

Prioritizing Water Distribution System Pipe Replacement Given Random Defects

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San Francisco Public Utilities Commission

Douglas York and Eugene Ling

San Francisco Public Works

THU07 Use of Risk in Pipeline Renewal Planning

8:30–11:00 a.m.

Room: Mandalay Bay Ballroom J

Track: Asset Management

Moderator: Paul Schumi

8:30 AWWA C900 PVC Water Main Pipe: 40 Years of Successful Service

Douglas Seargeant, Epcor Water Services, Inc.

9:00 SAWS Uses Finite Element and Remaining Useful Life Analysis to Defer \$40M Pipeline Replacement

Ashan McNealy, Pure Technologies, Inc. Andy Dettmer, Brian Ellis, Jennifer Steffans, Linda Bevis

9:30 Dallas Defers \$70M Capital Replacement of 84-inch PCCP Water Main Using Remaining Useful Life Analysis

Randall Payton, Dallas Water Utilities, Andy Dettmer, Johnny Partain, George Scaaf

10:00 Prioritizing Water Distribution System Pipe Replacement Given Random Defects

Charles Scawthorn, SPA Risk, LLC, Eugene Ling, David Myerson, Douglas York

10:30 Las Vegas Valley Water District Pipeline Risk Analysis

Roger Jordan, Las Vegas Valley Water District, Nass Diallo, Las Vegas Valley Water District, Laura Jacobsen



Larger Project's Team and Advisors



City and County of San Francisco Team:
Davis Myerson, Project Manager, SFPUC
Eugene Ling, Project Engineer, SFPW
Douglas York, Assistant Engineer, SFPW

Advisors



Jack Baker, Assoc. Prof., Stanford University
ground motions and uncertainty



Mike O'Rourke, Prof., Rensselaer Polytechnic Inst.
segmented pipe / permanent ground deformation



Tom O'Rourke, Prof., Cornell University
buried pipe / seismic shaking



Charles Scawthorn, Prof. (ret.), Kyoto University
system reliability, fire following earthquake, pipe vulnerability



Outline

- Project impetus
- Problem – how to identify which pipe to remediate so as to contribute most to system reliability?
- Solution - **PIPE Algorithm**
(Pipe Importance and Priority Evaluation)
- Application to San Francisco's AWSS system
- Results
- Summary



Project Impetus – fire following earthquake



Most Important Pipe Prioritization, Scawthorn

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Credit: T.D. O'Rourke, Cornell University



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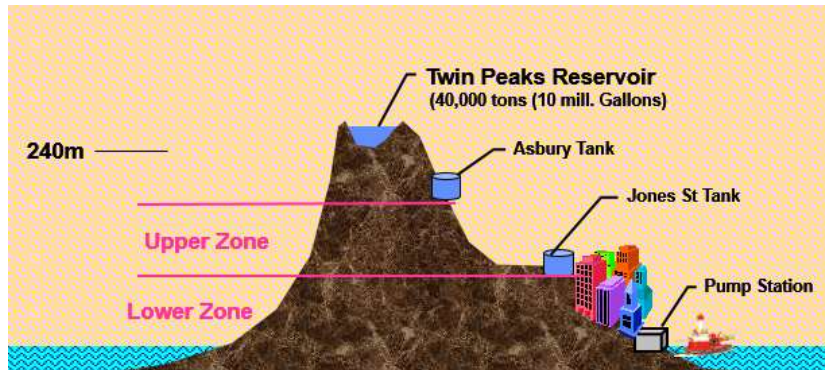
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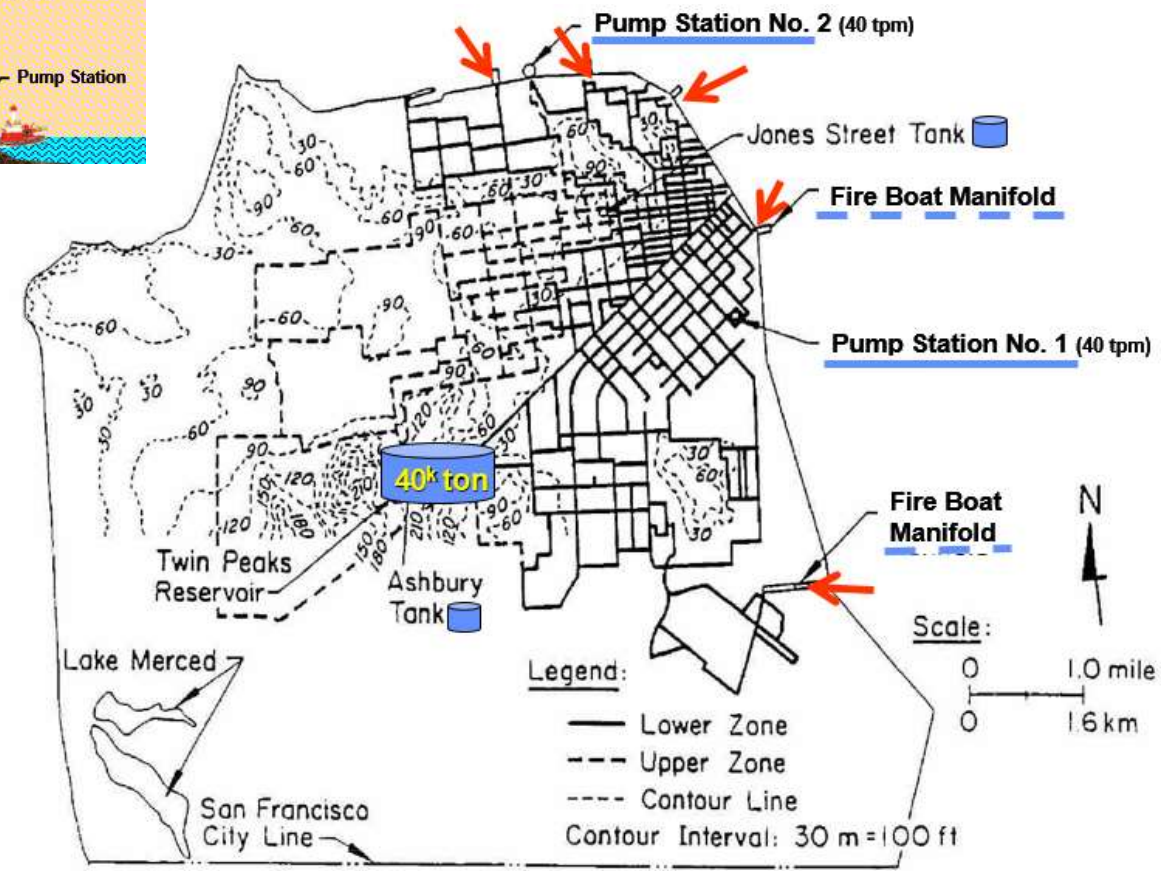
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San Francisco Auxiliary Water Supply System (AWSS)



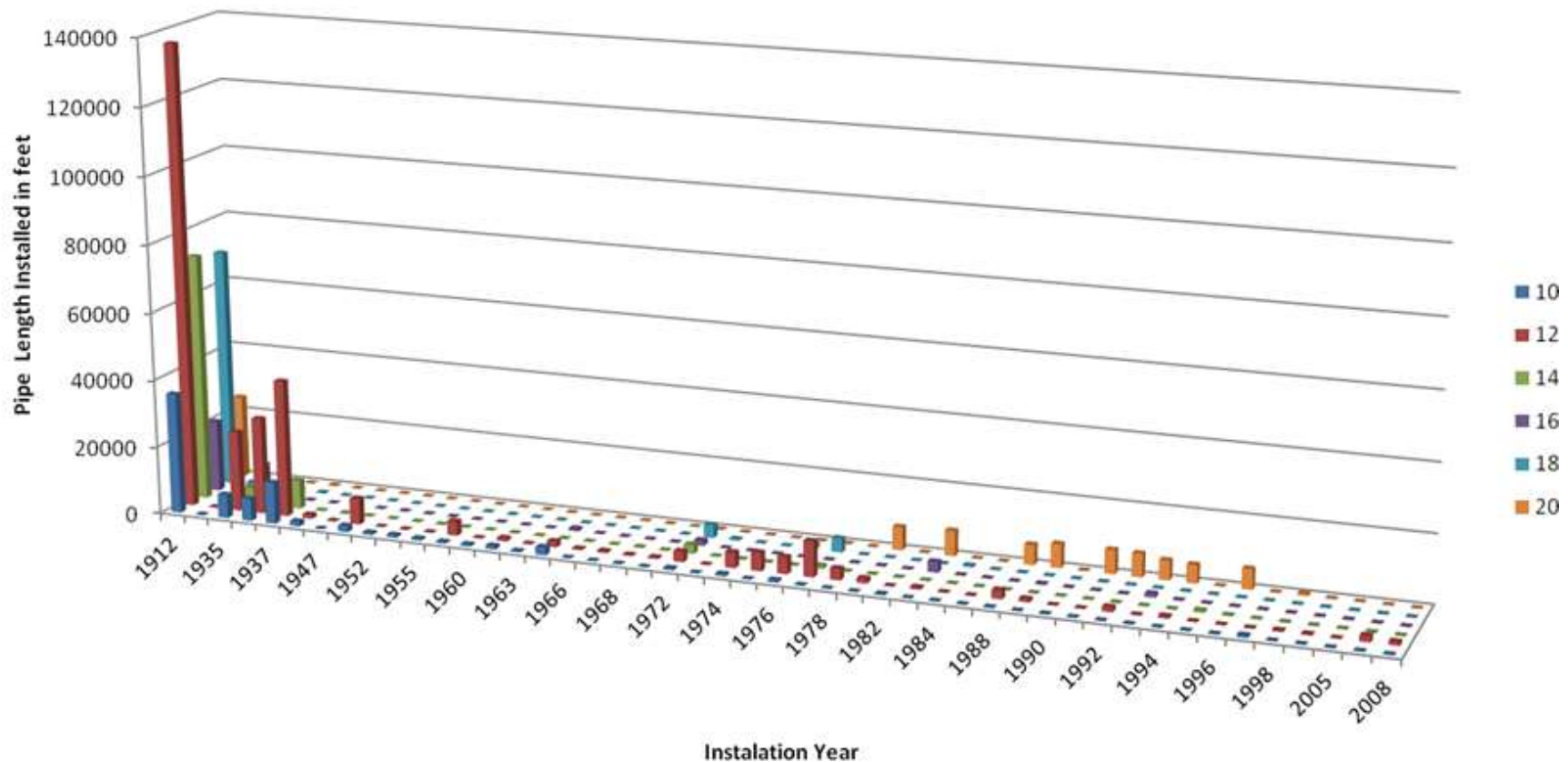
- 200 km. extra heavy wall pipe (mostly CI)
- 2 x 10,000 gpm (667 lps) pump stations
- Many other features...



Major pipe replacement need

AWSS pipeline network

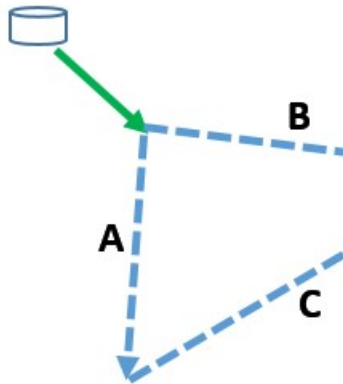
- Over 127 miles of 10" - 20" CIP & DIP Mains



Problem Statement

- AWSS pipe network > 130 miles, 60% from ~1912
- Aging, Infirm areas, possible corrosion...
→ Which to replace / abandon?
- In other words, *which pipes are the Most Important Pipes (MIP)?*
 - Meaning of *Important*?
 - Breaks most frequently?
 - Pipe that protects the greatest value?
 - Pipe that carries the most water?...
 - Determining MIP must consider many factors:
 - Hydraulics and place in the network (*e.g., source vs. deadend*)
 - Condition, age... (i.e., vulnerability)
 - Hazard (shaking, liquefaction...)
 - Size of likely fires

“most important pipe” problem – simplest case



p pipes

cases = 2^p

L*H largest diam
*H shortest path
*H most vuln

ch would you fix?

Cases	A	B
0	2889	475
1	0	557
2	3000	0
3	0	557
4	0	0
5	0	557
6	0	0
7	0	0

L (ft)	Diam (in)	vuln
3	8	
4	16	
5	32	
10	1024	
100	1.3E+30	
1000	1E+301	

fr(f) h1			
A	0.00005		
B	0.00050	0.010	0.10
C	0.00500	0.100	1.00

fix pipe	E(flow)
A	99.1%
B	99.2%
C	99.8%



Current approach

- Single pipe failure? Correct *but intuitively unsatisfying*
- Two pipe failures? Correct *if probability accounted for rigorously*
- N pipe failures? Very difficult
- Disaster → N pipe failures



Condition Assessment
and experiences v

Lowest

RISK

The
can

Issue:

- How to prioritize pipe replacement, accounting for multiple simultaneous failures, hydraulic connectivity....?
- (likelihood, consequence, or failure)

determining the
the probability can
performance and
ing, cost analysis,

American Water Works
Association
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Asset Management
Systems Guidebook
Version 1.0



American Water Works Association
Asset Management Committee
January 2018



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“Most Important Pipe” (MIP) problem

1. Atiquzzaman, M., Liong, S., & Yu, X. (2006). Alternative Decision Making in Water Distribution Network with NSGA-II. *JOURNAL OF WATER RESOURCES PLANNING AND MANAGEMENT*, 132(2), 2004–2008.
2. Al-Zahrani, M., & Syed, J. L. (2004). Hydraulic Reliability Analysis of Water Distribution System. *Journal of The Institution of Engineers*, 1(1). Journal Article.
3. Ang, W. K., & Jowitt, P. W. (2006). Solution for Water Distribution Systems under Pressure-Deficient Conditions. *Journal of Water Resources Planning and Management*, 132(3, June), 175–182.
4. Dasic, T., & Djordjevic, B. (n.d.). *Method for water distribution systems reliability analysis*.
5. Farmani, R., Walters, G. A., & Savic, D. A. (2005). Trade-off between Reliability and Cost in Water Distribution Networks. *JOURNAL OF WATER RESOURCES PLANNING AND MANAGEMENT*.
6. Fragiadakis, D. E., & Fragiadakis, D. E. (2005). Seismic risk analysis of urban water networks. *Earthquake Engng Struct. Dyn.*, 43, 357–374.
7. Fujivara, Y. (2005). Reliability analysis of water distribution networks in consideration of equity, redistribution, and pressure dependent demand. *WATER RESOURCES RESEARCH*, 34(7), 1843–1850.
8. Germanopoulos, G. (1986). Assessing the reliability of supply and level of service for water distribution systems. *Prof. Inst. Civil Engrs.*, 80(June), 413–428.
9. Gomes, J., & Karney, B. W. (2005). Water Distribution System Reliability under a Fire Flow Condition : In *Impacts of Global Climate Change* (pp. 1–12). EWRI.
10. Ozger, S. S. (1994). A SEMI-PRESSURE-DRIVEN APPROACH TO RELIABILITY ASSESSMENT OF WATER DISTRIBUTION NETWORKS, 1–8.
11. Schaetzen, W. de, Taylor, D., MacPherson, G., & Naiduwa, C. (2006). FIRE FLOW ANALYSIS FOR OPTIMAL NETWORK IMPROVEMENT. *8th Annual Water Distribution Systems Analysis Symposium*. Conference Paper, Cincinnati, Ohio, USA.
12. Schneiter, C. R., Haimes, Y. Y., Li, D., & Lambert, J. H. (1996). Capacity reliability of water distribution networks and optimum rehabilitation decision making Maintenance. *Water Resources Research*, 32(7), 2271–2278.
13. Torii, A. J., & Lopez, R. H. (2012). Reliability Analysis of Water Distribution Networks Using the Adaptive Response Surface Approach. *Journal of Hydraulic Engineering*, 138(March), 227–236
14. Wagner, B. J. M., Shamir, U., & Marks, D. H. (1988). WATER DISTRIBUTION RELIABILITY: ANALYTIC METHODS. *Journal of Water Resources Planning and Management*, 114(3).
15. Wagner, B. J. M., Shamir, U., & Marks, H. (1988). WATER DISTRIBUTION RELIABILITY: SIMULATION METHODS. *Journal of Water Resources Planning and Management*, 114(3), 276–294.
16. Wang, Y., Au, S.-K., & Fu, Q. (2010). Seismic Risk Assessment and Mitigation of Water Supply Systems. *Earthquake Spectra*, 26(1), 257–274.
17. Wu, Y., Xu, Y., Tan, Y., & Chen, J. (2010). Hydraulic State Estimation of Post-Earthquake Water Distribution Systems. *Water Distribution System Analysis 2010*. Conference Paper, Tucson, AZ.

Long history – unsolved until this Assessment

Solution: PIPE Algorithm

Pipe Importance and Priority Evaluation (PIPE) Algorithm

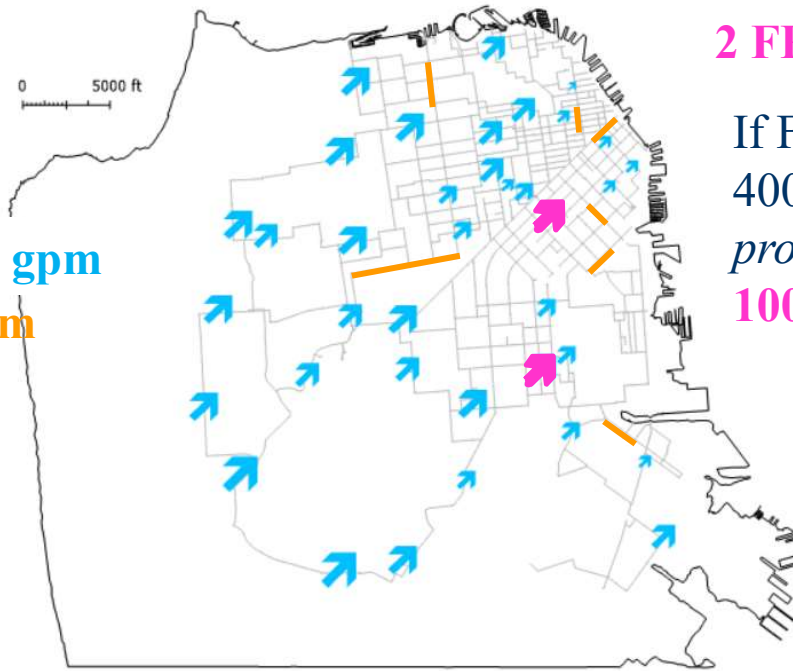
1. Monte Carlo simulation (Python wrapper on EPANET, adapted to do Pressure-driven hydraulic analysis (PDA, (considers multiple simultaneous pipe breaks and leaks given pipe vulnerabilities, PGV and PGD))
2. Regression analysis → *Average Deficit Contribution (ADC)*
3. *ADC* = each pipes' average contribution to flow deficit
(all simulations, considering FRA demands, hydraulics and breaks)
4. Rank pipes by *ADC* → highest *ADC* is “most important pipe”
(this pipe has the highest contribution to average deficit in demand)

PIPE Algorithm

EXAMPLE

Total Demand: 63,989 gpm

Leakage: 25,000 gpm



2 FRAs don't get required fire flow

If FRA 1 required fire flow = 4000 gpm and AWSS can only provide 3000 gpm → deficit = 1000 gpm

FRA 2: 3000 – 2500
→ deficit = 500 gpm

Sum all deficits = 1500 → to be minimized

N simulations:



Deficit j

1500
2657
1387
4231
...

=

FR = Leakage in pipe i of simulation j

124	142	32	86	0	324	0 ...
0	345	0	0	0	487	0 ...
23	0	0	0	432	0	0...
....						

Weights i

w1
w2
w3
...



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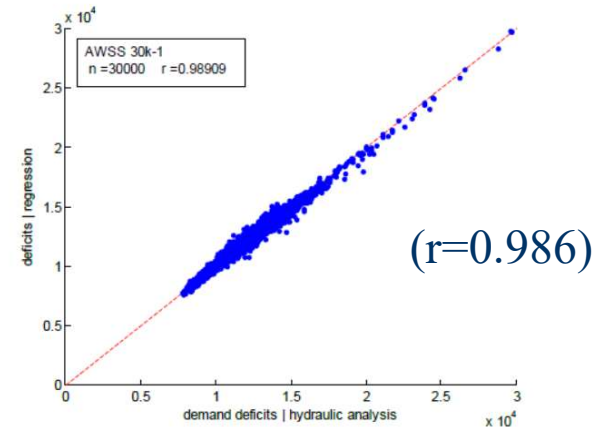
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PIPE Algorithm (cont.)

Solve for weights w_i

Weights accurately model system



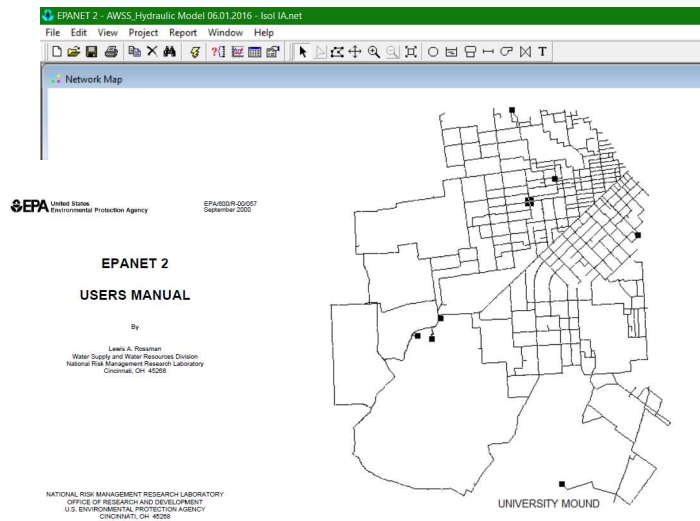
$$\begin{array}{c} \text{Deficit } j \\ \left| \begin{array}{c} 1500 \\ 2657 \\ 1387 \\ 4231 \\ \dots \end{array} \right| \\ \end{array} = \begin{array}{c} \text{FR = Leakage in pipe } i \text{ of simulation } j \\ \left| \begin{array}{ccccccccc} 124 & 142 & 32 & 86 & 0 & 324 & 0 & \dots \\ 0 & 345 & 0 & 0 & 0 & 487 & 0 & \dots \\ 23 & 0 & 0 & 0 & 0 & 432 & 0 & 0\dots \\ & & & & & & & \dots \\ & & & & & & & \dots \end{array} \right| \\ \begin{array}{c} \sum FR_1 \\ \sum FR_2 \\ \dots \end{array} \end{array} \begin{array}{c} \text{Weights } i \\ \left| \begin{array}{c} w1 \\ w2 \\ w3 \\ \dots \end{array} \right| \\ \end{array}$$

→ Pipe i 's Average Deficit Contribution =

$$ADC_i = \left(\sum_{j=1 \dots N} FR(i, j) \right) \frac{w_i}{N}$$



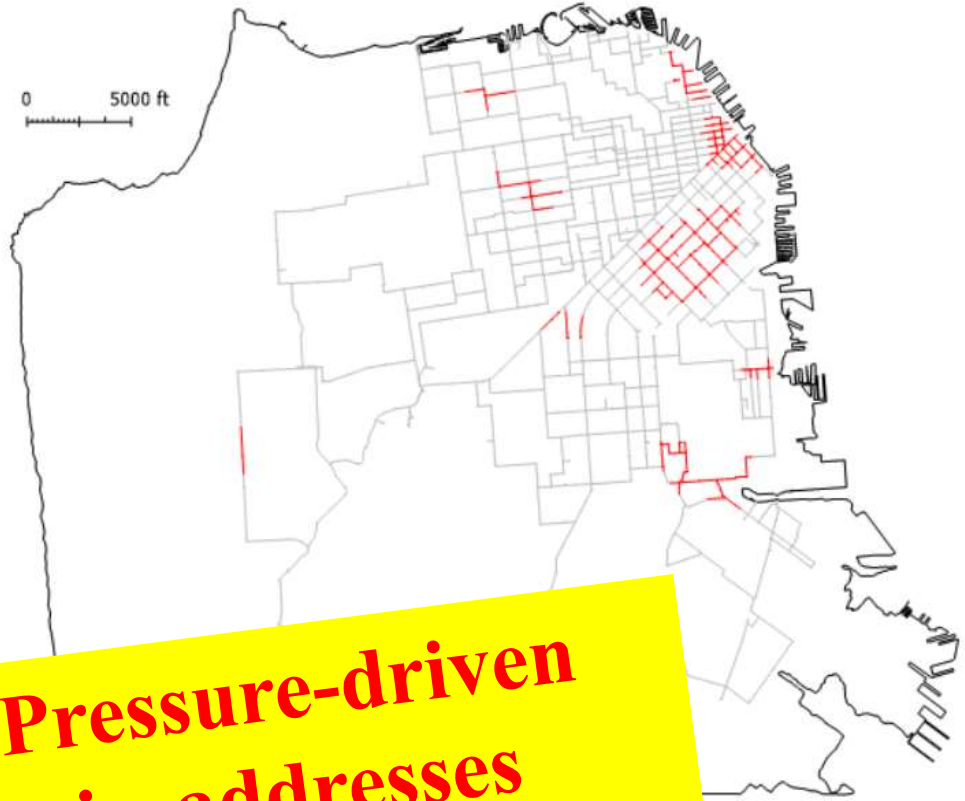
Analysis Tools



EPANET: very fast hydraulic analysis

*(general, not seismic,
demand driven,
cannot account for
negative pressures ...)*

**Need: Pressure-driven
analysis, addresses
reliability, identifies MIP**

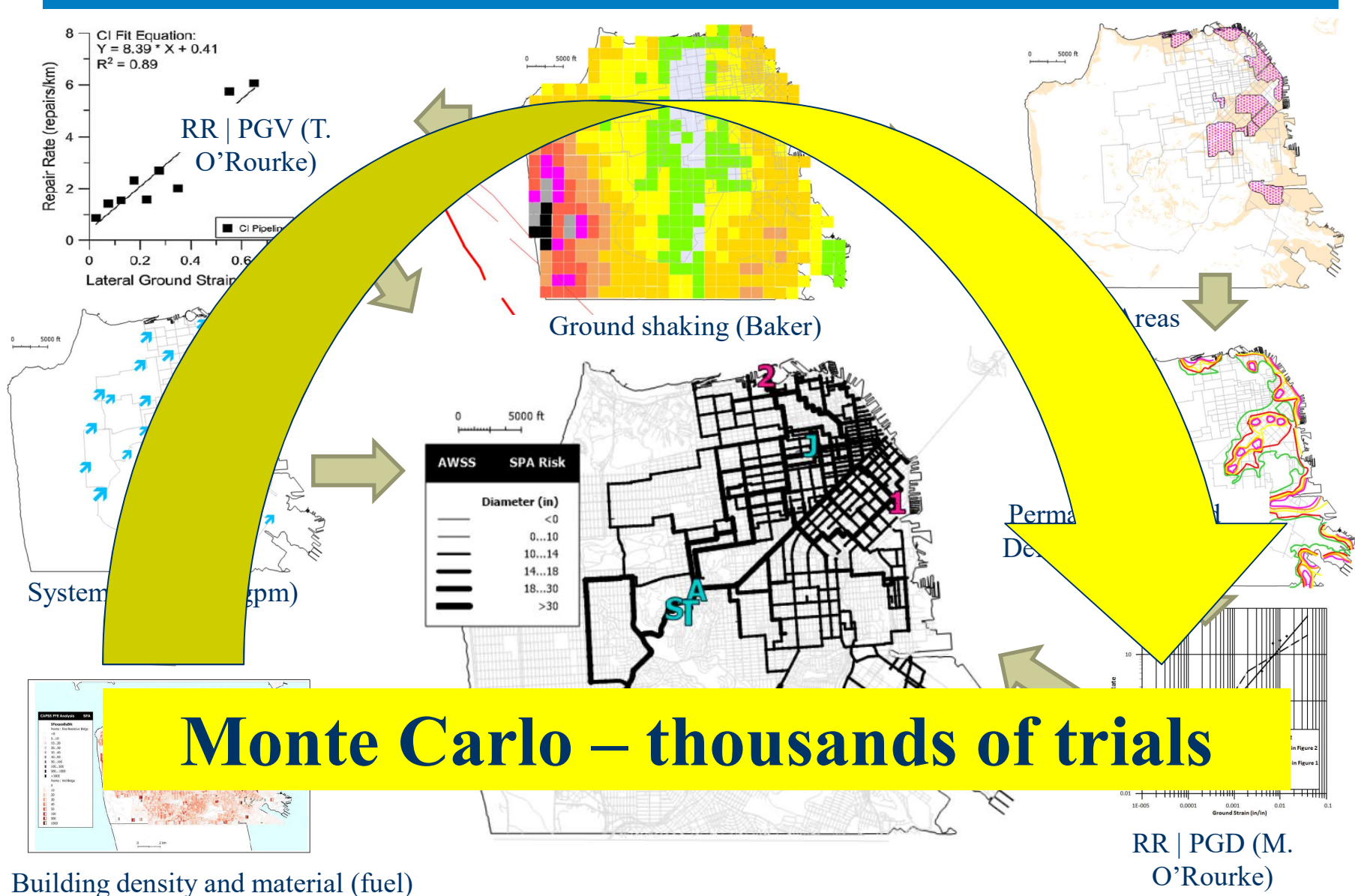


PIPE Algorithm (Summary)

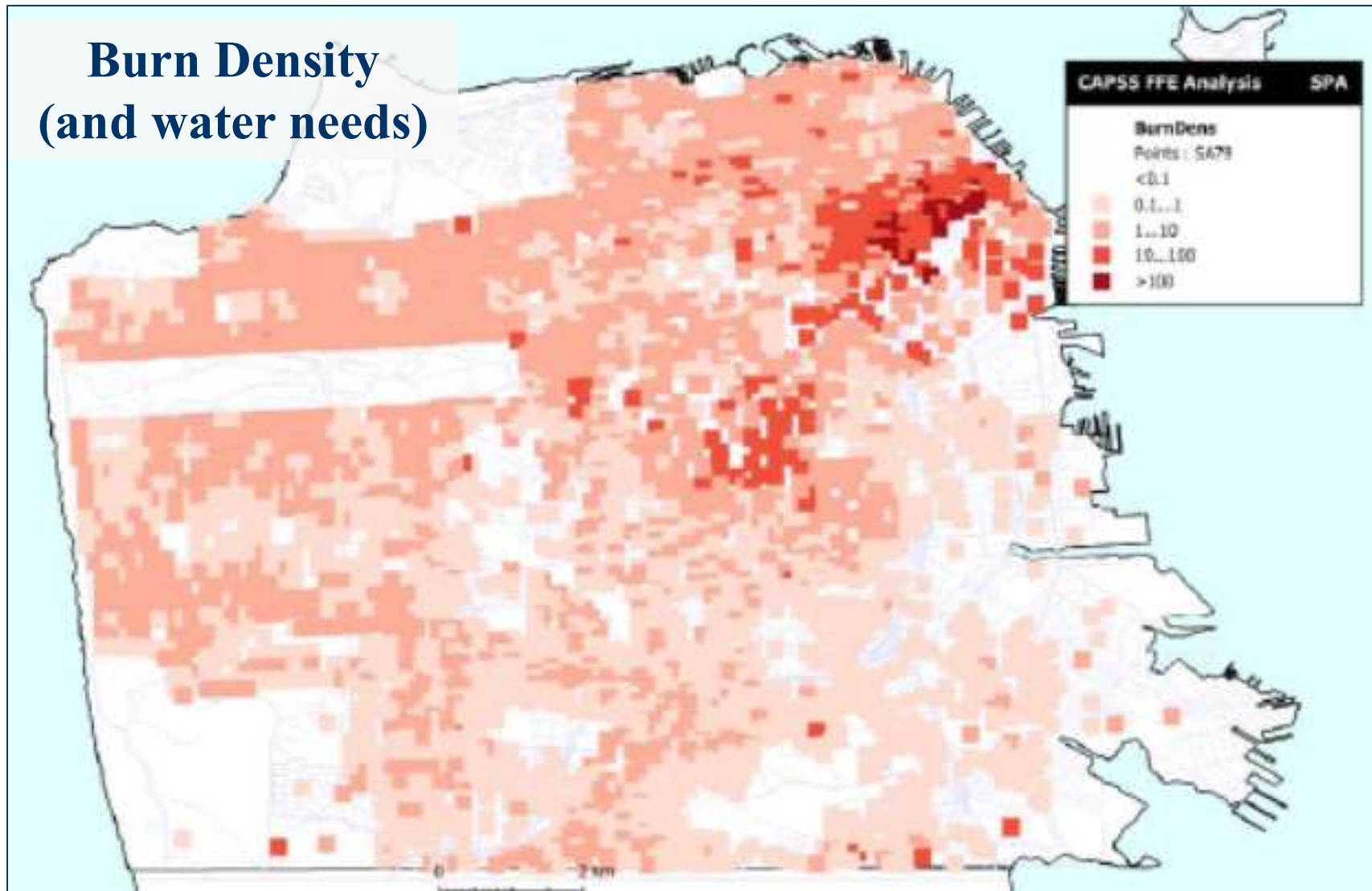
1. *ADC* is calculated for all pipes
2. Pipes are ranked in descending *ADC* order.
3. The ranking is the relative importance of each pipes' contribution to the average of deficits for all simulations.
4. The pipe with highest *ADC* is the pipe that contributes most to the demand's deficit, 2nd highest ranked pipe contributes next most, and so on.
5. If the highest ranked pipe is mitigated, that mitigation contributes most to overall average deficit reduction, and so on.
6. The approach incorporates:
 - *Ground motion → Damage*
 - *Monte Carlo simulation (i.e., uncertainty)*
 - *Pressure-driven hydraulic modeling (no negative pressures)*
 - *PIPE algorithm identifies “most important pipe”*
7. The approach is:
 - *Accurate*
 - *State-of-the-art / New (i.e., not done before)*
 - *Published ASCE Pipeline Conference...to be submitted for journal*



Steps in the analysis

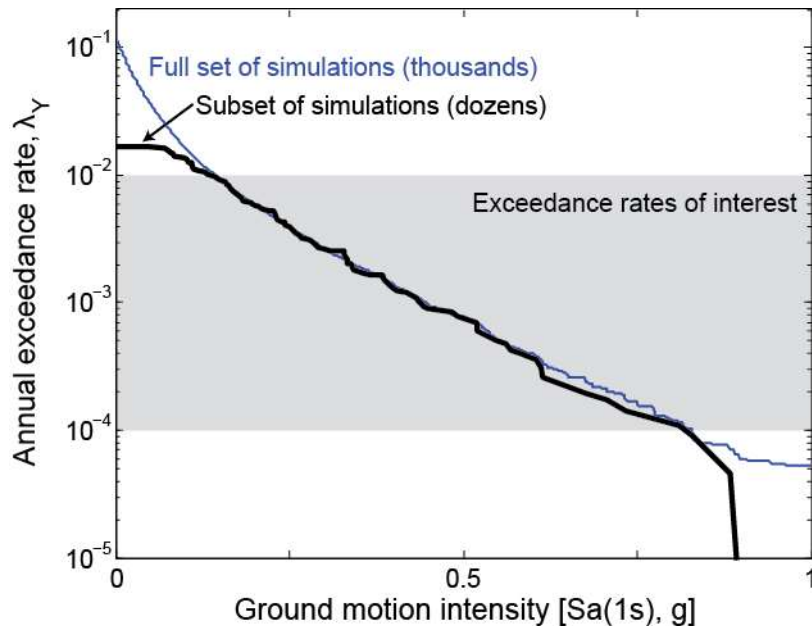


Application to AWSS – fire following earthquake demands

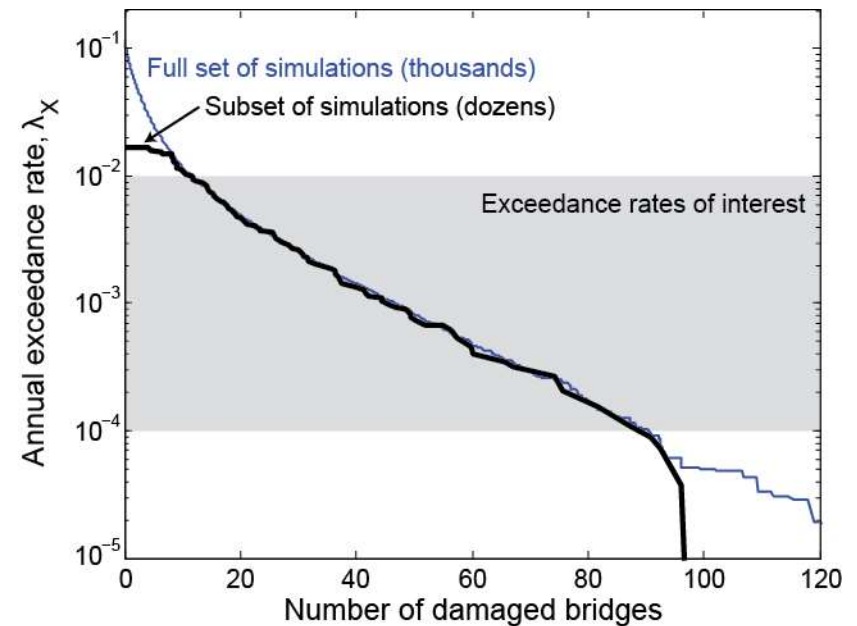


Ground motions considering uncertainty

Ground motion hazard at a site



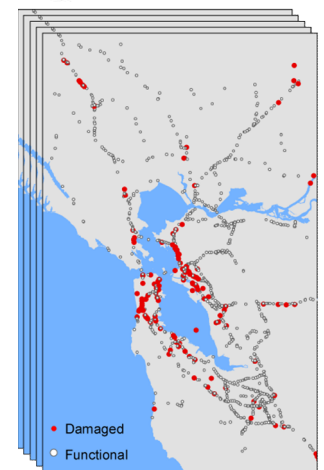
Proxy performance metric hazard



Select a subset of maps and reweight, to reproduce ground motion hazard at multiple sights and a proxy performance metric

Miller and Baker (2015). "Ground-motion intensity and damage map selection for probabilistic infrastructure network risk assessment using optimization."

EQ Engineering & Structural Dynamics, 44(7), 1139–1156.



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Stanford ground motion simulation approach

60,000 simulations
(all events)



91 simulations
(all events)



15 EQ Scenarios

For a given rupture scenario (e.g., M7.9 San Andreas):

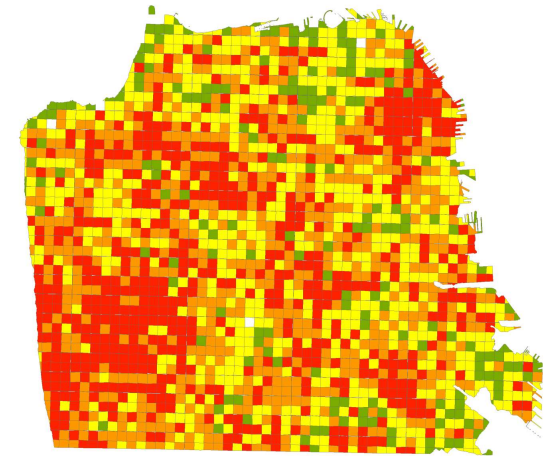
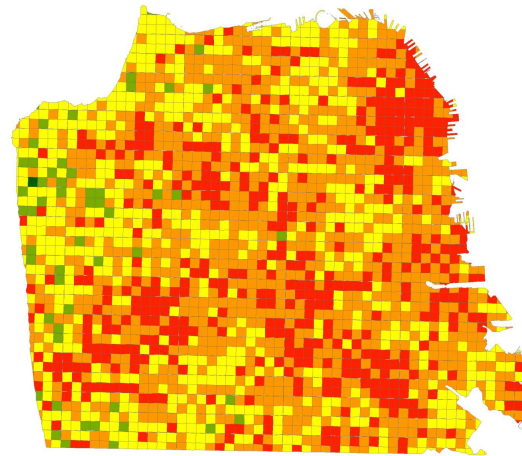
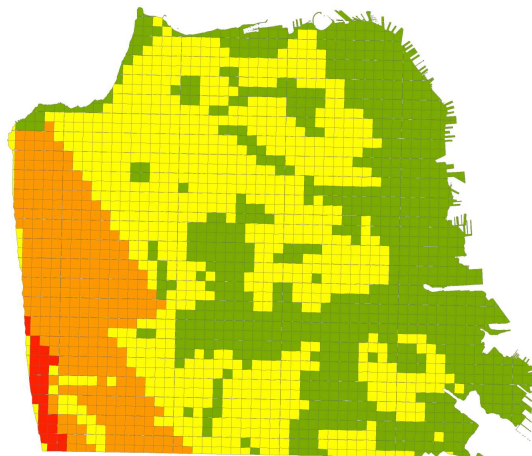
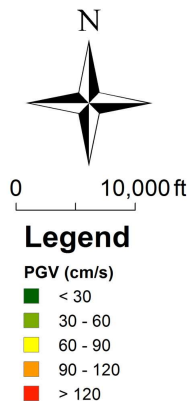
Median prediction

+

Spatially correlated
“residual”

=

Total ground
motion amplitude



Residuals are empirically calibrated from past earthquakes and account for ground motion variability

Miller and Baker (2015). “Ground-motion intensity and damage map selection for probabilistic infrastructure network risk assessment using optimization.” *EQ Engineering & Structural Dynamics*, 44(7), 1139–1156.



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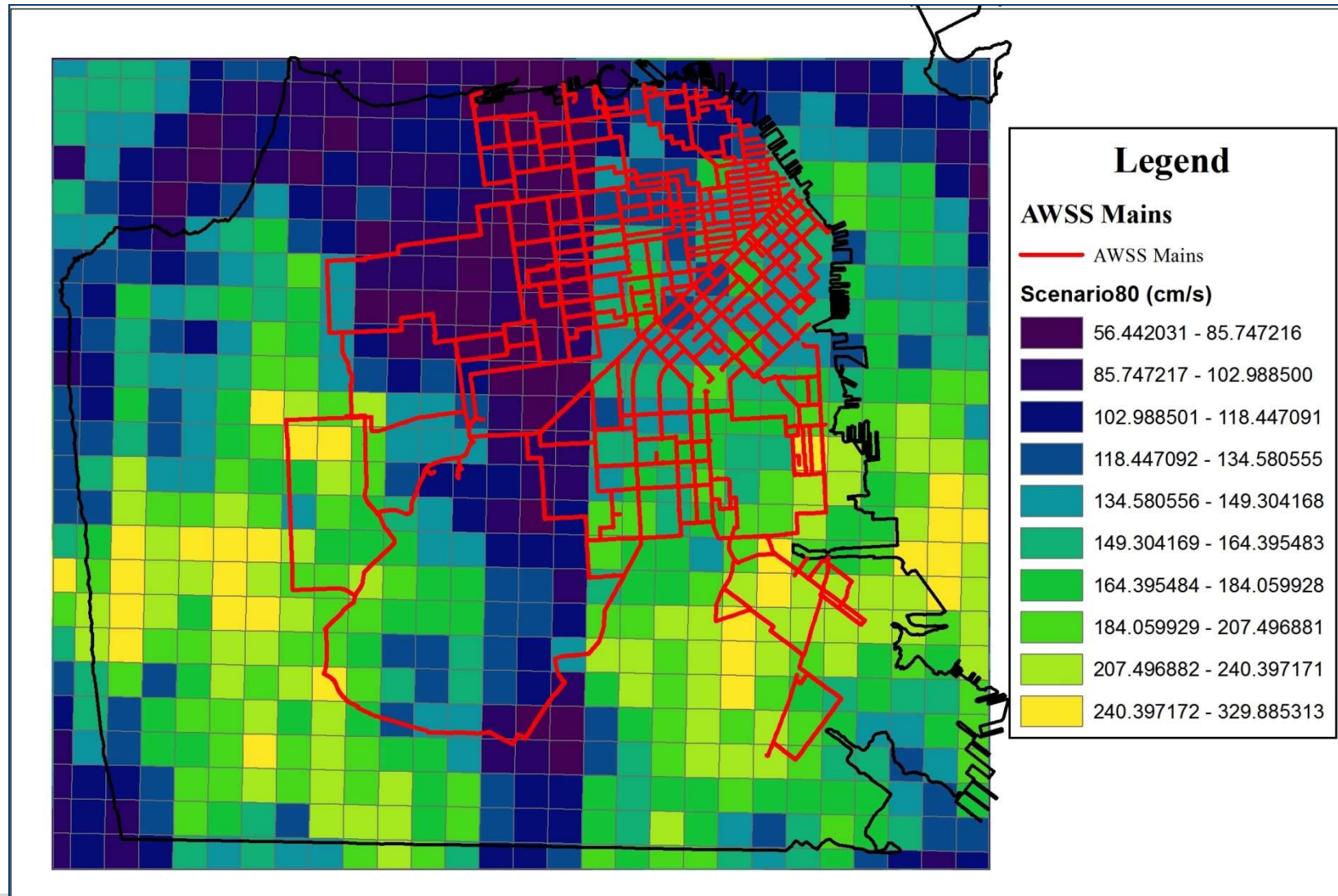
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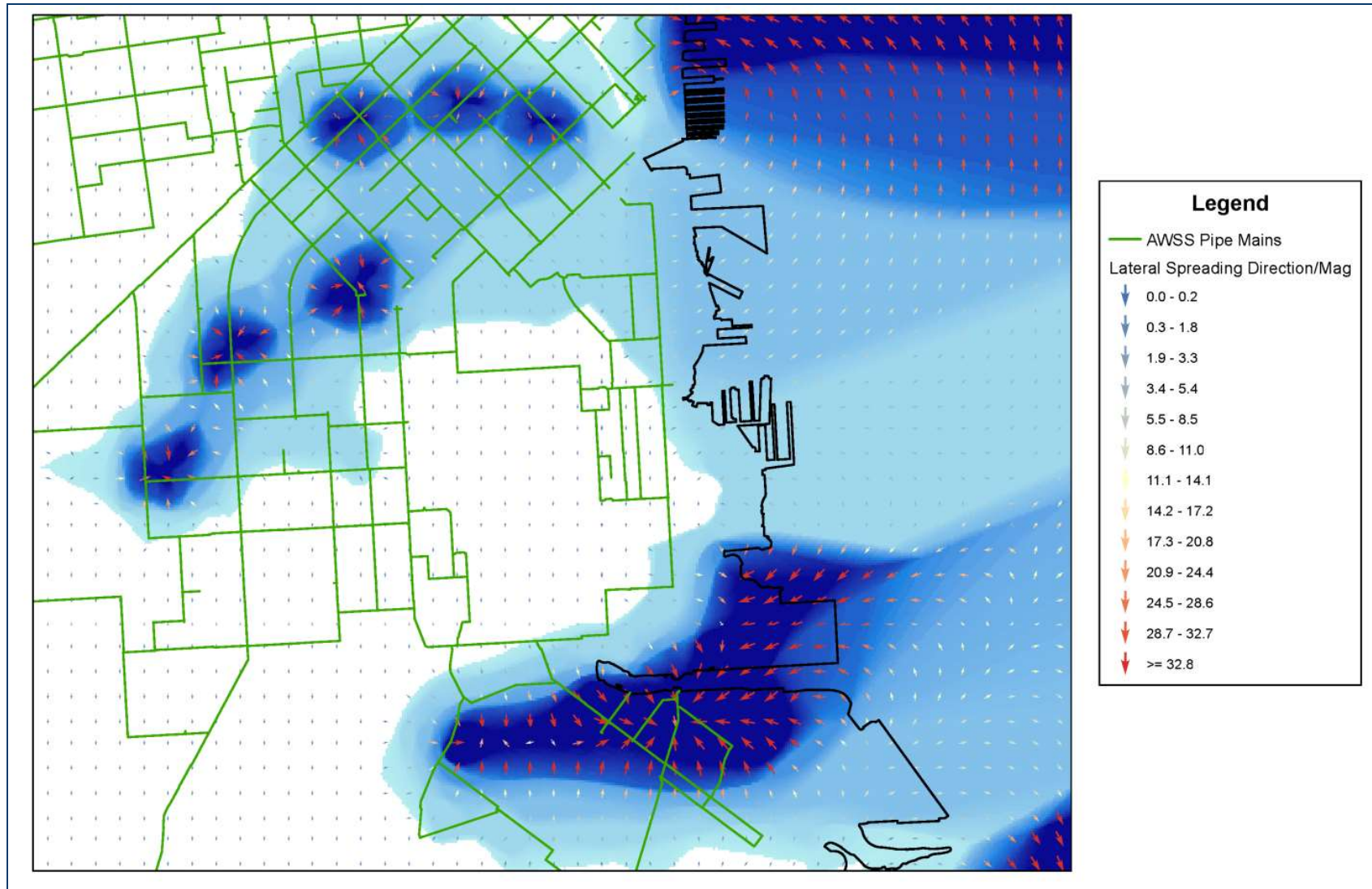
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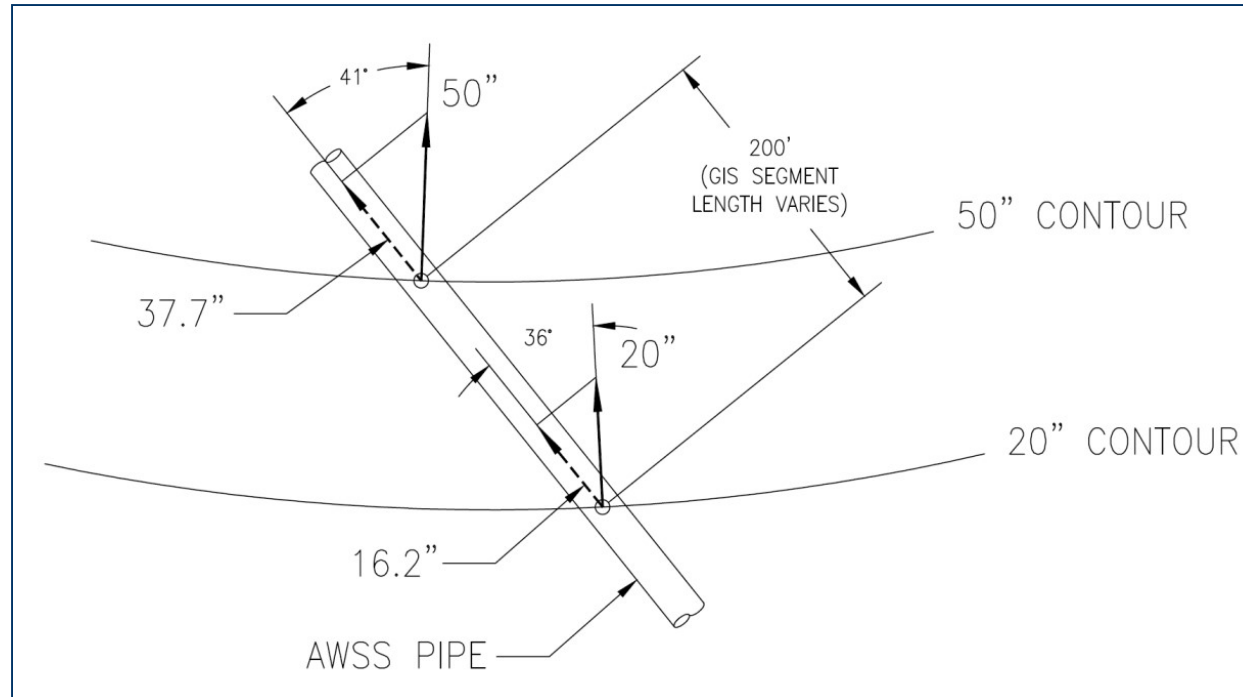
Desktop Study – Peak Ground Velocities



Permanent Ground Deformation



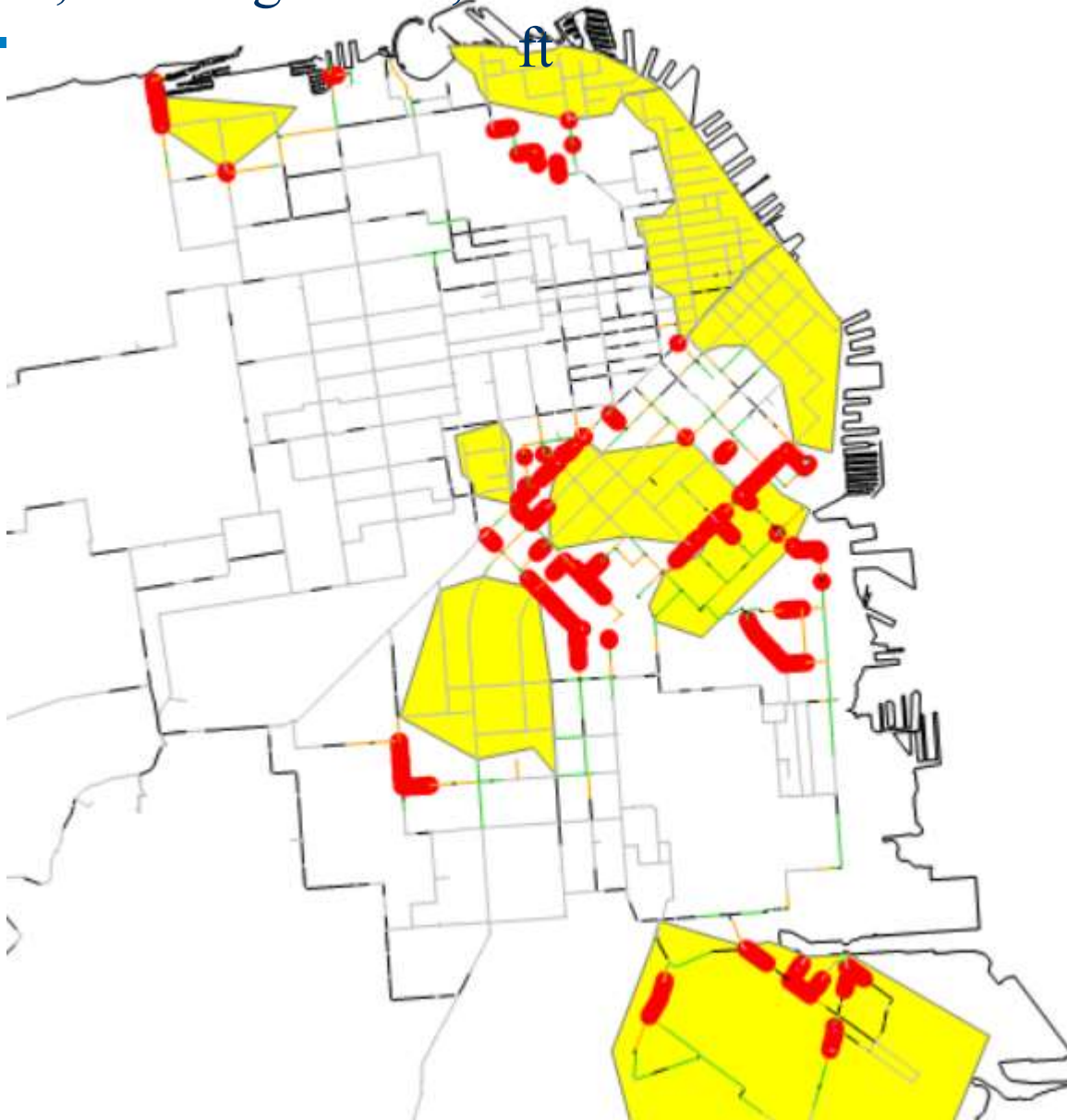
Permanent Ground Deformation



Mechanistic fragility curve – M. O'Rourke
Ground strain to repair rate calculation



100 MIPs, tot Length = 23,000
ft



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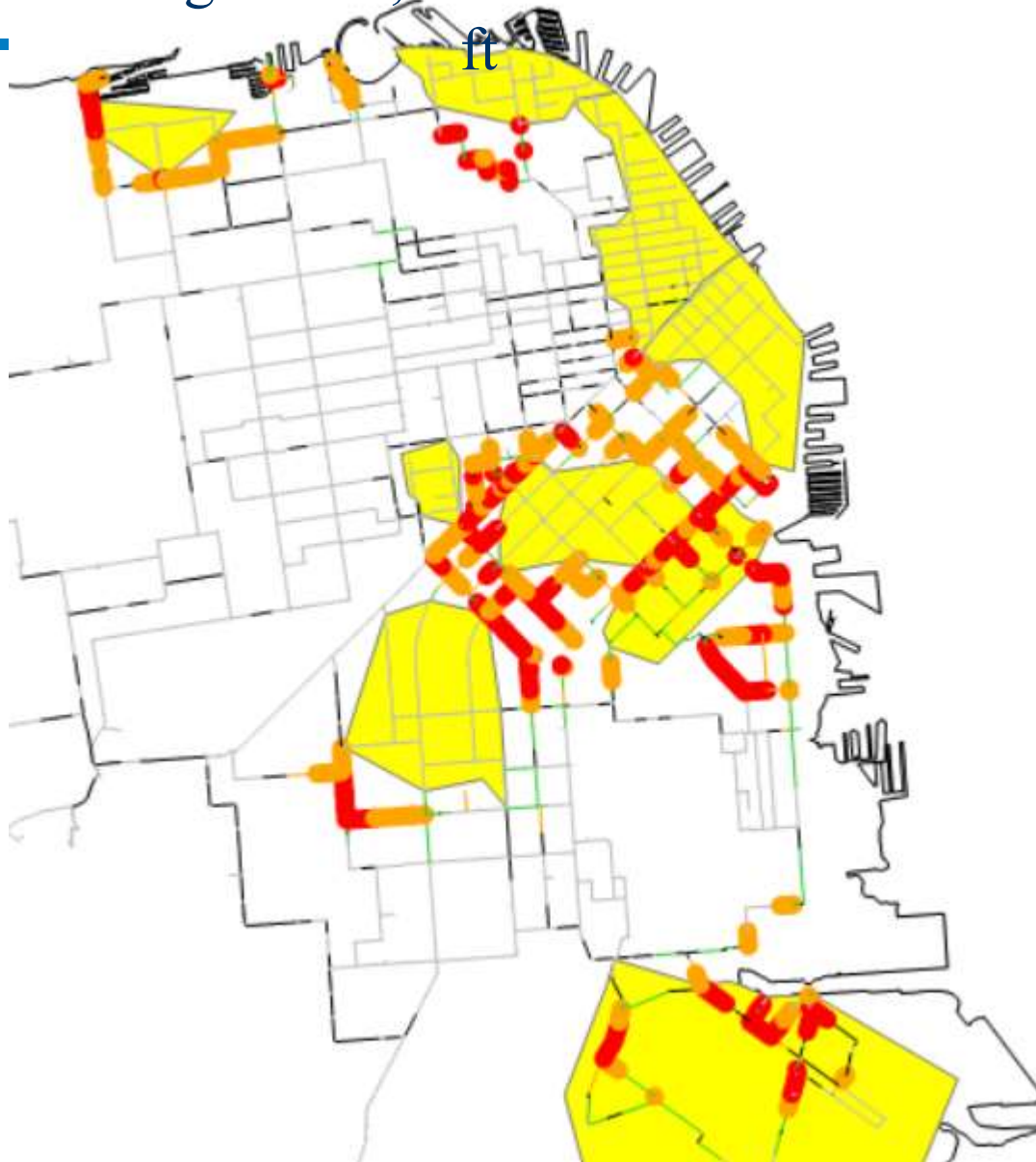
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Next 100 MIPs (ie, 101-201), tot L =
30,000 ft



200 MIPs, tot Length = 53,000
ft



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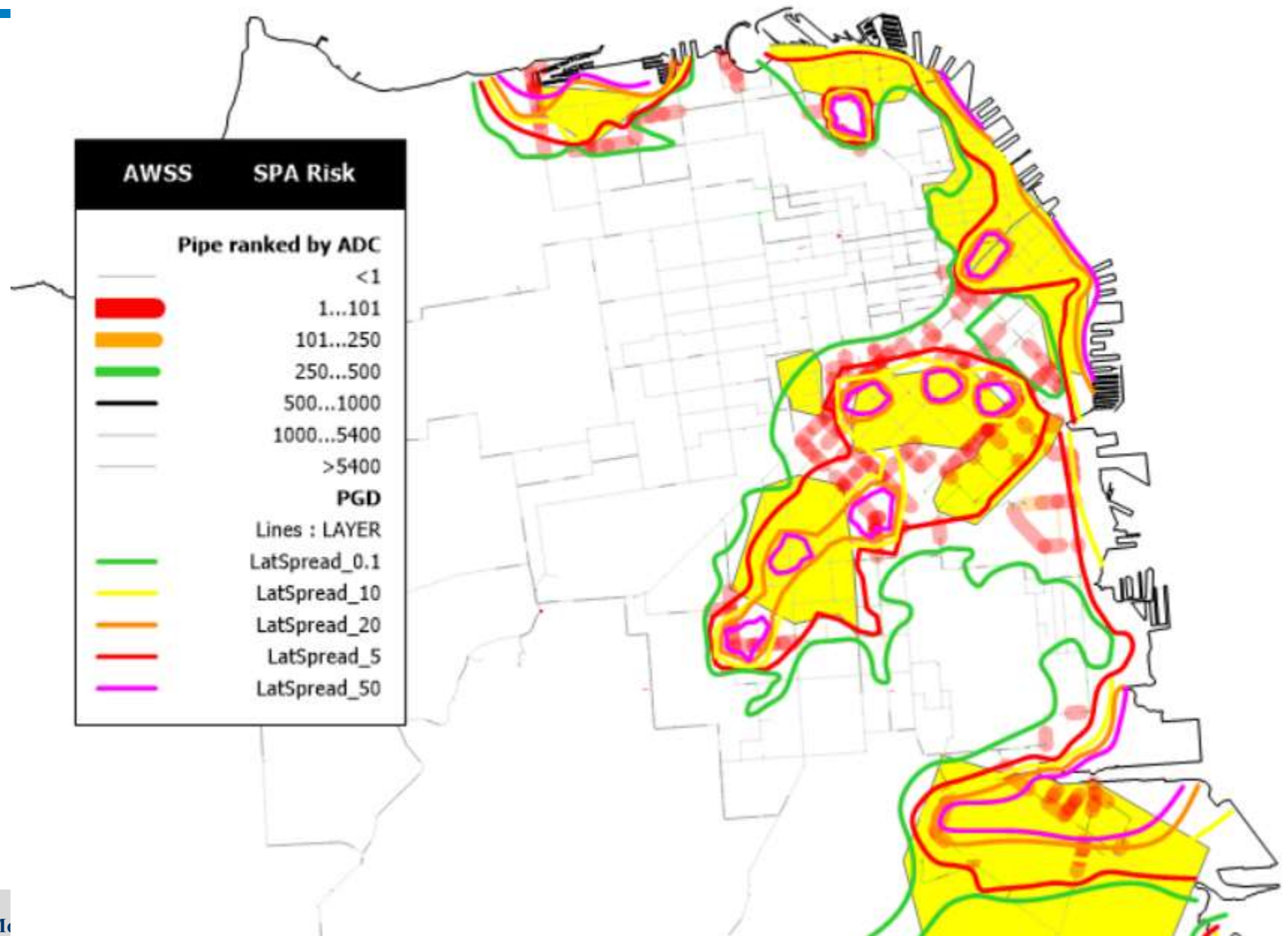
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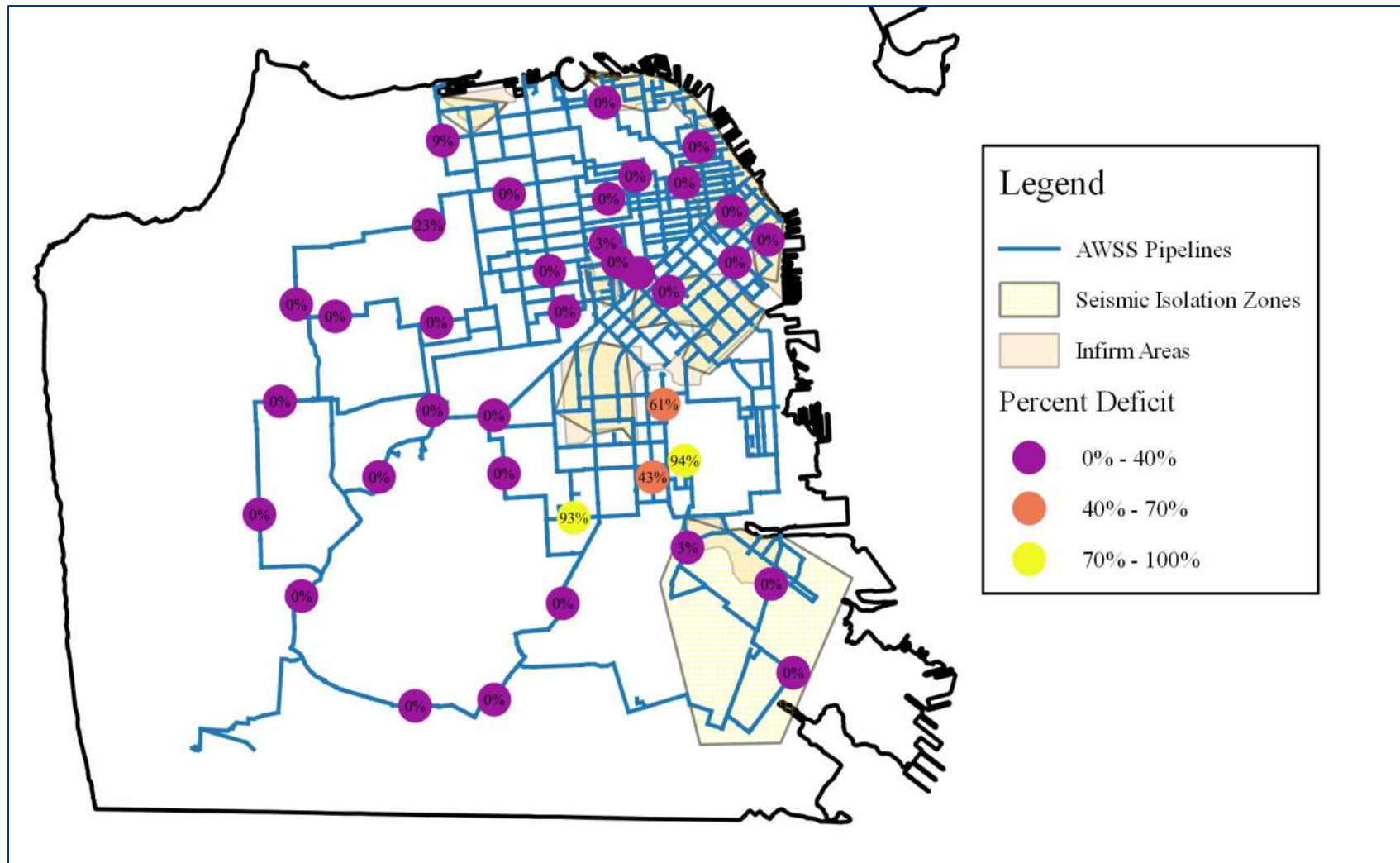
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Pipe priority is driven by PGD



Damaged Network Performance



Post Earthquake Base Case



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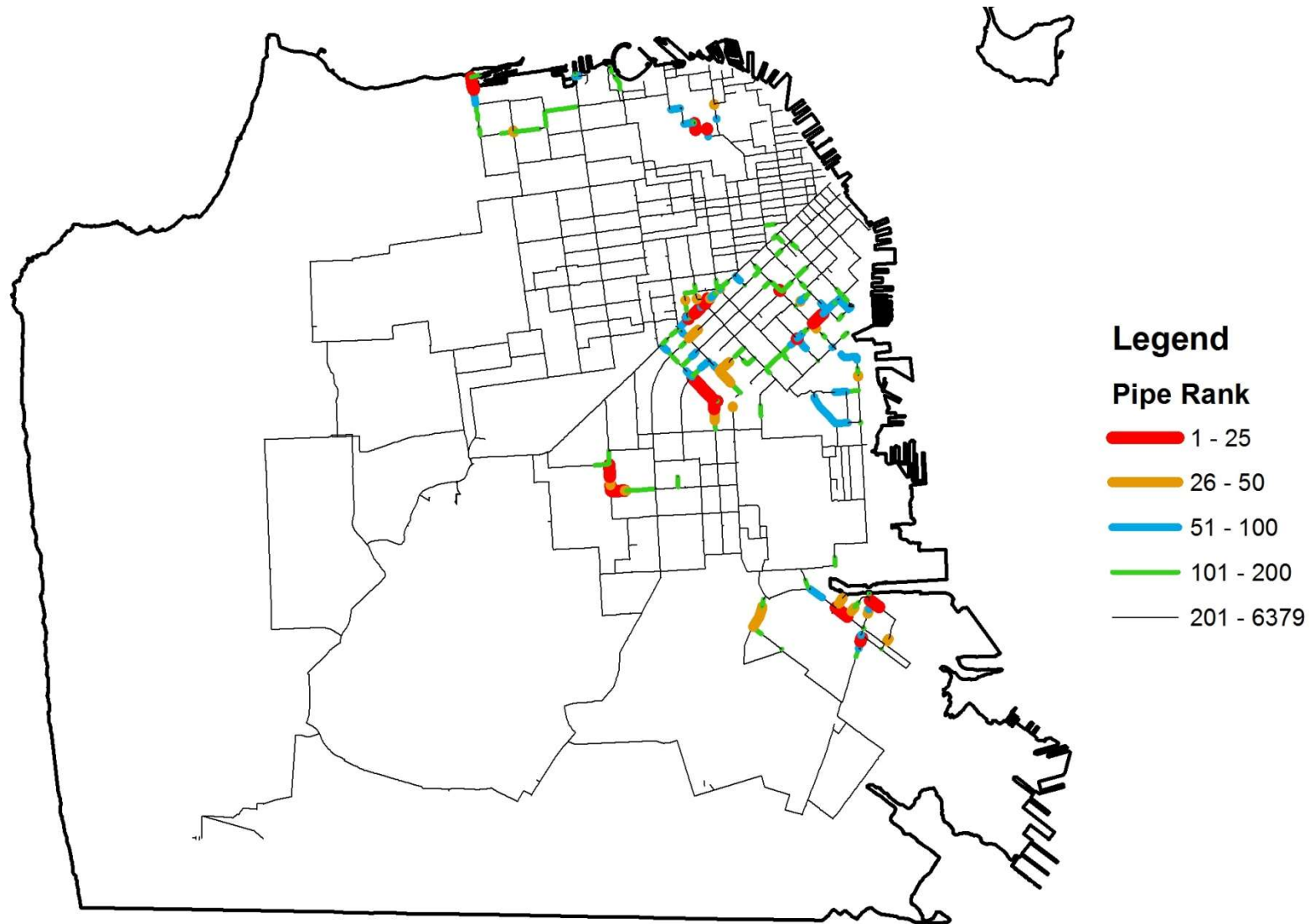
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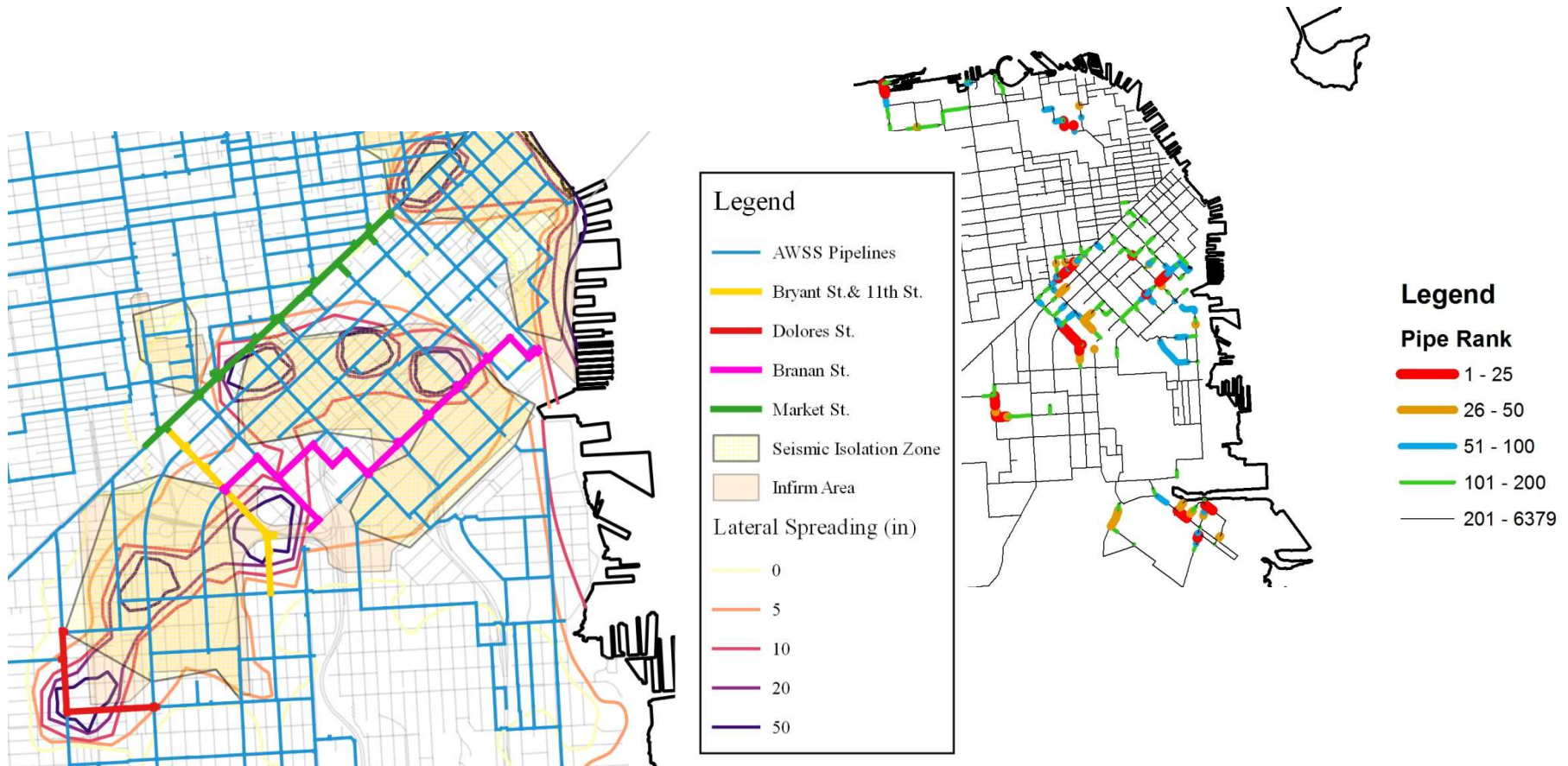
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System Analysis – Pipe Importance by ADC



System Analysis – Pipe Importance by ADC

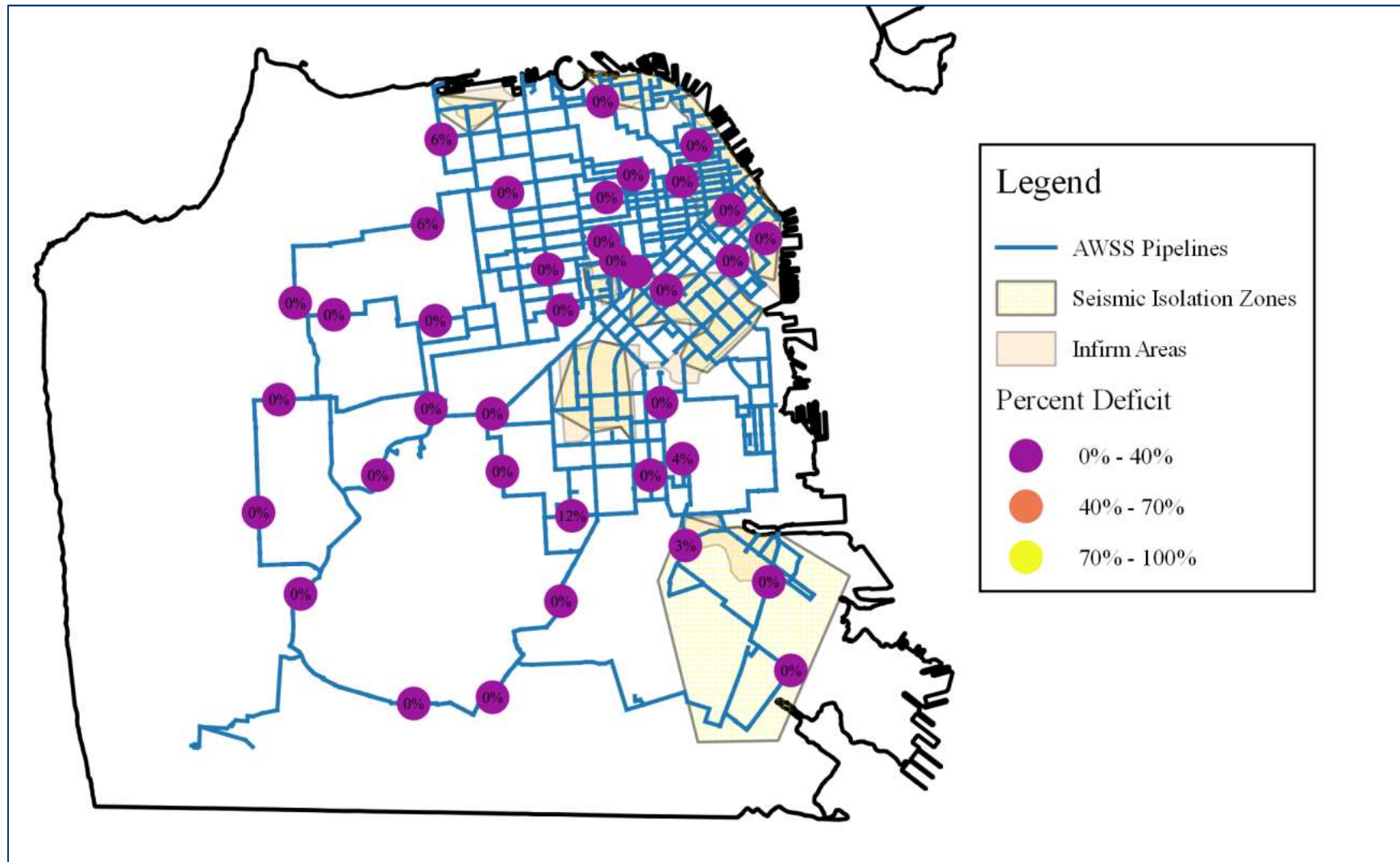


System Analysis – Results

Project	Length (ft)	ADC	Cost	GPM Supplied	GPM Increase	\$/GPM Increase	% Supplied	Worst FRA % Supplied
0	0	0	\$ -	57,499	-	\$ -	89.86%	5.82%
1	5,956	5,055	\$ 7,540,000	59,887	2,388	\$ 3,156	93.59%	31.41%
2	3,982	1,130	\$ 4,210,000	58,202	703	\$ 5,994	90.96%	17.65%
3	11,810	2,696	\$ 16,700,000	58,076	577	\$ 28,937	90.76%	12.02%
4	8,927	1,911	\$ 13,040,000	57,992	493	\$ 26,454	90.63%	10.95%
1 & 2	9,938	6,185	\$ 11,750,000	60,953	3,454	\$ 3,402	95.26%	55.84%
1 & 2 & 3	21,747	8,880	\$ 28,450,000	61,933	4,434	\$ 6,416	96.79%	72.56%
1 & 2 & 3 & 4	30,674	10,791	\$ 41,490,000	63,096	5,597	\$ 7,413	98.60%	87.81%



System Analysis – Pipe Importance by ADC



Conclusions

- A new method, the *Pipe Importance and Priority Evaluation (PIPE)* Algorithm, has been developed that allows identification of which pipe contributes most to system deficit, given complexities of hydraulic demands, network topology and seismic (or other) impacts.
- The PIPE algorithm has been applied to a large real world water system requiring high reliability
- Under non-earthquake conditions the AWSS (i.e.,) meets 100% of demands.
- With Infirm Areas *isolated* after an earthquake, the system will lose ~43,000 gpm through leaks and breaks and have a demand deficit of ~6,500 gpm. (~63,000 gpm and ~8600 gpm with IA's open)
- Application of the PIPE algorithm efficiently identified the least cost pipe replacement program.



Water Distribution System Pipe Replacement Given Random Defects

Thank you

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