# QUANTIFYING THE RESILIENCE OF INFRASTRUCTURE SYSTEMS

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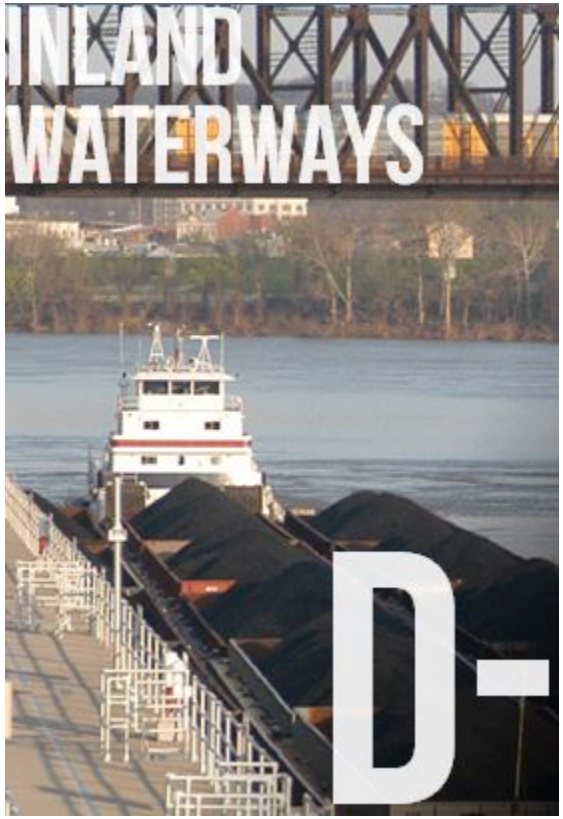
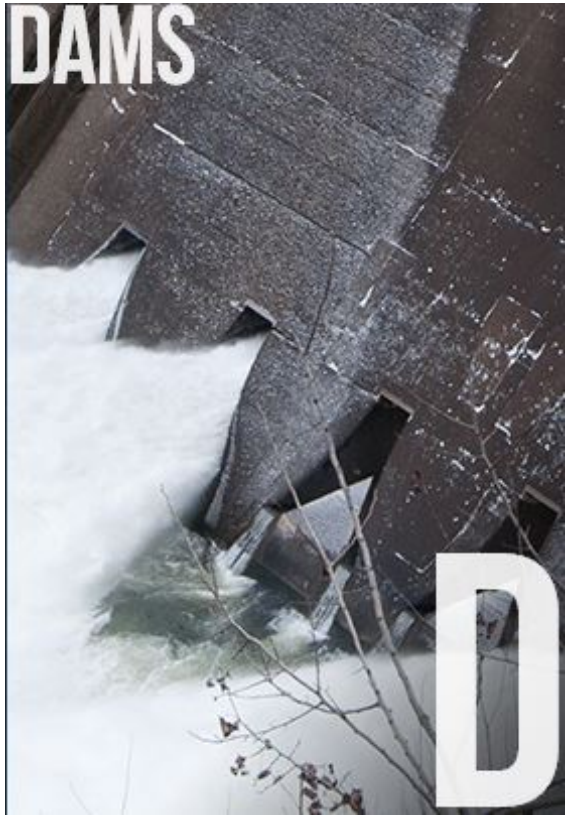
# ASCE REPORT CARD ON AMERICA'S INFRASTRUCTURE



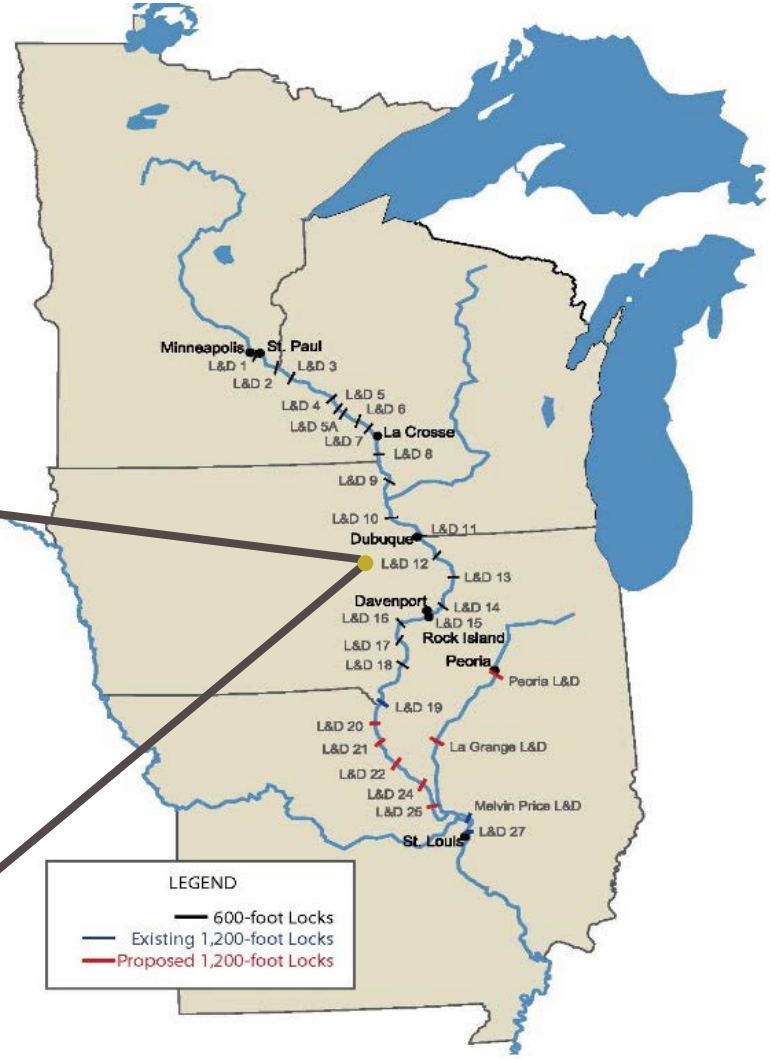

The average age of the 84,000 dams in the country is 52 years old

By 2020, 70% of the total dams in the United States will be over 50 years old

# WHY INLAND WATERWAYS?

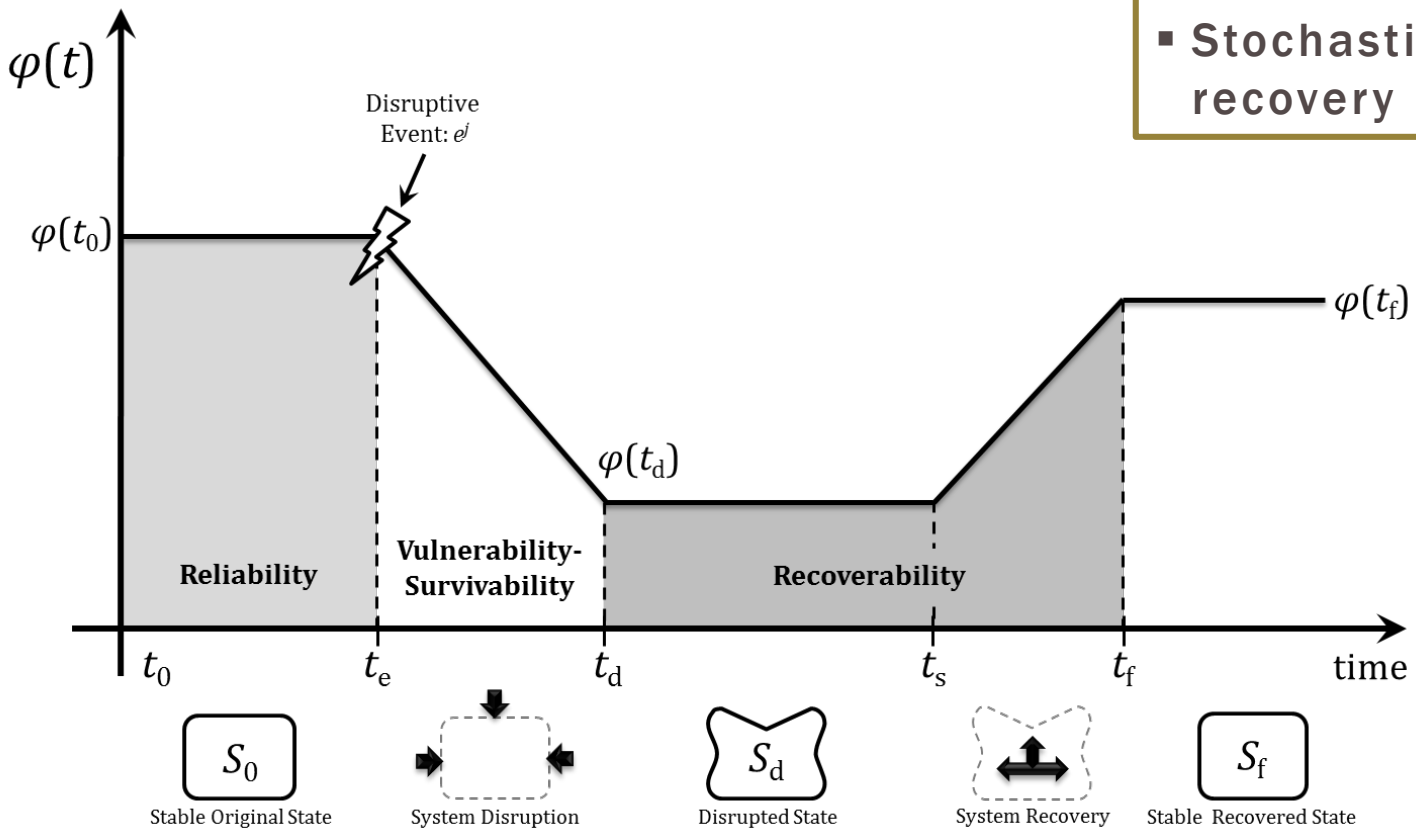
- Over 200 lock chambers
- Over 566 million tons of freight (~51 million truck trips)
- Over $152 billion equivalence of goods
- Low-cost and fuel-efficient freight mode

15-barge grain tow, hauling approximately 22,500 tons of export grain, exits Lock & Dam 13



# AFTER A DISRUPTION

**Recovery management**
- Post-disaster strategies
- Stochastic behavior of recovery




Henry, D. and J.E. Ramirez-Marquez. 2012. Generic Metrics and Quantitative Approaches for System Resilience as a Function of Time. Reliability Engineering and System Safety, 99(1): 114-122.

# QUANTIFYING RESILIENCE

- Cost/impact measures associated with a disruptive event
  - Expected loss of service cost
  - Total network restoration cost
  - Interdependent impact of resilience

- Importance measures
  - Resilience-based component importance measure
  - Resilience worth

# DIRECT COST

- The **loss of service cost** is a function of the severity of the disruptive event and the service function for network component $i$

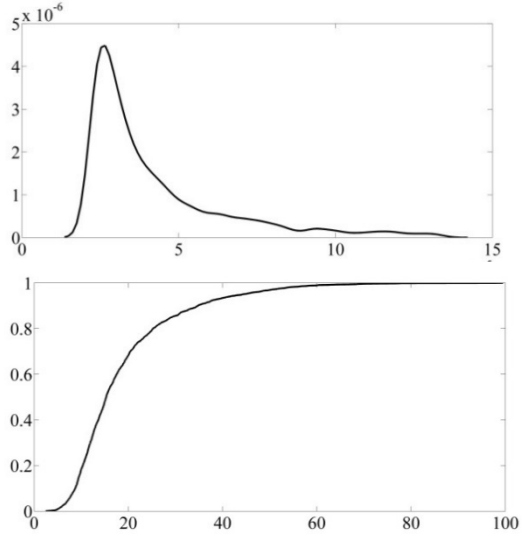
$$\varphi(t_d) = \varphi(t_0) - \sum_{i=1}^{m} \varphi_i(t_0) \times \frac{d}{365}$$

- The **total cost of restoration** accounts for potential parallel recovery activities

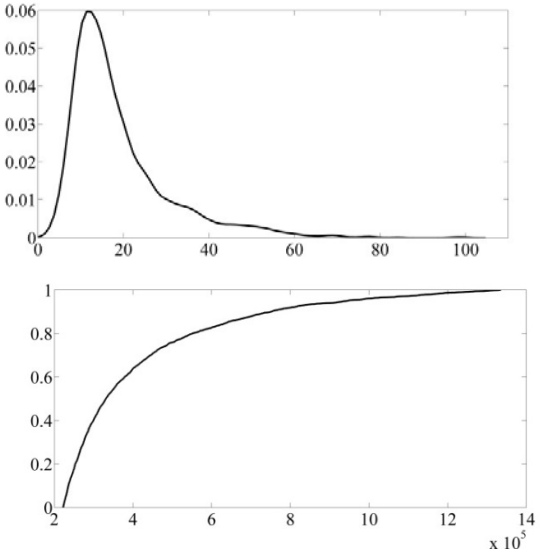
$$C_{\text{total}}\left(e^j\right) = \sum_i \theta_i C_i^j$$

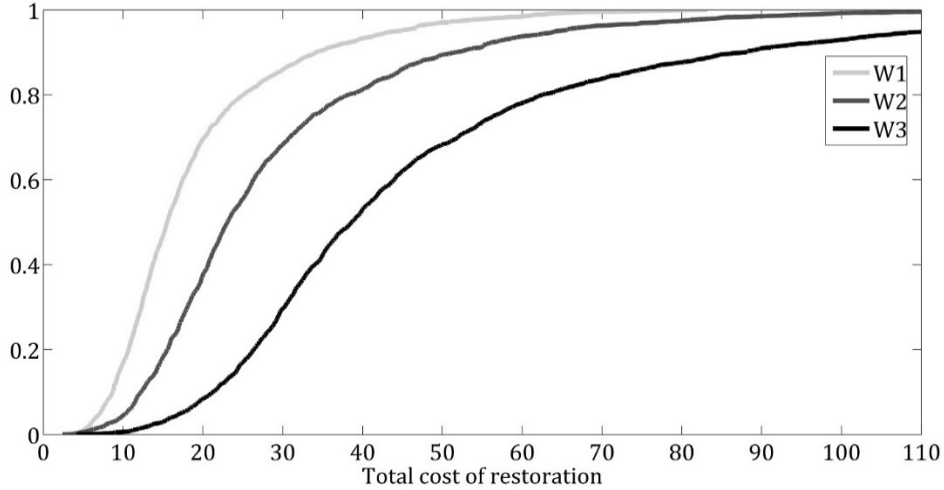
# DIRECT COST

## Network Restoration Cost




## Loss of Service Cost




Network Restoration Cost under different recovery strategies

# INDIRECT COST - DYNAMIC INOPERABILITY MODEL

- For $n$ interdependent sectors

$\boldsymbol{n} \times \boldsymbol{n}$ matrix for controlling recovery

$$\mathbf{q}(t+1) = [\mathbf{I} - \mathbf{K}^*(\mathbf{I} - \mathbf{A}^*)]\mathbf{q}(t) + \mathbf{K}^*\mathbf{c}^*(t), t = 0,1,2, \ldots$$

$\boldsymbol{n} \times \mathbf{1}$ vector of sector inoperabilities

$\boldsymbol{n} \times \boldsymbol{n}$ matrix of sector interdependence

$\boldsymbol{n} \times \mathbf{1}$ vector of sector demand perturbations

- Model trajectory depends upon $\mathbf{A}^*, \mathbf{K}^*, \mathbf{q}(0), \mathbf{c}^*(t)$
- $\mathbf{K}^*$ influences the rate at which balance in demand and supply is restored

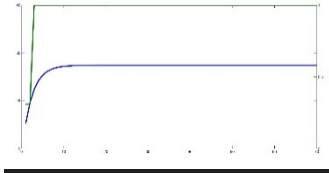
# INTERDEPENDENT IMPACT OF RESILIENCE

- To more accurately model **resilience** with the dynamic interdependency model, we develop a dynamic resilience matrix, $\mathbf{K}(t)$
  - We more explicitly account for **vulnerability** and **recoverability** from the resilience paradigm described previously

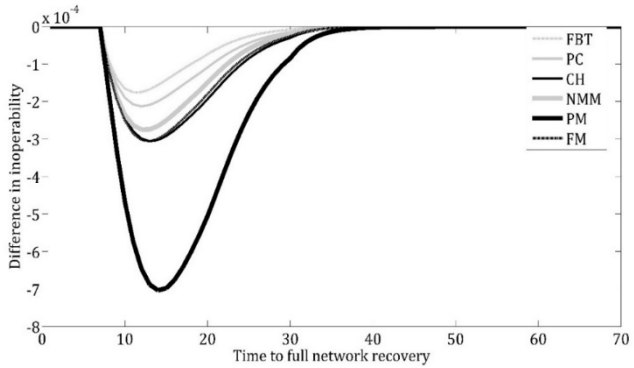
$$\mathbf{K}^*(t) = \frac{\mathbf{K}^*(0)}{Я_{\varphi}(t|e^j)}$$

- The new resilience-based interdependency model for economic impact is

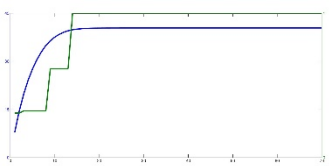
$$\mathbf{x}^T\mathbf{q}(t+1) = \mathbf{x}^T\left[\left(\mathbf{I} - \mathbf{K}^*(t)\right)\mathbf{q}(t) + \mathbf{K}^*(t)\mathbf{A}^*\mathbf{q}(t)\right]$$



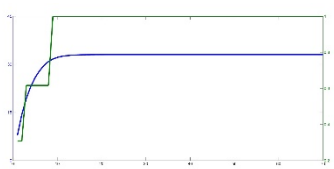
# ENDENT IMPACT OF RESILIENCE




- The interdependency model allows for an industry-specific analysis of the trade-off between recovery strategies



d=5, W1



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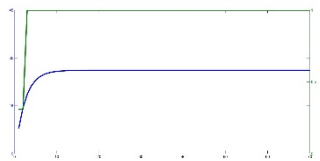

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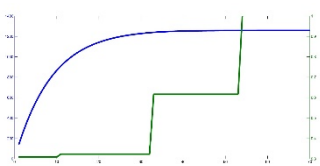

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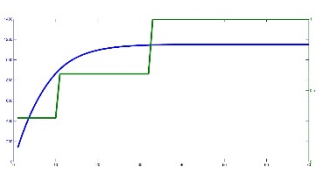

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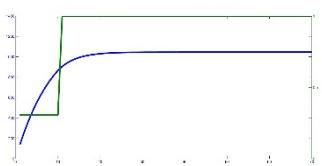


d=20, W3

- Economic losses across the six primary waterway industries (blue curve, left vertical axis) and network resilience (green curve, right vertical axis) over time for the three recovery strategies and two disruptive scenarios

# RESILIENCE-BASED COMPONENT IMPORTANCE MEASURE

Network performance loss due to disruption of link i

Time to full network restoration

$$\mathrm{CI}\text{Я}_{\varphi,i}\left(t_{\mathrm{r}}|e^{j}\right)=\frac{\varphi\left(\mathbf{x}(t_0)\right)-\varphi\left(\left(\mathbf{x}(t_0),x_i\left(t_d|V_i^{\,j}\right)\right)\right)}{\max_i\left\{\varphi\left(\mathbf{x}(t_0)\right)-\varphi\left(\left(\mathbf{x}(t_0),x_i\left(t_d|V_i^{\,j}\right)\right)\right)\right\}}T_{\varphi\left(\boldsymbol{x}(t_0)|V_i^{\,j}\right)}$$

Maximum loss among all the links

# RESILIENCE WORTH

Time to total network recovery

Time to total network recovery when component *i* *is invulnerable*

$$\text{WЯ}_{\varphi,i}\left(t_r|e^j\right) = \frac{T_{\varphi\left(\boldsymbol{x}(t_0)|V_i^j\right)} - T_{\varphi\left(\boldsymbol{x}(t_0)|V_i^j=0\right)}}{T_{\varphi\left(\boldsymbol{x}(t_0)|V_i^j\right)}}$$

$$0 < \text{WЯ}_{\varphi,i}\left(t_r|e^j\right) < 1$$

# DATA-DRIVEN APPROACH

Prior distribution (prior knowledge, expertise)

→

Bayesian kernel model (binary historical data, attributes)

→

Posterior distribution of the resilience worth

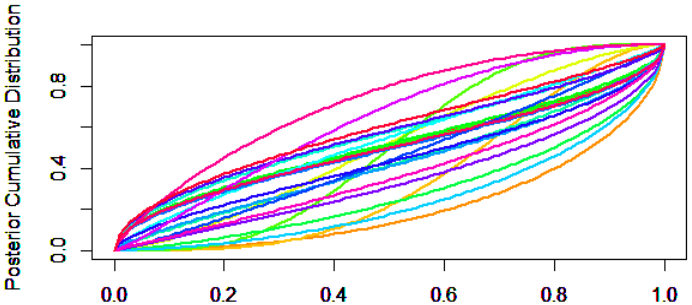
- Expected value of the posterior distribution

$$\mathrm{W}\text{Я}_{\varphi,i}\left(t_r|e^j\right) = \bar{\theta}_i = \frac{\alpha^*}{\alpha^* + \beta^*}$$

- Posterior probability distribution

$$f\left(\mathrm{W}\text{Я}_{\varphi,i}\left(t_r|e^j\right)\right) = \frac{\mathrm{W}\text{Я}^{\alpha^*-1}(1 - W\text{Я})^{\beta^*-1}}{\mathrm{B}(\alpha^*, \beta^*)}$$

# POSTERIOR DISTRIBUTION OF THE RESILIENCE WORTH

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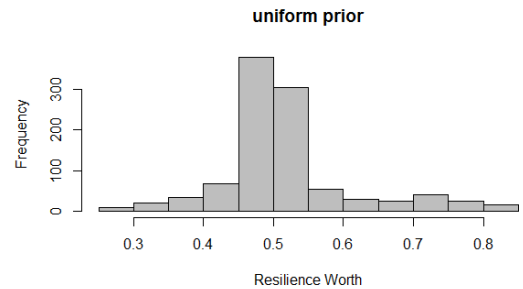


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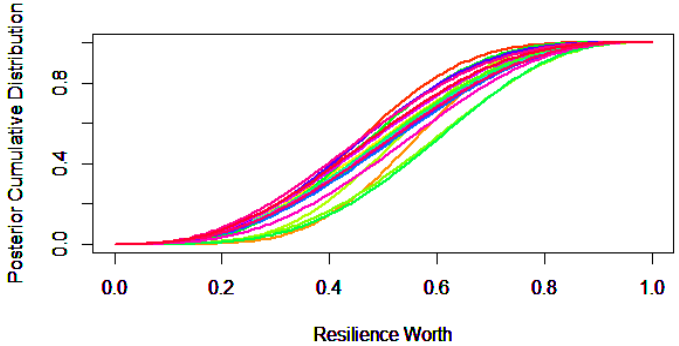


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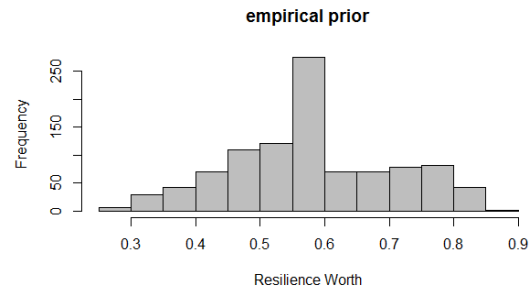


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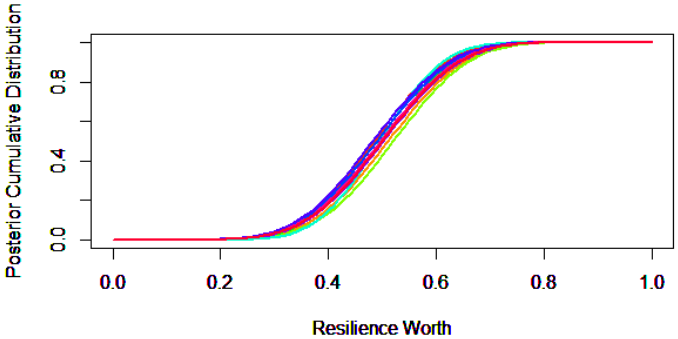


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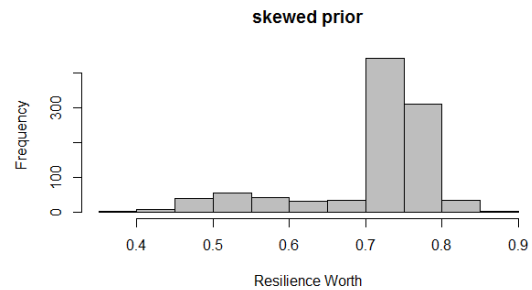


TP=0.99
TN=0.12
ACC=0.16

# END OF PRESENTATION

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