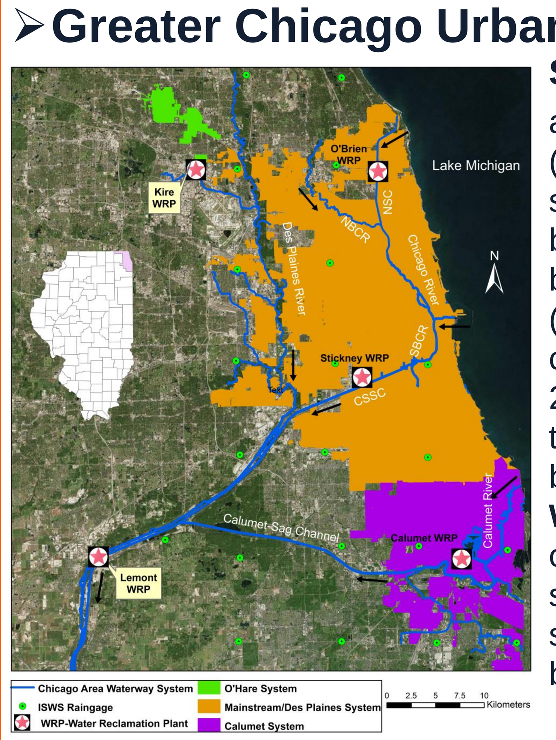


(Einfalt, 2005; Ochoa-Rodriguez et al. 2019)

- The developments in GIS and detailed urban drainage models, emerging data resources and computational power facilitated the integration of radar rainfall estimates in urban hydrology.

Background and Materials

➢ Greater Chicago Urban Drainage System



System Overview:

a. **City of Chicago** and **51** suburbs (see left) have a total area of **375 mi²** served by combined sewers.

b. Intercepting sewers (over 400 mi) were built to diver primarily dry weather flows (DWF).

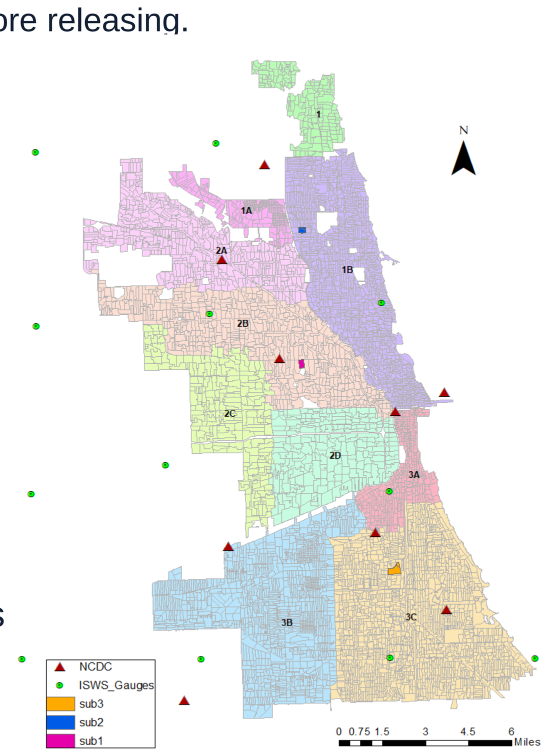
c. Deep tunnels (109 mi) completed in 2006 and storage reservoirs (18.5 BG) that are in construction (to be completed by 2029) parallel to the **Chicago Area Waterway System (CAWS)** are to divert overflow from **369** permitted combined sewer outfalls, temporarily store during storms and direct to WTP for treatment before releasing.

➢ Study Area

a. Based on a simplified representation of the entire sewer system in City of Chicago (>24 in).

b. The watershed has been divided to nine model areas which were further delineated into 6594 subcatchments (see right) with median size of 4.7x10⁴ m².

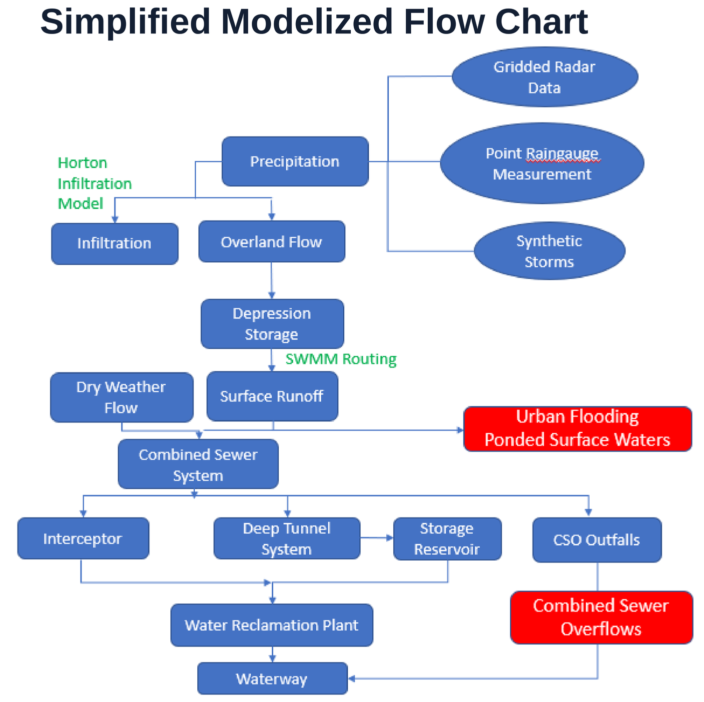
c. Areal-averaged imperviousness is 63%.



METHOD

➢ Integrated Hydrologic and Hydraulic Model

Simplified Modelized Flow Chart



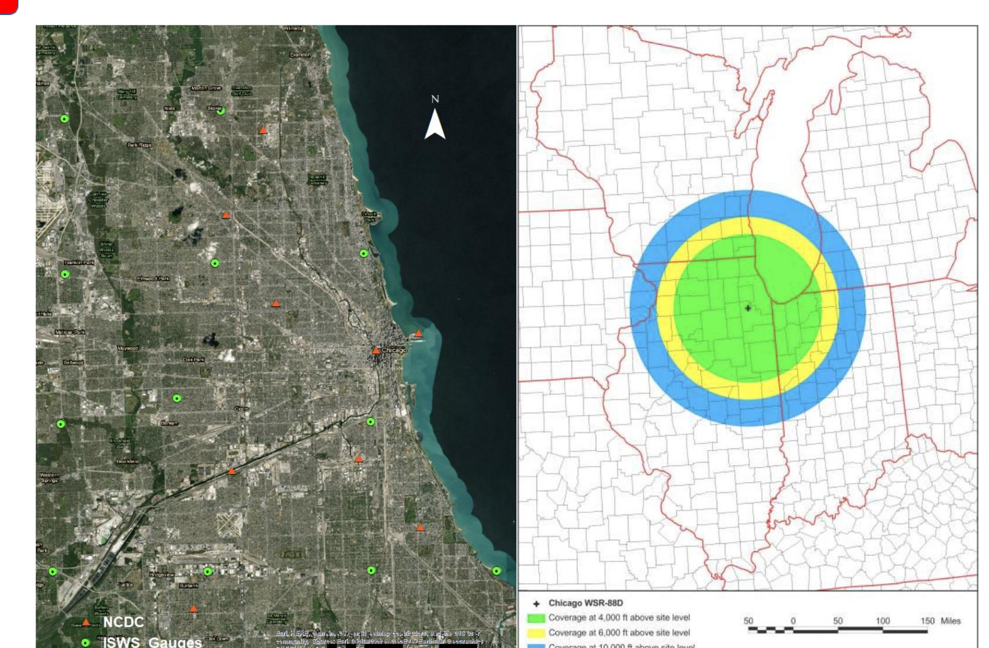
- 1-D detailed numerical model originally developed for entire drainage system across City of Chicago (for the Department of Water Management) using the InfoWorks CS package is employed to integrate rainfall derived from raingauge network and radar
- Solves the 1-D Saint-Venant Equations in conjunction with Preissmann slot for pressurized flow simulating the complex flow in the highly looped city sewer network.

➢ Description of Rainfall Data

a. **Rain gauge:** Illinois State Water Survey (ISWS) operated, 9 out of a 25-membered hourly rain gauge network spaced ~10 km apart.

b. **National Climate Data Center (NCDC) Stations:** distributed **precipitation frequency** (PF) analysis are used to generate synthetic storms.

c. **NEXRAD Radar Level III Data**: a single WSR-88D dual-polarimetric weather radar with precipitation resolved every 5 minutes at 500 m and 1km, a Z-R relationship is deployed to generate quantitative precipitation estimation (QEP) at each grid.

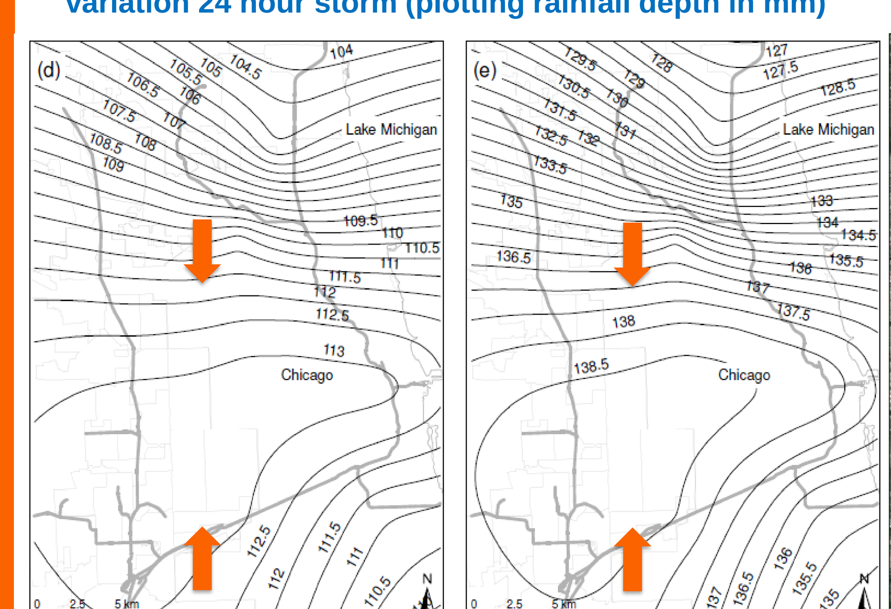


Rain gauge and NCDC weather stations (left); NEXRAD radar coverage for KLOT, Chicago, IL., (right) courtesy http://www.ncdc.noaa.gov/oa/ncdc.html

Results & Discussions

- ➢ **Synthetic storms: 100-year** ARI design storms with **6 hour** durations based on NCDC PF data (rainfall depth) and Huff distribution (temporal).
- ➢ **Historical storms :** rainfall data from the **ISWS** and **NEXRAD radar** for storms on **April 17-18, 2013 (25-year recurrence interval).**
- ❖ **Storage conditions:** For synthetic storms, two storage conditions w/o storage from deep tunnel system; For historical storms, no storage from deep tunnel system were included.

- **Maps showing regional rainfall frequency and spatial variation 24 hour storm (plotting rainfall depth in mm)**



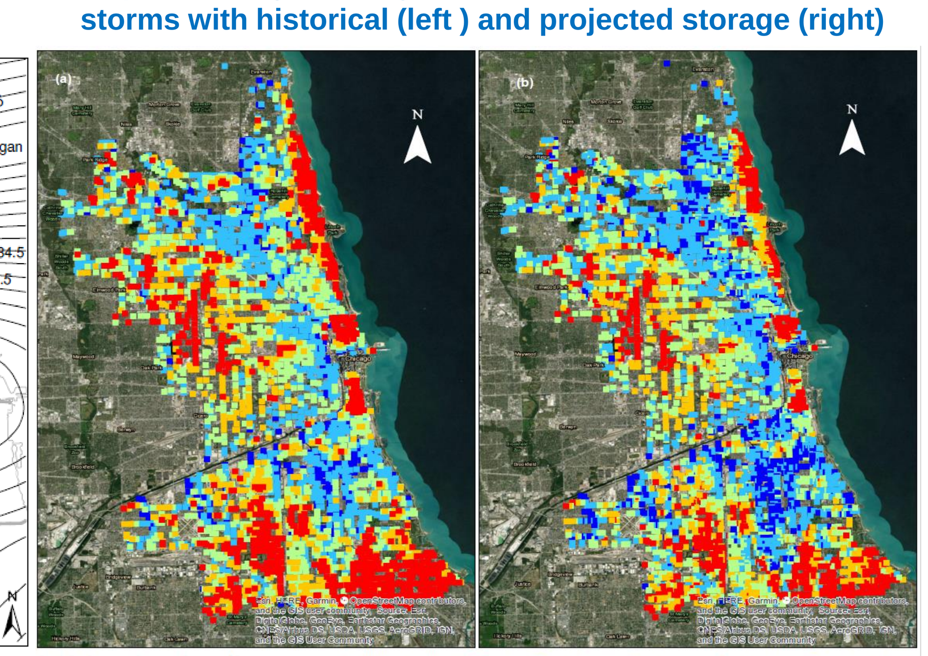
10 year 24 hour | 100 year 24 hour

Highlight #1

a. Intense storms of the same duration follow the same spatial pattern. More rain are likely to fall in middle system, i.e. Chicago metropolitan area.

b. Greater spatial gradient is observed for more intense storms.

- **Maps showing flooding risks from 100 Year 6 hour ARI storms with historical (left) and projected storage (right)**



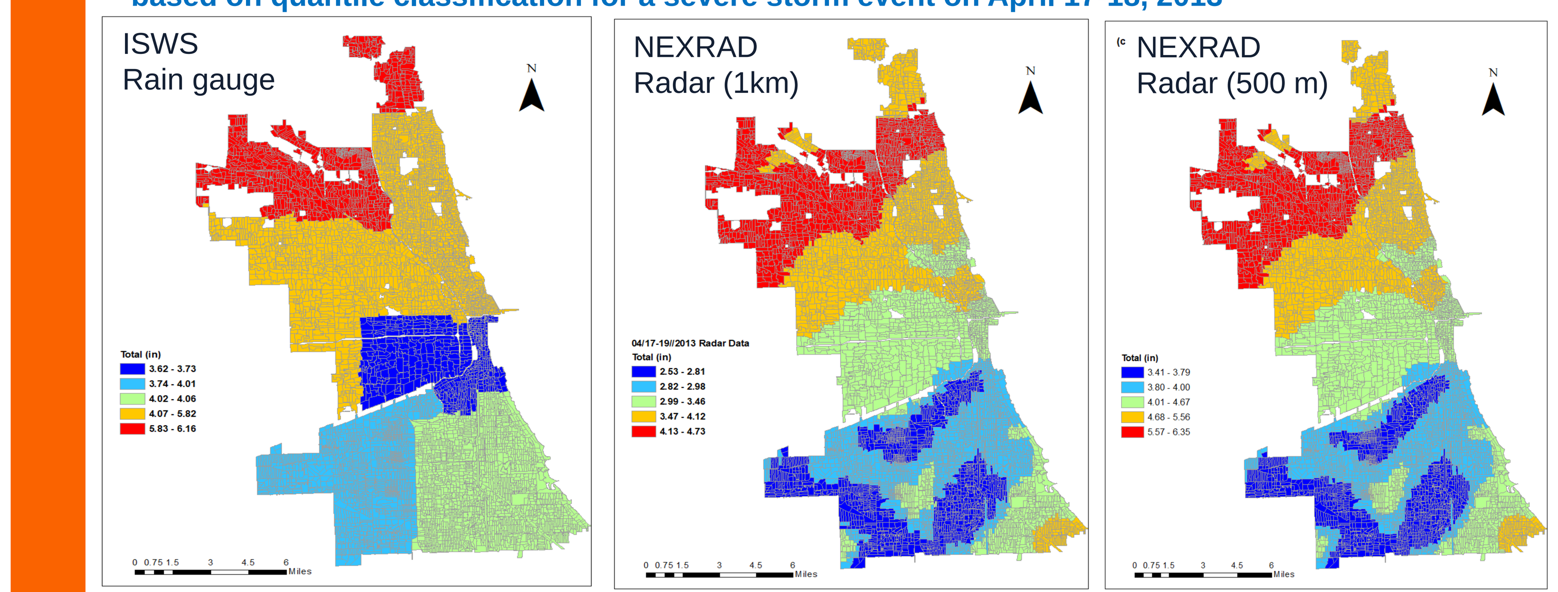
Highlight #2

a. Less flooding risks predicted in the areas near CAWS, areas along Northshore and southern suburbs are more prone to flooding.

b. With additional storage provided by tunnel and reservoir system, the flooding risks is reduced extensively from inland to near shore areas.

Results

- **Maps showing comparison between Radar derived and Rain gauge data based on quantile classification for a severe storm event on April 17-18, 2013**

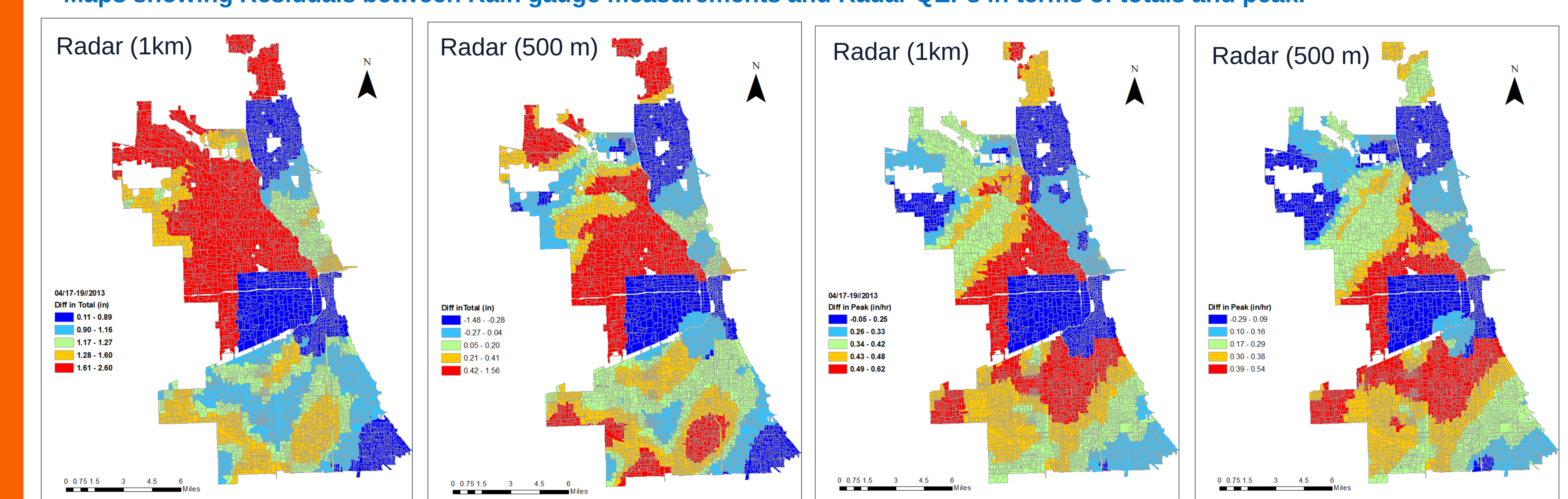


Highlight #3

a. The rainfall follows the alike spatial pattern for two radar data sets resolved at 500 m and 1km; however, the magnitudes differs with the former about 40% greater than the latter.

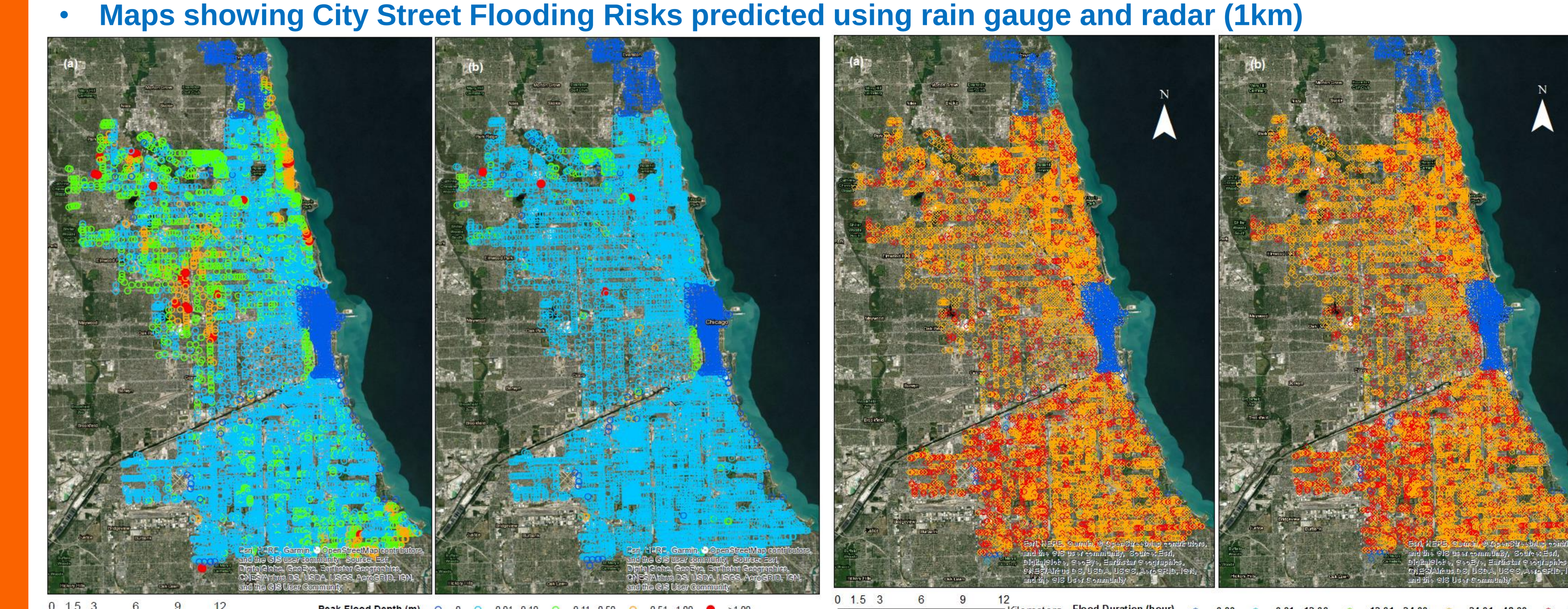
b. The radar data in finer resolution resembles the rain gauge data quantitatively better.

- **Maps showing Residuals between Rain gauge measurements and Radar QEPs in terms of totals and peak.**



➢ Impact on simulated hydrologic response

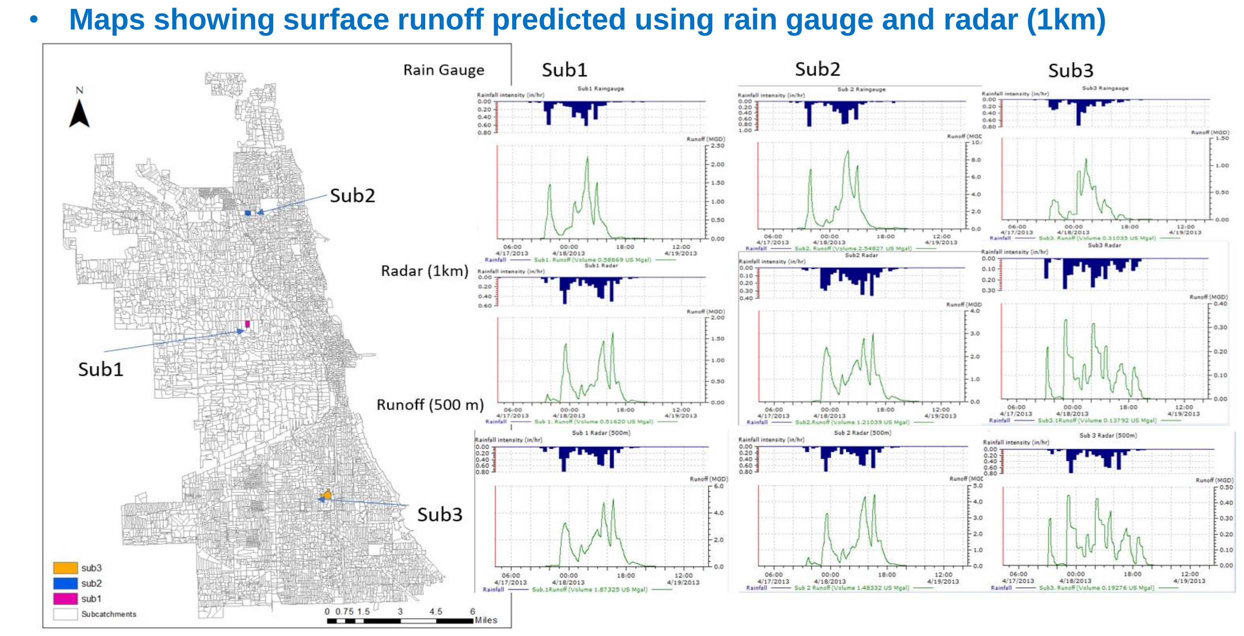
- **Maps showing City Street Flooding Risks predicted using rain gauge and radar (1km)**



Highlight #4

a. The differences in rainfall input result in dramatic differences in the simulated floods in terms of peaks and spread.

- **Maps showing surface runoff predicted using rain gauge and radar (1km)**



b. At different geographical location the rainfall derived from different approaches and at various resolution differ in their spatial and temporal pattern due to inherent differences between direct and indirect measurements, which further result in obvious differences in predicted surface runoff, the volume, peak and hydrograph passages. Regardless, the two sets of radar data resemble in temporal structure, however, differs in magnitudes.

ACKNOWLEDGEMENTS

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Please also visit us at A21P-2852 for more about the Radar.

ILLINOIS