SAND2020-5623C

Modeling of Compressible Gas Systems in Limited Information Environments

17 June 2020

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Bottom Line Up Front

- We've built systems dynamics models of critical infrastructure systems, particularly petroleum fuels, that have been successful with various levels of detail/quality of data;
- We've leveraged the techniques used in building models made for incompressible fluids and made strategic changes to be able to use the same structure for compressible gases (e.g., natural gas);
- Data is always an issue. We use an iterative process where we look to build models with sufficient level of detail focused on the question at hand, rather than waiting for perfect detail to build a model; and
- Questions drive both the scale of modeling we conduct and the resources we dedicate looking for additional data.

History

NetFlow Dynamics (NFD)

- Originated as National Transportation Fuels Model (NTFM)
- Uses System Dynamics as its basis
- Flexible model
- Applied to infrastructure systems for multiple Federal customers

Developed to give subject matter expert analysts the capability to:

- Integrate data from multiple sources and create an internally-consistent and balanced system representation
- Simulate operation of the infrastructure under a wide range of disruption scenarios

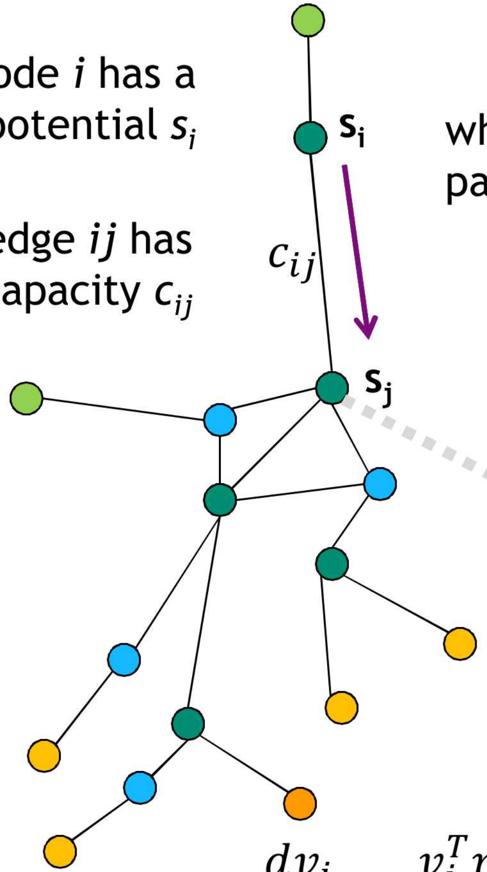
Designed to answer questions of the form:

- Which regions would experience shortages of fuel after a specified disruption to one or more components of the fuel infrastructure?
- What would be the duration and magnitude of the shortages?

System Dynamics Fundamentals of NFD: Satisfy demand subject to mass balance and capacity constraints

Each node i has a potential s_i

Each edge ij has a capacity c_{ij}

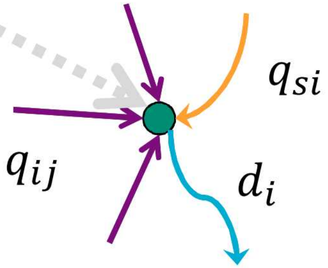


Flow rates are given by : $q_{ij} = c_{ij}\, f\big((s_i - s_j)u_{ij}\big)$ (1)

where u_{ij} is a utilization parameter and the function f(x) is: $f(x) \equiv 1 - e^{-x}$ (2)

In equilibrium, the net flow at each node i is 0: $\sum_j q_{ji} + q_{si} - d_i = 0 \quad \forall i$ (3)

The equilibrium solution $\{\hat{s}_i\}$ is obtained by solving equations (1-3)



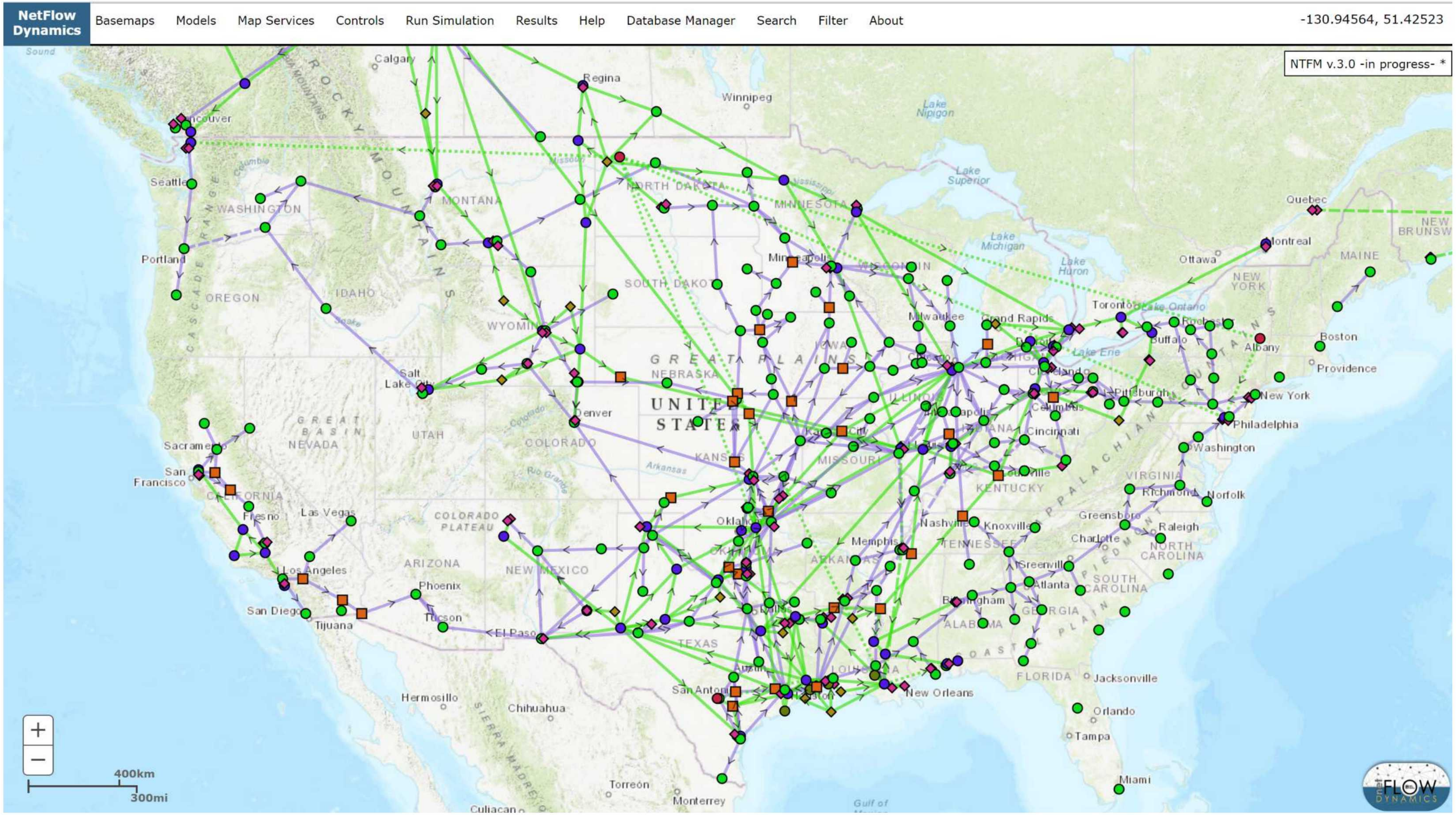
In the transient case, net inflow into a node results in the accumulation of stored fluid:

$$\sum_j q_{ji} + q_{si} - d_i = \frac{dv_i}{dt} = \frac{v_i^T p}{2b}\left[\frac{1}{2}\left\{1 + \frac{(\frac{s-a}{b})}{\left[1 + (\frac{s-a}{b})^2\right]^{\frac{1}{2}}}\right\}\right]^{p-1} \left[1 + (\frac{s-a}{b})^2\right]^{-3/2} \frac{ds_i}{dt} \quad \forall i$$

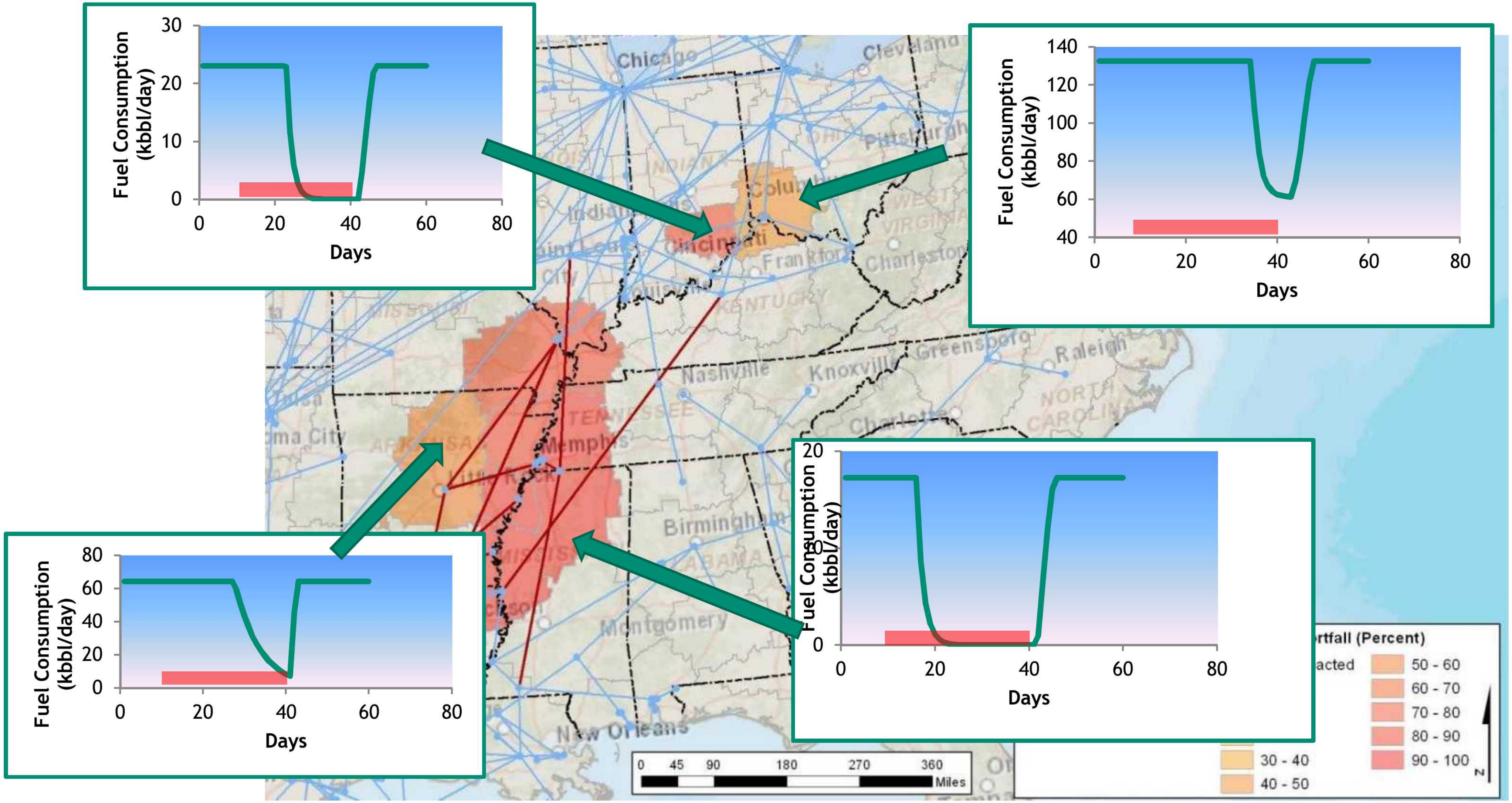
where p, a and b are storage parameters

Corbet et al., Reliability Engineering and System Safety 169 (2018) 451–465

When data is available, this can lead to exquisite networks…



…enabling the analysis of disruptive events with the ability to identify non-intuitive results



This is the point at which you might be saying: How dare you!

Motivating questions concern large/persistent disruptions

- What level of service does the remaining capacity permit?
- How should restoration be prioritized?

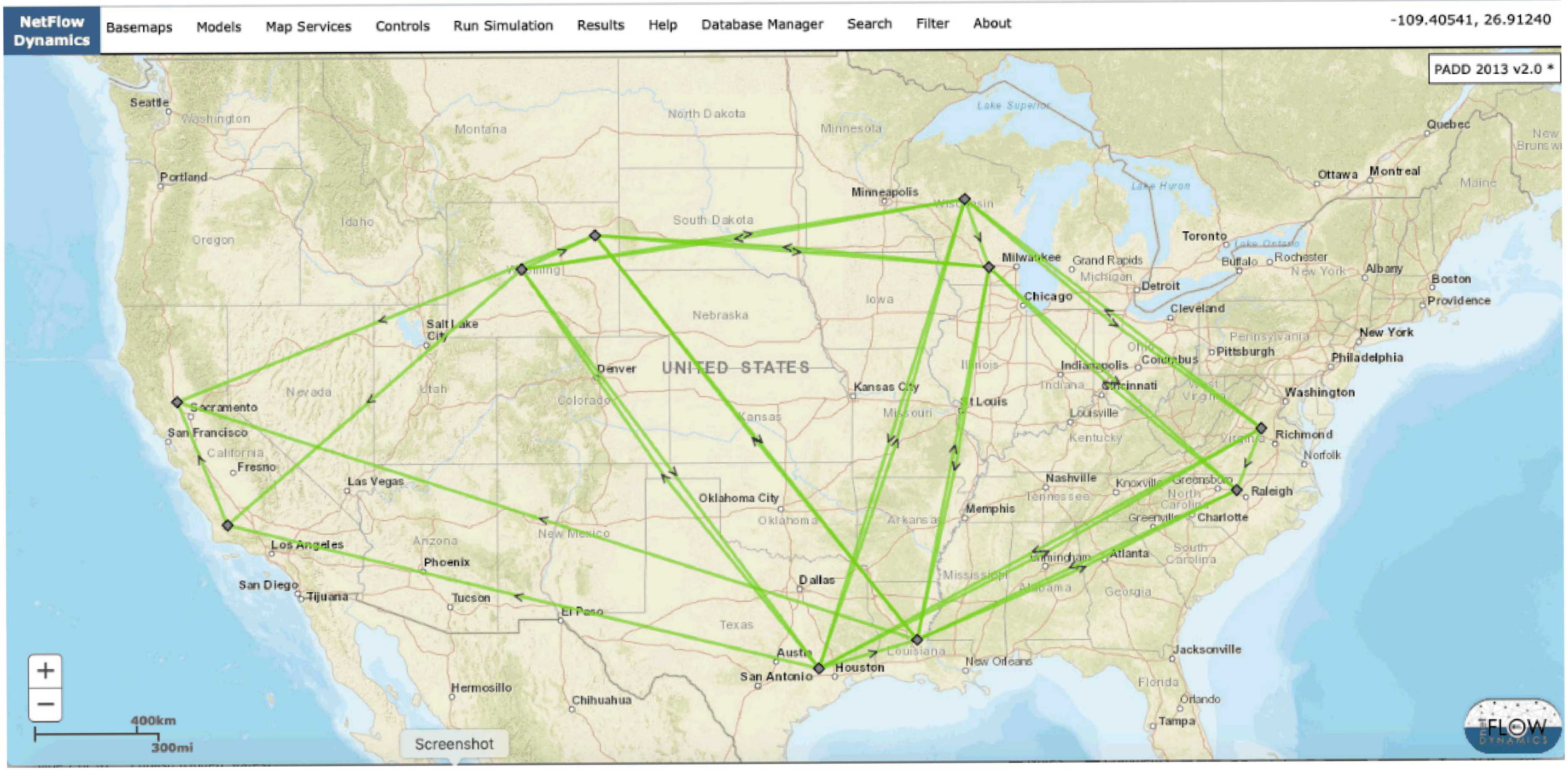
Answers are controlled by the relationships among pipeline capacities, sources, sinks, and significant storage

Controlling scenario parameters (location, intensity, initial state) are often arbitrary or variable

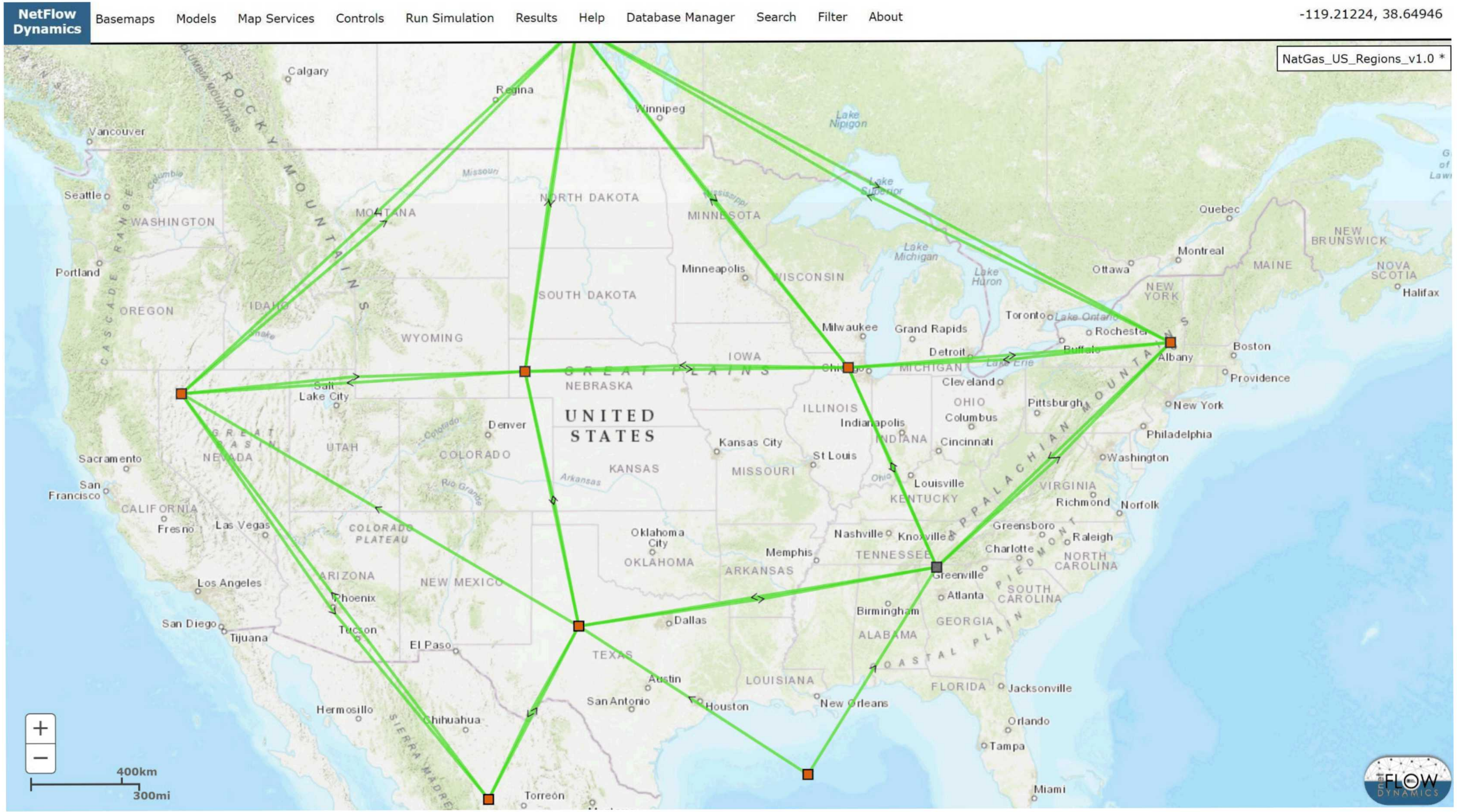
System responses depend on how the remaining pieces are used (slides follow)

We need to efficiently explore the space of possibilities to define which consequences *must* occur, which *might* occur, and which *can't* occur. Better resolution of pipeline physics will not make this classification more accurate.

But every mighty oak starts as an acorn: PADD Level Petroleum Model

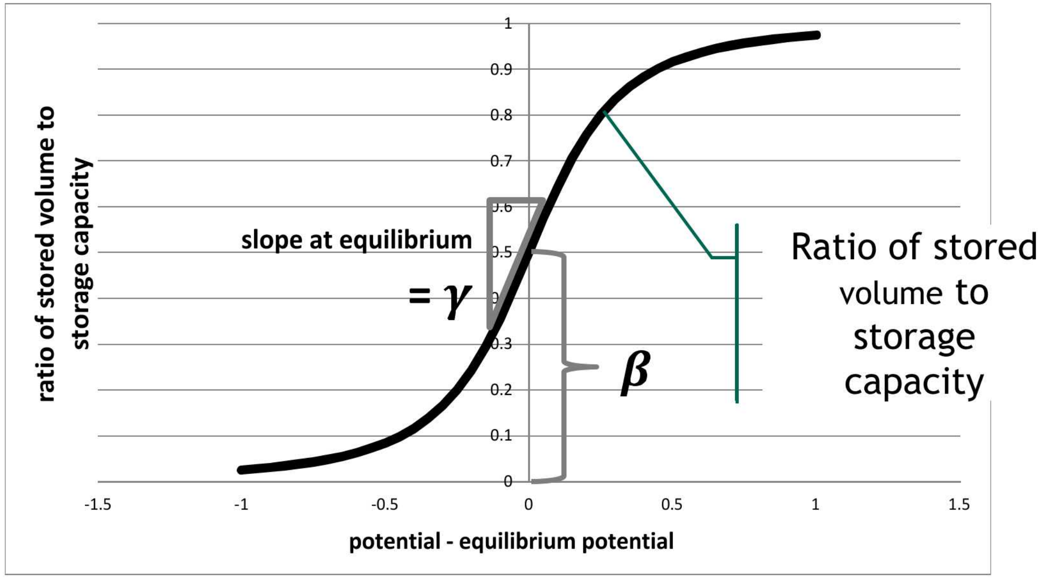


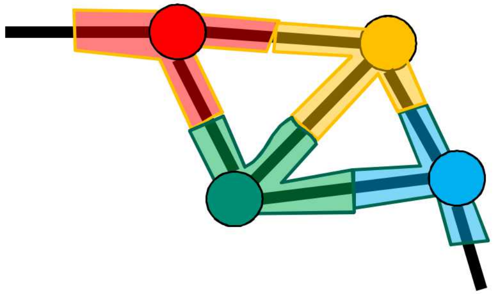
And so we repeated the process, for compressible gases



But Storage is Different for Compressible Gases!

Input parameters specify the fraction of capacity used at equilibrium β, and the responsiveness of stored volume to changes away from equilibrium γ



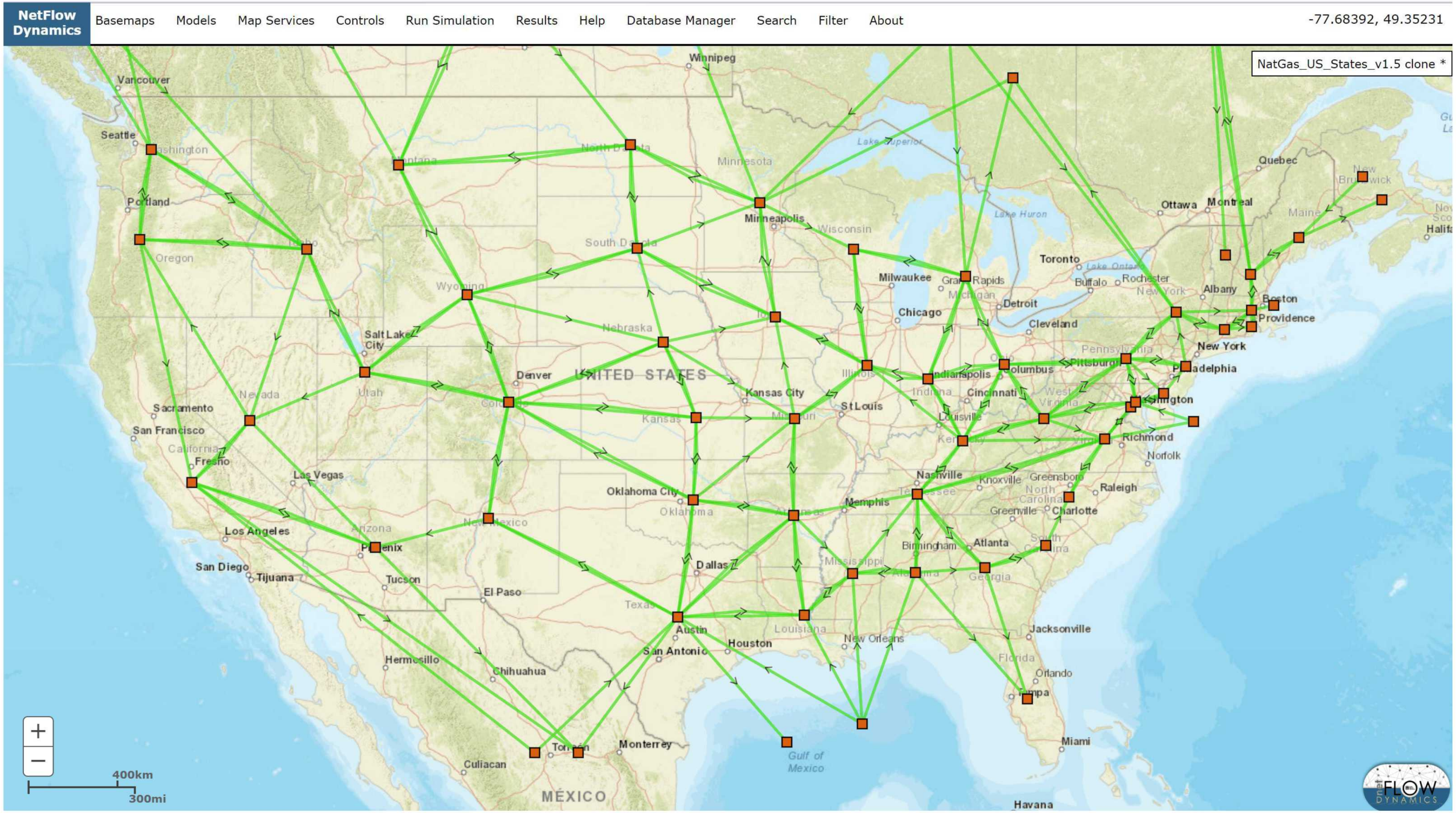


Storage is represented at network nodes with *incompressible flow* along links

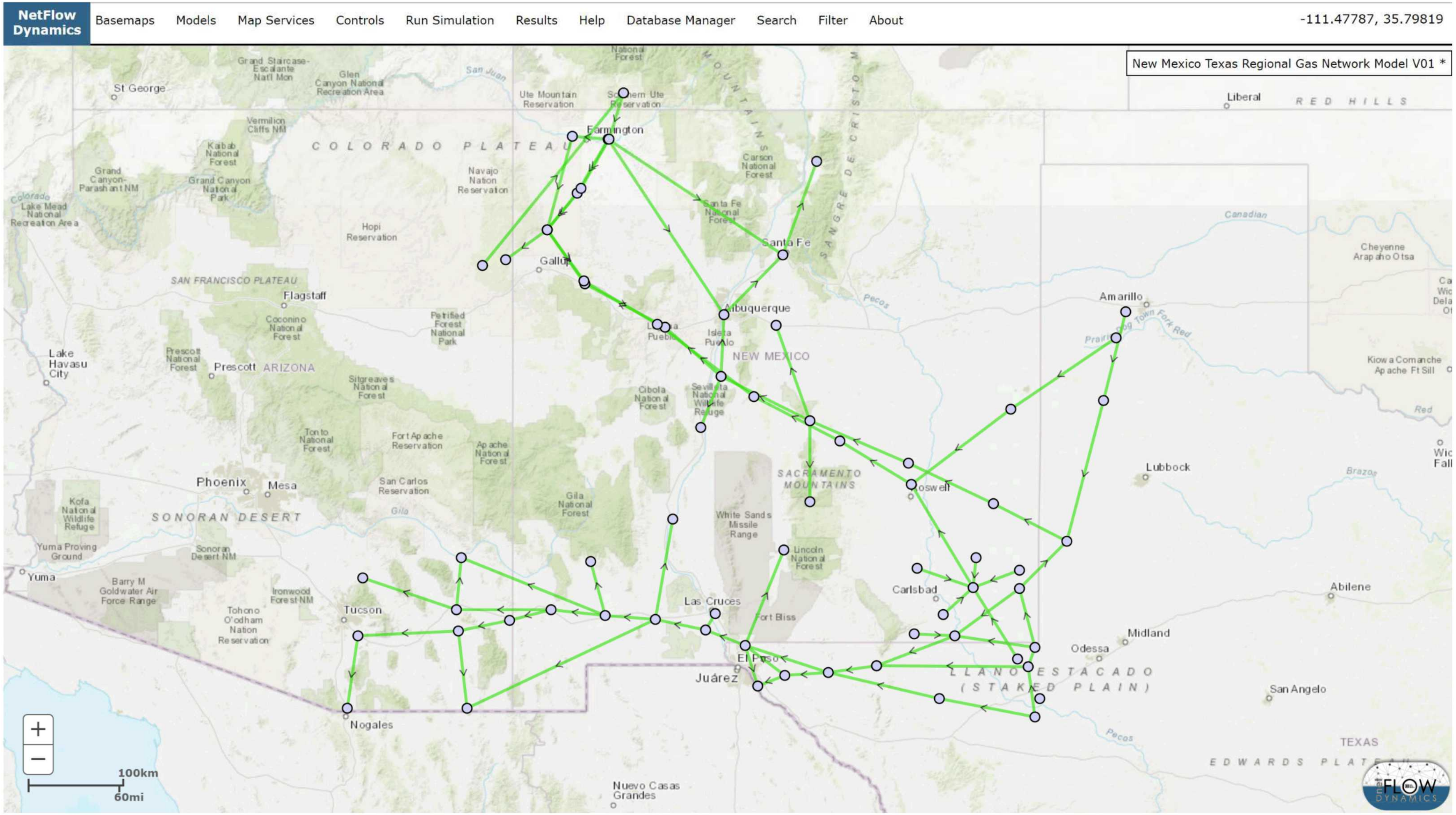
For natural gas systems:

- Nodal storage represents variation in line pack in connected pipelines
- Storage is assigned based on pipeline diameter and operating pressure swings

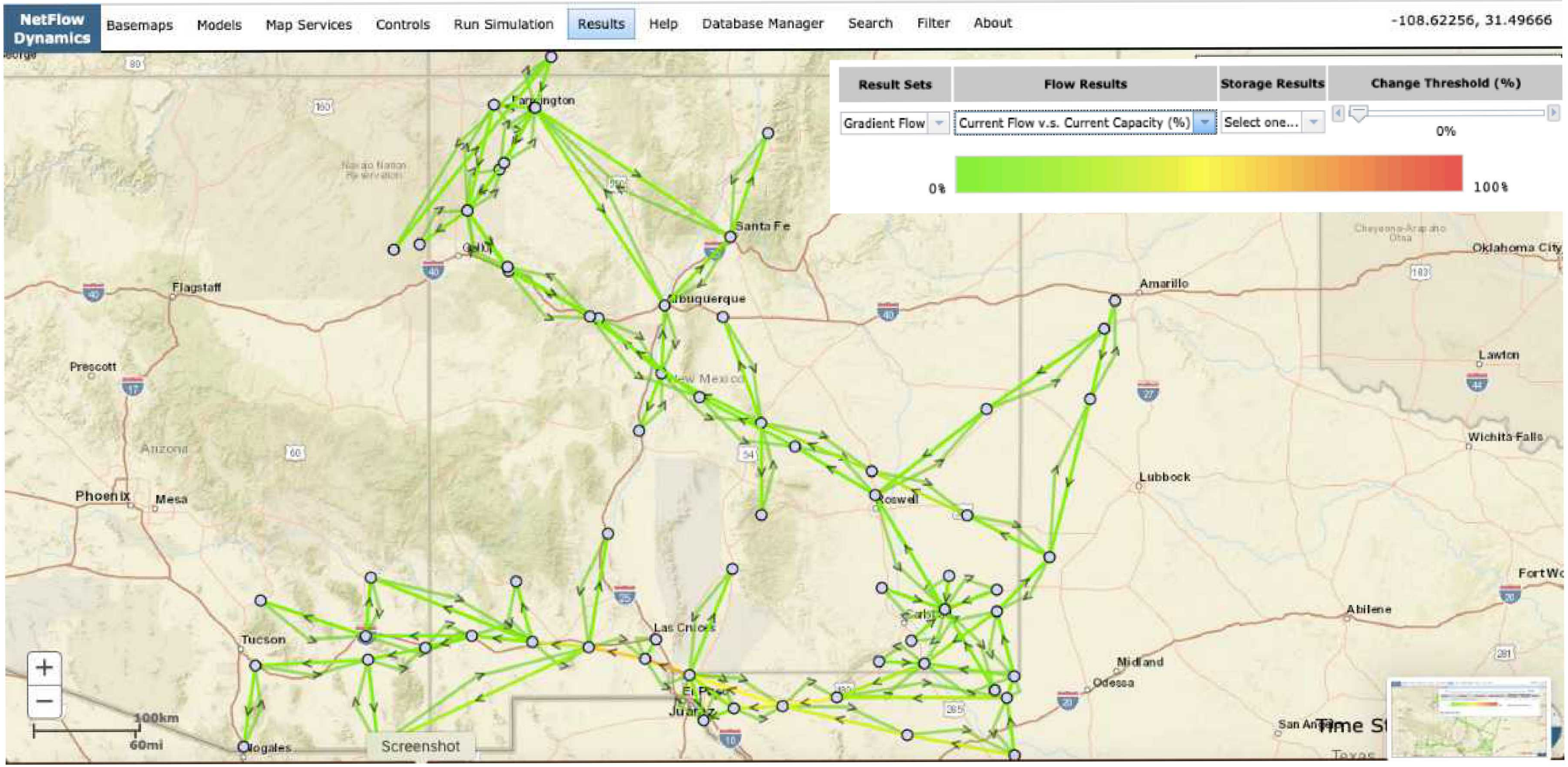
We grow the acorn as needed: State-level network reflecting production/consumption/flow



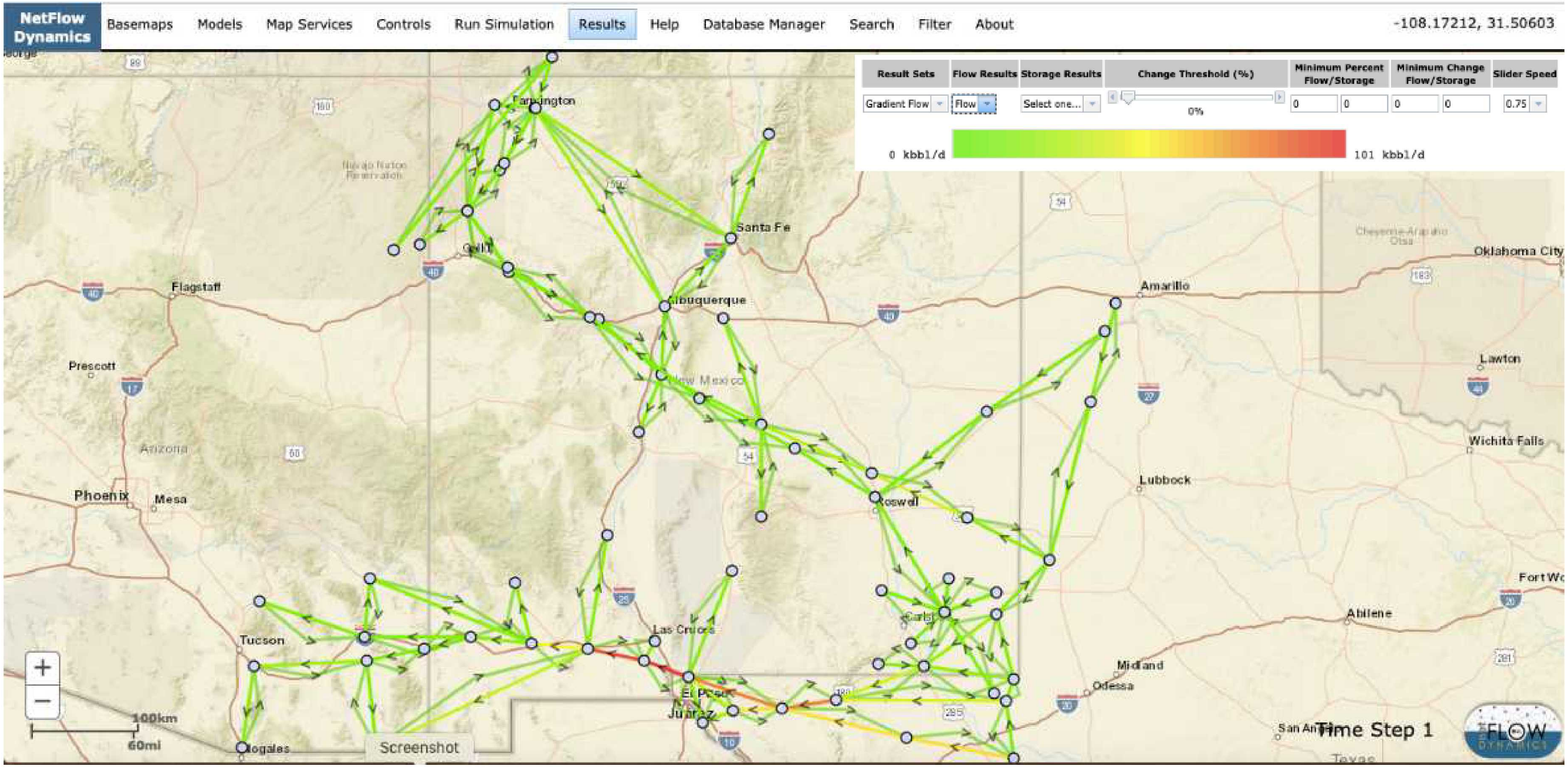
Or focus the growth in particular areas: Small-scale NG Network



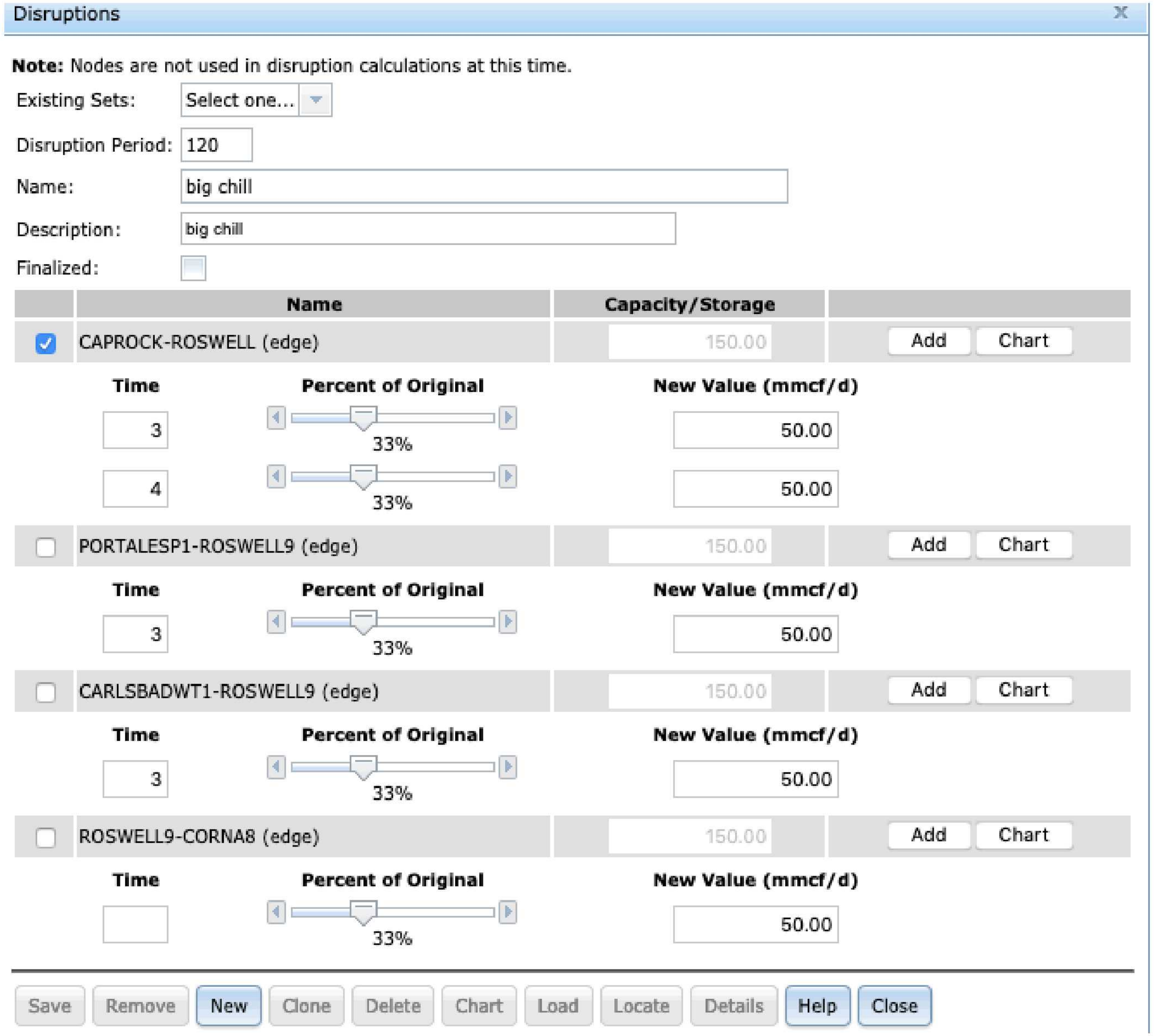
Look at the Network under Nominal Conditions: Current Flow vs Current Capacity (%)



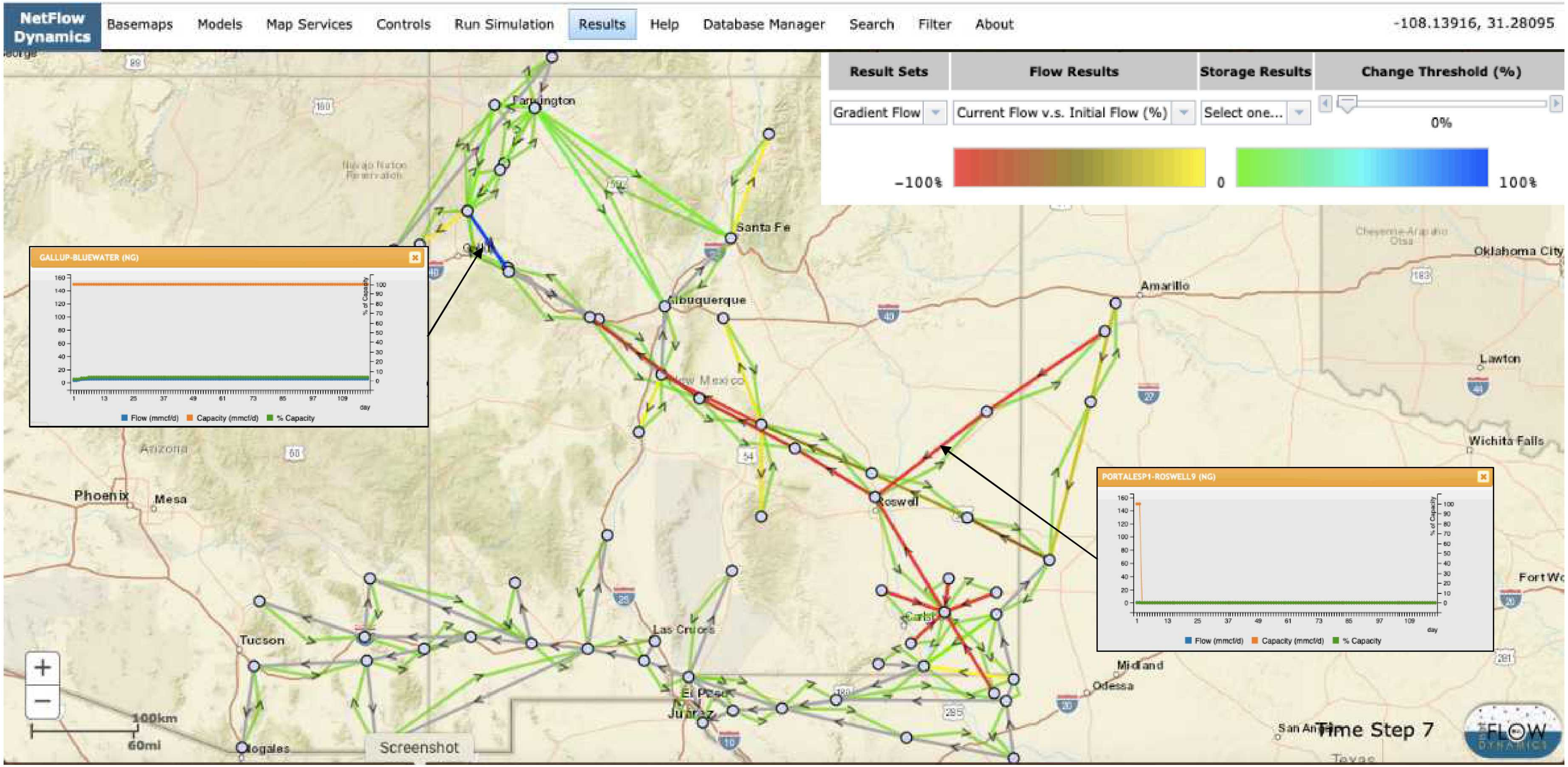
Look at the Network under Nominal Conditions: Flow



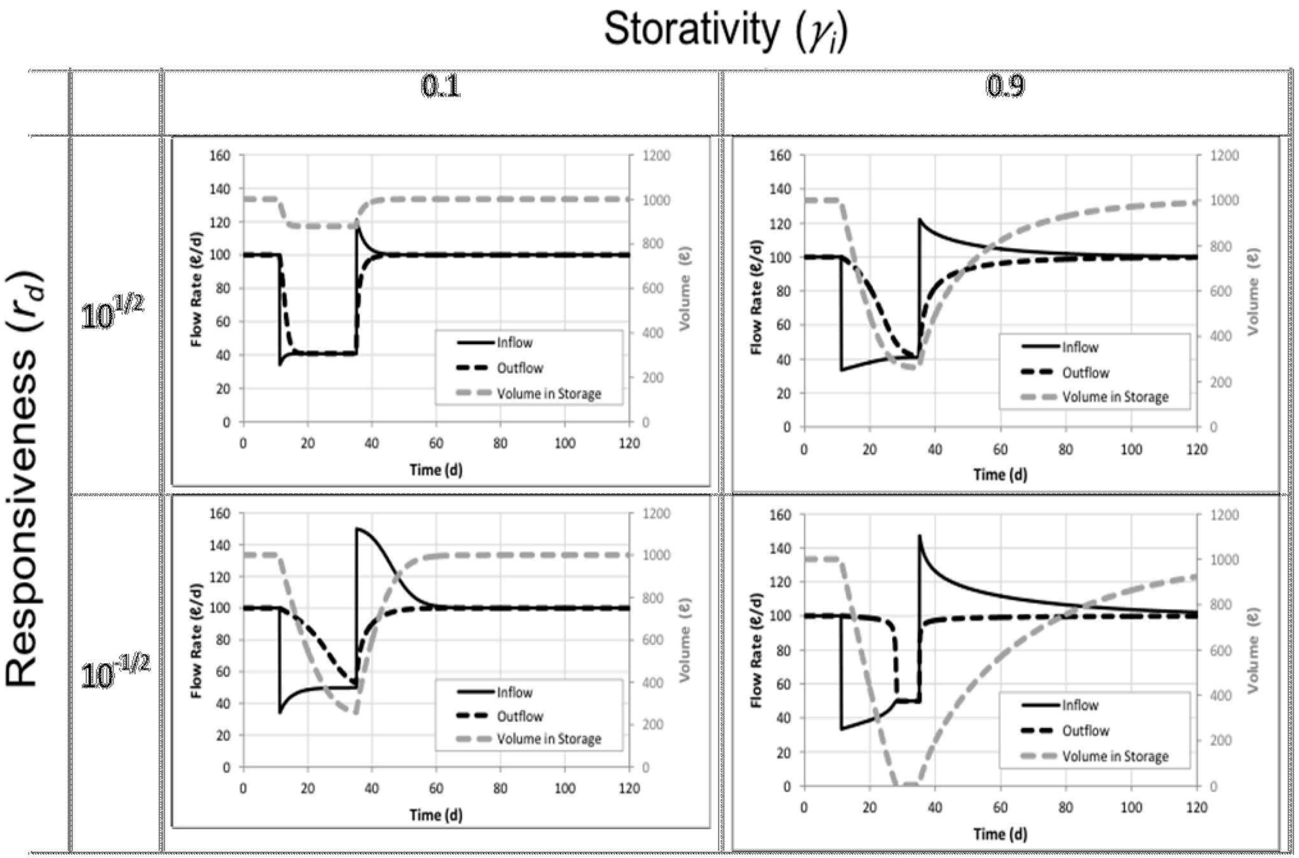
Perturb the Network



Compare the Perturbation to the Baseline



Sensitivity of disruption response to selected parameters



Elastic Demand

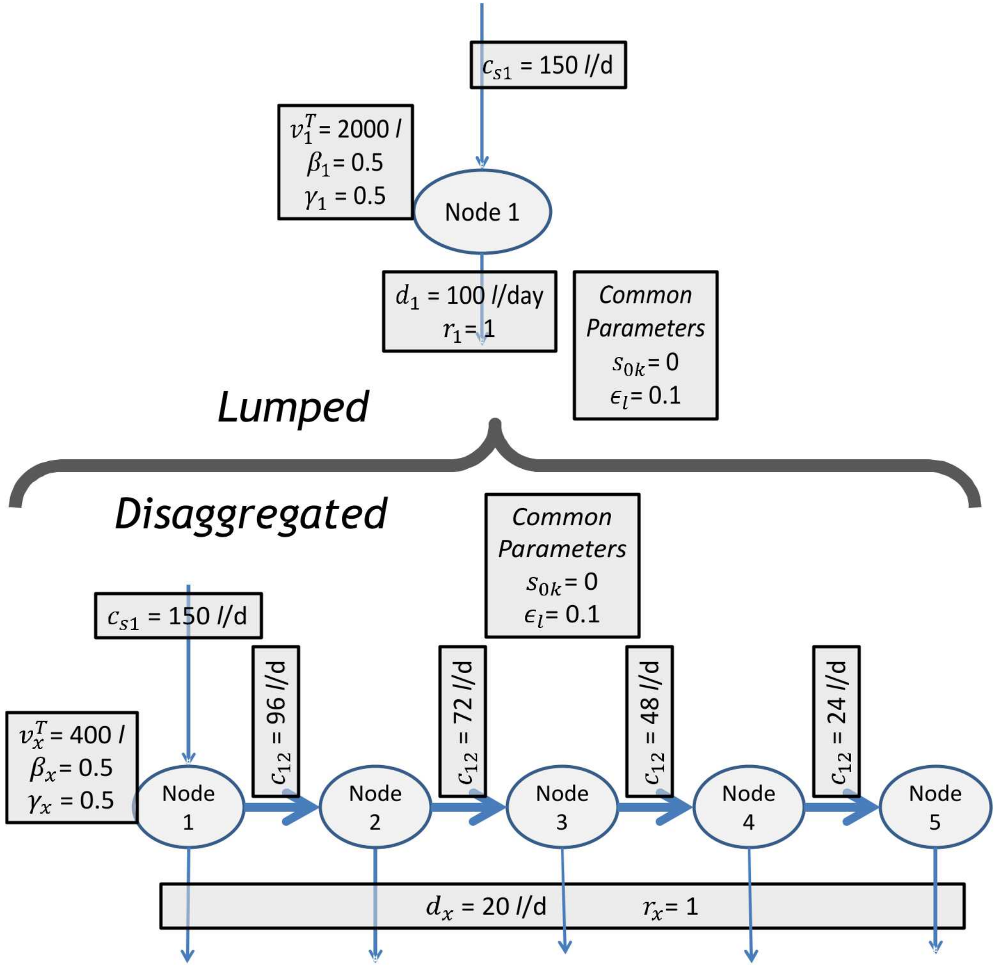
Inelastic Demand

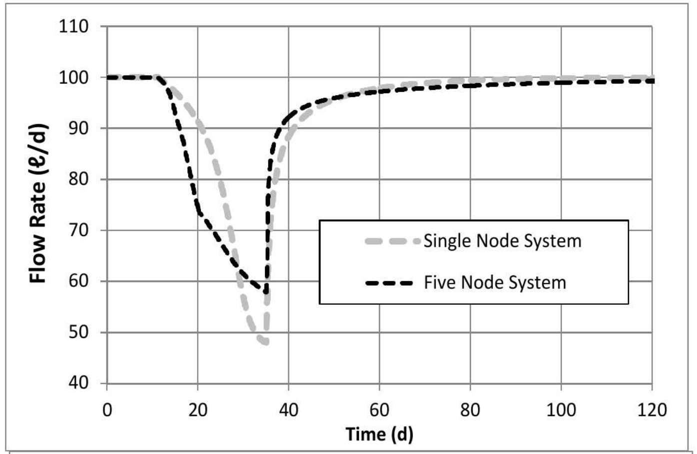
Inelastic Storage

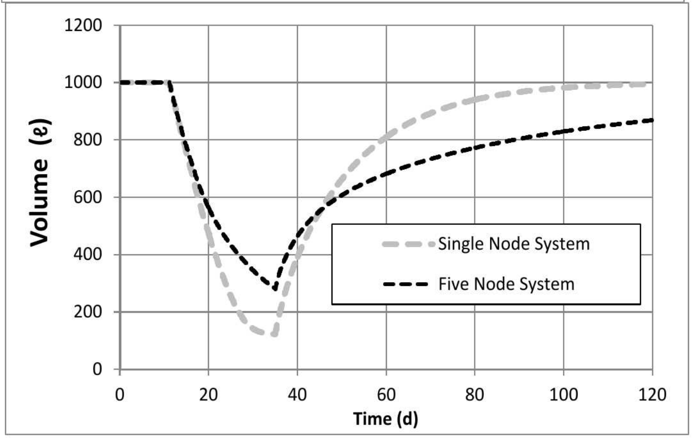
Elastic Storage

Intensity and duration of response depends on how demand and storage are managed

Sensitivity to network resolution







Conclusion

- We've leveraged the techniques used in building models made for incompressible fluids and made strategic changes to be able to use the same structure for compressible gases (e.g., natural gas)
- Data is always an issue.
  - We use an iterative process where we look to build models with sufficient level of detail focused on the question at hand, rather than waiting for perfect detail to build a model;
- Questions drive
  - the scale of modeling we conduct
  - the resources we dedicate looking for additional data
- We continue to apply this capability to regions of interest to our customers, and to build it such that it can be integrated with other capabilities