Exploring the Interdependencies between Transportation and Stormwater Networks: The Case of Norman, Oklahoma

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Motivation

- The functionality of infrastructure systems (e.g. Transportation, Power, Water, Social, etc.) is crucial for social lifeline and productivity; however, such systems are vulnerable to **external disruptions** and **cascading failures**.
- Instead of functioning in isolation, physical infrastructures (i.e. roads or stormwater) act as a **large and complex connected systems**.
- The **interdependence** between **transportation and stormwater systems** is particularly important due to the recent rise in **flooding** events leading to adverse traffic impacts.
- New insights and understudied factors that govern how transportation systems critically depend on neighboring stormwater systems is a research need for the sustainability of infrastructure.

Introduction

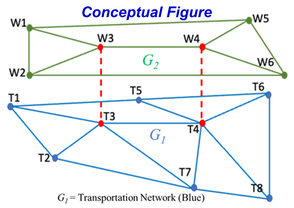
- Due to increase in **pluvial surface flooding** (defined as excessive precipitation induced flooding beyond the capacity of the stormwater drainage system), both stormwater and road systems becomes **vulnerable to disruption**. Hence the functionality of road and stormwater networks are interdependent. In addition, due to geographic colocation, stormwater and road networks are spatially interdependent.
- **Therefore, the research goal of this research is to investigate the functional and spatial interdependency of transportation and stormwater systems.**
- The objectives to satisfy the goal are threefold:
  1. to explore the **spatial interdependency** of transportation and stormwater network,
  2. to investigate the **aggregate behavior** of these systems when spatial, functional, and connectivity metrics are combined, and
  3. to compare the **individual and multilayer networks' topological credentials** (Topological credential of a network is defined as the quantification of criticality and vulnerability of its components (e.g. nodes and edges) based on their topology in the network by applying network metrics (e.g. degree, centrality) to study the change in properties due to interdependency.

Research Questions

- To what spatial level are the transportation and stormwater systems interdependent?
- What is the best indicator of spatial interdependency?
- What is the best way to incorporate functional and spatial interdependencies?
- What is the best analysis framework to capture interdependency?
- How does the topological credentials change from individual level to multilayer level?

The Concept of Interdependency using Graph Based Approach

Conceptual Figure



G_1 = Transportation Network (Blue)

G_2 = Stormwater Network (Green)

G_m = Multilayer Network (G_1 + G_2) (Red+Blue+Green)

W_{i0} = nodes from stormwater network

T_{i0} = nodes from transportation network

Methodology:

- Multilayer graph representation of road and stormwater networks
- Spatial autocorrelation analysis using Moran's *I*
- Weighted analysis of road, stormwater, and multilayer networks
- Weight is assigned as following way: AADT for road network, Conduit Capacity for stormwater network, and Moran's *I* significance value for multilayer network.

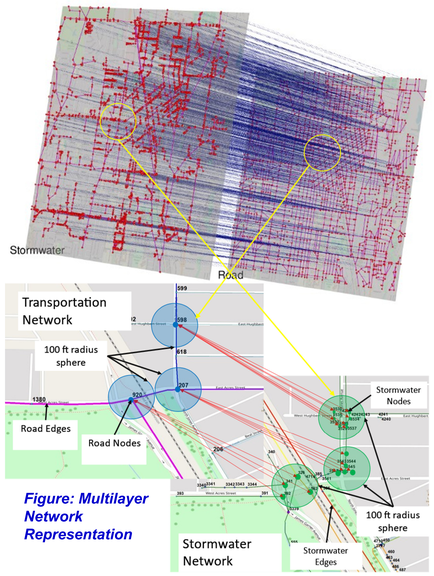
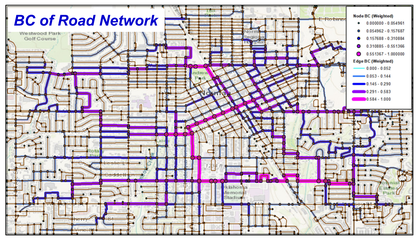
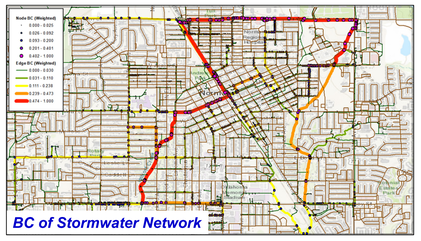
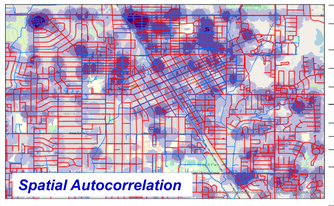


Figure: Multilayer Network Representation

Network and Spatial Analysis







$$I = \frac{N}{W}\frac{\sum_i \sum_j w_{ij}(x_i-\bar{x})(x_j-\bar{x})}{\sum_i (x_i-\bar{x})^2}$$

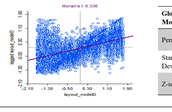
$$I_{local} = \frac{x_i-\bar{x}}{\alpha}\sum_{j=1}^{N} w_{ij}\,(x_i-\bar{x})$$

where $\alpha = \frac{\sum_{i=1}^{N}(x_i-\bar{x})^2}{N}$

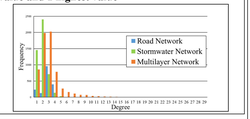
N = number of observations,
$\bar{x}$ = mean of the variable,
w = spatial weight,
W= sum of all spatial weight

Graph Properties	*Unweighted*			*Weighted*		
	Road Network	*Stormwater Network*	*Multilayer Network*	*Road Network*	*Stormwater Network*	*Multilayer Network*
Nodes	1,716	4,737	6,454	Same for unweighted graph		
Edges	2,476	5,455	9,952	Same for unweighted graph		
Diameter	68	232	72	10.64	92.53	15
Density	0.00168	0.00040	0.00048	Same for Weighted graph		
Mean Path Length	25.54	87.6	25.24	3.38	33.95	3.78
Node Properties						
Average Degree	2.89	1.92	4.33	-	-	-
Eigenvector Centrality (Number of Nodes within the threshold [>.5/1]*)	-	-	-	20	20	28
Node Betweenness Centrality (Number of Nodes within the threshold [>.5/1]*)	-	-	-	33	116	23
Link Property						
Edge Betweenness Centrality (Number of Nodes within the threshold [>.5/1]*)	-	-	-	55	115	29

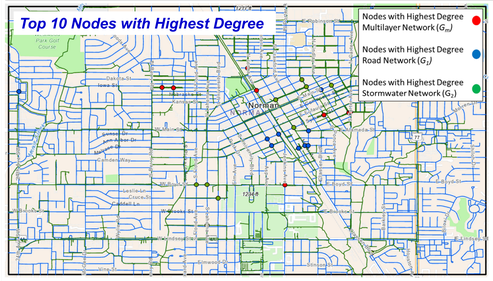
*Values are normalized between 0 to 1; .5 is the threshold value and 1 highest value



Global Moran's I	(+ve) 0.3362
Permutation	999
Standard Deviation	0.0076
Z-score	44.2758



Multilayer Network Analysis



Degree:

The degree (Di) of a node is the number of edges that are connected to it.

For Single Layer Network,

$$D_i = \sum_{j=1}^{n} A_{ij}$$

For multilayer Network,

$$D_i = B(M_j^i)U$$

B = binary function,
U = rank-2 tensor
Aij = Adjacency Matrix

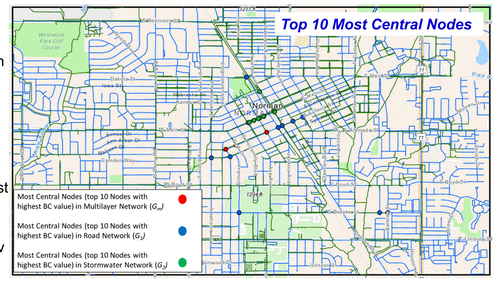
Betweenness Centrality (BC):

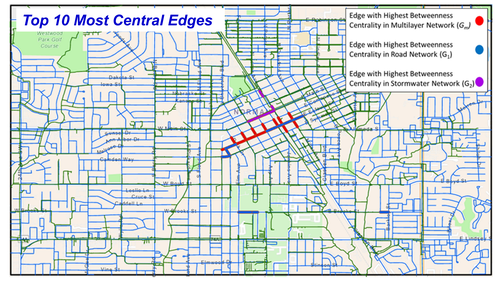
BC of node/edge is defined as the number of shortest paths in the network that pass through that node/edge.

EC is expressed as:

$$BC = \sum_{i,j} \frac{\gamma_{ij}(n)}{\gamma_{ij}}$$

Where, γ_{ij} = number of shortest paths between node *i* and *j*, $\gamma_{ij}(v)$ = number of shortest paths that pass-through node v (not the v as end point).





Findings

- Spatial autocorrelation estimated by **global Moran's *I*** turns out to be a good **indicator of spatial interdependence**. Moreover, **spatial weight generated** from **local Moran's *I*** produces logical estimates of topological credentials.
- Most of the **central roads** are identified as **local roads** whereas the study considered collectors, arterials road too. In a city area where **local roads are more connected** (e.g. grid pattern, radial pattern) produces higher degree nodes and central edges compared to less connected road classes.
- Most of the **central conduits** are found in the **natural creeks** in the **stormwater network**. Creeks are identified to **carry high volume of stormwater** as well as are connected with pipelines (Bishop Creek, Inhofe Creek in the study area).
- For **multilayer network**, **most central nodes and edges** are found within **proximity to that of stormwater and road networks (betweenness centrality)**.
- **Topological credentials** (degree and betweenness centrality) also indicate the criticality of the similar nodes and edges. One of challenges of 'interdependency of systems' study is to identify **vulnerable locations for cascading failure**. This study indicates that **topological credentials of multilayer network have to potential to overcome this challenge**.