# National Water Pipeline Database – PIPEiD Webcast

June 10, 2021

# Housekeeping

- Submit questions through the question box at any time.  We will do a Q&A at the end of the webcast.
- Slides and a recording of the webcast will be available at www.waterrf.org.
- A certificate of completion will be automatically generated at the end of the webcast. Any questions, please contact Michelle Suazo at msuazo@waterrf.org.
- Survey at the end of the webcast.

THE Water Research FOUNDATION

# National Water Pipeline Database - PIPEiD


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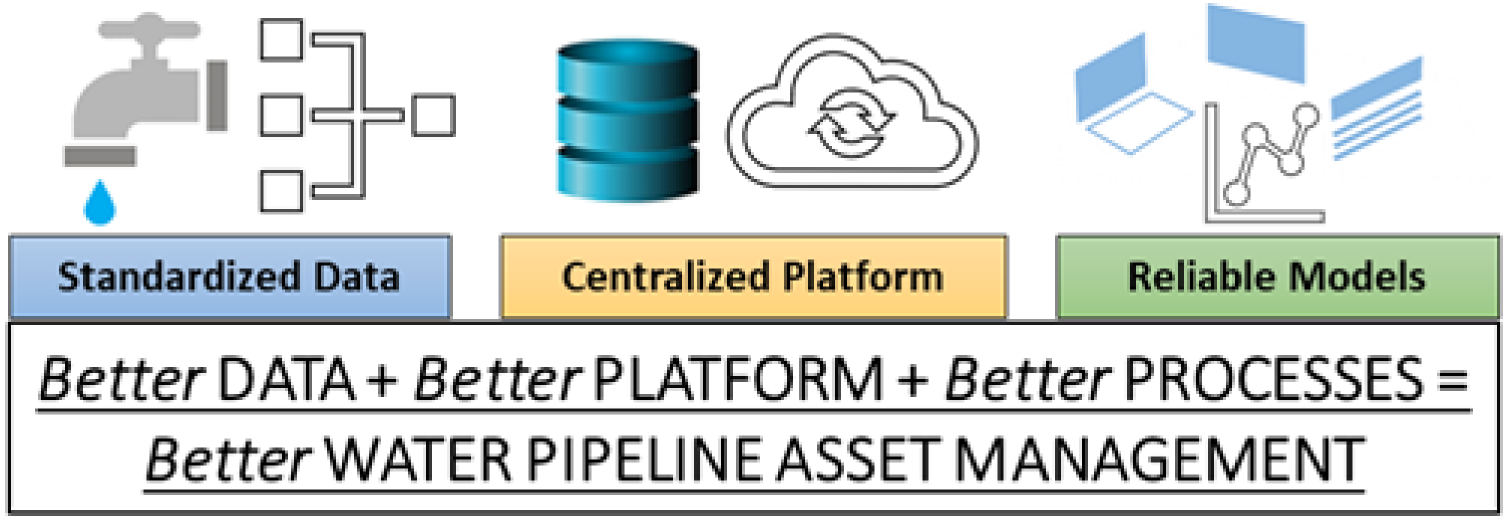
VIRGINIA TECH

SWIM Sustainable Water Infrastructure Management

PIPEiD PIPELINE *infrastructure* DATABASE

# National Water Pipeline Infrastructure Database Webcast Series

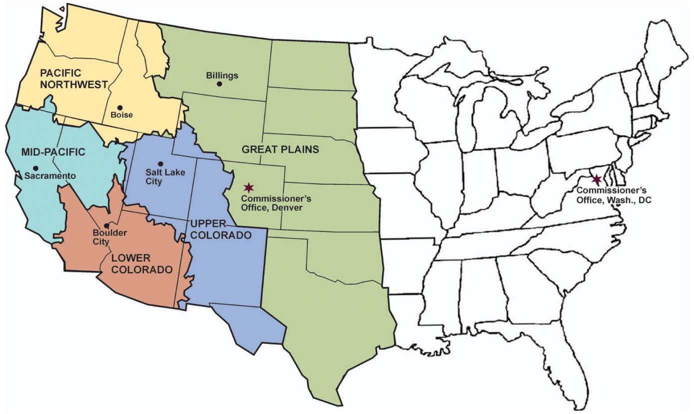



**June 3rd: Water Pipeline Infrastructure System Knowledge and Understanding, and Data Structure and Database Management for Asset Management**

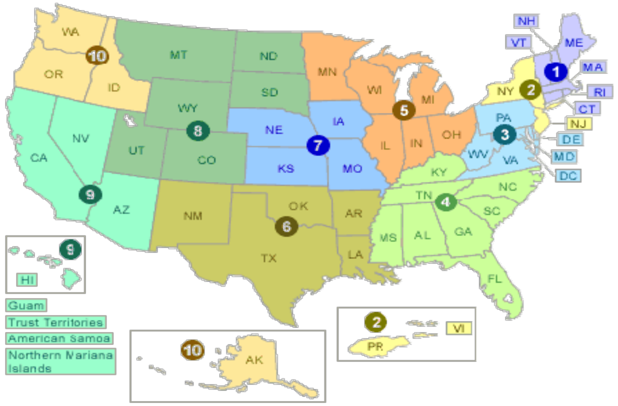
**June 8th: Water Pipeline Infrastructure System Descriptive and Correlation Analysis, and Survival/Weibull Curve Analysis for Asset Management**

**June 10th: Water Pipeline Infrastructure System Performance and Risk Analysis, and Life Cycle Economic Analysis for Advanced Asset Management**

BUREAU OF RECLAMATION




**100 Federal Facilities**




**500 Water Utilities**

## UNDER CONGRESSIONAL DIRECTION

## United States Senate Committee on Appropriations for Water & Energy Development

**Federal Register - OMB Control Number: 1006-0031**

## COLLECTION AND COMPILATION OF WATER PIPELINE FIELD PERFORMANCE DATA

- The purpose of this project is to collect high-quality field performance data on pipeline reliability for water pipelines of different materials, including cast iron, ductile iron, pre-tensioned concrete, reinforced concrete, steel, pvc, hdpe, others.
- This project will also develop a database capable of efficiently storing the collected data and supporting data analytics and analysis of the performance of water pipeline infrastructure systems across the county.

**This Project will lay the Foundation of a National Database of Water Utility Infrastructure.**

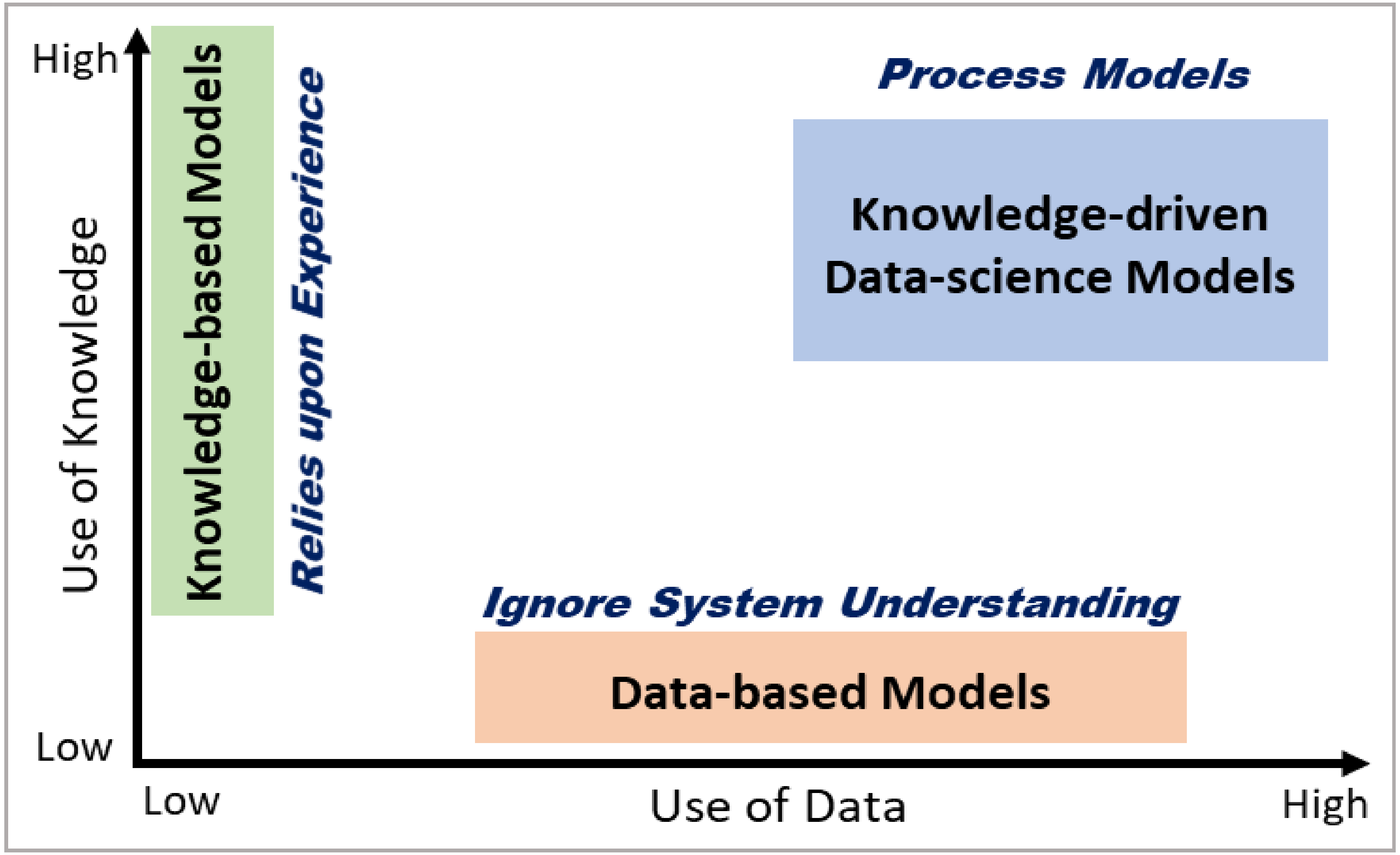
# Virginia Tech News & Release of Reports
## Friday, April 23, 2021

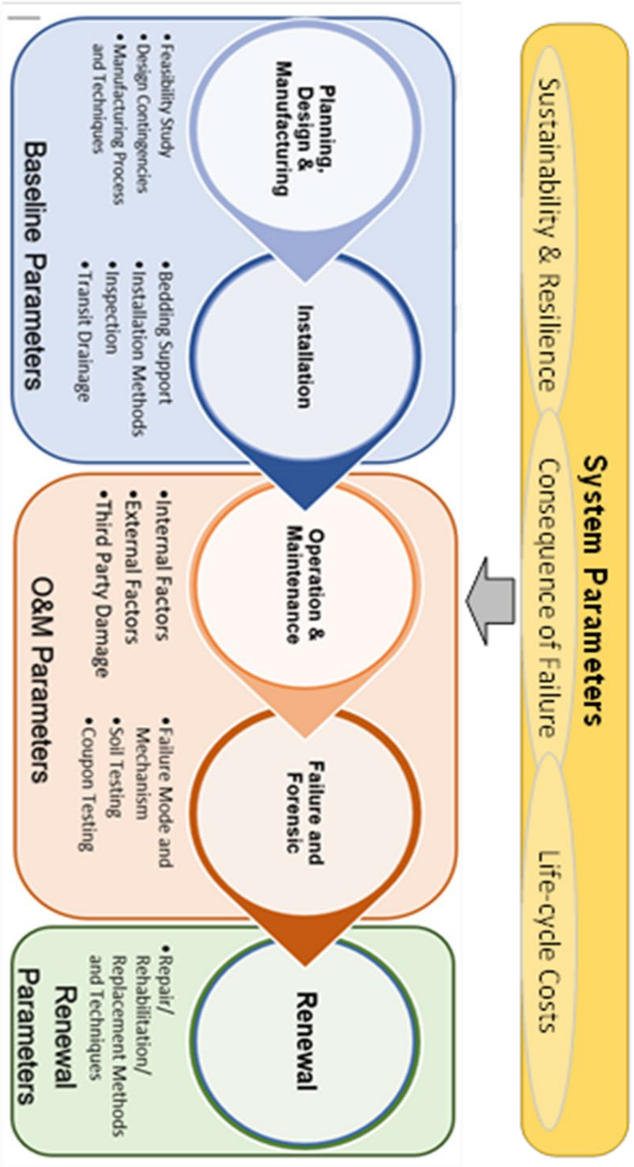
# Researchers collect data from water utilities for insights on the health of the nation’s pipelines

The team will fold the data and tools for its analysis into an online database designed to improve management of pipeline infrastructure systems for performance, resilience, and sustainability.

*April 22, 2021*

# Artificial Intelligence Application for Water Pipelines



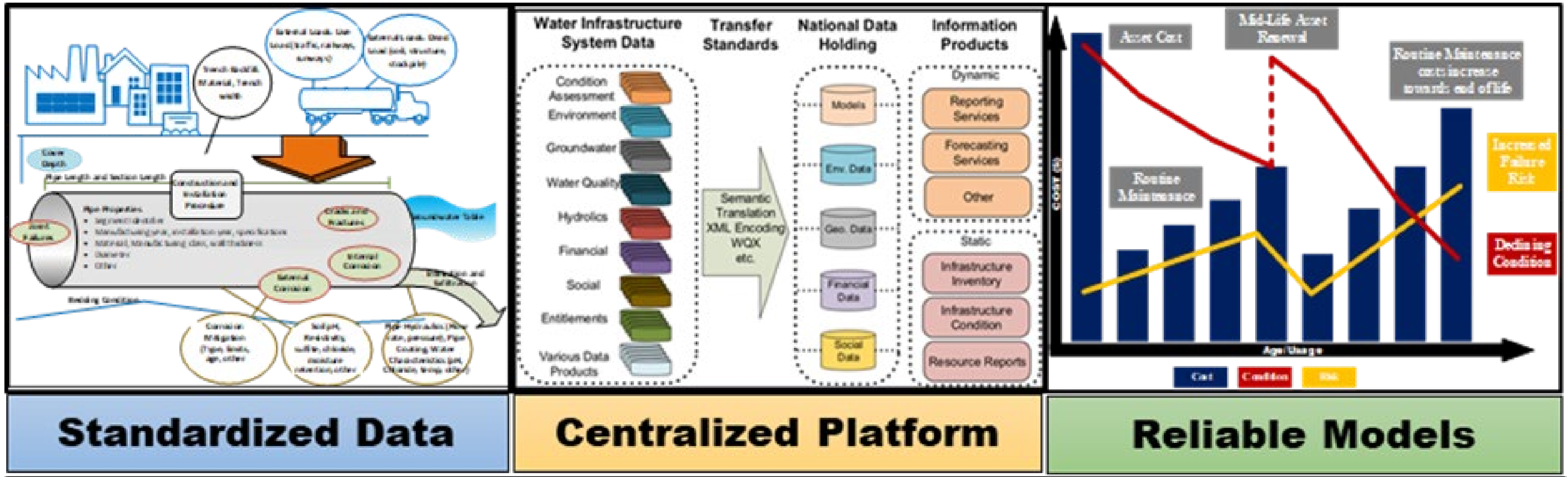

 

# Artificial Intelligence Application for Water Pipelines

***System-Centric*** **aspect would focus on systems of systems Understanding of water pipelines**

***Data-Centric*** **aspect would focus on substantial datasets of water pipeline**

***Model-Centric*** **aspect would focus on annotation and sharing of robust models**

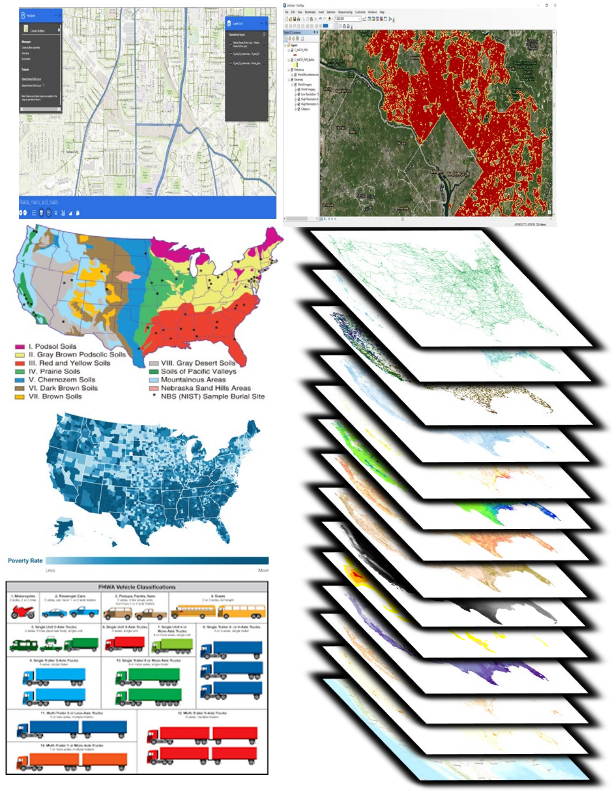


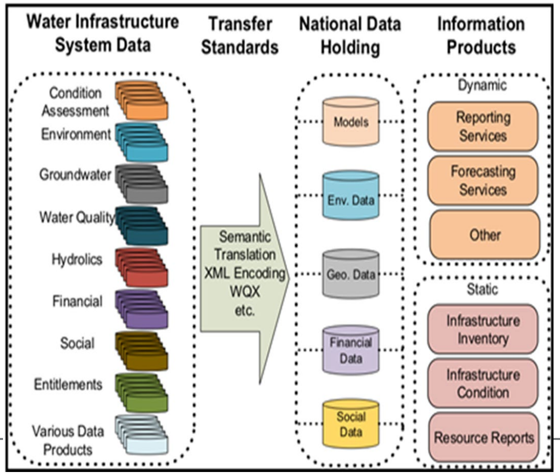

***Better*** **DATA +** ***Better*** **PLATFORM +** ***Better*** **PROCESSES**
**=** ***Better*** **WATER PIPELINE ASSET MANAGEMENT**

# PIPEiD Database Architecture

## Data Source






- Local – For specific Water Utility
- Regional – For specific Ecological Cohorts
- Global – For entire USA

Ecological Cohorts
- Climatic conditions (arid, coastal, arctic, mountainous)
- Natural event conditions (earthquakes, hurricane, cyclone, floods)
- Operational conditions (soil temperature, groundwater, traffic loading, railway tracks and others)

**Performance Analysis Framework**

- Metallic: CI, ST, DI, GI, WI
- Plastic: PVC, PE
- Cementitious: PCCP, RCP, BWP, AC

**Diameter**: <16" | 16"-36" | >36"

- **Design and Installation**
  - Lining/Coating
  - Bedding specifications
  - Joint characteristics
- **Corrosion**
  - Internal
    - Water Corrosivity
    - Corrosion Protection (Lining)
    - Friction Factor
  - External
    - Soil Corrosivity
    - Stray Current
    - Corrosion Protection (Coating/ Wrapping/ Cathodic Protection)
    - Soil Moisture
    - Groundwater Corrosivity
- **Loading**
  - Internal
    - Hydraulic Pressure
    - Frequency of Pressure Surge Events
    - Proximity to valves and pump stations
    - Water Temperature
  - External
    - Traffic Loading (Roads, Railways)
    - Frost Loading
    - Frost Action
    - Improper bedding
    - Soil Temperature Regime
- **Failure and Defect Analysis**
  - Mean Age at First Failure
  - Successive Failures
  - Failure Mode
  - Failure Root Cause
  - Failure Rate
- **Unpredictable Events**
  - Frequency of earthquakes (Proximity to fault lines)
  - Coastal Area (Saltwater Intrusion)
  - Third party damage

**Target Deliverables**

**Descriptive Analysis**
- Characteristics: Material, Lining, Coating, Cathodic Protection distribution
- Trend Analysis: Installation and Failure Trends
- Performance Analysis: Influence of performance parameters

**Statistical Analysis**
- Descriptive Analysis: Distribution, Correlation, Clustering
- Failure Analysis: Survival curves and Useful Life Prediction
- Performance analysis: Performance Index and Performance Curves

**Risk Analysis**: Risk Matrix developed using LoF, CoF and Criticality

**Economic Analysis**: Future spending, Lifecycle Costs and Optimum Replacement times and methods

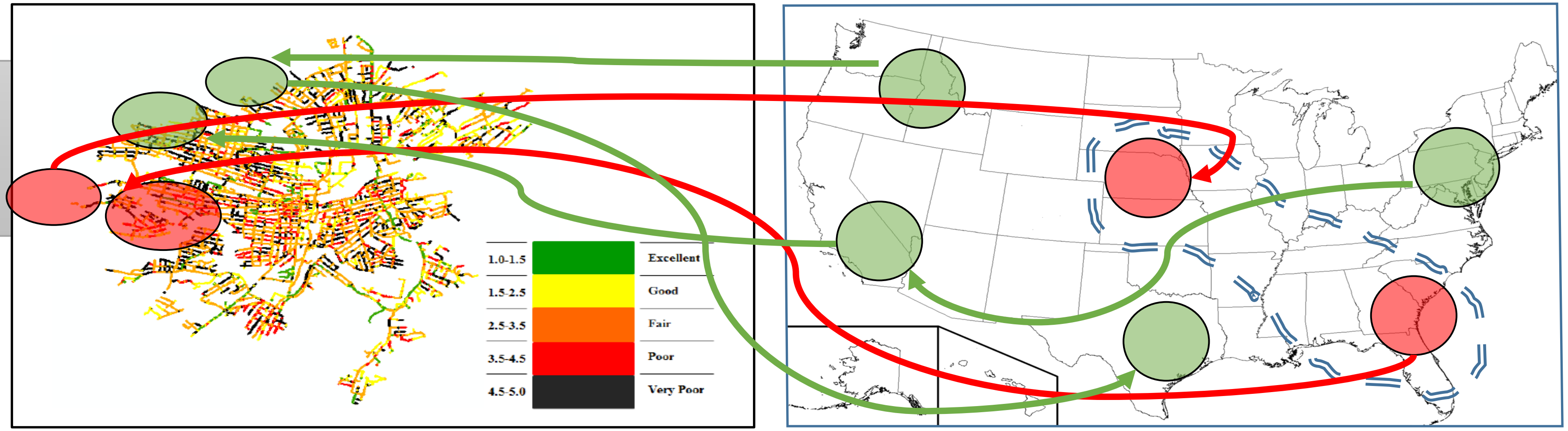
SPATIAL ANALYSIS

# Water Utilities Data and Analysis

Data Collection, Compilation and Database Management → Statistical Qualitative and Quantitative Analysis for Hypothesis Testing → Information and Knowledge to Support Advanced Water Pipeline Asset Management

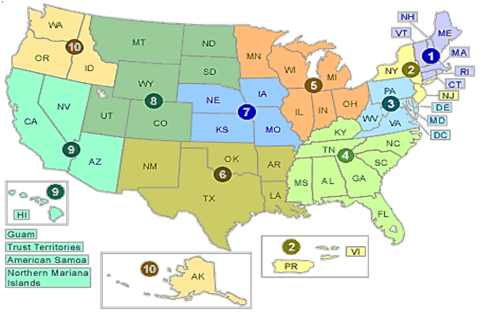
Cross Scale Interaction → Cohort Analysis → Global Trend Emerges

**LOCAL ANALYSIS**




**REGIONAL ANALYSIS**

**Identify the high-level trends across the country and around the world**






**GLOBAL ANALYSIS**

# Key Findings & Deliverables

1. Understanding the Pipeline Infrastructure Systems
2. Developing the data Standard to Support Analysis
3. Developing the Protocol for Database Management

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4. Understanding the Pipeline Descriptive Analytics

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5. Understanding Pipeline Performance Characteristics
6. Understanding Risk Assessment & Management
7. Life-Cycle Cost and Economic Analysis

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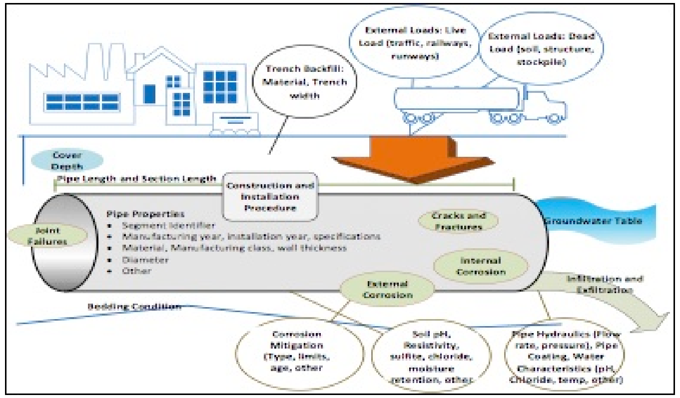
Visualization & Decision-Support System – PIPEiD Website

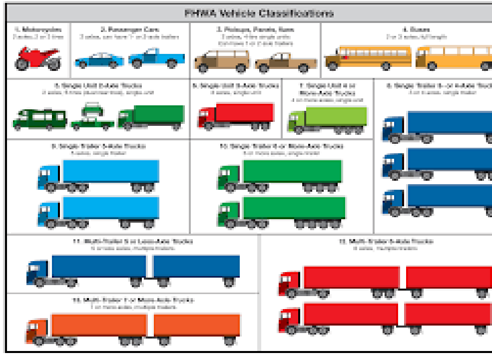
# Benefits for Participating Water Utilities

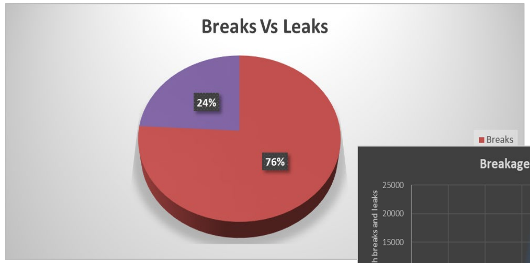
- **Standardized Data**
  - **Comprehensive Standardized Data**
  - ***External Data Service***
    - **Utility data will be combined with external data sources like EPA, USGS, SSURGO, NLCD, etc.**

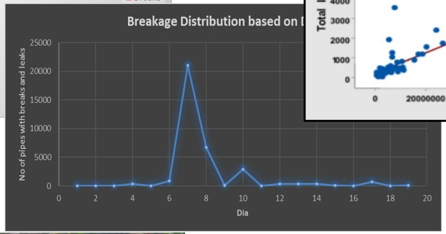
- **Data Analytics**
  - **Strategical – General Information**
  - **Tactical – Pipe Performance Analysis**
  - **Operational – Advanced Models/Tools**

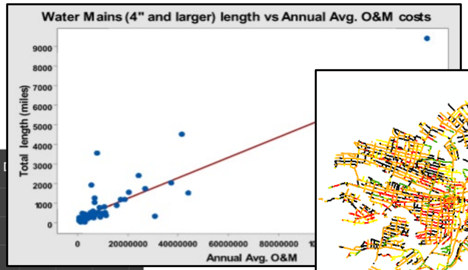
- **Decision Support**
  - **Preliminary Analysis of the Standardized Utility Data**
  - **Visualization of GIS Web-applications for decision support**

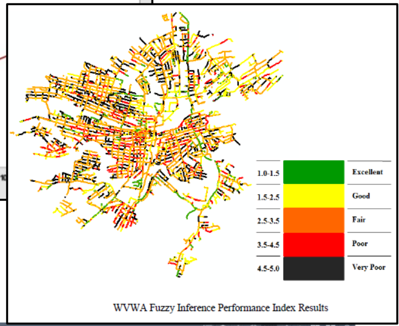


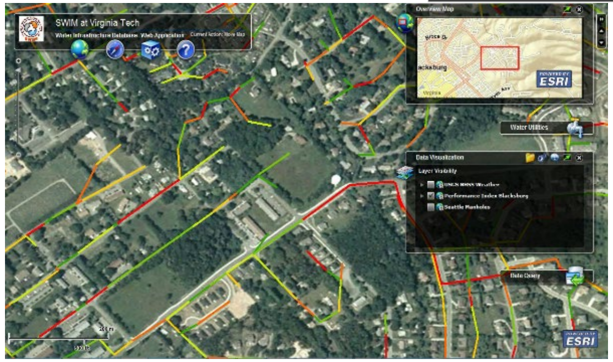



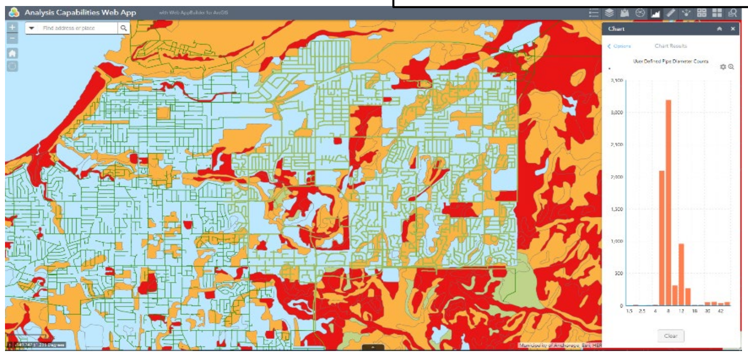



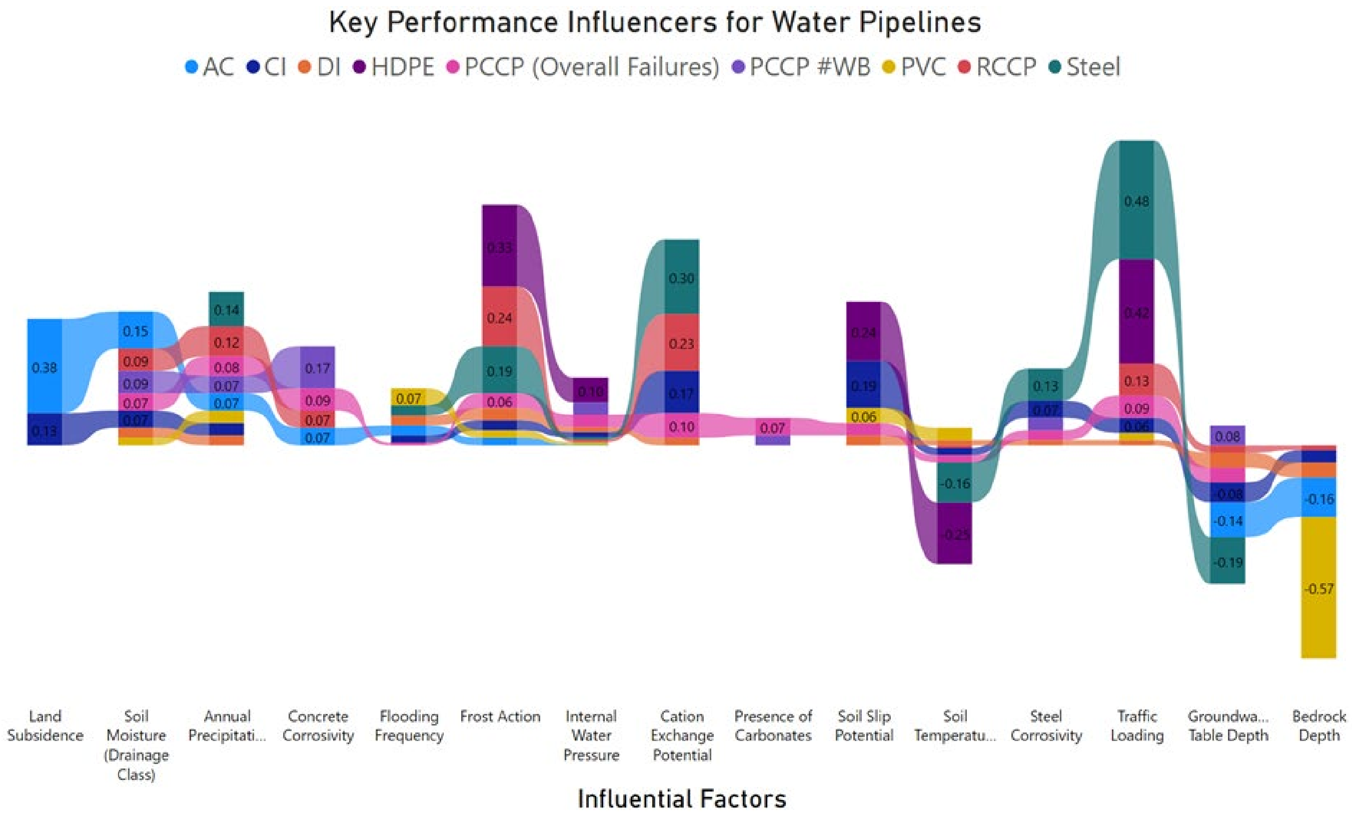



# Correlation Analysis

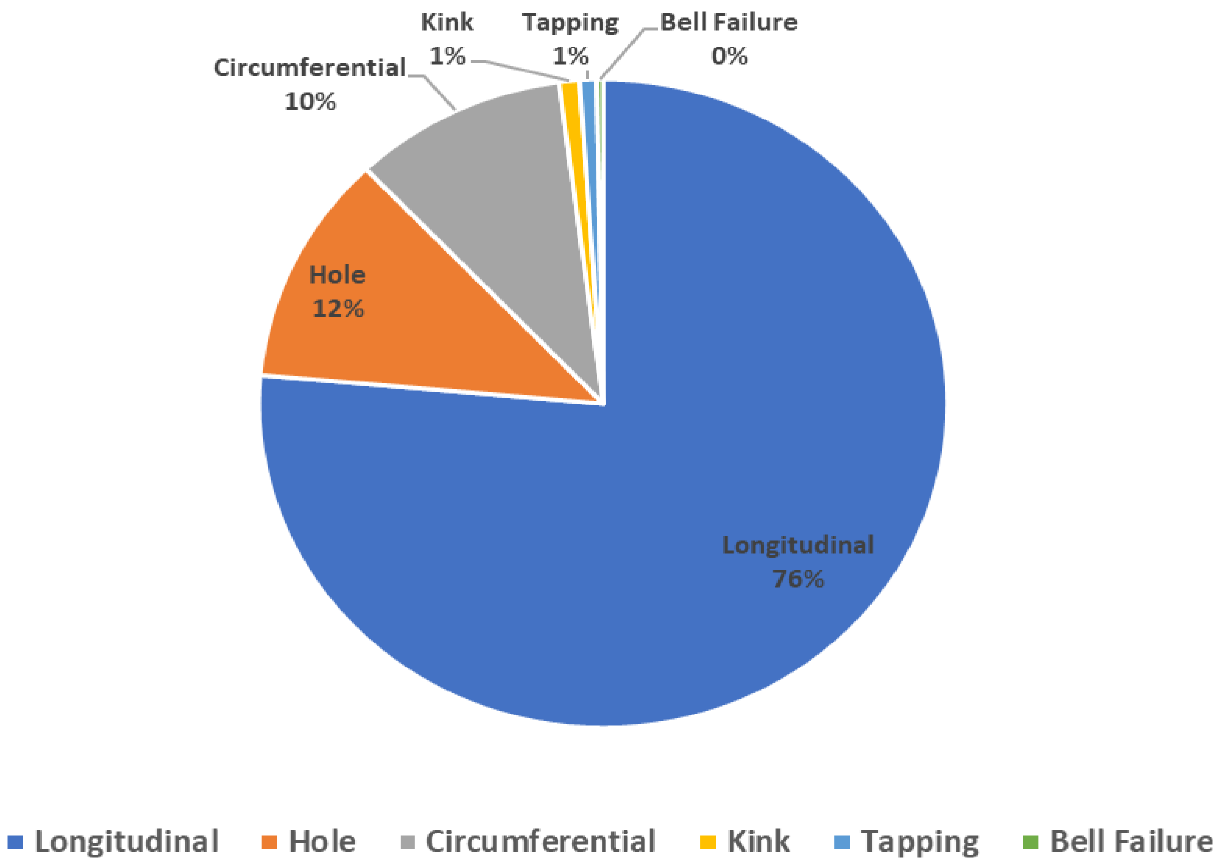
## WATER PIPELINE PERFORMANCE INFLUENCING FACTORS

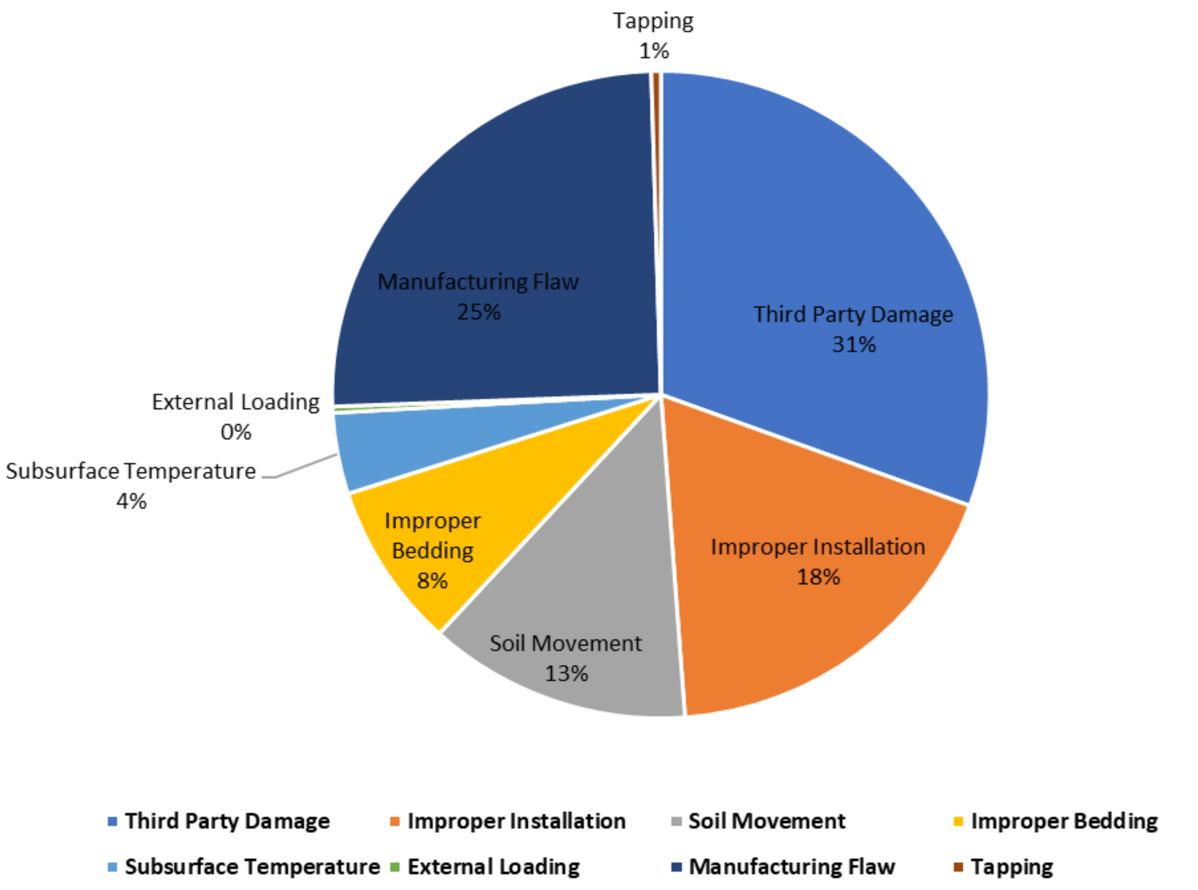



| Metallic | | | Cementitious | | | Plastic | |
|---|---|---|---|---|---|---|---|
| Steel | CI | DI | PCCP | RCCP | AC | PVC | HDPE |
| Cation Exchange Potential | Soil pH | Soil pH | Cation Exchange Potential | Cation Exchange Potential | Land Subsidence | Bedrock Depth | Frost Action |
| Traffic Loading | Soil Corrosivity | Soil Chlorides | Concrete Corrosivity | Frost Action | | Bedding Quality | Traffic Loading |
| Internal Water Pressure | Redox Potential | Redox Potential | Soil Moisture | | | | Internal Water Pressure |
| Corrosion Protection | Soil Resistivity | C Factor (Unlined) | Traffic Loading | | | | Bedding Quality |
| | C Factor (Unlined) | Internal Water Pressure | Carbonate Presence and Reactivity | | | | |
| | Internal Water Pressure | Corrosion Protection | Bedding Quality | | | | |
| Soil Corrosivity | Land Subsidence | Soil Sulfates | Metallic Corrosivity | Traffic Loading | Bedrock Depth | Soil Slip Potential | Soil Slip Potential |
| Soil Moisture | Internal Water Agg. | Soil Resistivity | Soil Slip Potential | Soil Moisture | Soil Moisture | Soil Temp. | Soil Temp. |
| Frost Action | Stray Current | Soil Type | Frost Action | Concrete Corrosivity | Internal Water Aggressivity | Frost Action | Water Temp. |
| Soil Temp. | | Soil Slip Potential | Internal Water Pressure | Bedrock Depth | Carbonate Presence and Reactivity | Traffic Loading | Soil Type |
| Soil Type | | Frost Action | Corrosion Protection | Corrosion Protection | | Internal Water Pressure | Buried Depth |
| G/W Table Depth | | G/W Table Depth | Internal Water Aggressivity | Internal Water Aggressivity | | Water Temp. | |
| Stray Current | | Stray Current | | Carbonate Presence and Reactivity | | Soil Type | |
| | | Internal Water Agg. | | | | Buried Depth | |
| | Soil Sulfates | Soil Moisture | Soil Temperature | | Frost Action | | |
| | Soil Moisture | Soil Temp. | | Soil Type | Soil Type | | |
| | Soil Chlorides | Internal Water Pressure | | | | | |
| | Traffic Loading | | | | | | |
| | Internal Water Pressure | | | | | | |

# Descriptive Analysis

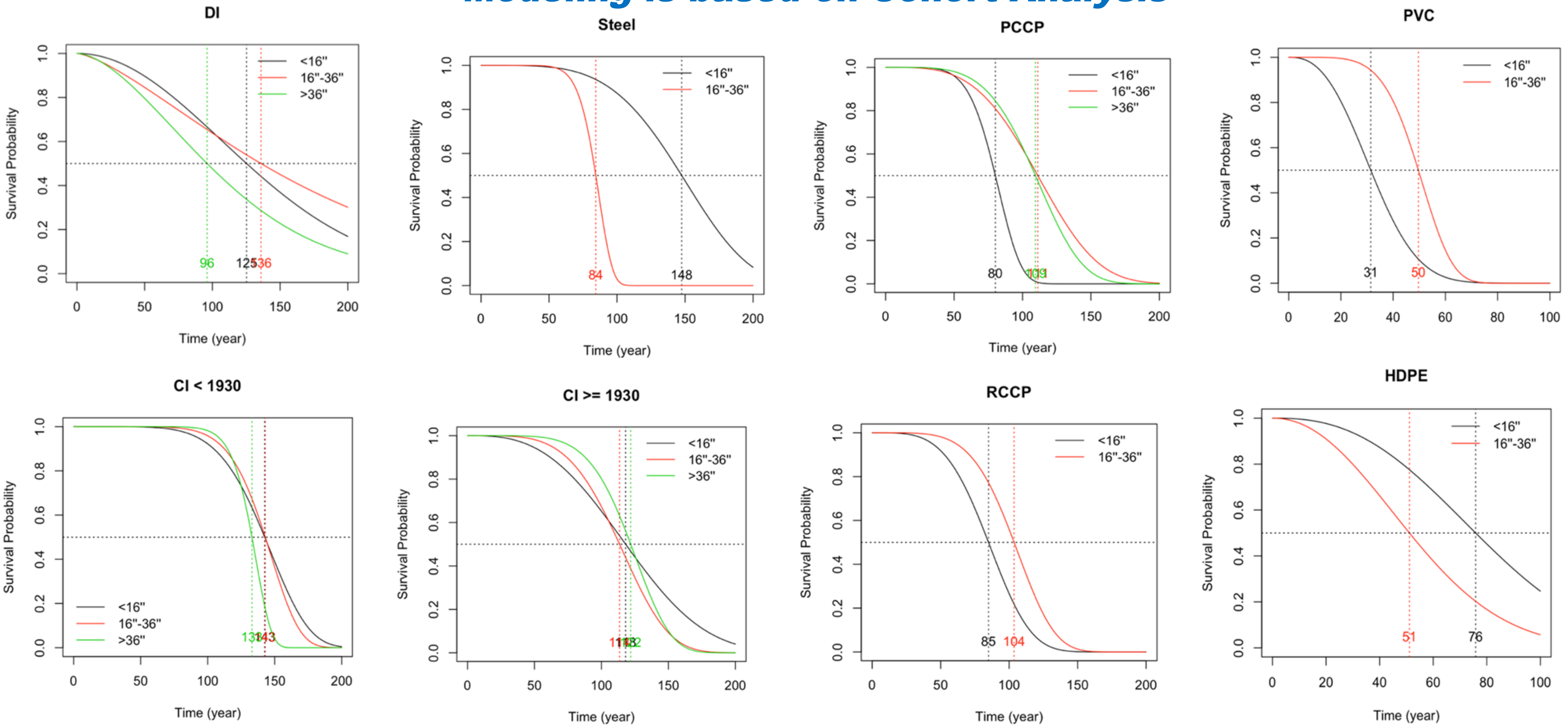
## WATER PIPELINE FAILURE MODE & MECHANISMS



# Remaining Useful Life Estimation Using Mixed Methods

## *Modeling is based on Cohort Analysis*

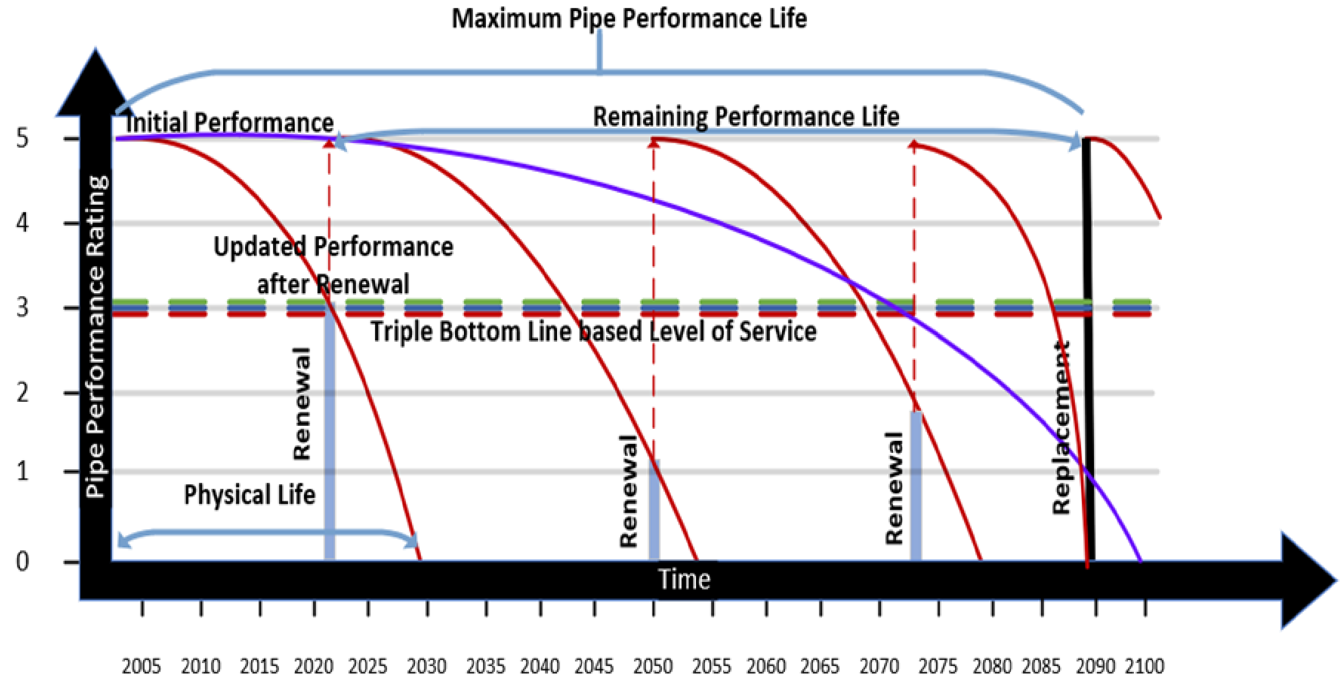


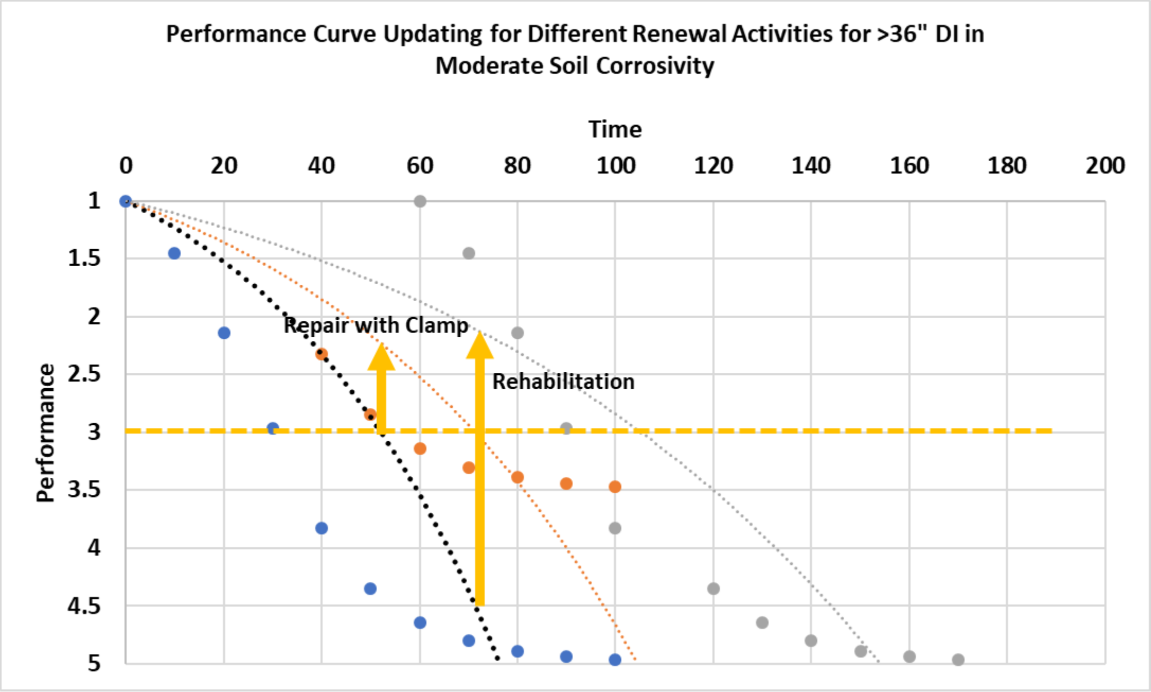
# Water Pipeline Performance Analysis

*Model can run on the pipe segment*

**Given the different scaling methods, the 1-5 scale is mostly widely used, and it is also proved to be a balanced tradeoff between the granularity and statistical significance.**

| Grade | Representation | Range |
|---|---|---|
| 1 | Excellent | 100-81 |
| 2 | Good | 80-61 |
| 3 | Fair | 60-41 |
| 4 | Poor | 40-21 |
| 5 | Failed | 20-0 |



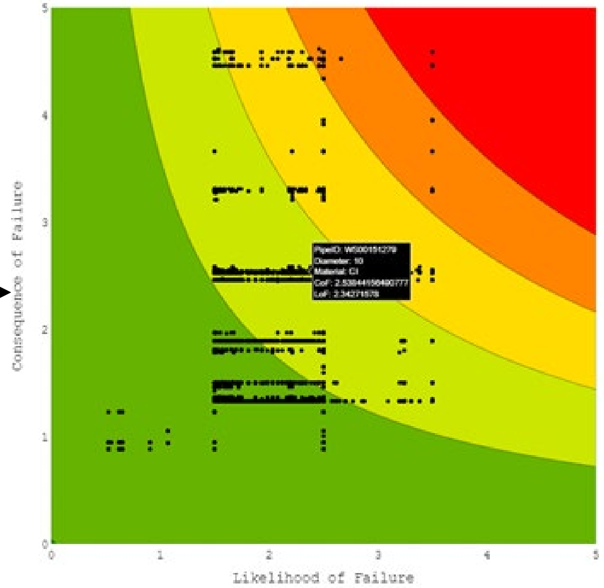
# Water Pipeline Risk Matrix Development

## *Model can run on the pipe segment*

- LoF values obtained from Performance model
- CoF values obtained from Fuzzy Logic model
- LoF and CoF obtained on 1-5 scale
- 5x5 Risk Matrix
- CoF model takes a triple bottom line approach
  - 5 modules: Economic Impact, Environmental Impact, Social Impact, Operational Impact and Renewal Complexity capture 19 parameters
  - Models assumptions vary with diameter range
  - Model can be applied to all materials

| Likelihood of Failure Score | Description | Color |
|---|---|---|
| 1 | Very Good | Dark Green |
| 2 | Good | Light Green |
| 3 | Fair | Yellow |
| 4 | Poor | Orange |
| 5 | Very Poor | Red |

| Consequence of Failure Score | Color Coding | Description |
|---|---|---|
| 1 | Dark Green | Insignificant |
| 2 | Light Green | Minor |
| 3 | Yellow | Moderate |
| 4 | Orange | Major |
| 5 | Red | Catastrophic |



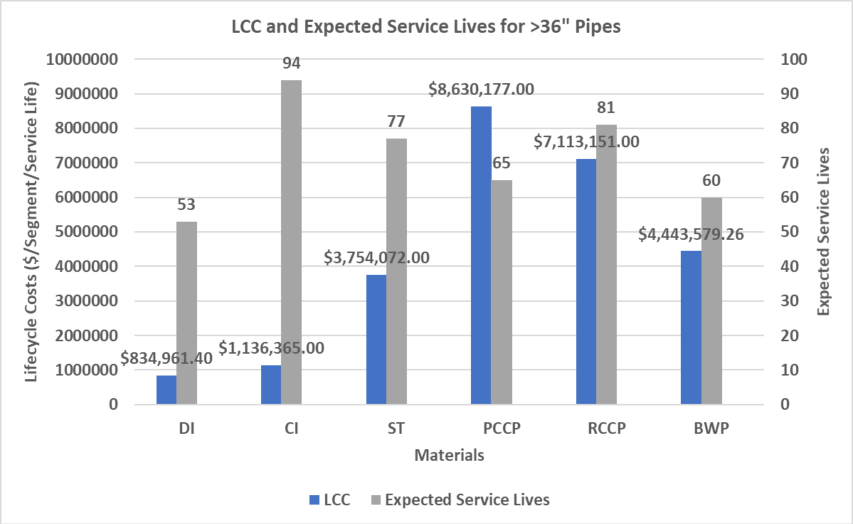

# *Likelihood of Failure and Consequence of Failure*

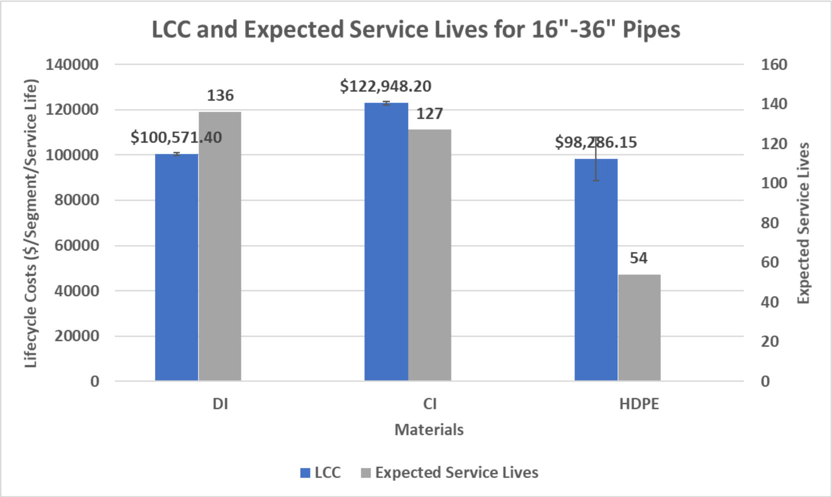
# Lifecycle Economic Analysis of Water Pipelines

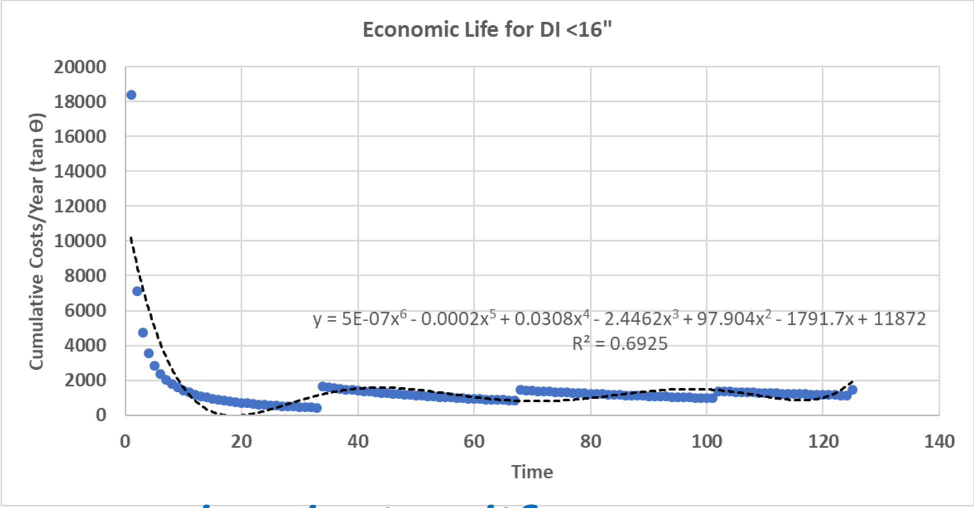
- Probabilistic estimates for parameters based on Monte Carlo simulation of data distributions
- Renewal timings predicted based on pipe performance in ecological conditions
- Results presented for Lifecycle costs and Expected Service Lives with 95% confidence intervals
- Currently in piloting stage with participating water utilities
- Analysis performed in the preliminary results (on the right) for material and diameter stratifications. Final results will include estimates for ecological conditions

**Lifecycle Costs for Water Pipeline Material and Diameter Categories**

| Material | Diameter | Lifecycle Costs ($/segment) ± 95% CI | Expected Service Life (Years) |
|---|---|---|---|
| DI | <16” | $180,913±490 | 125 |
| | 16"-36" | $100,571.4±609 | 136 |
| | >36" | $834,961.4±16,622 | 53 |
| Steel | >36" | $3,754,072±75721 | 94 |
| CI | <16" | $281,417±594 | 130 |
| | 16"-36" | $122,948±824 | 127 |
| | >36" | $1,136,365±34,520 | 94 |
| RCCP | >36" | $7,113,151±72,677 | 81 |
| PCCP | >36" | $8,630,177±6,133 | 65 |
| BWP | >36" | $4,443,579±81,368 | 60 |
| PVC | <16" | $119,769±411 | 55 |
| HDPE | <16" | $241,715.6±6,278 | 78 |
| | 16"-36" | $98,286±9,551 | 54 |



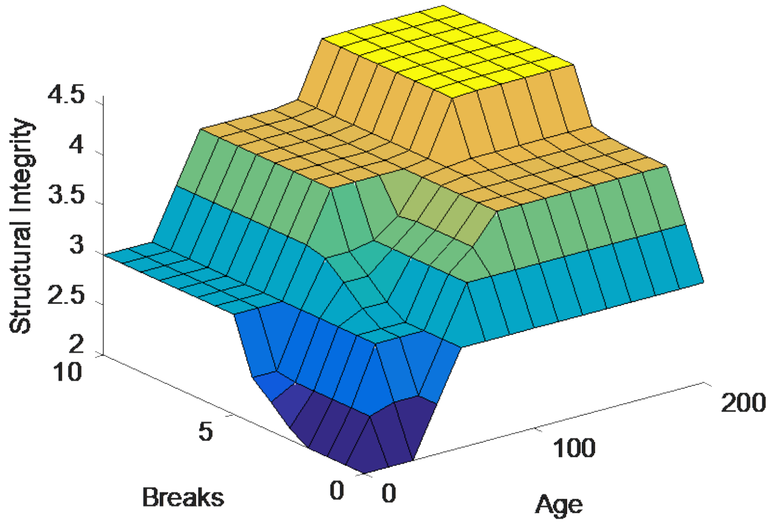



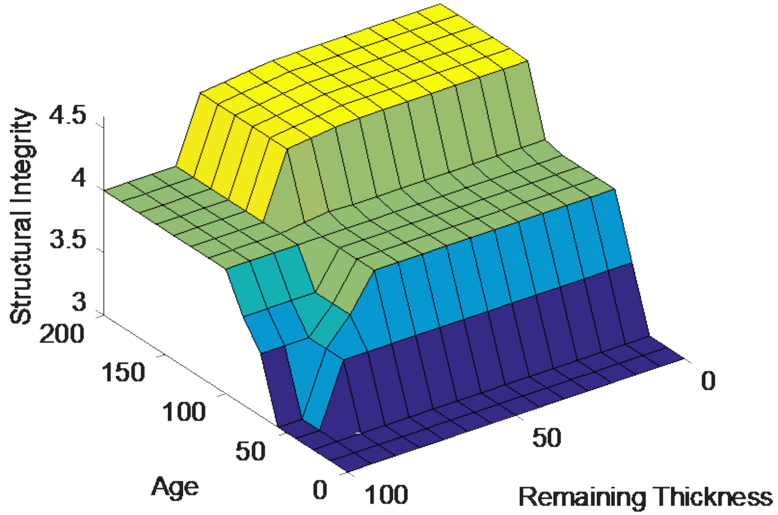




*Analysis should be based on service life – not the design life*

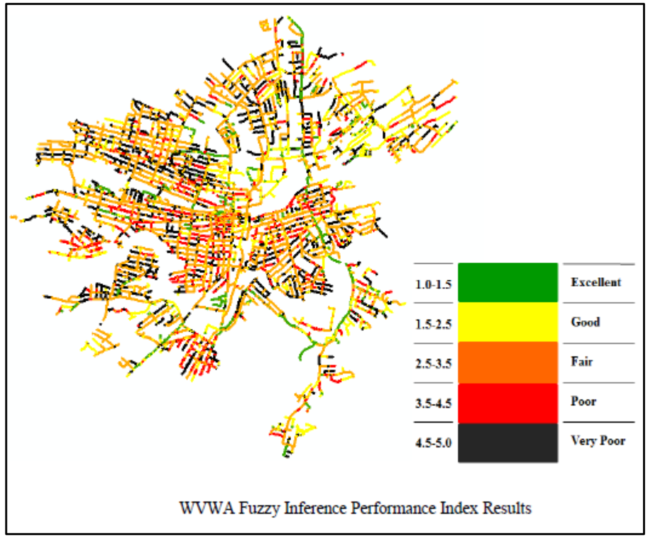
# Piloting of AI-Driven Platform at National Scale

## SENSITIVITY ANALYSIS

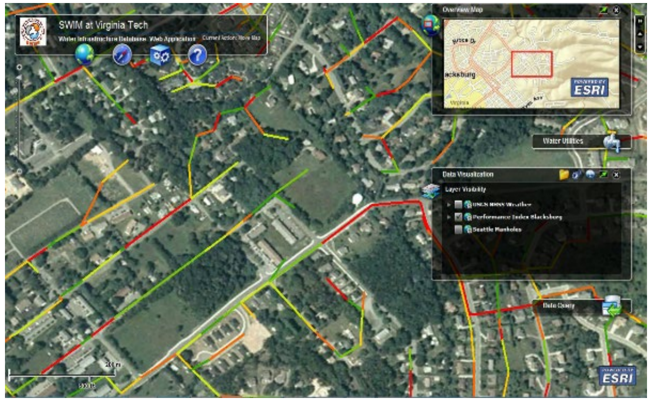


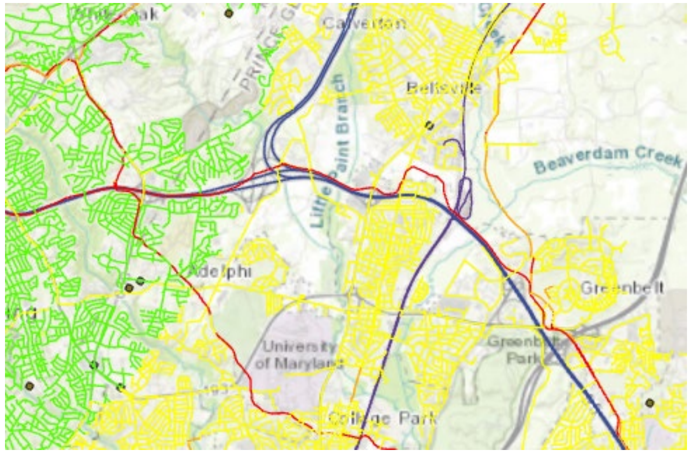

## EXISTING UTILITY MODELS




WVWA Fuzzy Inference Performance Index Results




## BLIND TESTING



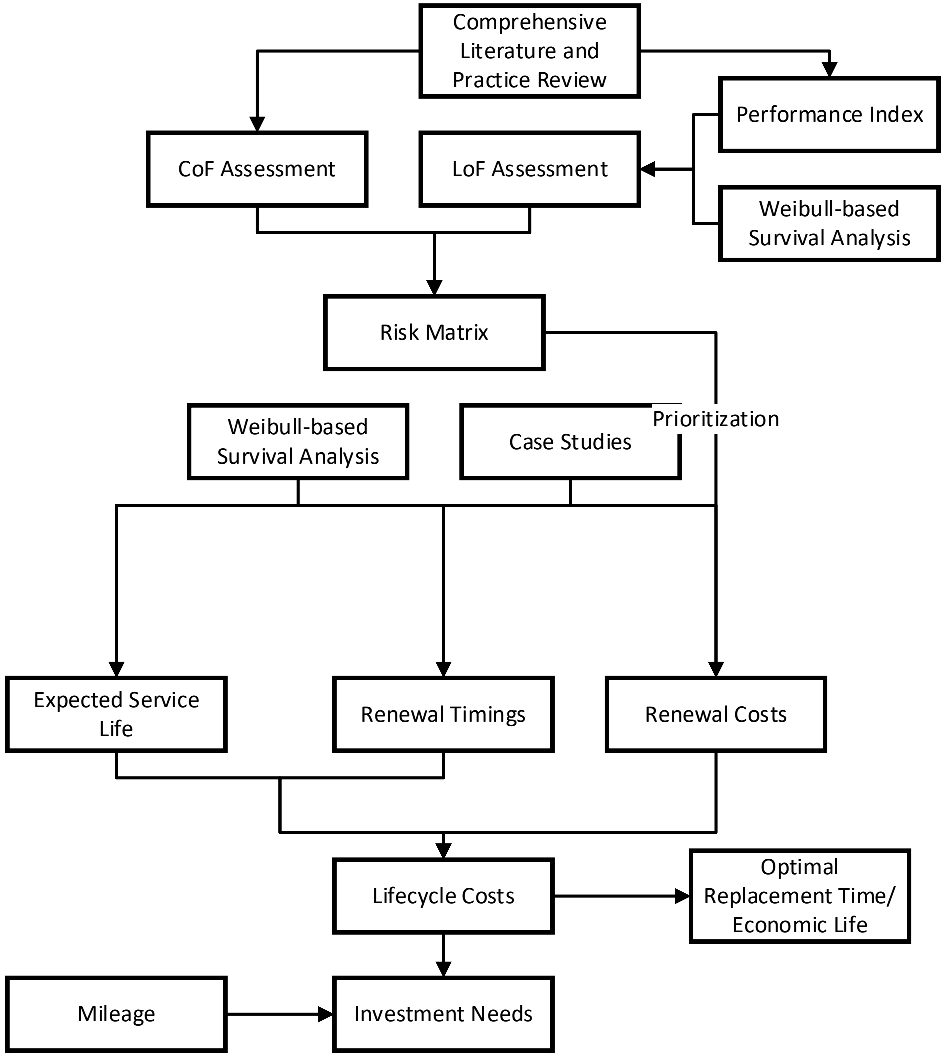

PIPEiD

PIPELINE *infrastructure* DATABASE

# Water Pipeline System Risk Management and Life-cycle Economic Analysis

# RISK AND ECONOMIC ANALYSIS-METHODOLOGY

*Building on results from Performance Analysis and combining with results from CoF model to develop Risk Matrix. Risk Analysis used for prioritizing pipes for renewal*

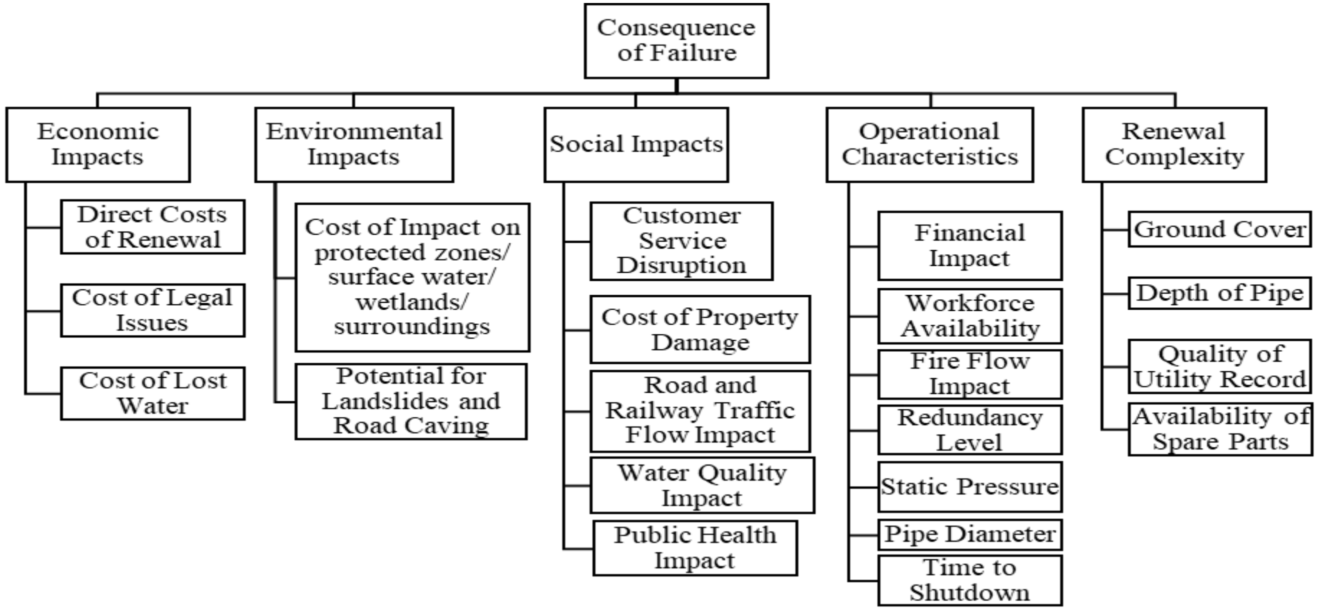


# COF MODEL DATA STRUCTURE

| Score | Category | Description |
|---|---|---|
| **0-1** | Insignificant | Minimum to no renewal costs, environmental impacts, social disruption, easily renewable |
| **1-2** | Minor | Minor impact due to failure on renewal costs, environmental impact or social impact and is easy to renew |
| **2-3** | Moderate | Some CoF parameters have moderate impacts on renewal costs, environmental impact or social impact or is not very easy to renew |
| **3-4** | Major | May have a high impact on renewal costs, environmental impact or social impact or is very hard to renew |
| **4-5** | Catastrophic | Critical and may have a very high impact on renewal costs, environmental impact or social impact. |

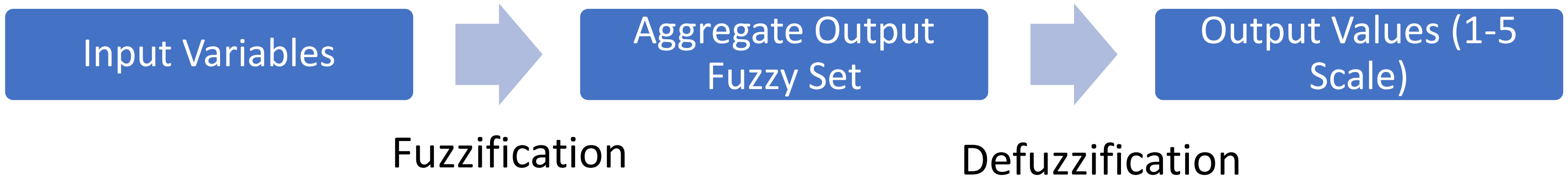
- 1-5 Rating System for Water Pipe
- Balanced trade-off between granularity and statistical analysis

- Includes 5 modules and 21 parameters
- Covers TBL parameters and Operational and Renewal Complexities
- Based on extensive literature, practice review, and interview with water utility experts



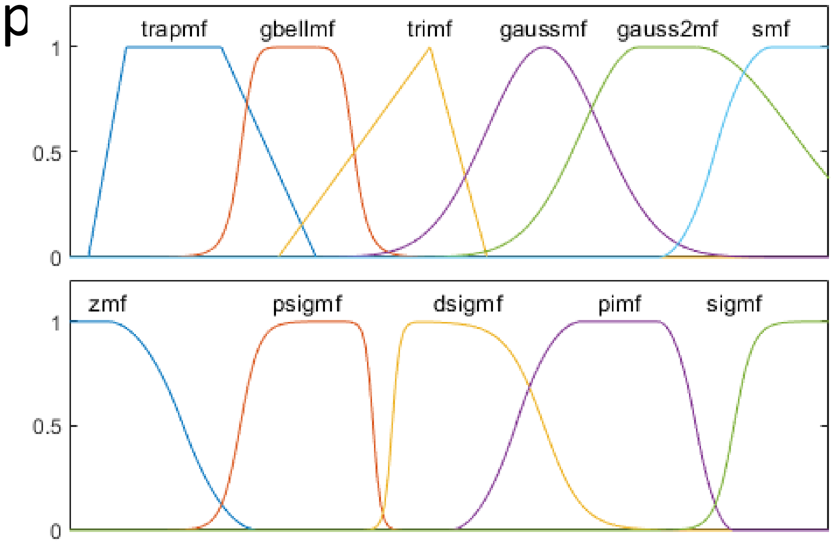
# COF MODEL DEVELOPMENT USING FUZZY LOGIC

**Modeling Process**

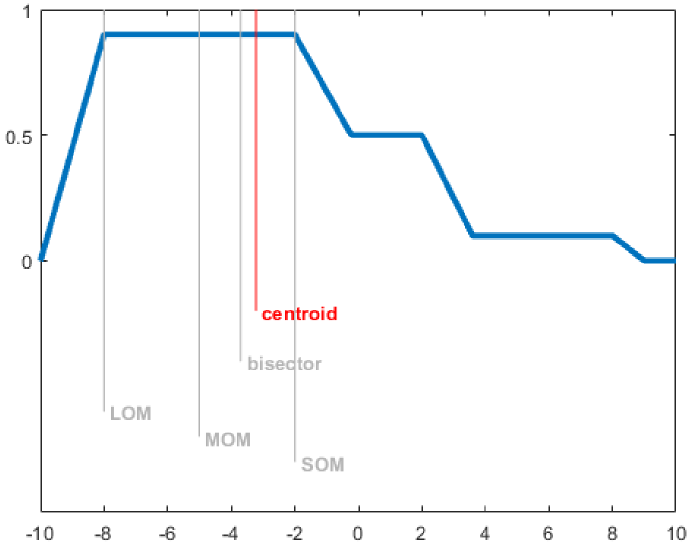



- Mamdani Fuzzy Inference System
- Triangular fuzzy membership function mostly used in combination with trapezoidal and gaussian
  - Widely used
  - Easier to develop
- Centroid method for defuzzification

Types of membership functions

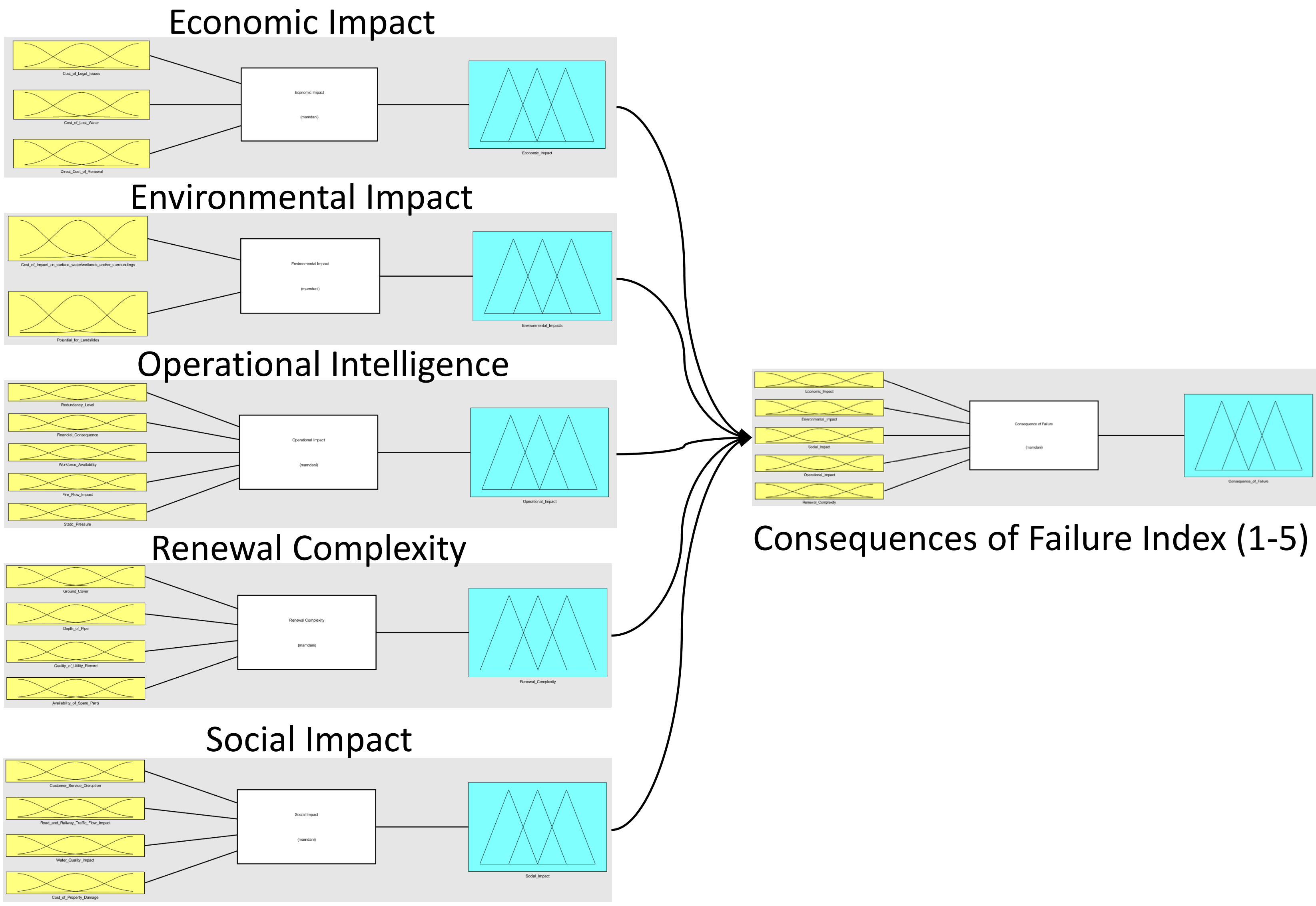



Defuzzification Method



# FUZZY INFERENCE SYSTEM DEVELOPMENT

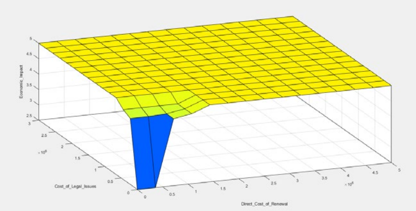
- Model divided into 6 modules
- Reduces number of rules
- Helps in model evaluation



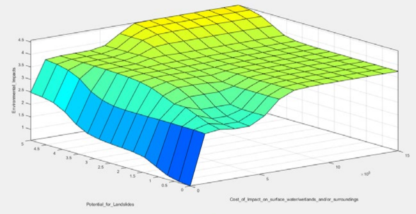
# SENSITIVITY ANALYSIS

*Internal Verification of Models based on Global Sensitivity Analysis to understand influence of parameters on outputs*

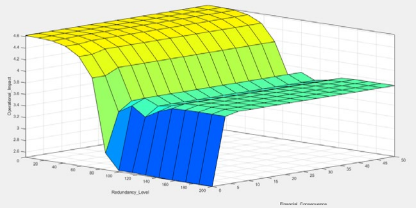
Economic Impact



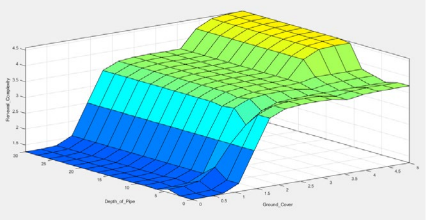
Environmental Impact



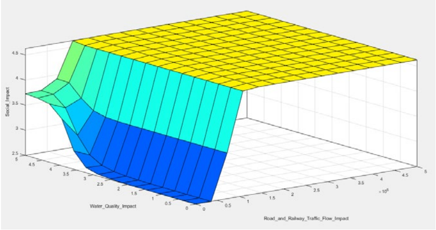
Operational Intelligence

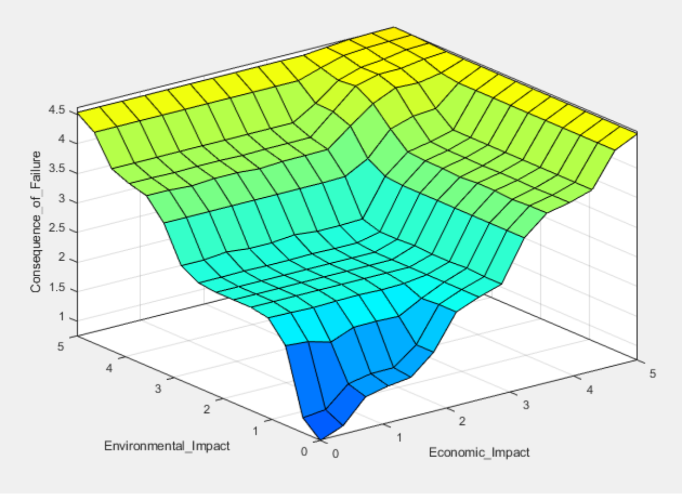


Renewal Complexity



Social Impact

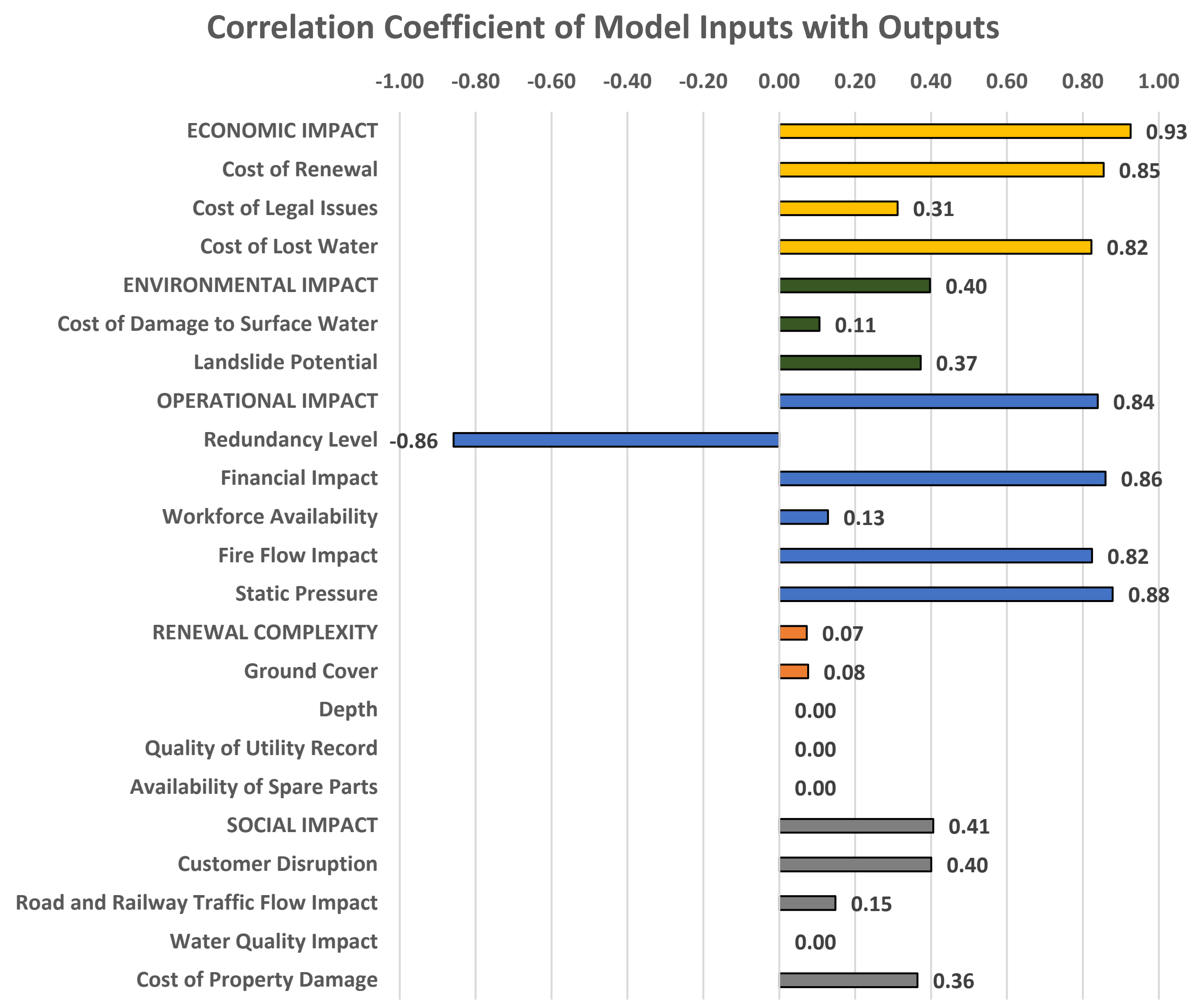





Consequences of Failure

# MODEL CORRELATION WITH INPUT PARAMETERS

*Economic Impact module and associated parameters has one of the highest impacts on the overall model output*

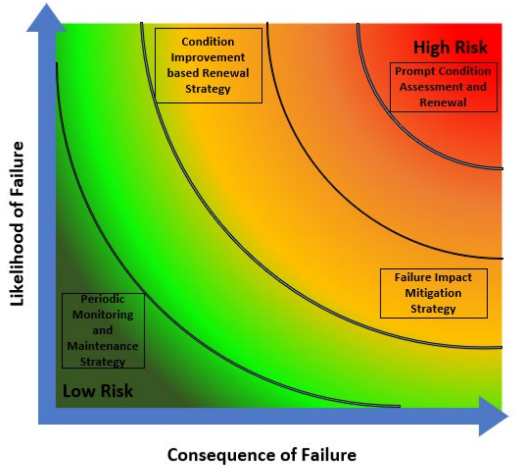


# RISK MATRIX DEVELOPMENT

- LoF values obtained from Performance model
- CoF values obtained from Fuzzy Logic model
- LoF and CoF obtained on 1-5 scale
- 5x5 Risk Matrix
- CoF model takes a triple bottom line approach
  - 5 modules: Economic Impact, Environmental Impact, Social Impact, Operational Impact and Renewal Complexity capture 19 parameters
  - Models assumptions vary with diameter range
  - Model can be applied to all materials

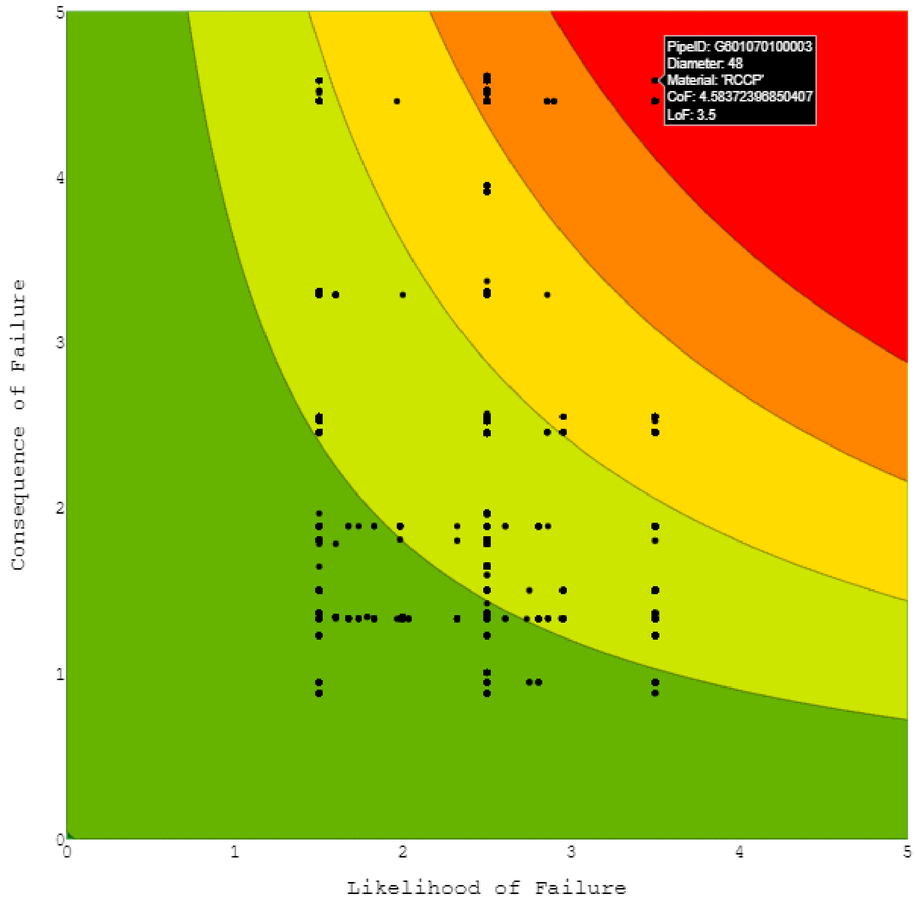
| Likelihood of Failure Score | Description | Color |
|---|---|---|
| 1 | Very Good | Dark Green |
| 2 | Good | Light Green |
| 3 | Fair | Yellow |
| 4 | Poor | Orange |
| 5 | Very Poor | Red |

| Consequence of Failure Score | Color Coding | Description |
|---|---|---|
| 1 | Dark Green | Insignificant |
| 2 | Light Green | Minor |
| 3 | Yellow | Moderate |
| 4 | Orange | Major |
| 5 | Red | Catastrophic |



# RISK MATRIX DEVELOPMENT

- 5x5 risk matrix plotted with 4 different risk zones
  - Red- Very High Risk
  - Orange – High Risk
  - Yellow – Moderate Risk
  - Green – Low Risk
- Risk Matrices developed for different scenarios
  - Pipes in high corrosivity ecological cohorts
  - Serving critical infrastructures
  - Different pipe materials
  - Large and small diameter pipes
- Piloting with water utilities emphasized importance of Risk Policy.

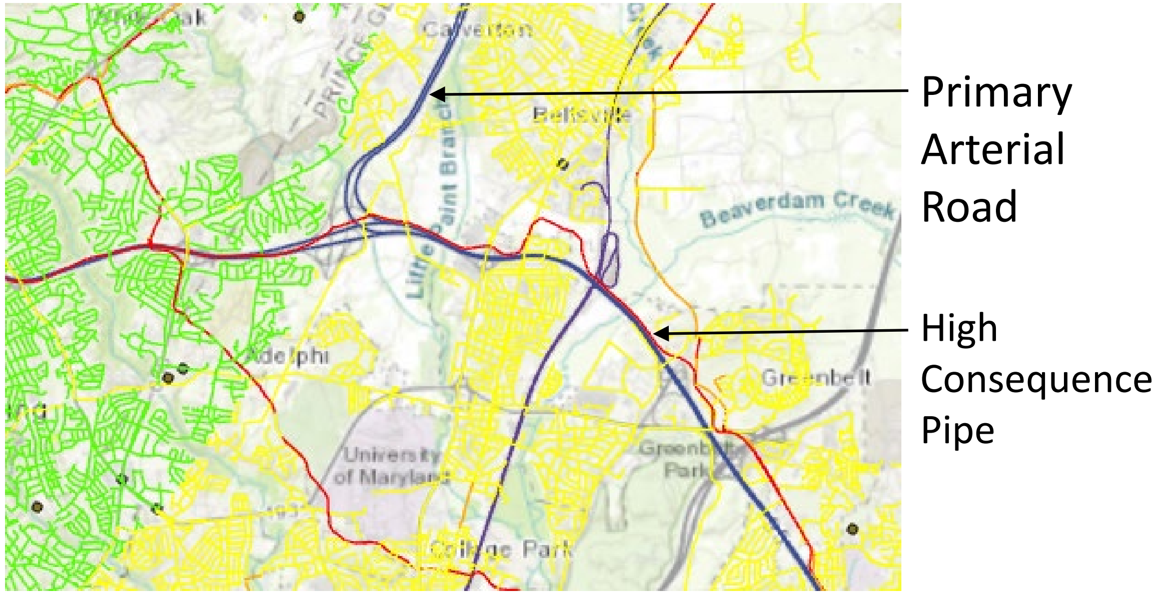



Pipe information provided to help support prioritization decisions based on Risk Policy

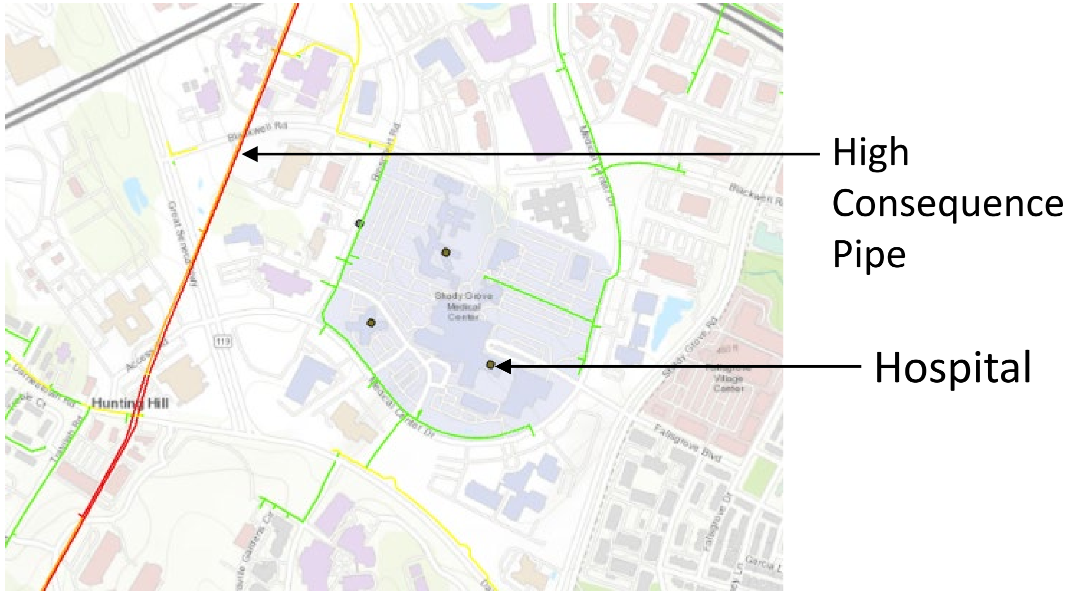
# RISK ANALYSIS RESULTS

*Model responds to complex risky scenarios like*

- *Cascading functional disruption: Transmission pipes*
- *Higher societal disruption potential: Interstates and rail tracks; hospitals and high density commercial areas*
- *Higher environmental damage: Protected wetlands, landslides*
- *Operational impacts: Fire flow*
- *Renewal Complexity: Pipes underneath bridges, near interstates or water bodies*



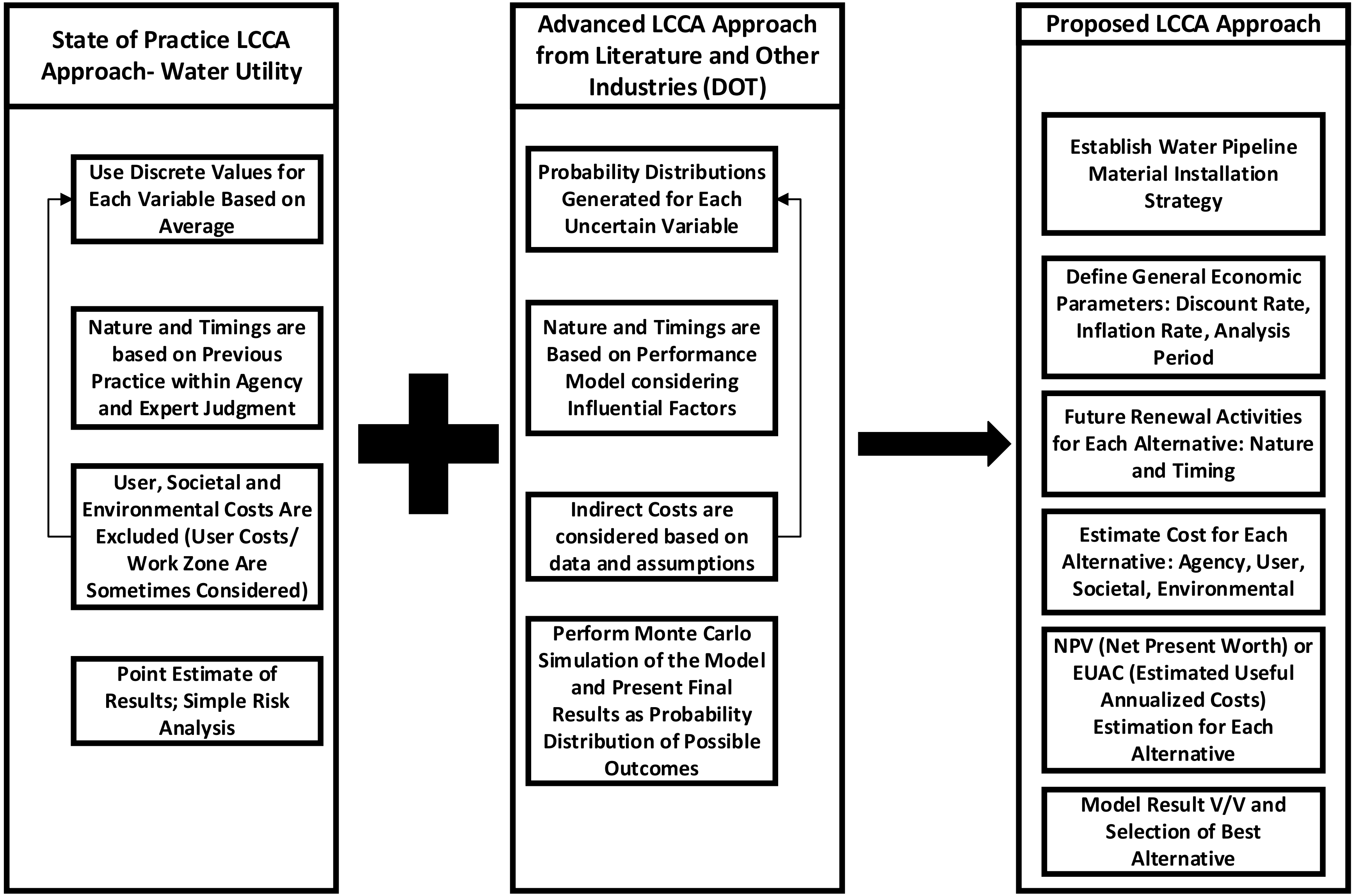

High consequence pipe near primary roadways




High consequence pipe near critical facilities (hospitals)

# LIFECYCLE ECONOMIC ANALYSIS- METHODOLOGY

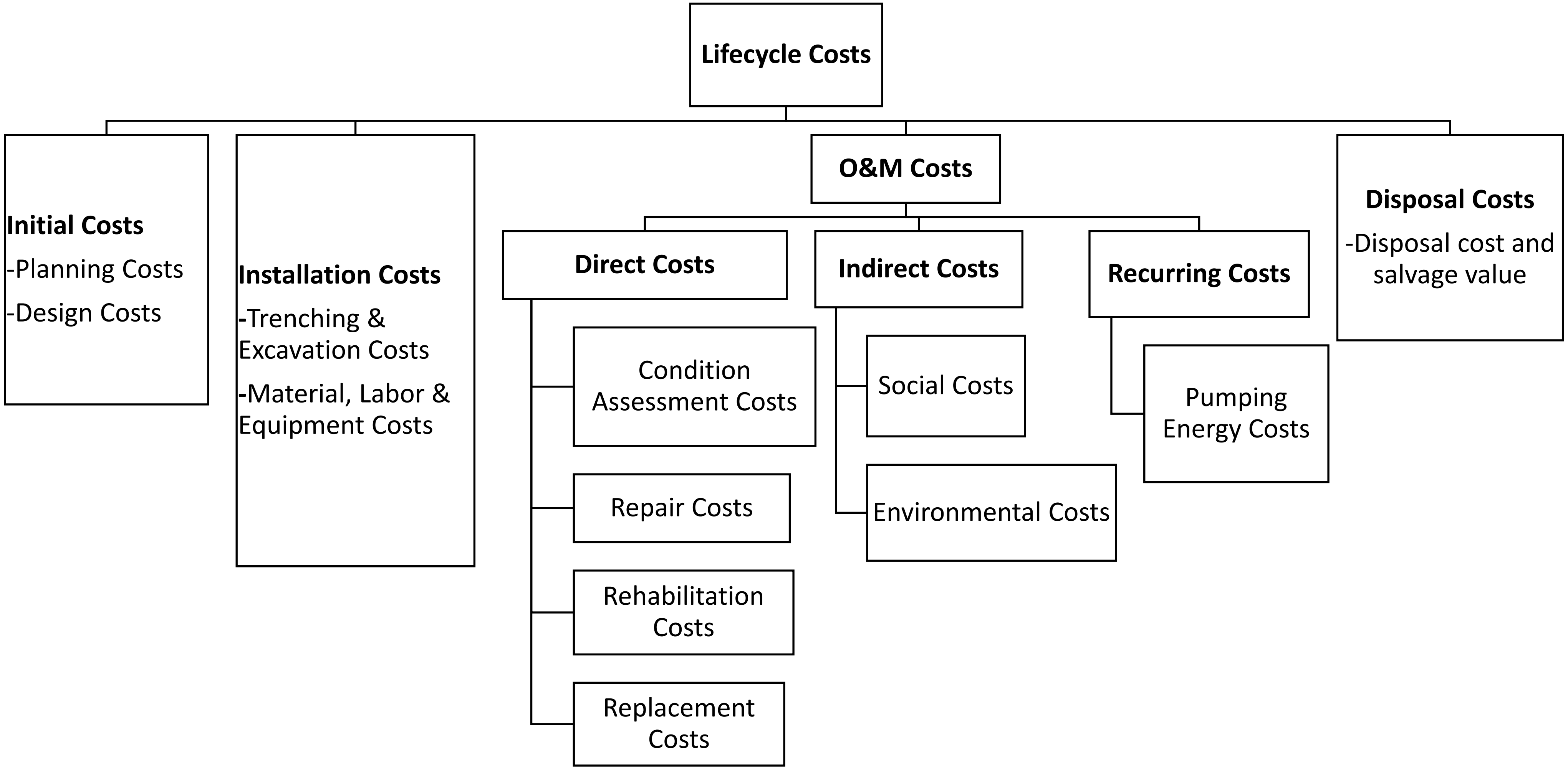
- Probabilistic analysis for uncertain variables based on data availability (point estimates where data is scarce)
- Renewal (Repair, Rehabilitation and Replacement) timings predicted based on performance analysis, not predefined/recurring assumptions.
- NPV compared for each alternative




*Need to move from Design Life to Performance Life based LCCA*

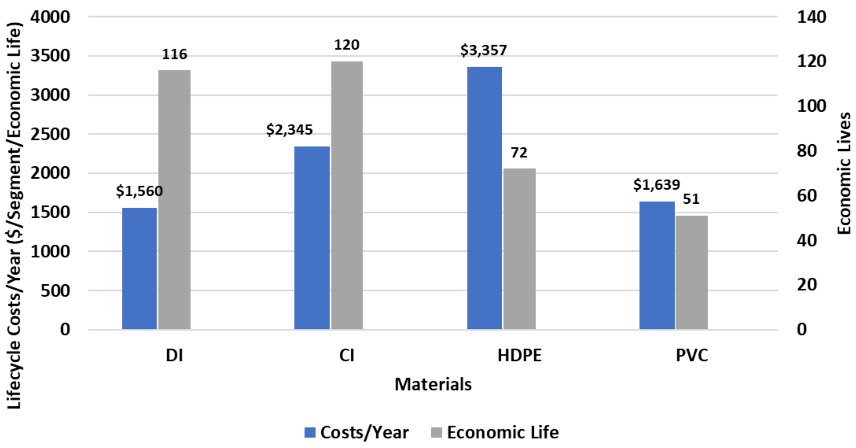
# DATA STRUCTURE

*Comprehensive data structure developed using extensive literature, practice review and interviews with water utility experts*

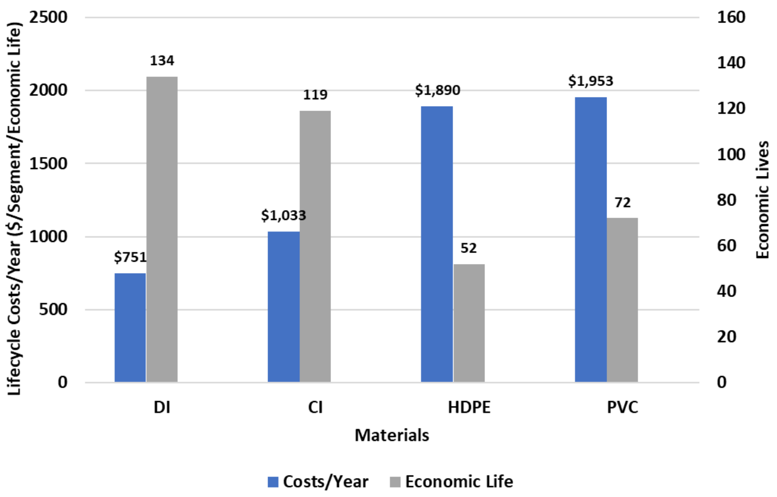


# LIFECYCLE ECONOMIC ANALYSIS- RESULTS

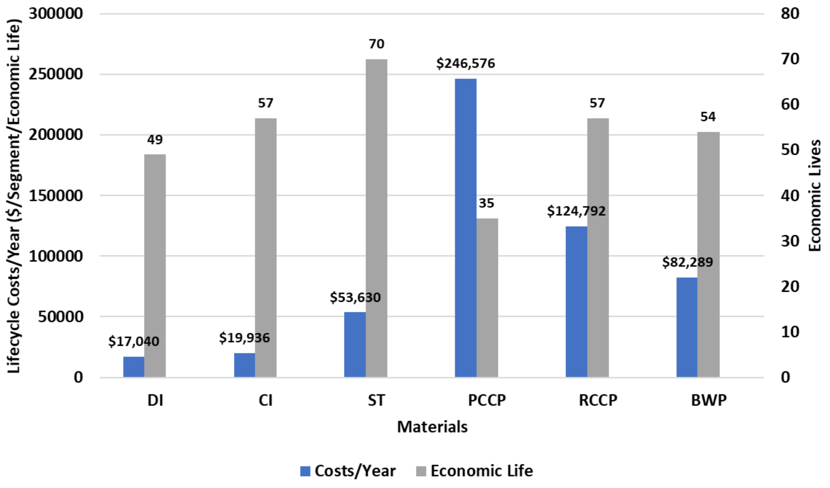
*Lifecycle cost estimates should be based on performance life rather than design life.*
*Less than 16in DI and PVC had among the lowest lifecycle costs. For larger diameter cementitious pipes, Bar Wrapped Pipes (BWP) had one of the lowest normalized lifecycle costs.*




Less than 16in diameter




16in-36in diameter

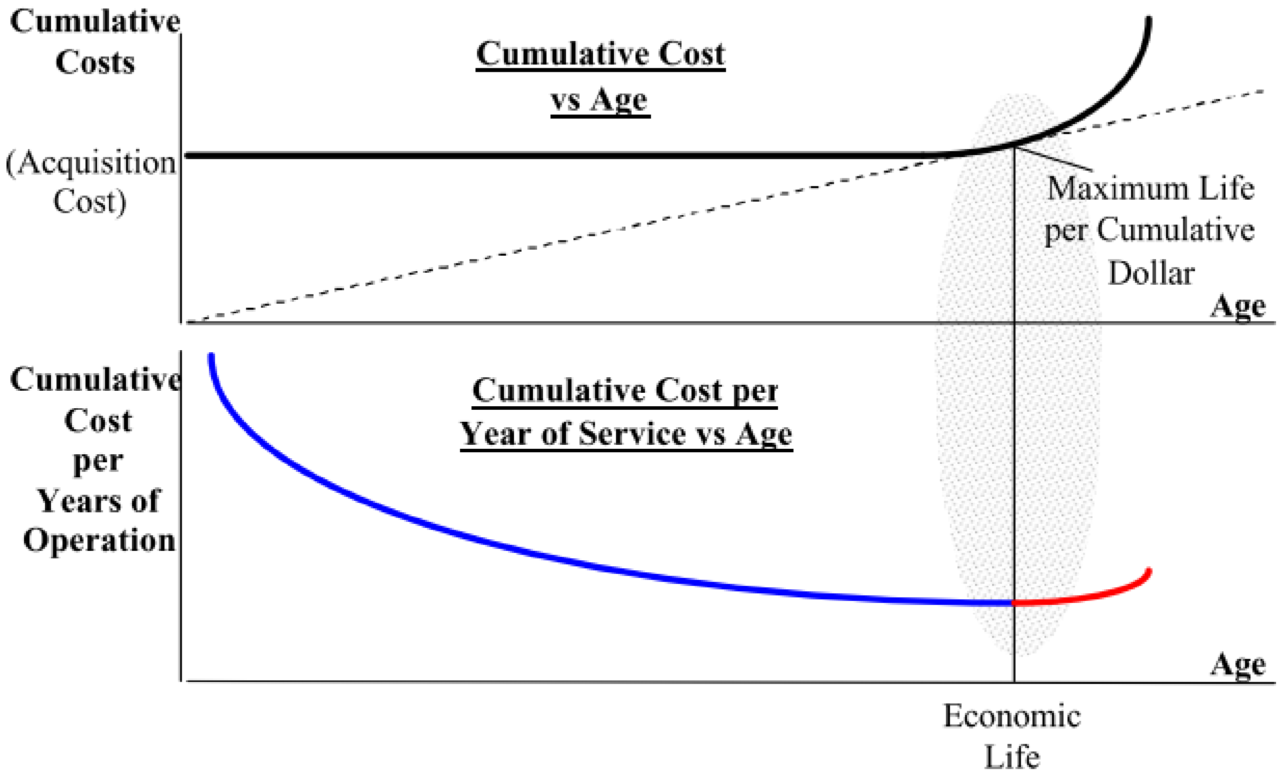



Greater than 36in diameter

***Analysis performed for different cohorts like soil corrosivity, pipe protections and lifecycle stages***

# OPTIMAL REPLACEMENT TIME-METHODOLOGY

- Based on minimization of cost function
- Optimal Replacement Times based on Multicriteria cost optimization (For example, cost minimization and service life maximization) investigated through advanced mathematical techniques
- Previous studies included optimal replacement times without account for repair times.




Estimating Economic Life or Optimal Replacement Times (Buckland and Hastings 2001)

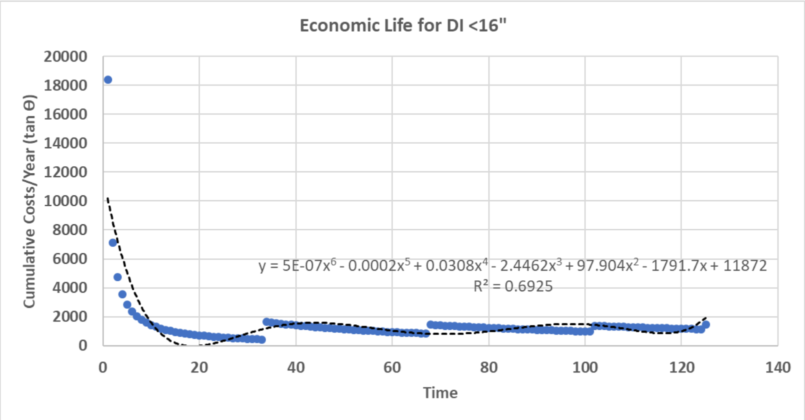
# OPTIMAL REPLACEMENT TIME- RESULTS

***Economic lives of metallic pipes can vary based on soil corrosivity and corrosion protection.***

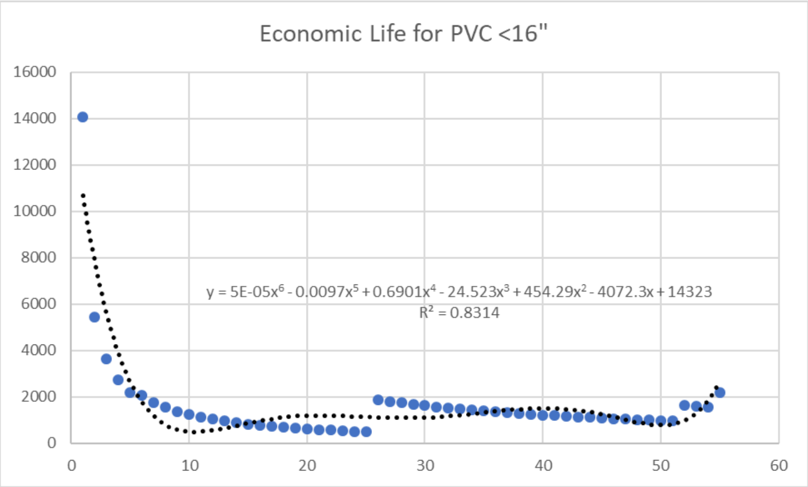
***For DI pipe, PE encasement with cathodic protection extends the economic life by at least 20 years compared with only PE encasement.***

***Steel pipes with bonded dielectric coatings and cement mortar linings can have better economic lives than other corrosion mitigation measures.***

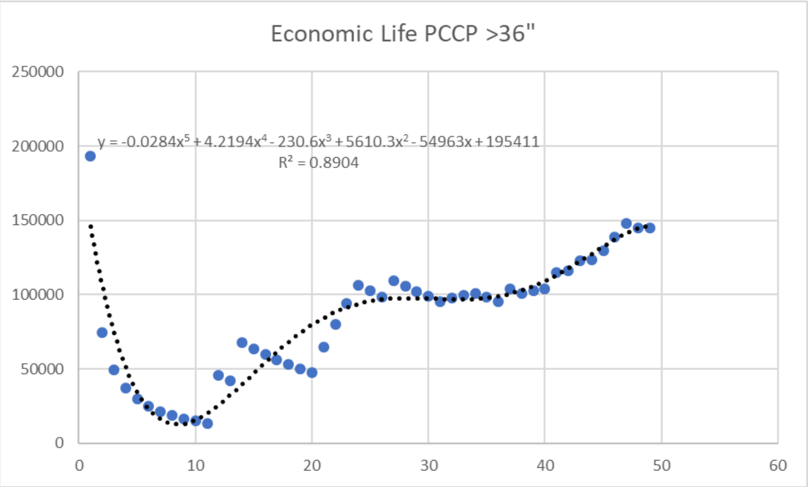
***PCCP with bonding straps show better economic lives than impressed current.***




<16” DI: Sixth Order Polynomial. First minima can be ignored as too soon and can be repaired at low cost. Economic Life= 116 years)




<16” PVC: Sixth Order Polynomial. Economic Life= 52 years)




>36” PCCP: Fifth Order Polynomial. First and second minima can be ignored. Economic Life= 35, 49 years)

# ECONOMIC ANALYSIS RESULTS SUMMARY

***Lifecycle Economic Analysis and Optimal Replacement Time analyses can help in replacement decision making and evaluate replacement material alternatives***

***Local environmental conditions, and water utility management practices can cause these figures to vary.***

| Material | Diameter | Lifecycle Costs ($/segment) ± 95% CI | Economic Life | Costs/Year |
|---|---|---|---|---|
| DI | <16" | $180,913±491 | 116 | $1,560 |
| | 16"-36" | $324,194±609 | 134 | $751 |
| | >36" | $1,708,974±16,622 | 49 | $17,040 |
| Steel | >36" | $1,939,023±37,861 | 70 | $53,630 |
| CI | <16" | $281,417.2±594 | 120 | $2,345 |
| | 16"-36" | $266,946±1,649 | 119 | $1,033 |
| | >36" | $1,173,886±34,520 | 57 | $19,936 |
| RCCP | >36" | $7,113,151±72,677 | 57 | $124,792 |
| PCCP | >36" | $8,630,177±6,133 | 35 | $246,576 |
| BWP | >36" | $2,973,169±74,587 | 54 | $82,289 |
| PVC | <16" | $83,564±274 | 51 | $2,348 |
| | 16"-36" | $140,601±26,000 | 72 | $1953 |
| HDPE | <16" | $241,715±6,278 | 72 | $3,357 |
| | 16"-36" | $411,795±38,204 | 52 | $1,890 |

Lifecycle Economic Analysis and Optimal Replacement Life Results Summary

PIPEiD

PIPELINE infrastructure DATABASE

# National Water Pipeline Database Summary

More than 500 Water Utilities and 100 Federal Facilities across the U.S. participated in the study.

Around 275,000 Miles of Water Pipeline Data Collected and about 150 Water Pipeline Performance Parameters Analyzed.

- Reports submitted to the U.S. Senate Committee on Appropriations for Water and Energy development and Standing Committee on Energy & Natural Resources

- Reports are peer reviewed by 25-Member Technical Review Committee appointed by OMB, Washington D.C., and 7-Member External Review Panel appointed by the U.S. Bureau of Reclamation

# Key Findings & Deliverables

1. Understanding the Pipeline Infrastructure Systems

2. Developing the data Standard to Support Analysis

3. Developing the Protocol for Database Management

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4. Understanding the Pipeline Descriptive Analytics

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5. Understanding Pipeline Performance Characteristics

6. Understanding Risk Assessment & Management

7. Life-Cycle Cost and Economic Analysis

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Visualization & Decision-Support System – PIPEiD Website

# PIPEiD Research Primer

NATIONAL WATER PIPELINE INFRASTRUCTURE DATABASE: REPORT TO THE U.S. CONGRESS

## Collection and Compilation of Water Pipeline Field Performance Data

*to support the National Pipeline Infrastructure Database (PIPEiD)*

**REPORT PRIMER**

**February 1st, 2021**



PIPEiD
PIPELINE *infrastructure* DATABASE

PIPEiD

PIPELINE *infrastructure* DATABASE

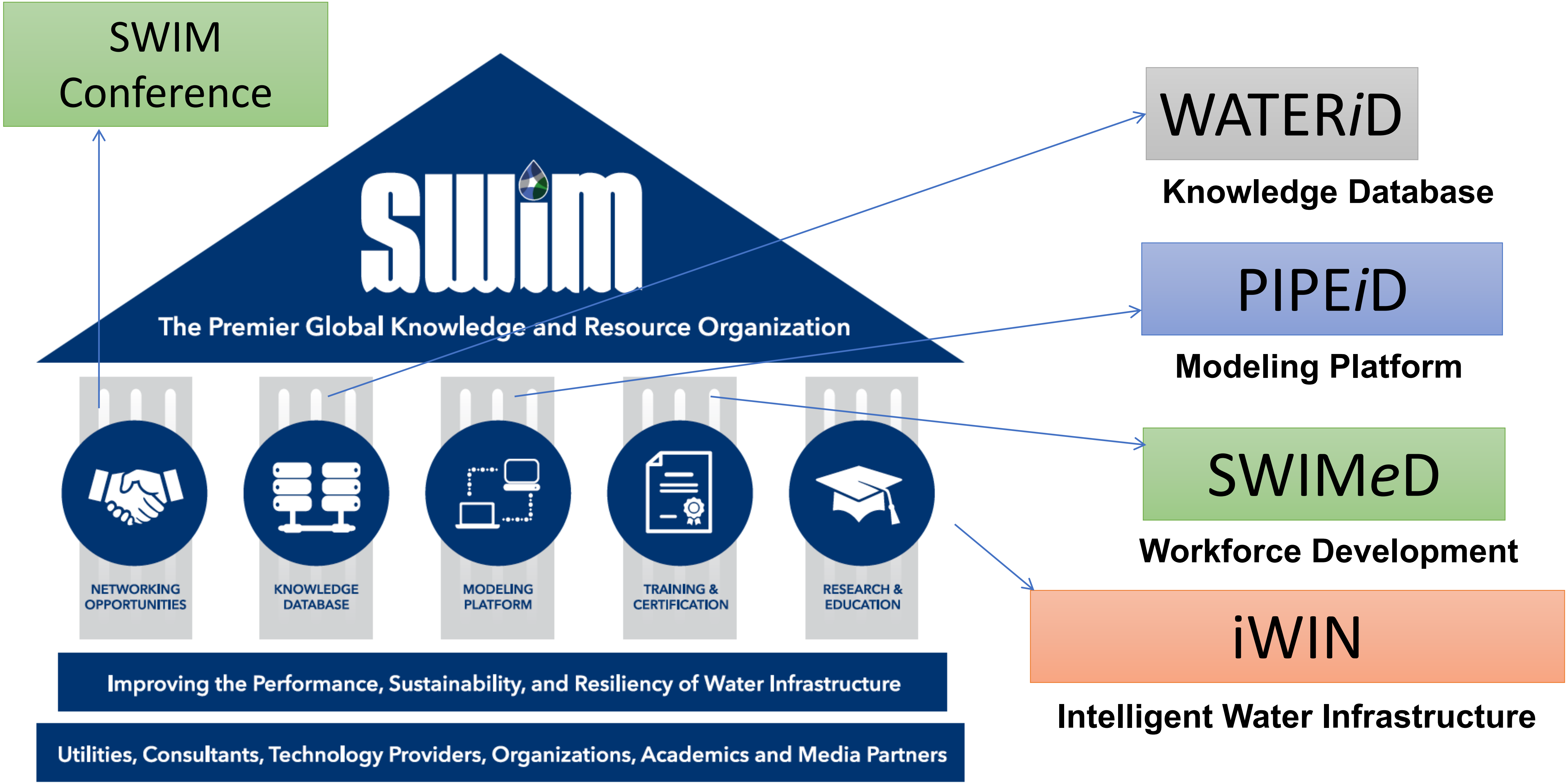
# Congressional Reports

https://www.swim.cee.vt.edu/congressional-reports/



# SWIM Center Core Activities



# National Water Pipeline Infrastructure Database Webcast Series

June 3rd: Water Pipeline Infrastructure System Knowledge and Understanding, and Data Structure and Database Management for Asset Management

June 8th: Water Pipeline Infrastructure System Descriptive and Correlation Analysis, and Survival/Weibull Curve Analysis for Asset Management

June 10th: Water Pipeline Infrastructure System Performance and Risk Analysis, and Life Cycle Economic Analysis for Advanced Asset Management

# Q&A

# Thank you!

**Comments or questions, please contact:**

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For more information, visit www.waterrf.org

Sustainable Water Infrastructure Management

SWIMeD
SWIM *education* Program

WATERiD
WATER *infrastructure* DATABASE

PIPEiD
PIPELINE *infrastructure* DATABASE