TOWARDS MULTIHAZARD RESILIENCE
Interdependent Infrastructure Systems Under Global Change

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2 | INTRODUCTION
Research support

Funding

- Linking Hazard, Exposure and Risk Across Multiple Hazards
- NSERC CRD with Chaucer Synd.: 2015-2020 **$1,375,600** NSERC CRSNG Chaucer Institute for Catastrophic Loss Reduction Building resilient communities

Research topics

1. Detailed study of insurance claims and exposure data for wind, flood, earthquake
2. Integration of general and specific earthquake loss estimation platforms
3. New methods for quantifying earthquake hazard.
4. Improved risk modeling for wind storms by accounting for the effects of storm duration.
5. Mapping climate change impacts on flood hazard in Canada
6. Tool for mapping resilience of urban regions across Canada for all hazards

Research team

- Prof. S. P. Simonovic, PI
- Prof.. K. Tiampo
- Prof. S. Molnar
- Prof. G. Kopp
- Dr. G. Michel
- Mr. P. Kovacs

3 | MESSAGES

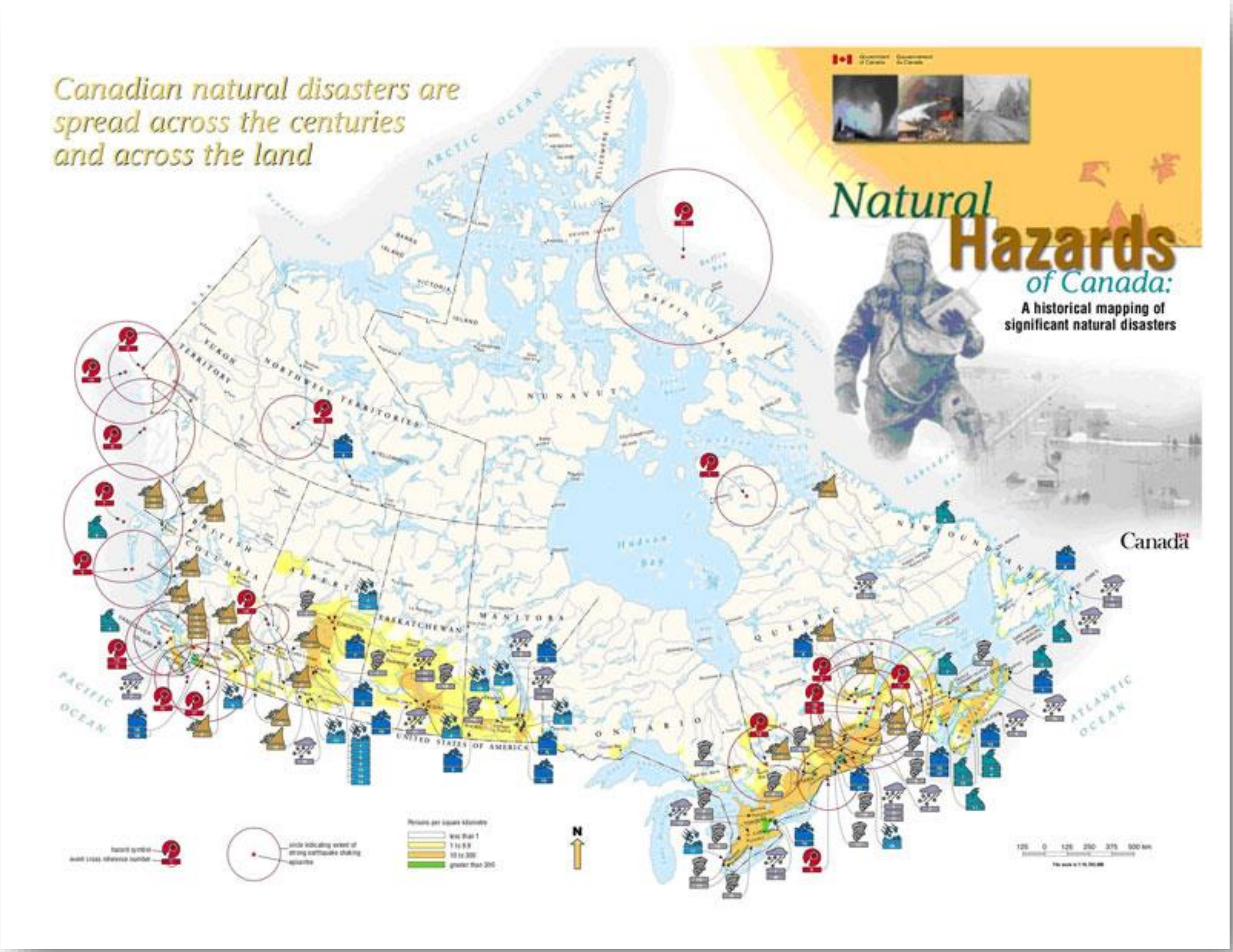
- Resilience as a new development paradigm:
  - Practical link between adaptation to global change and sustainable development
- Systems approach needed for quantification of resilience
  - Understanding of local context of vulnerability and exposure is fundamental for increasing resilience
  - Consideration of time and space an integral part of quantification
  - Modelling single and multiple hazard conditions requires different modelling

4 | OUTLINE

- Introductory remarks
- From risk to resilience
- Quantitative resilience of infrastructure systems
  - Systems approach (simulation, time and space)
  - Single hazard case
  - Multi hazard case
- An example – Greater Toronto Area
- Conclusions

4 | INTRODUCTION

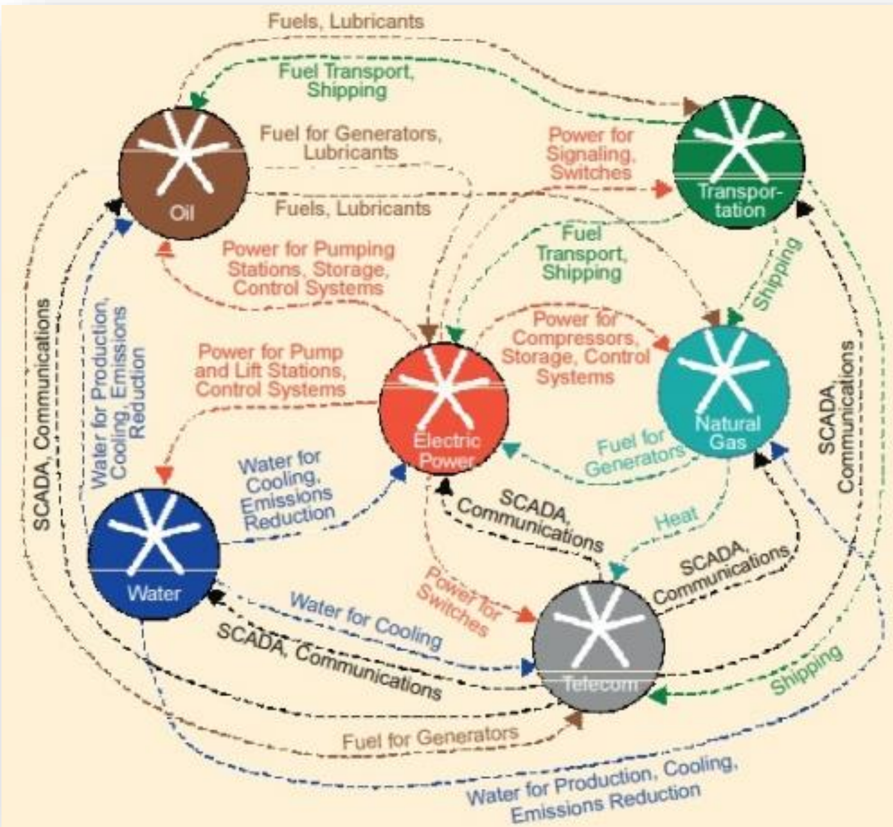
Natural hazards – single and multiple



5| INTRODUCTION

Infrastructure – single and interconnected

6| INTRODUCTION
Infrastructure response

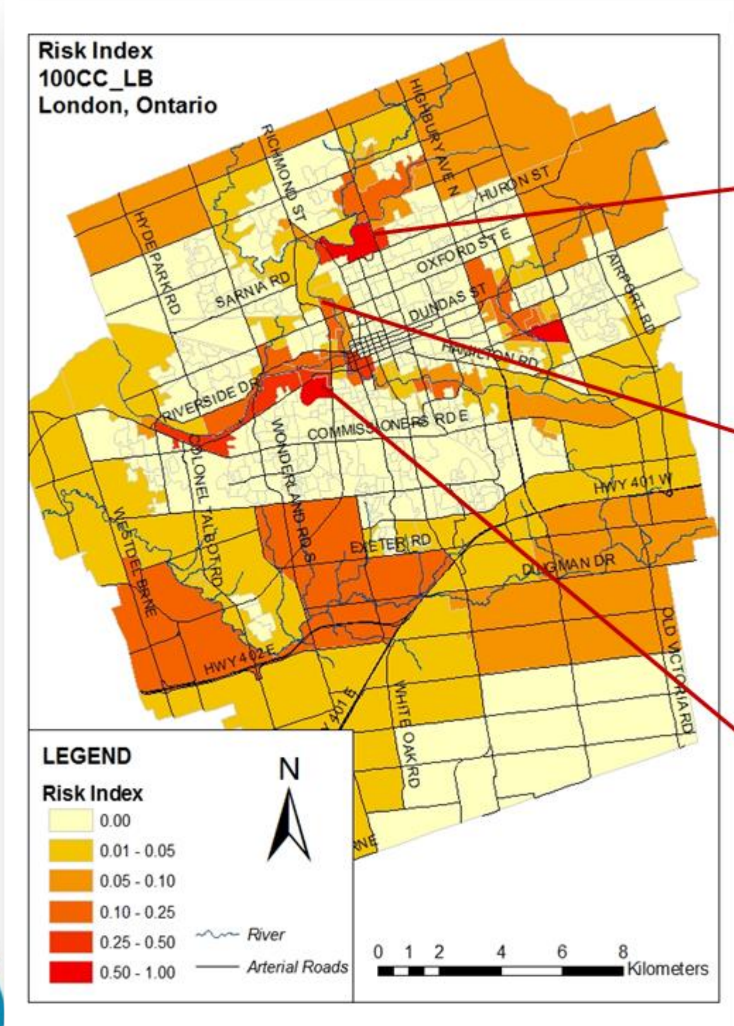


Infrastructure interdependence (*Rinaldi et al., 2001*)

- Cascading failures (throughout the whole infrastructure system at regional and national scales)
- Effective protection and recovery are hard and costly
- Infrastructure system resilience is often overestimated
- Traditional approach – risk based

7| RISK TO RESILIENCE

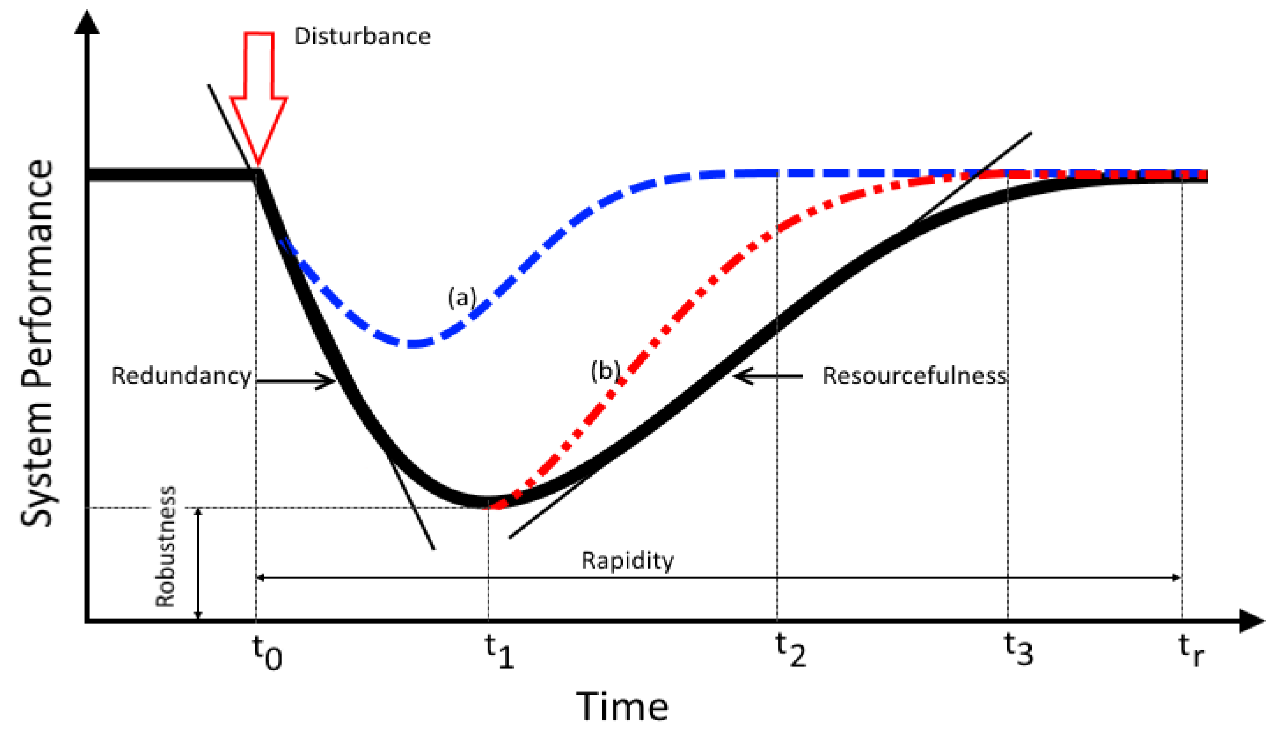
Need for paradigm change



robability

RISK TO RESILIENCE

Need for paradigm change



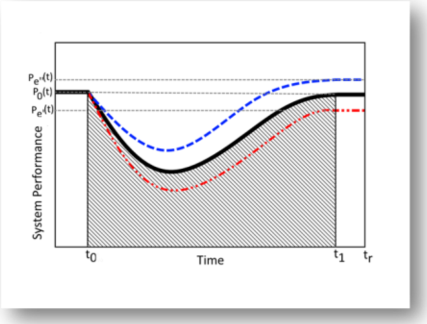
RISK TO RESILIENCE

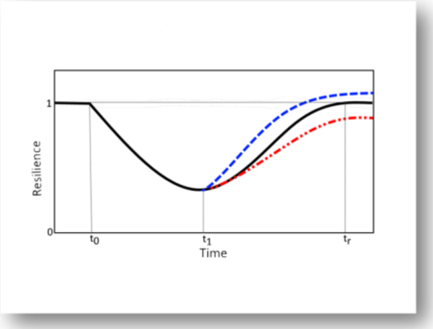
Definition

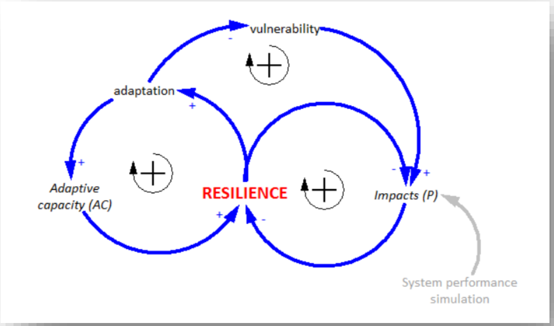
- *Simonovic and Peck, 2013*
  - …the ability of a system and its component parts to anticipate, absorb, accommodate or recover from the effects of a system disruption in a timely and efficient manner, including through ensuring the preservation, restoration or improvement of its essential basic structures and functions…

11 | RISK TO RESILIENCE

Implementation – temporal and spatial dynamics







- System performance and system adaptive capacity
- Transformation of system performance into resilience

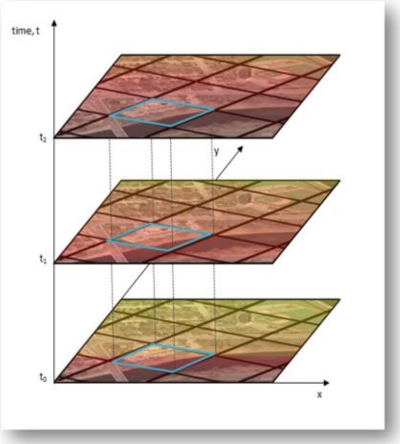
$$\rho^i(t,s) = \int_{t_0}^{t} [P_0^i - P^i(\tau,s)]d\tau$$

$$r^i(t,s) = 1 - \left(\frac{\rho^i(t,s)}{P_o^i \times (t - t_o)}\right)$$

$$R(t,s) = \{\prod_{i=1}^{M} r^i(t,s)\}^{\frac{1}{M}}$$

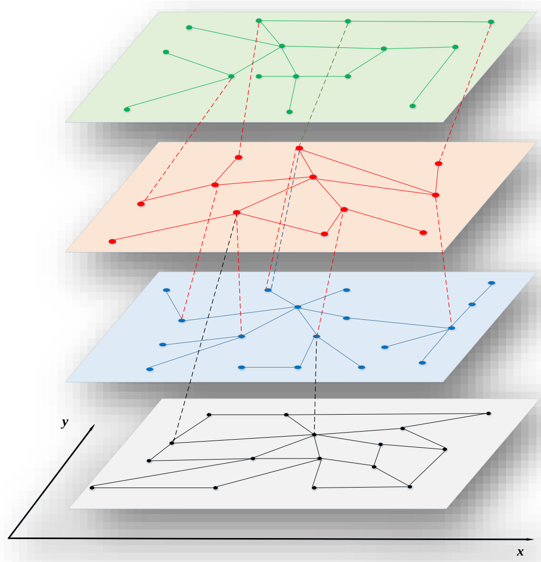
$$\frac{\partial R(t,s)}{\partial t} = \prod_i [AC^i(t,s) - P^i(t,s)]$$

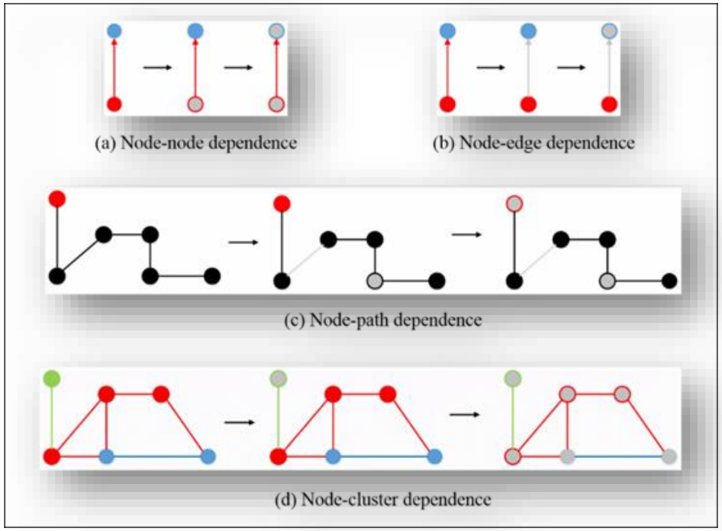
$$where\ t \in [t_0, t_r]$$



12 | QUANTITATIVE RESILIENCE

Urban infrastructure network system – single hazard





- Four layers:
  - **Streets**
  - **Water supply**
  - **Energy supply**
  - **Information**
- Nodes and edges (two states)
- Intra and interconnections
- Single and multiple disasters

- Five recovery strategies
  - First repair first failures
  - First repair last failures
  - First repair important components independently
  - First repair the obvious dependent elements
  - First repair the hidden dependent elements

QUANTITATIVE RESILIENCE

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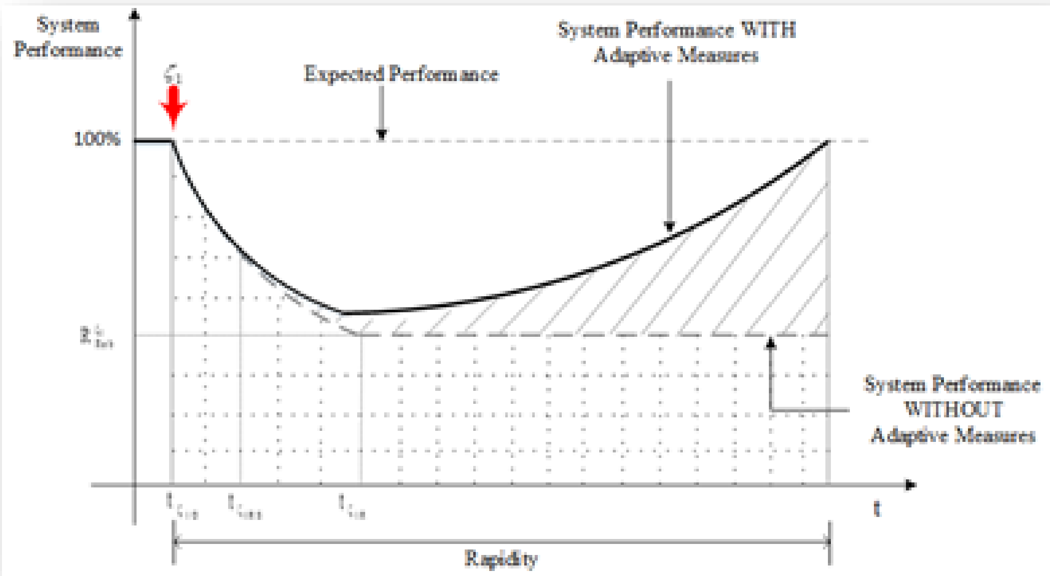


$$R^{\zeta_1}_{Rob}(t_{\zeta_{1RM}}) = \frac{\sum_{\phi}(n_o^{\phi}(t_{\zeta_{1RM}}) + e_o^{\phi}(t_{\zeta_{1RM}}))}{\sum_{\phi}(N^{\phi} + E^{\phi})}$$

$$R^{\zeta_1}_{Res}(t) = \int_{\phi} f\left(RS^{\phi,\zeta_1}(t)\right)$$

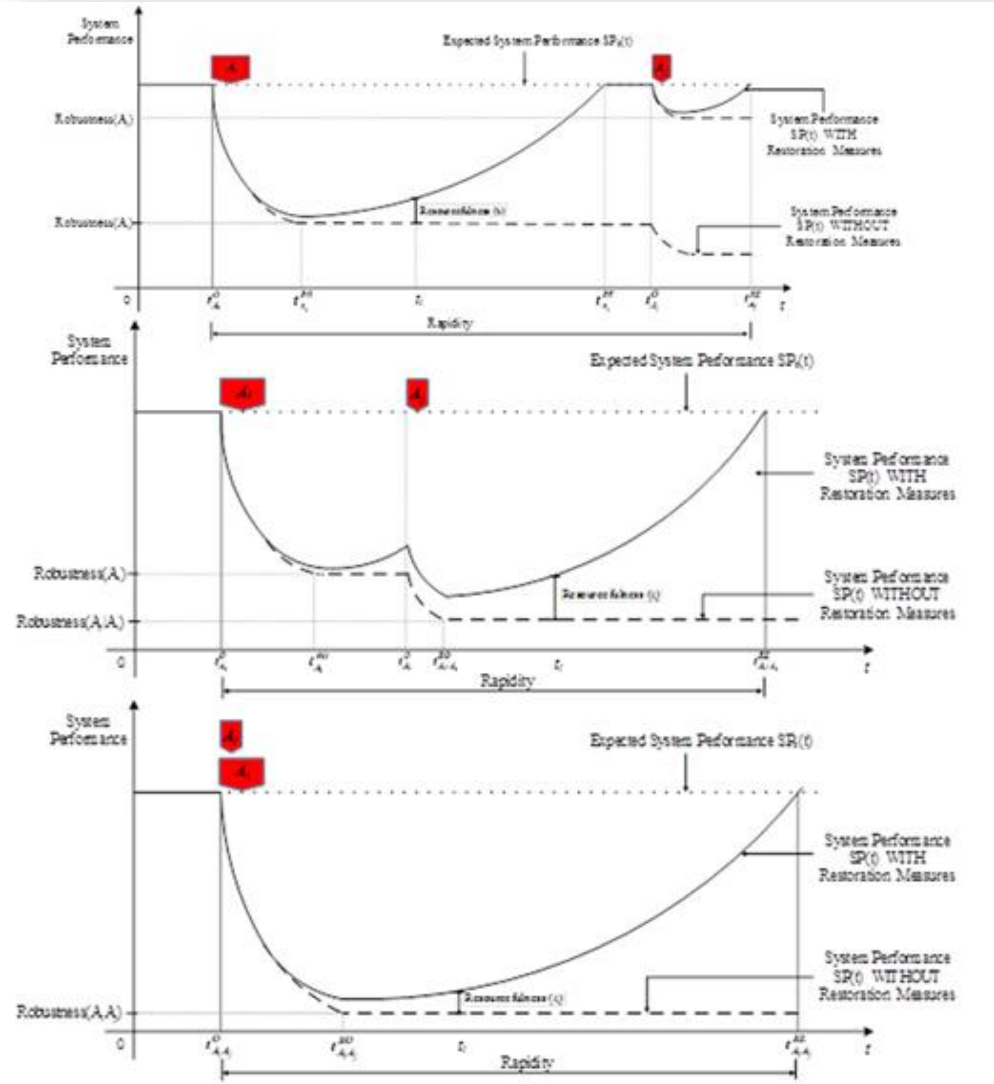
$$R^{\zeta_1}_{Rap} = \max\left\{R^{\phi,\zeta_1}_{Rap}(t)\right\}$$

$$r_{\phi}^{\zeta_1} = \rho_{PA}^{\phi,\zeta_1} + \rho_{RR}^{\phi,\zeta_1} = \frac{\int_{R_{Rap}^{\varphi,\zeta_1}} SP_0^{\phi,\zeta_1}(t)}{1 \times R_{Rap}^{\phi,\zeta_1}} + \frac{\int_{R_{Rap}^{\varphi,\zeta_1}} (R_{Res}^{\phi,\zeta_1}(t)\text{-}SP_0^{\phi,\zeta_1}(t))}{1 \times R_{Rap}^{\phi,\zeta_1}}$$

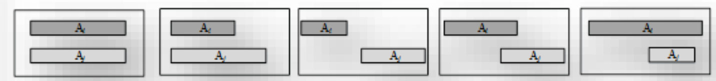
$$r^{\zeta_1} = \rho_{PA}^{\zeta_1} + \rho_{RR}^{\zeta_1} = \frac{\int_{\phi}\int_{R_{Rap}^{\varphi,\zeta_1}} SP_0^{\phi,\zeta_1}(t)}{1 \times R_{Rap}^{\zeta_1}} + \frac{\int_{\phi}\int_{R_{Rap}^{\varphi,\zeta_1}} (R_{Res}^{\phi,\zeta_1}(t)\text{-}SP_0^{\phi,\zeta_1}(t))}{1 \times R_{Rap}^{\zeta_1}}$$

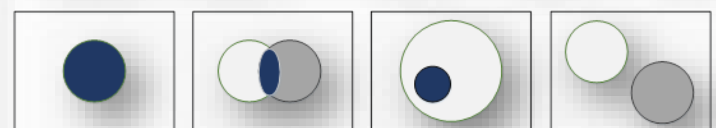
14 | QUANTITATIVE RESILIENCE

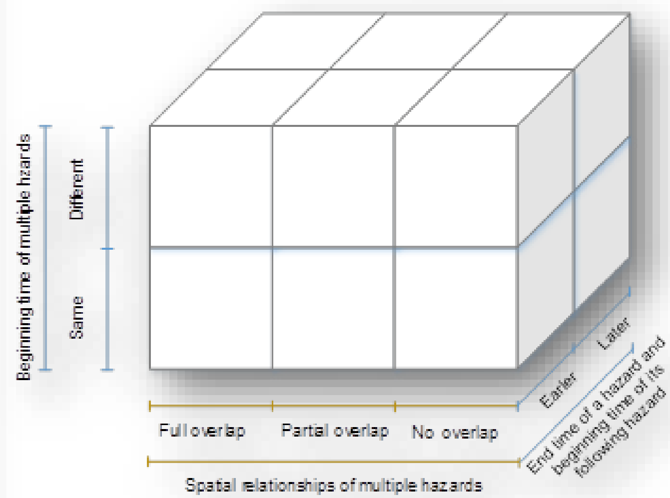
Urban infrastructure network system – two hazards



$$r_F^{A_1,\dots,A_m}(t)=\frac{\sum_{i=1}^{m}\int_{t_{A_i}^{0}}^{t_{A_i}}E\left(SP(t)\right)dt}{\int_{t_{A_1}^{0}}^{t}E\left(SP_0(t)\right)dt}=1-\frac{\sum_{i=1}^{m}\int_{t_{A_i}^{0}}^{t_{A_i}}E\left(SL(t)\right)dt}{\int_{t_{A_1}^{0}}^{t}E\left(SP_0(t)\right)dt}=1-\frac{\sum_{i=1}^{m}\int_{t_{A_i}^{0}}^{t_{A_i}}\frac{\sum_{u=1}^{N}P_u(t)I_u}{N}dt}{\int_{t_{A_1}^{0}}^{t}\frac{\sum_{u=1}^{N}P_u^{E}(t)I_u}{N}dt}$$

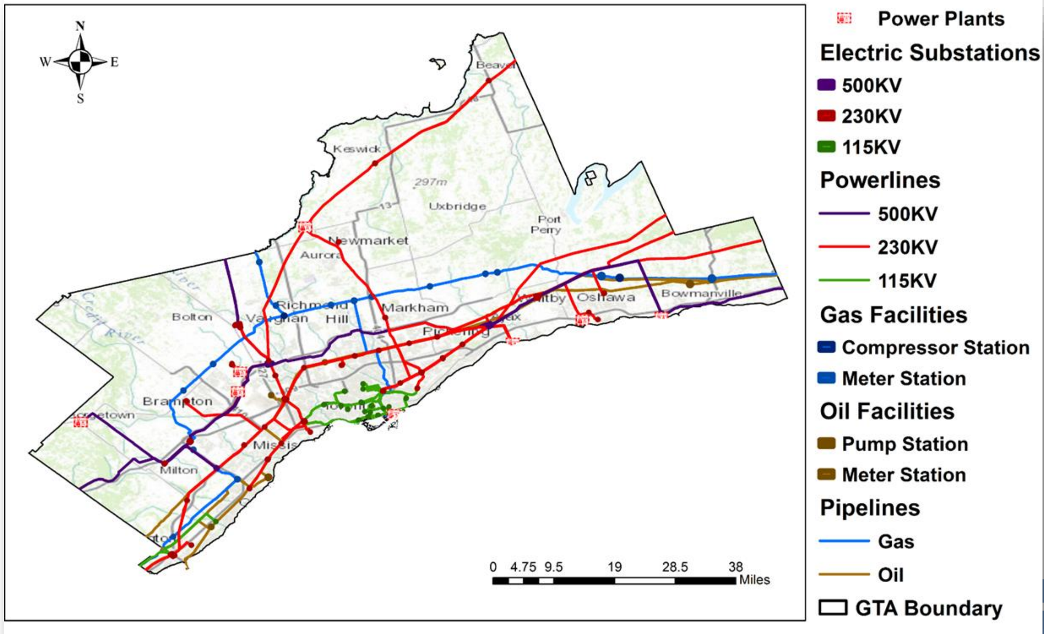






15 | QUANTITATIVE RESILIENCE – GTA CASE STUDY

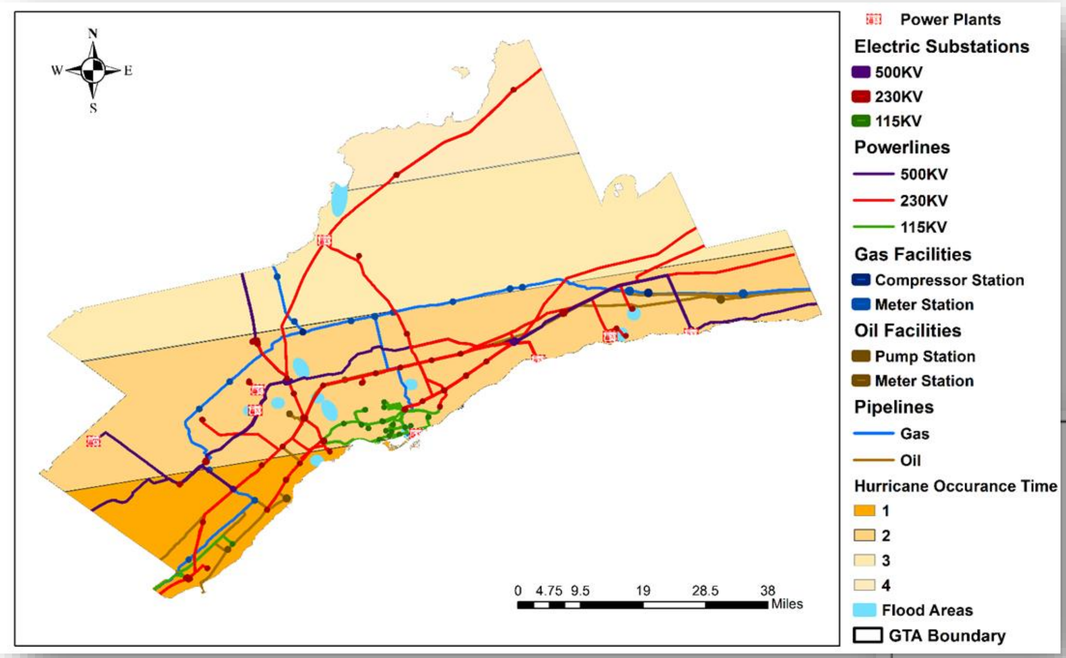
Urban infrastructure network system – two hazards

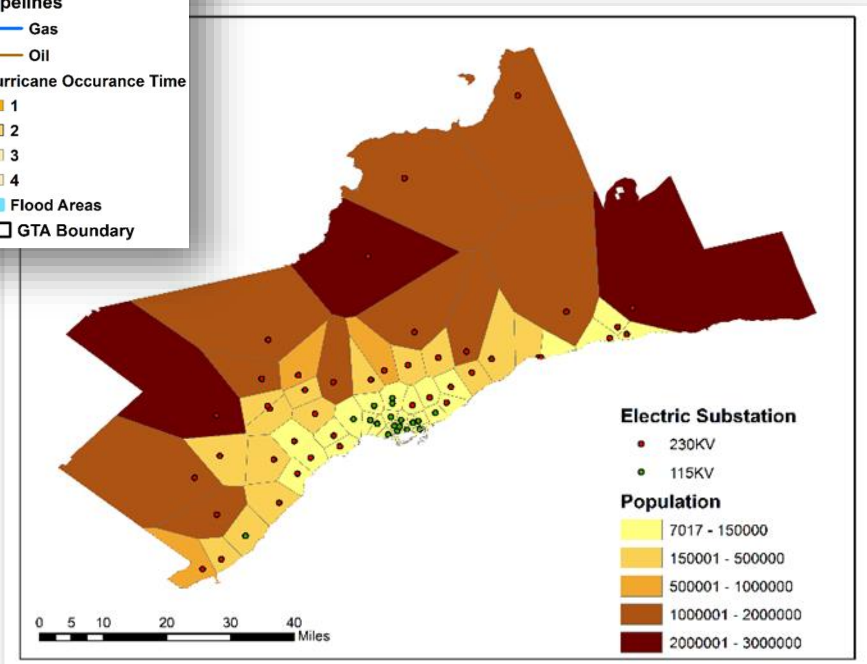


Infrastructure		Number
Electric Transmission Network		
Power Generation	Nuclear	2
	Gas -fired	6
Transmission Stations	500kv	4
	230kv	43
	115kv	26
Power line	500kv	13
	230kv	64
	115kv	30
Gas Transmission Network		
Compressor Stations		2
Meter Stations		15
Pipelines		22
Oil Transmission Network		
Pumping Stations		4
Meter Stations		1
Pipelines		6

16 | QUANTITATIVE RESILIENCE – GTA CASE STUDY

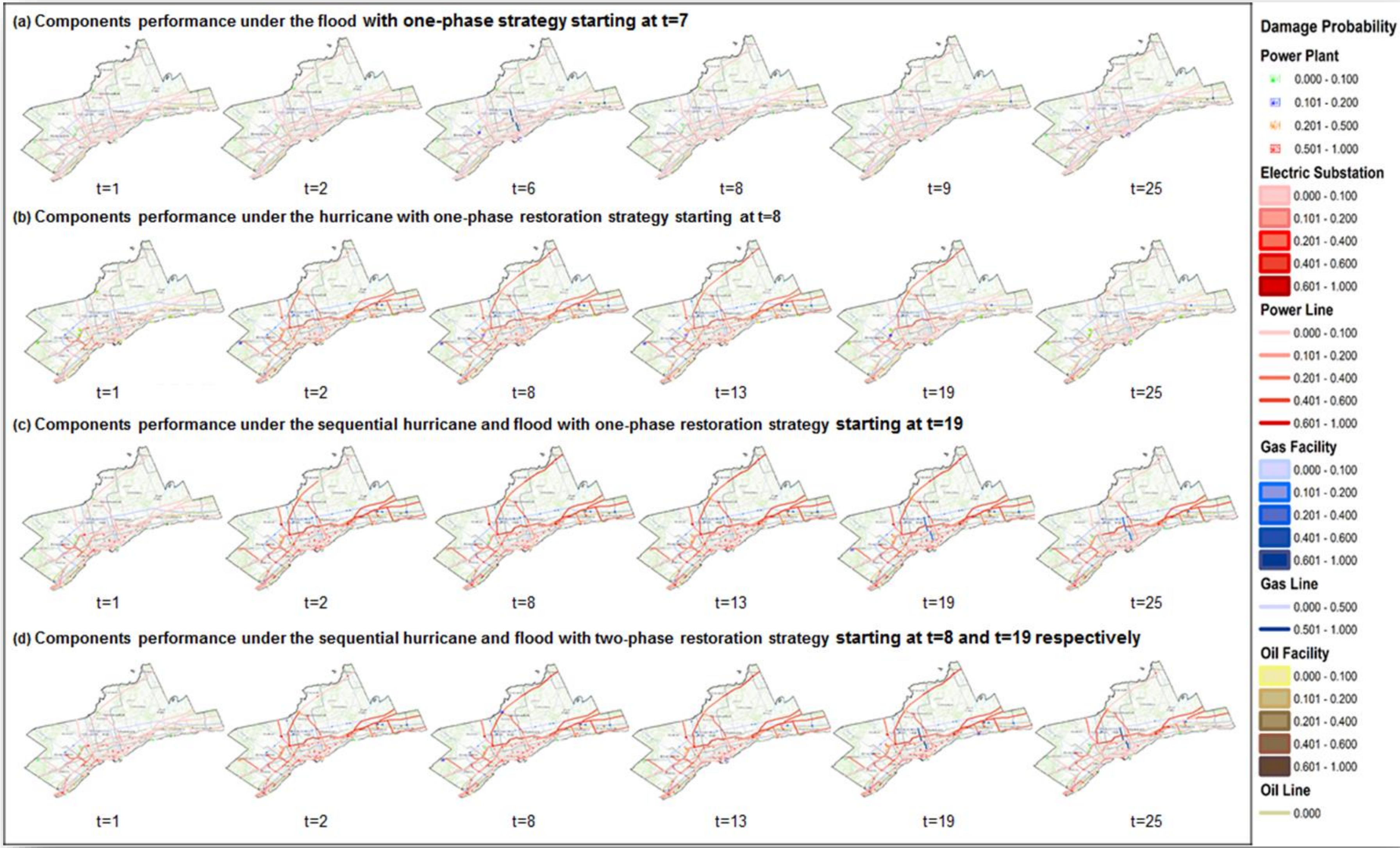
Urban infrastructure network system – two hazards





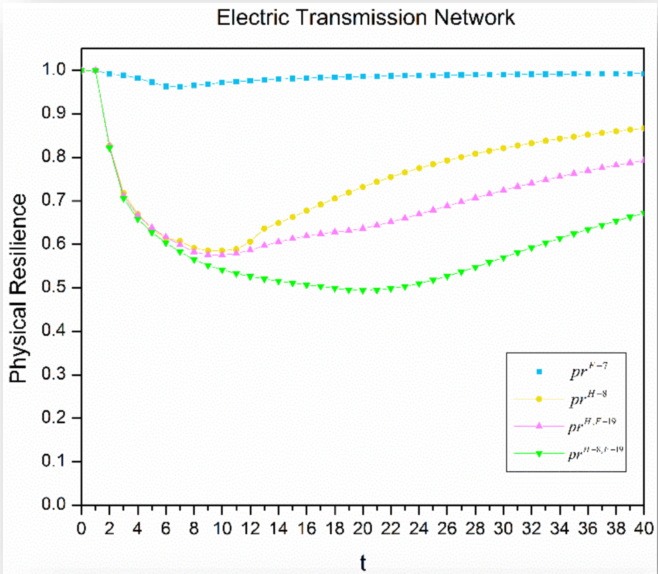
17 | QUANTITATIVE RESILIENCE – GTA CASE STUDY

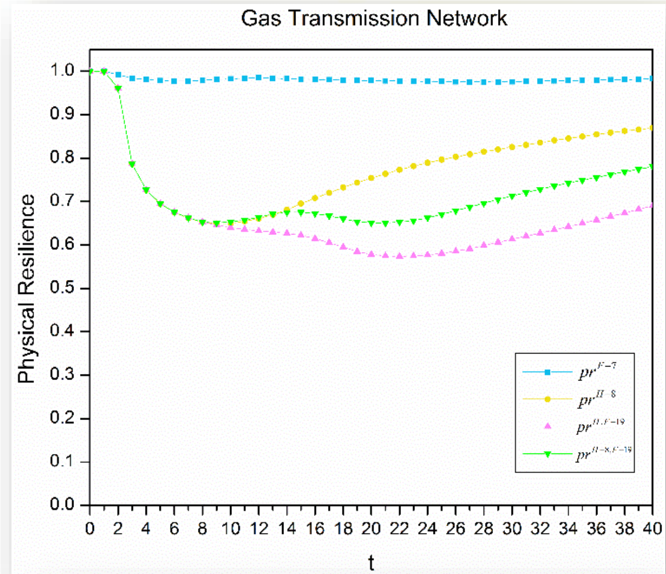
Urban infrastructure network system – two hazards

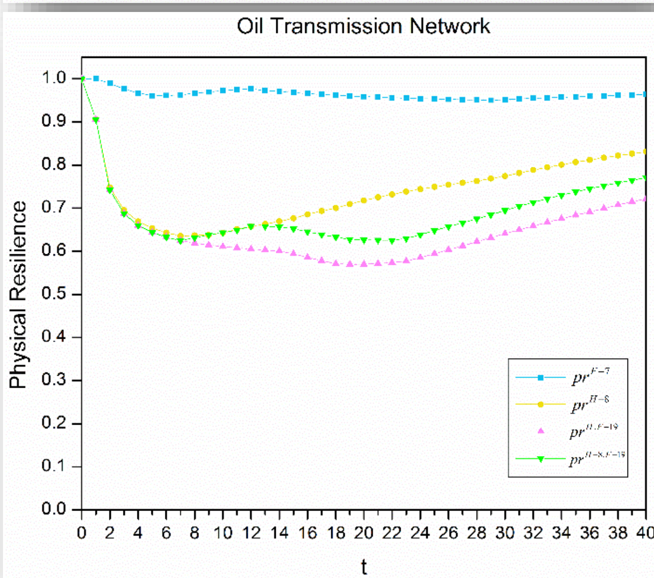


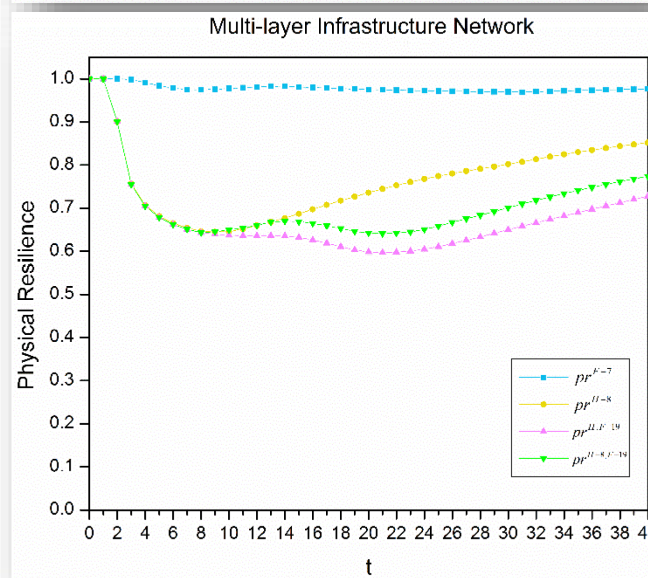
QUANTITATIVE RESILIENCE – GTA CASE STUDY

Urban infrastructure network system – two hazards



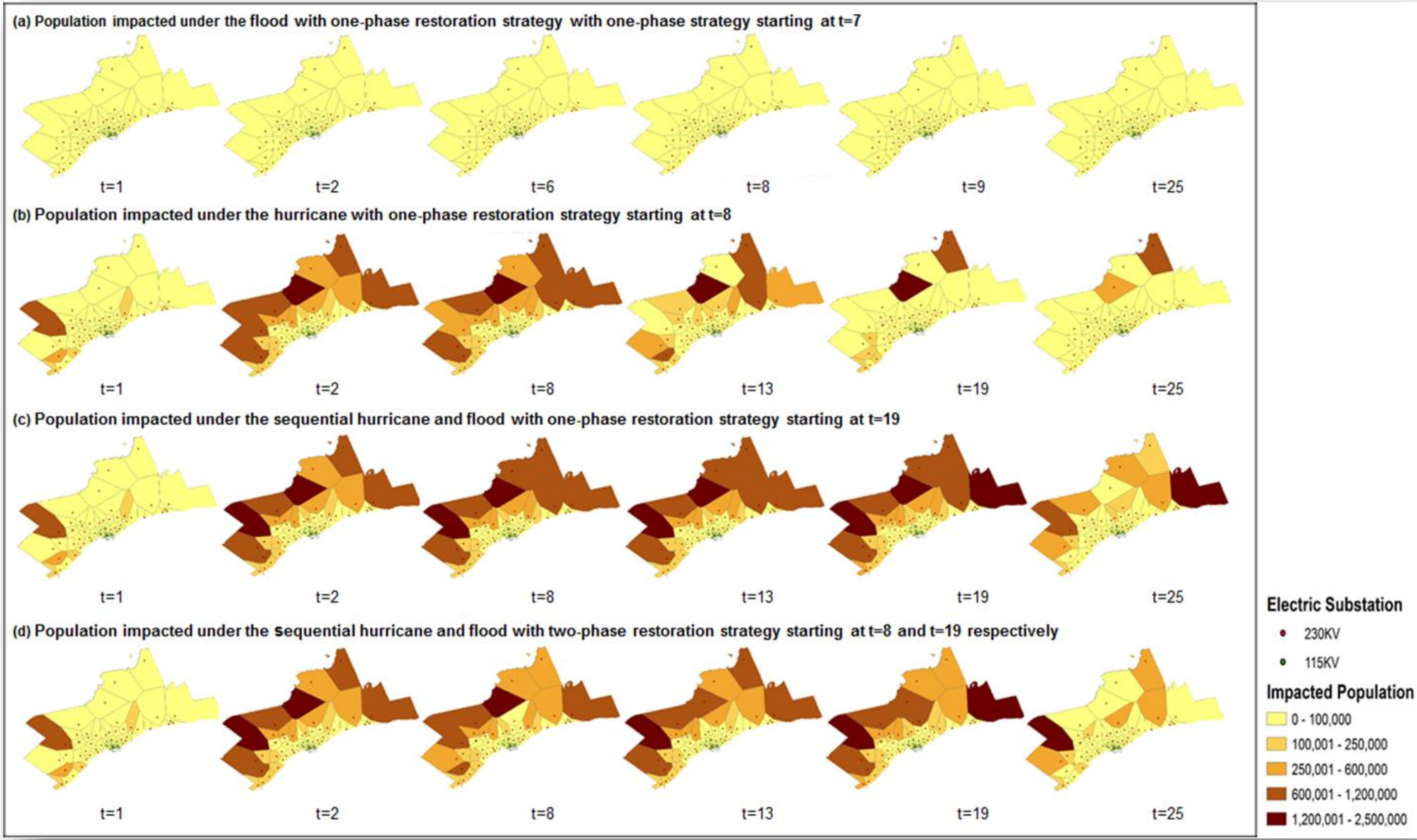






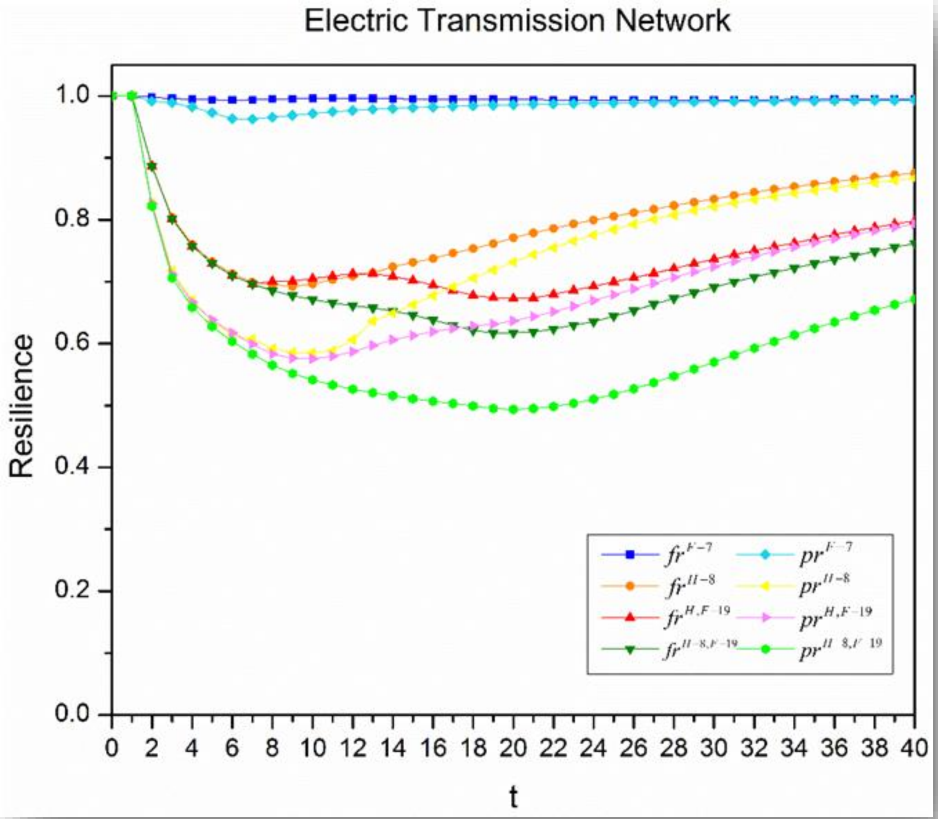
19 | QUANTITATIVE RESILIENCE – GTA CASE STUDY

Urban infrastructure network system – two hazards



QUANTITATIVE RESILIENCE – GTA CASE STUDY

Urban infrastructure network system – two hazards



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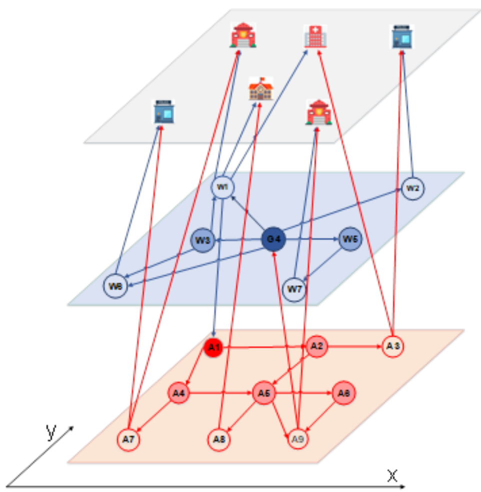
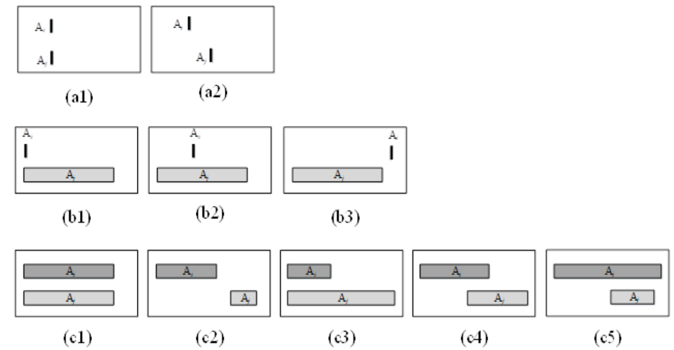
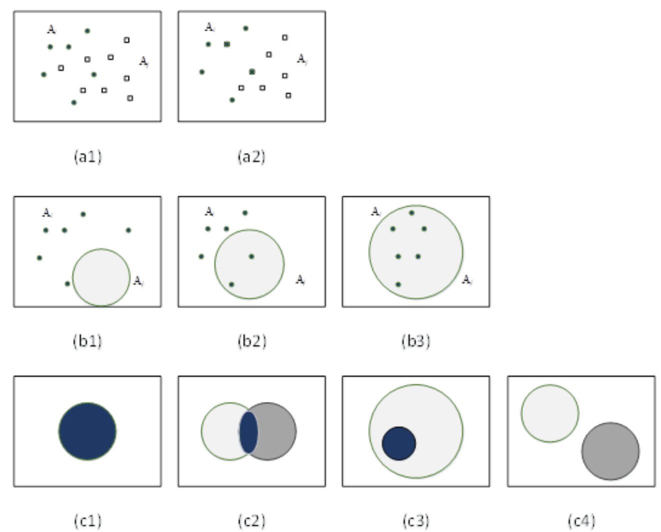
Towards general model – multiple hazard



- Network layers:
  - **Streets**
  - **Water supply**
  - **Energy supply**
  - **Information**
- Non-network infrastructure
  - **Critical facilities**



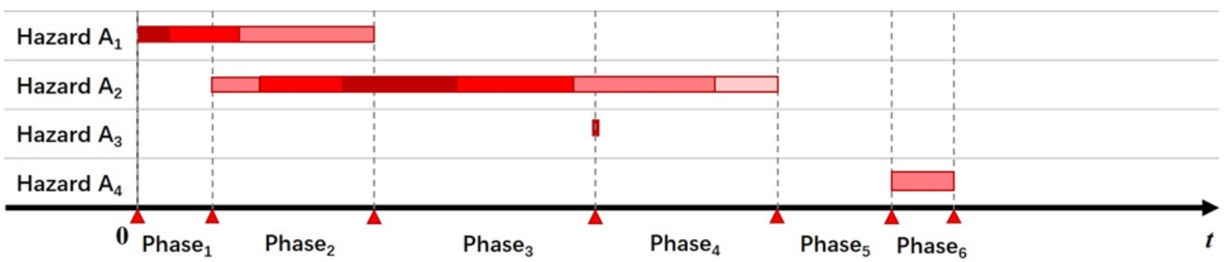
- Temporal relationships



- Spatial relationships

QUANTITATIVE RESILIENCE

Towards general model – multiple hazard



- Single hazard impacts:

$$DI_{IS}^{A_i}(t) = f(IS^K, L^{A_i}(t), S^{A_i}(t))$$

- Multiple hazard impacts during phase *j* at specific time:

$$TU_{P_j} = \min\{\min_l\{D_{A_i}^{LC_{l-1}^l}\}, \min_p D_{A_i}^{SC_{p-1}^p}, \min_K\{D_{FP}^K\}, \min_K\{D_{RD}^K\}, \min_K\{D_{RE}^K\}\}$$

$$D_{A_i}^{LC_{l-1}^l} = t_{A_i}^{LC_l} - t_{A_i}^{LC_{l-1}} \qquad D_{A_i}^{SC_{p-1}^p} = t_{A_i}^{SC_p} - t_{A_i}^{SC_{p-1}}$$

- State function equation of each component:

$$FS_{c_m^k}^{A_i}(t+1) = g(FS_{c_m^k}^{A_i}(t), DS_{c_m^k}^{A_i}(t), RE_{IS}^{A_i}(t))$$

- Physical and functional system performance:

$$SP_P^{A_i,k}(t) = \frac{\sum_m FS_{c_m^k}^{A_i}(t)}{\sum_m FS_{c_m^k}(t)} \qquad SP_F^{A_i,k}(t) = \frac{\sum_m POP_{c_m^k} FS_{c_m^k}^{A_i}(t)}{\sum_m POP_{c_m^k}}$$

- Robustness:

$$ROB_p^{A_i,k} = \min SP_p^{A_i,k}(t) \qquad ROB_F^{A_i,k} = \min SP_F^{A_i,k}(t)$$

- Redundancy:

$$RED^{A_i,k} = \underset{m}{mean}\{DB_{c_m^k}^{A_i}\}$$

- Resourcefulness:

$$RES^{A_i,k} = \underset{m}{mean}\{RS_{c_m^k}^{A_i}\}$$

- Rapidity:

$$RAP^{A_i,k} = t^{A_i,k} - t_{A_i}^o$$

- **Resilience:**

$$R_P^{A_i,k} = 1 - \frac{\int SP_P^{A_i,k}(t)}{\int SP_{P,0}^k} \qquad R_F^{A_i,k} = 1 - \frac{\int SP_F^{A_i,k}(t)}{\int SP_{F,0}^k}$$

23 | CONCLUSIONS

- Resilience as a new development paradigm:
  - practical link between adaptation to global change and sustainable development
- Systems approach needed for quantification of resilience
  - Understanding of local context of vulnerability and exposure is fundamental for increasing resilience
  - Consideration of time and space an integral part of quantification
  - Modelling single and multiple hazard conditions requires different modelling

RESOURCES

www.slobodansimonovic.com

1. Simonovic, S.P. (2016) “From risk management to quantitative disaster resilience: a paradigm shift”, *International Journal of Safety and Security Engineering,* 6(2):85-95.
2. Kong, J., and S.P. Simonovic, (2018) “A Model of Infrastructure System Resilience”, *International Journal of Safety and Security Engineering*, 8(3):377-389.
3. Kong, J., S.P. Simonovic, and C. Zhang (2018) “Sequential hazards resilience of interdependent infrastructure system: A case study of Greater Toronto Area energy infrastructure system”, *Risk Analysis*, 39(5)1141-1168, DOI: 10.1111/risa.13222.
4. Kong, J., and S.P. Simonovic, (2019) “Probabilistic multi hazard resilience model of interdependent infrastructure system”, *Risk Analysis*, 39(8):1843-1863, DOI: 10.1111/risa.13305 .

23 | OPPORTUNITY

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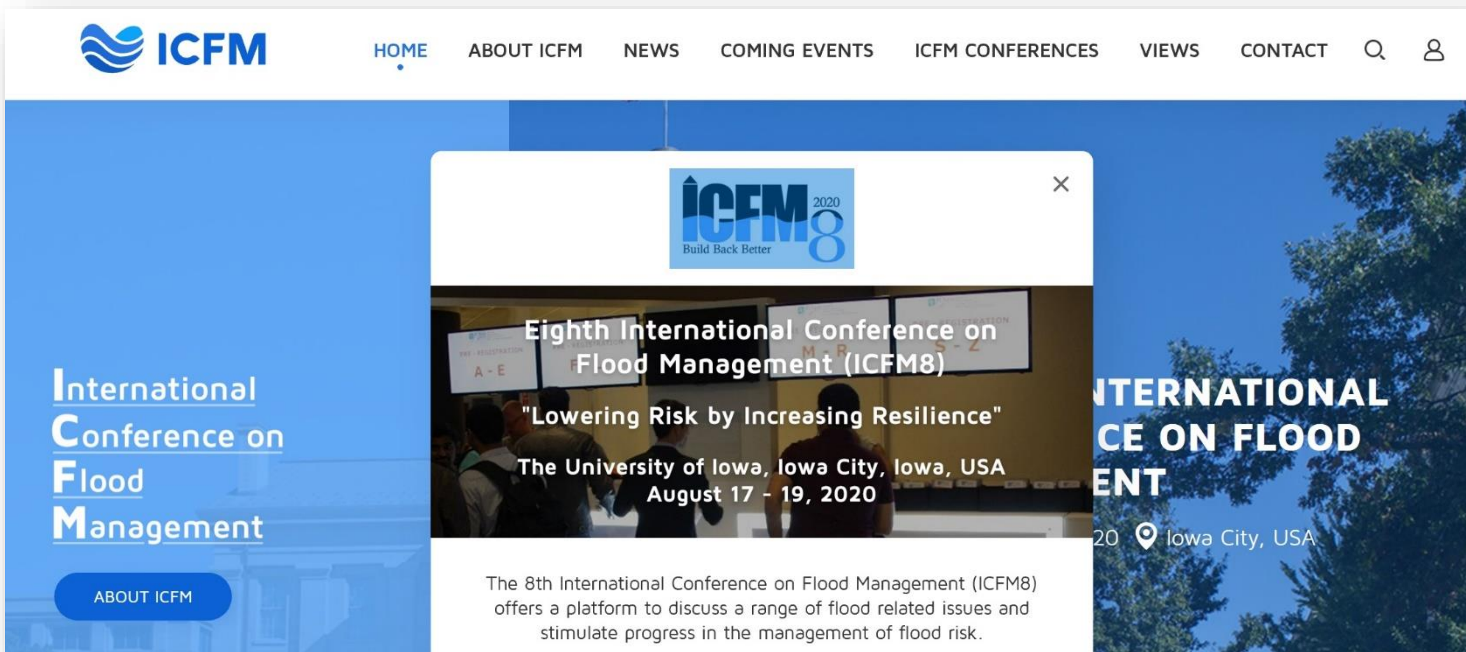

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Application of the Systems Approach to the Management of Complex Water Systems

Special Issue Editor

Prof. Dr. Slobodan P. Simonovic

University of Western Ontario, London, Canada

Email: simonovic@uwo.ca

Submission Deadline: 31 March 2020

This Special Issue offers an opportunity to review numerous applications of the systems approach to water resource management and draw lessons from worldwide experience relevant to the solution of future water problems.

Keywords

- Water resource management
- Systems analysis
- Sustainability
- Complexity
- Climate change
- Uncertainty
- Risk
- Resilience
- Decision support

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Building Resilient Communities
Pour construire des communautés solides

Q&A

Slobodan P. Simonović

Research facility

- Computer-based research laboratory
- Research:
  - *Subject Matter* - Systems modeling; Risk and reliability; Water resources and environmental systems analysis; Computer-based decision support systems development.
  - *Topical Area* - Reservoirs; Flood control; Hydropower energy; Operational hydrology; Climatic Change; Integrated water resources management.
- > 70 research projects
- Completed: 8 visiting fellows, 19 PosDoc, 22 PhD and 43 MESc
- Current: 2 PosDoc, 2 PhD, 2 MESc and 2 visiting scholars

FIDS
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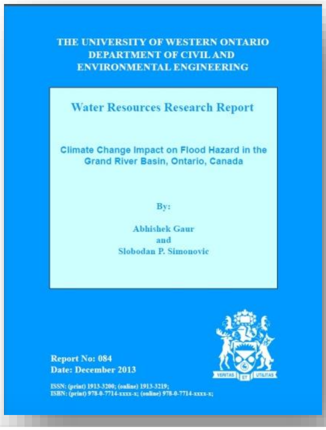
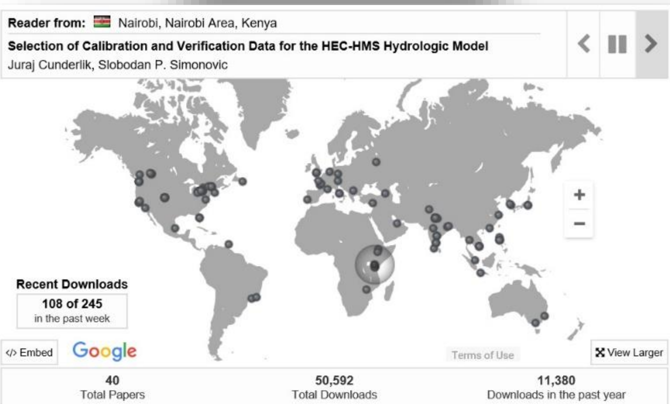
1989 - 2014

27 | Slobodan P. Simonović
Research results

- > 540 professional publications
- > 235 in peer reviewed journals
- 3 major textbooks

- Water Resources Research Reports 105 volumes
- > 75,000 downloads since 2011





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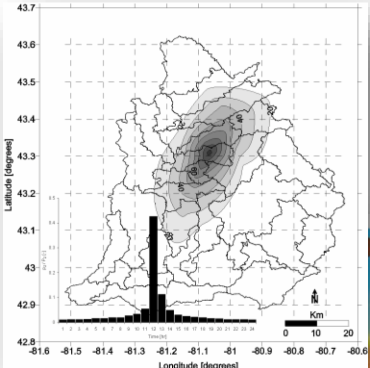
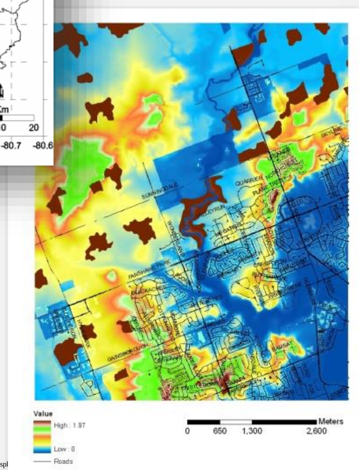
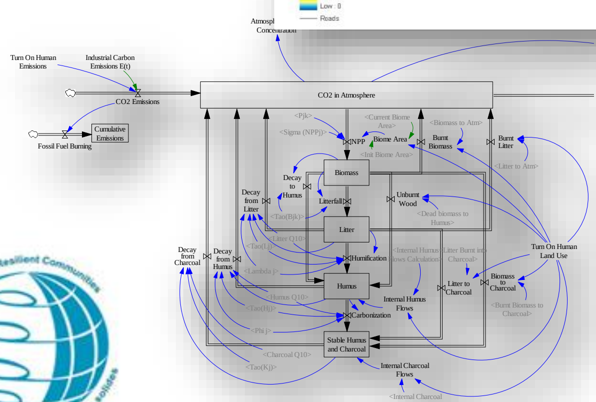
Current research projects







- Water Resources Management Capacity Building in the Context of Global Change
- Systems Engineering Approach to the Reliability of Complex Hydropower Infrastructure
- Linking Hazard, Exposure and Risk Across Multiple Hazards