Assessing the Long-Term Financial Sustainability of Water Mains

Using Monte-Carlo Simulation

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NEW ENGLAND WATER ENVIRONMENT ASSOCIATION
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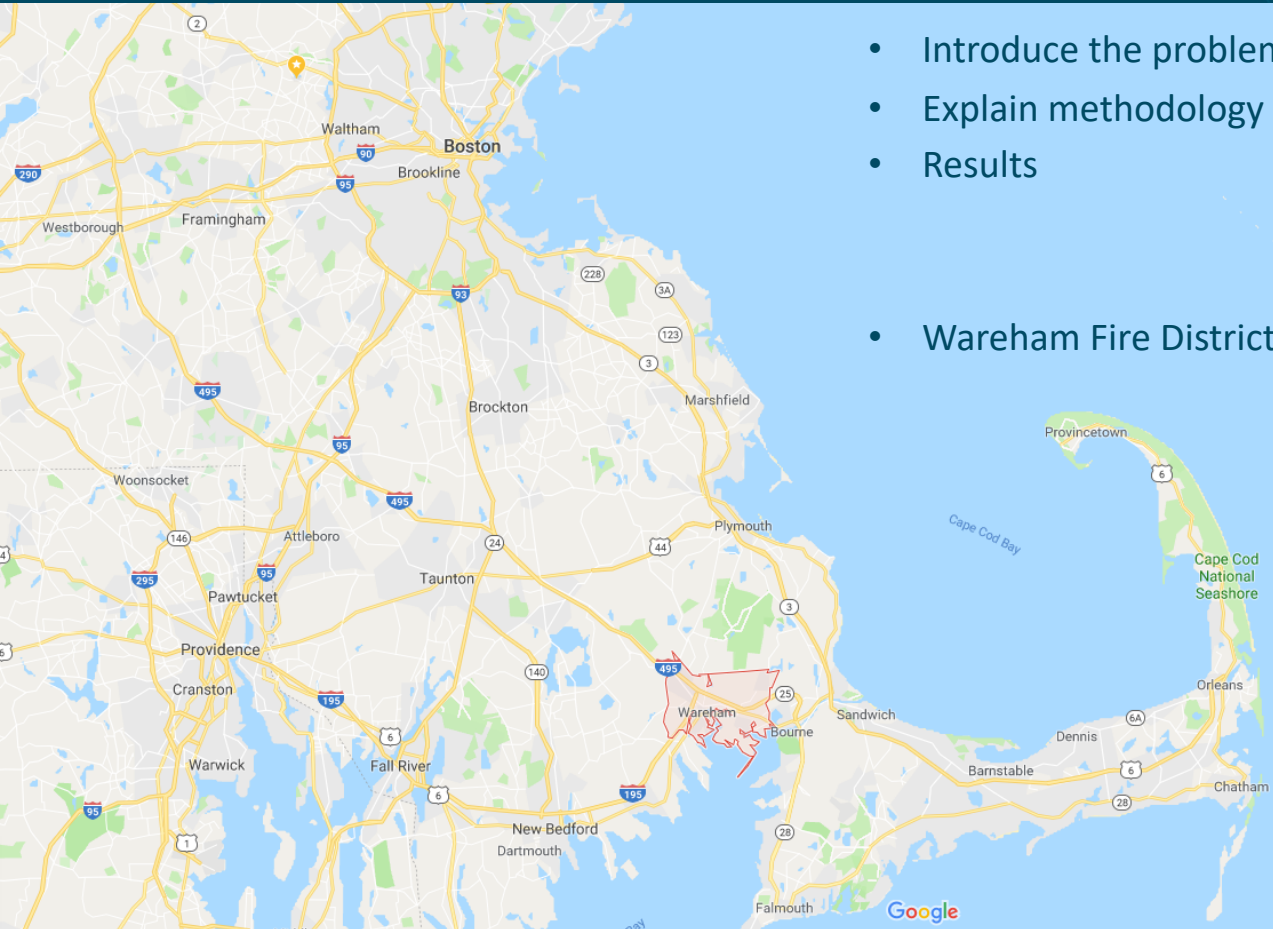
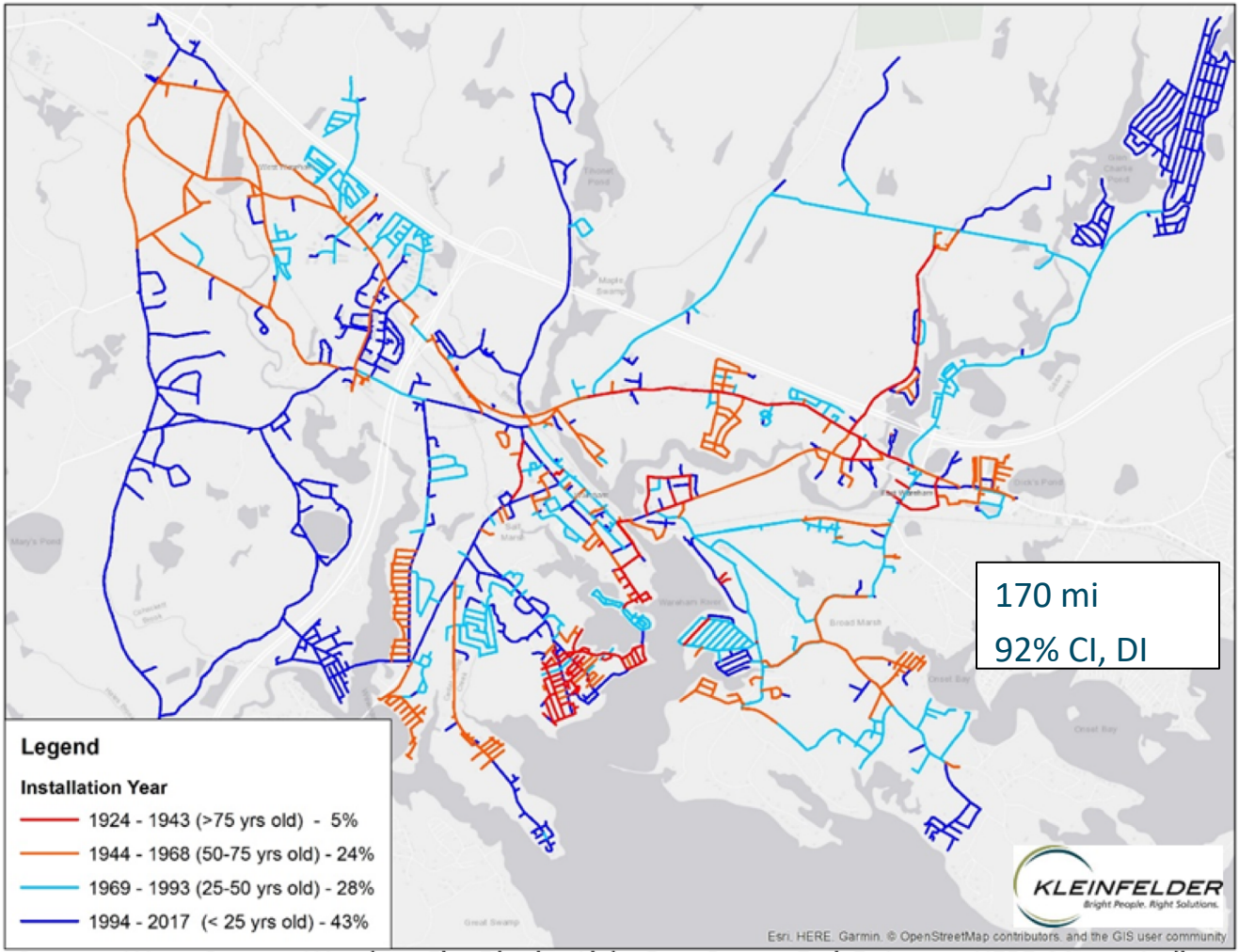
In this Presentation



- Introduce the problem
- Explain methodology
- Results

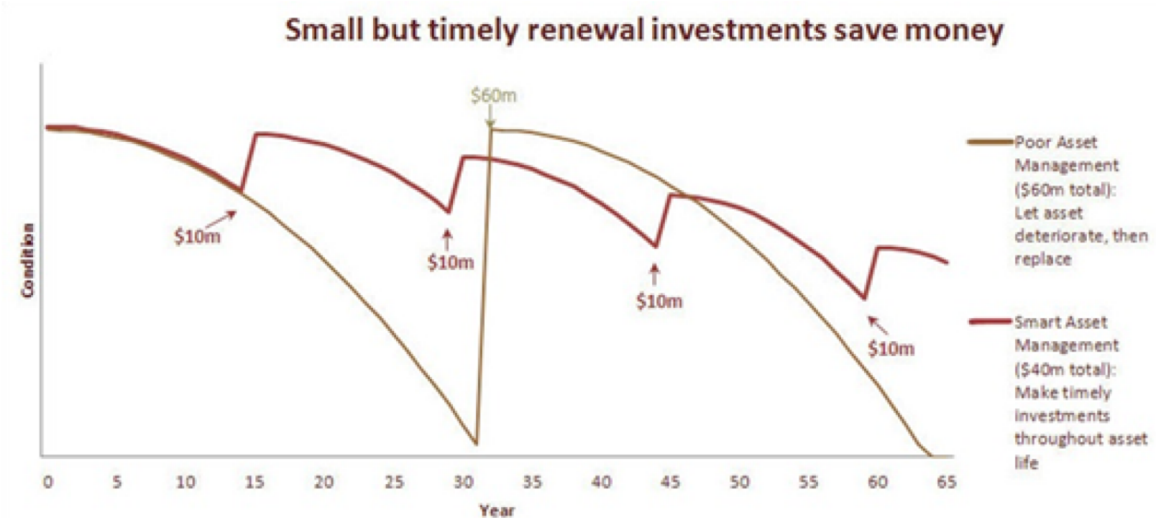
- Wareham Fire District



Sources: Water System: Wareham Fire District; Light Gray Canvas:Esri, DeLorme, HERE, MapmyIndia

Lifecycle Costs

- As time goes by, things deteriorate
- Reactive maintenance is costly
- You can't expect to be financially sustainable based only on past performance without knowing what's going to happen in the future



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Reactive Maintenance

Pros

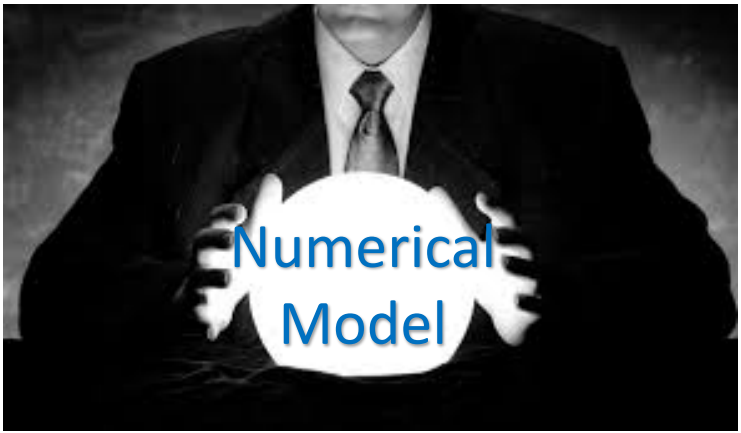
- You only spend when “needed”
- Low initial costs

Cons

- Shorter equipment life
- Expensive: Indirect costs, time
- No budget control

To be pro-active…

- What is the service life of Wareham's water mains?
- What are our forecasted future expenditures?



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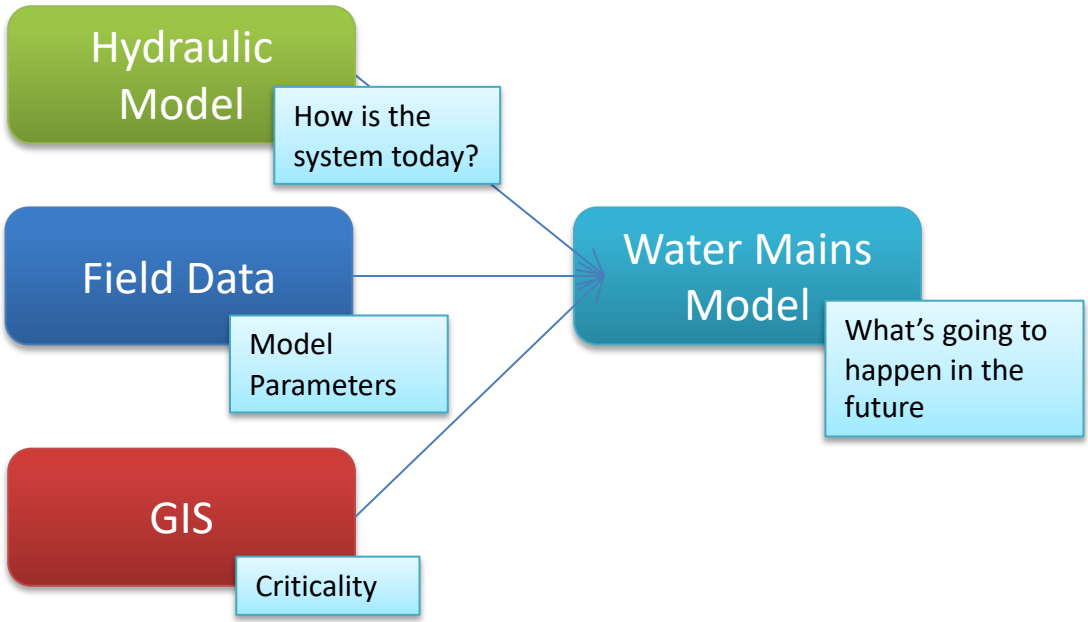
Data requirements



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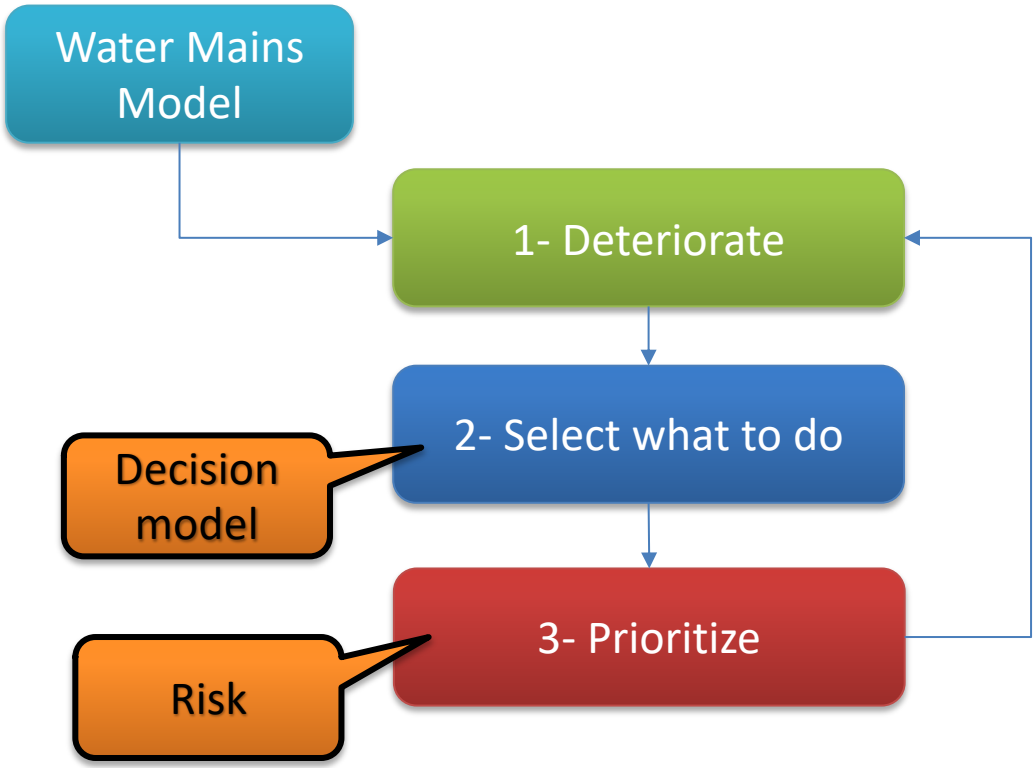
What's the model going to do?



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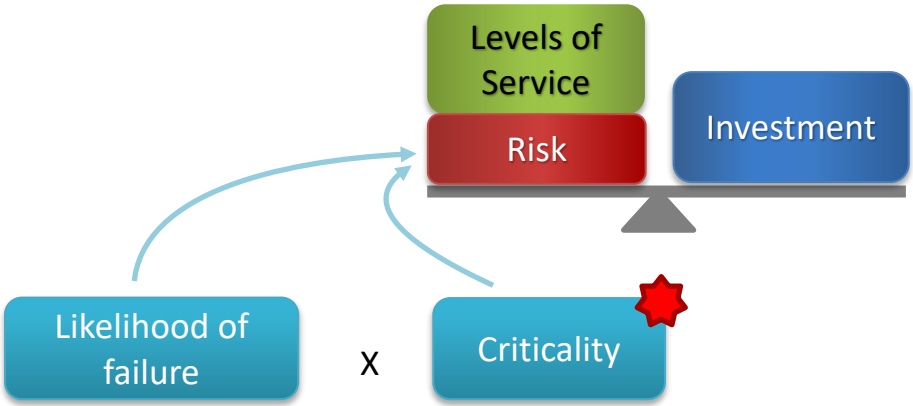
Past Efforts: Risk Analysis



- Age
- Material
- Hydraulic Model
- WO data

- Health & safety impacts to customers
- Economic impacts to the community
- Revenue and financial losses
- Negative public relations (traffic, land use)

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Prioritization

Prioritize

Budget: $10 M

High Consequence ----------Low Consequence

Priority	1	2	3	4	5	6	7	8	9	10
Total	$ 1,353,548	$ 229,907	$ 3,406,859	$ 14,073,077	$ 9,418,163	$ 37,187,217	$ 16,603,389	$ 8,115,041	$ -	$ -
Accum	$ 1,353,548	$ 1,583,454	$ 4,990,313	$ 19,063,390	$ 28,481,553	$ 65,668,770	$ 82,272,159	$ 90,387,200	$ 90,387,200	$ 90,387,200
In CIP	Yes	Yes	Yes	Partial	No	No	No	No	No	No

from the *decision* model

Changes “actions” from the decision model to “Do Nothing”

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Decision Model

Select what to do

Do Nothing	Structural Lining	Replace with DI	Replace with Larger DI
• OK • Not enough budget	• AC • Corrosion	• AC, DI, CI • Corrosion, tuberculation	• AC, DI, CI • Fire Flow

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Multisystem level

Aging effects		Physical exercise effects
Brain function		
↓	Neurogenesis	↑
↑	Neurodegeneration	↓
↑	Cognitive alterations	↓
Cardiovascular function		
↓	$\dot{Q}$max	↑
↑	Blood pressure	↓
↓	Regional blood flow	↑
↓	Blood volume	↑
↓	Body fluid regulation	↑
↓	Endothelial function	↑
↓	Autonomic function	↑
↓	Vagal tone and HRV	↑
↓	Cardiac pre conditioning	↑
Lung function		
↓	Ventilation	↑
↓	Gas exchange	↑
Muscle function		
↓	Muscle strength/power	↑
↓	Muscle endurance	↑
↓	Muscle quality	↑
↓	Balance and mobility	↑
↓	Motor performance & control	↑
↓	Flexibility and joint ROM	↑
↓	O_2 arterio-venous difference	↑
Body composition		
↑	Weight	↓
↓	Fat-free mass	↑
↓	Muscle mass	↑
↑	Regional adiposity	↓
↓	Bone density	↑
Metabolism		
↓	Resting metabolic rate	↑
↓	Muscle protein synthesis	↑
↓	Fat oxidation	↑

↓ Physical fitness ↑ Physical fitness

Cellular hallmarks of aging

Physical exercise effects	Aging effects
↓ DNA and mtDNA damage: ↑ Systemic antioxidant defense and DNA repair ↓ Genomic instability ↓ Multisystem pathology and premature mortality	Genomic instability
Prevents telomere shorthening: ↑ Telomerase activity ↑ TERT activity and expression ↑ Shelterin complex	Telomere attrition
PBMCs and tissue-dependent regulation: ↑ DNA methylation (*e.g.* ASC, BDNF, PGC-1α, PDK4, PPAR-δ,) ↑ miRNA regulation (*e.g.* miR-33, 1, 133a, 499-5p, 208a, 126, 146a, 206) ↑ Histone PTMs (HATs, HDACs, jmjC, LSD)	Epigenetic alteration
Induces autophagy in brain, heart, skeletal muscle, liver, pancreatic β cells and adipose tissue through several mechanisms (IGF-1, AKT/mTOR, Akt/FoxO3a, beclin1) and modulates ubiquitin-proteasome system	Loss of Proteostasis
Activates nutrient-sensing pathway in muscle: ↑ mTOR ↑ AMPK ↑ SIRT ↑ Glut 4 ↑ Testosterone ↑ GH ↑ IGF-1	Deregulated nutrient-sensing
Mitochondrial fuction and biogenesis improvement by regulating: ↑ PGC-1 ↑ SIRT ↑ Antioxidant defense ↑ Respiratory chain assembly ↑ mtDNA shifting	Mitochondrial dysfunction
Regulates cellular senescence through: ↑ NK-cell activity ↑ Antigen-presentation ↓ Inflammation ↓ Senescent cells ↓ $p16^{INK4a}$ ↑ Senescence markers ↑ Telomere activity ↑ mtDNA shifting ↓ Apoptosis	Cellular senescence
Stimulates proliferation and migration of different types of stem cells	Stem cell exhaustion
Anti-"inflammaging" effects: ↑ IL-4 ↑ IL-6 ↑ IL-10 ↑ IL-13 ↓ NLRP3 ↑ IL-1β ↑ AUF1 (see **Table 1**)	Altered intercellular communication

Deterioration

Condition? Capacity? Strength?

a gradual decline, as in quality, serviceability, or vigor.

the process of becoming progressively worse

uncertainty

time

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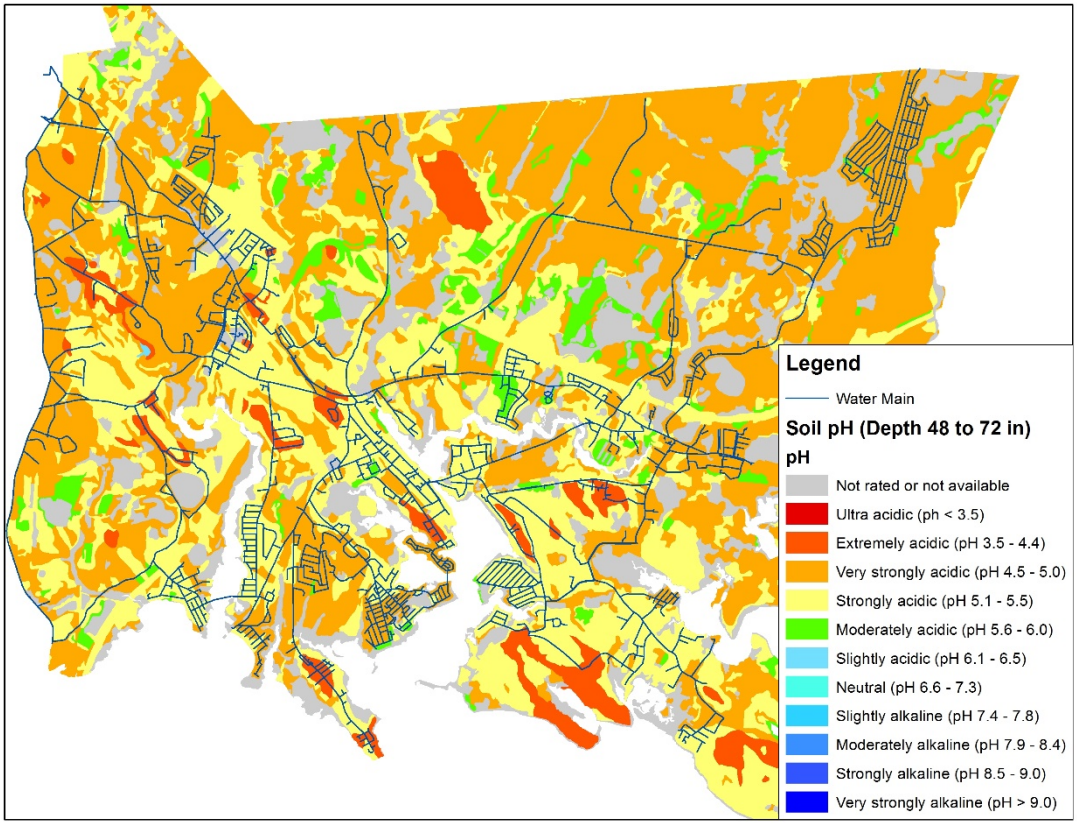
Soil pH



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Soil Corrosivity

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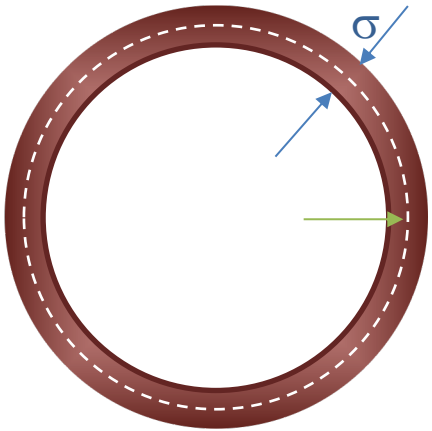
Deterioration: Failure Modes

Corrosion



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Corrosion: In Situ Testing

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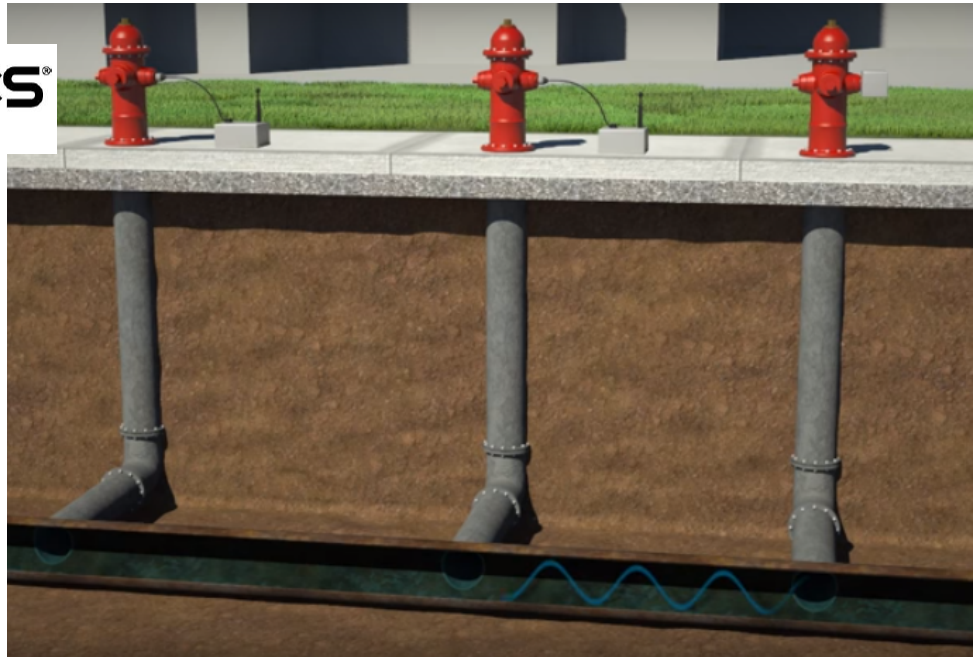

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Field Testing Results – In Situ Testing

- AC Pipe

Street	Pipe Asset ID(s)	Distance	Pipe Material	Internal Diameter	Equivalent Thickness	Remaining Thickness	% Change from Nominal
		(ft)		(in)	(in)	(in)	
Pepper Mill Rd	1000372, 1001462	359	AC	8	0.76	0.51	-33%
Pepper Mill Rd	1000372	293	AC	8	0.76	0.52	-32%
Pepper Mill Rd	1000372, 1001391	286	AC	8	0.76	0.52	-31%
Gault Rd	1000909	177	AC	12	1.09	0.59	-46%
Gault Rd	1000909	497	AC	12	1.09	0.68	-38%
Gault Rd	1000909	622	AC	12	1.09	0.72	-34%
Main Street	1001228	644	AC	8	0.76	0.44	-42%
Main Street	1956417, 1001228	482	AC	8	0.76	0.48	-37%

Field Testing Results – In Situ Testing

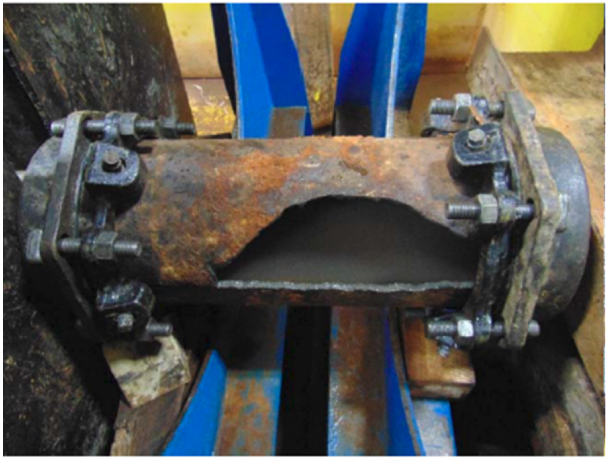
- Iron Pipe

Street	Pipe Asset ID(s)	Distance	Pipe Material	Internal Diameter	Equivalent Thickness	Remaining Thickness	% Change from Nominal
		(ft)		(in)	(in)	(in)	
Driftwood Lane	1001581, 1956541	222	PCI	10.02	0.54	0.31	-43%
Warr Avenue	1000408	184	PCI	10.02	0.54	0.38	-30%
Warr Avenue	1000407, 1000408	644	PCI	10.02	0.54	0.33	-38%
Pilgrim Avenue	1000064, 1001217, 1001190	563	PCI	6.04	0.43	0.24	-45%
Broadmarsh Avenue	1000873, 1001190	684	PCI	6.04	0.43	0.26	-40%
Broadmarsh Avenue	1000873, 1001190	226	PCI	6.04	0.43	0.28	-36%
Plymouth Avenue	1000345, 1001532	385	DI	12.46	0.41	0.37	-8%
Plymouth Avenue	1001532	647	DI	12.46	0.41	0.39	-4%
Plymouth Avenue	1001532	639	DI	12.46	0.41	0.35	-15%
Lake Avenue	1000919, 1001184, 1001756	605	DI	8.39	0.36	0.26	-30%
Lake Avenue	1000087,1001184, 1001756	662	DI	8.39	0.36	0.34	-5%
Lake Avenue	1000087, 1001756	658	DI	8.39	0.36	0.28	-23%
Cranberry Highway	1001729	722	PCI	10.02	0.54	0.42	-22%
Cranberry Highway	1001729, 1001290, 1004737	440	PCI	10.02	0.54	0.46	-15%

When to Consider Replacing Pipe – Field Results

Estimated Minimum Pipe Thickness Before Break –12 inch pipe → Bending stress controls

Stress	Required Thickness, in.
Ductile Iron	
Int. Press. Hoop Stress	0.05
Bending	0.19
Cast Iron	
Int. Press. Hoop Stress	0.08
Bending (20 ft span)	0.51
Bending (15 ft span)	0.30
Bending (10 ft span)	0.13



Specimen	Manufacture Thickness	Minimum Bending Thickness	% of Original Thickness
Ductile – Class 52	0.37 inch	0.19 inch	51% (49% corroded)
Cast Iron – 15 ft Span	0.65 inch	0.30 inch	46% (53% corroded)

50%

Model Inputs

Unit Costs

Material	Diameter	Replace with DI	Replace with DI+	Structural Lining
Metal	6	$ 150.00	$ 150.00	$ 200.00
Metal	8	$ 150.00	$ 180.00	$ 200.00
Metal	10	$ 180.00	$ 190.00	$ 200.00
Metal	12	$ 190.00	$ 225.00	$ 200.00
Metal	16	$ 225.00	$ 260.00	$ 250.00
Metal	20	$ 260.00	$ 280.00	$ 250.00
Metal	24	$ 280.00	$ 320.00	$ 250.00
AC	6	$ 180.00	$ 180.00	$ 250.00
AC	8	$ 180.00	$ 216.00	$ 250.00
AC	10	$ 216.00	$ 228.00	$ 250.00
AC	12	$ 228.00	$ 270.00	$ 250.00
AC	16	$ 270.00	$ 312.00	$ 300.00
AC	20	$ 312.00	$ 336.00	$ 300.00
AC	24	$ 336.00	$ 400.00	$ 300.00

FM: Corrosion % Corrosion > than	FM: Turberculation C value < than	Fire Flow Adequacy Capacity Score < than
50%	50	5

Deterioration Model (Corrosion)

	Thickness (in)			Deterioration Rates (mm/yr)		
Class Type	Min	Likely	Max	Min	Likely	Max
AC-6	0.455	0.555	0.685	0.120	0.163	0.270
AC-8	0.555	0.760	0.810	0.120	0.163	0.270
AC-10	0.830	0.927	1.060	0.120	0.163	0.270
AC-12	0.960	1.090	1.190	0.120	0.163	0.270
AC-16	1.230	1.334	1.485	0.120	0.163	0.270
AC-20	1.640	1.728	1.820	0.120	0.163	0.270
AC-24	1.980	2.068	2.160	0.120	0.163	0.270
AC-30	1.560	1.645	1.900	0.120	0.163	0.270
SCI-6	0.440	0.453	0.480	0.021	0.053	0.298
SCI-8	0.429	0.532	0.652	0.021	0.053	0.298
SCI-10	0.500	0.530	0.609	0.021	0.053	0.298
SCI-12	0.540	0.653	0.737	0.021	0.053	0.298
PCI-6	0.385	0.430	0.550	0.025	0.053	0.249
PCI-8	0.484	0.540	0.691	0.025	0.053	0.249
PCI-10	0.496	0.579	0.725	0.025	0.053	0.249
PCI-12	0.474	0.644	0.795	0.025	0.053	0.249
DI-6	0.250	0.270	0.310	0.027	0.071	0.480
DI-8	0.250	0.330	0.388	0.027	0.071	0.480
DI-10	0.260	0.290	0.350	0.027	0.071	0.480
DI-12	0.280	0.370	0.403	0.027	0.071	0.480
DI-16	0.340	0.360	0.400	0.027	0.071	0.480
DI-20	0.380	0.393	0.420	0.027	0.071	0.480
DI-24	0.430	0.433	0.440	0.027	0.071	0.480

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The Model

Asset ID	GIS Material	Diam	Year Installed	Nominal Wall Thickness (mm)	Deterioration Rate (mm/yr)	Thickness if Replaced with DI	Thickness if Replaced with DI+	Det. Rate if Replaced (mm/yr)	Calculated ESL from Corrosion (yrs)	CoF Social	CoF Eco	CoF	Priority [1-10]
1000001	AC	6	1949	13.108	0.153	7.112	8.382	0.071	42.705	7.73	1.00	7.73	3.00
1000002	DI	8	1998	8.120	0.095	8.382	8.890	0.071	42.599	4.45	1.00	4.45	6.00
1000008	DI	20	1970	10.286	0.121	10.160	11.049	0.071	42.513	5.09	1.00	5.09	5.00
1000010	AC	8	1978	18.013	0.155	8.382	8.890	0.071	58.104	4.45	1.00	4.45	6.00
1000011	AC	8	1967	17.838	0.173	8.382	8.890	0.071	51.494	2.82	1.00	2.82	8.00
1000018	AC	6	1950	13.643	0.128	7.112	8.382	0.071	53.467	4.45	1.00	4.45	6.00

Capacity Score	Replace w DI Cost	Replace with DI+ Cost	Structural Lining Cost	Age 2018	Corr. (mm) @2018	Corr. (%) @2018	Cval @2018	Capacity @2018	Action-Corr@2018	Action Tub@2018	Action-FireF@2018
1.00	$ 14,580	$ 14,580	$ 20,250	69.0	10.59	80.8%	80.00	1.00	Structural Lining	Do Nothing	Replace with DI+
10.00	$ 78,176	$ 93,811	$ 104,234	20.0	1.91	23.5%	80.00	10.00	Do Nothing	Do Nothing	Do Nothing
10.00	$ 649,755	$ 699,736	$ 624,764	48.0	5.81	56.5%	100.00	10.00	Replace with DI	Do Nothing	Do Nothing
10.00	$ 82,841	$ 99,410	$ 115,058	40.0	6.20	34.4%	80.00	10.00	Do Nothing	Do Nothing	Do Nothing
10.00	$ 4,944	$ 5,932	$ 6,866	51.0	8.83	49.5%	80.00	10.00	Do Nothing	Do Nothing	Do Nothing
10.00	$ 30,332	$ 30,332	$ 42,127	68.0	8.68	63.6%	120.00	10.00	Structural Lining	Do Nothing	Do Nothing

PrelimAction@2023	Costs@2023	Include in CIP@2023	Partials	Action@2023		Previously Replaced?	Age 2028
Replace with DI+	$ 14,580	No	$ -	Do Nothing	0	No	79.0
Do Nothing	$ -	No	$ -	Do Nothing	0	No	30.0
Replace with DI	$ 649,755	No	$ -	Do Nothing	0	No	58.0
Do Nothing	$ -	No	$ -	Do Nothing	0	No	50.0
Structural Lining	$ 6,866	No	$ -	Do Nothing	0	No	61.0

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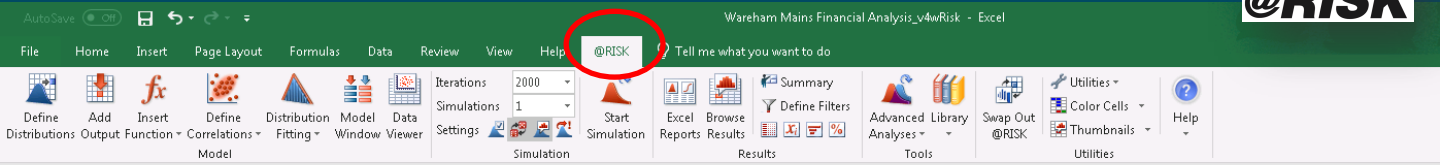
The Monte-Carlo…



T1331 =RiskPert(Q1331,R1331,S1331)

	A	B	C	D	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE
11	Asset ID	GIS Material	Diam	Year Installed	Min Norm Wall Thickness	Likely Wall Thickness (mm)	Max Wall Thickness	Nominal Wall Thickness (mm)	Min Det. Rate (mm/yr)	Likely Det Rate (mm/yr)	Max Det Rate (mm/yr)	Deterioration Rate (mm/yr)	Thickness if Replaced with DI	Thickness if Replaced with DI+	Det. Rate if Replaced (mm/yr)	Calculated ESL from Corrosion	CoF Social	CoF Eco	CoF
12	1000001	AC	6	1949	11.557	14.453	17.399	14.368	0.120	0.163	0.270	0.142	7.112	8.382	0.071	50.720	7.73	1.00	7.73
13	1000002	DI	8	1998	6.350	8.382	9.855	7.202	0.027	0.071	0.480	0.128	8.382	8.890	0.071	28.143	4.45	1.00	4.45
14	1000008	DI	20	1970	9.652	10.160	10.668	9.838	0.027	0.071	0.480	0.123	10.160	11.049	0.071	39.864	5.09	1.00	5.09
15	1000010	AC	8	1978	14.097	19.304	20.574	18.833	0.120	0.163	0.270	0.162	8.382	8.890	0.071	58.301	4.45	1.00	4.45
16	1000011	AC	8	1967	14.097	19.304	20.574	19.021	0.120	0.163	0.270	0.227	8.382	8.890	0.071	41.850	2.82	1.00	2.82
17	1000018	AC	6	1950	11.557	14.453	17.399	14.236	0.120	0.163	0.270	0.210	7.112	8.382	0.071	33.891	4.45	1.00	4.45
18	1000021	AC	12	1952	24.384	27.686	30.226	28.768	0.120	0.163	0.270	0.139	9.398	9.398	0.071	103.854	6.73	1.00	6.73
19	1956418	AC	8	1967	14.097	19.304	20.574	19.551	0.120	0.163	0.270	0.171	8.382	8.890	0.071	57.290	2.82	1.00	2.82
20	1956514	AC	8	1972	14.097	19.304	20.574	18.753	0.120	0.163	0.270	0.150	8.382	8.890	0.071	62.654	4.45	1.00	4.45
21	1000407	CI <1939	10	1936	12.598	15.113	18.415	16.704	0.025	0.053	0.249	0.058	8.890	9.398	0.071	144.370	6.82	6.40	6.82
22	1000785	AC	24	1974	50.292	53.086	54.864	53.440	0.120	0.163	0.270	0.149	11.049	11.007	0.071	179.502	5.82	1.00	5.82
23	1000680	DI	8	2001	6.350	8.382	9.855	8.873	0.027	0.071	0.480	0.175	8.382	8.890	0.071	25.296	4.45	1.00	4.45
24	1000031	AC	8	1972	14.097	19.304	20.574	18.768	0.120	0.163	0.270	0.182	8.382	8.890	0.071	51.604	2.82	1.00	2.82
25	1000036	DI	6	1993	6.350	7.112	7.874	7.185	0.027	0.071	0.480	0.040	7.112	8.382	0.071	90.778	3.55	1.00	3.55
26	1000039	CI <1939	10	1936	12.598	15.113	18.415	14.933	0.025	0.053	0.249	0.028	8.890	9.398	0.071	265.854	4.45	1.00	4.45
27	1000041	AC	8	1968	14.097	19.304	20.574	16.358	0.120	0.163	0.270	0.139	8.382	8.890	0.071	58.740	4.45	1.00	4.45
28	1000048	DI	6	1998	6.350	7.112	7.874	6.723	0.027	0.071	0.480	0.096	7.112	8.382	0.071	34.890	6.82	1.00	6.82
29	1000054	CI <1939	6	1936	9.779	10.922	13.970	10.775	0.025	0.053	0.249	0.091	7.112	8.382	0.071	59.418	4.45	3.40	4.45
30	1006777	DI	12	1953	7.112	9.398	10.236	8.926	0.027	0.071	0.480	0.057	9.398	9.398	0.071	78.293	6.73	1.00	6.73
31	1006780	AC	8	1979	14.097	19.304	20.574	17.789	0.120	0.163	0.270	0.204	8.382	8.890	0.071	43.542	2.82	1.00	2.82
32	1000057		6			14.453	17.399	12.922	0.120		0.270	0.228	7.11		0.071	367	3.55	1.00	3.55
			6						0.120			0.209			0.071				
1376	1956			1949	31.242		37.719	34.615	0.120	0.163	0.270			10.1		124.074	6.73	1.00	
1377	1004648	DI	12	1979	7.112	9.398	10.236	8.406	0.027	0.071	0.480	0.040	9.398	9.398	0.071	29.996	6.73	1.00	6.73
1378	1956554	DI	12	1993	7.112	9.398	10.236	9.333	0.027	0.071	0.480	0.039	9.398	9.398	0.071	121.081	5.82	1.00	5.82
1379	1956543	AC	12	1949	24.384	27.686	30.226	27.885	0.120	0.163	0.270	0.166	9.398	9.398	0.071	84.240	6.73	1.00	6.73
1380	1001082	AC	8	1972	14.097	19.304	20.574	17.986	0.120	0.163	0.270	0.129	8.382	8.890	0.071	69.790	6.82	1.00	6.82
1381	1956540	DI	12	2005	7.112	9.398	10.236	9.685	0.027	0.071	0.480	0.083	9.398	9.398	0.071	58.497	6.73	1.00	6.73
1382	1956508	DI	12	2005	7.112	9.398	10.236	9.876	0.027	0.071	0.480	0.185	9.398	9.398	0.071	26.718	5.09	1.00	5.09

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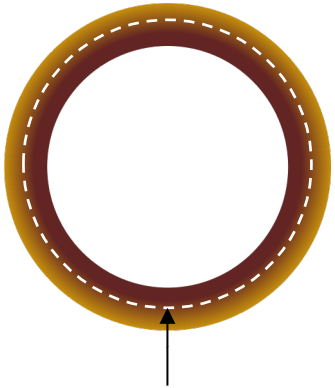
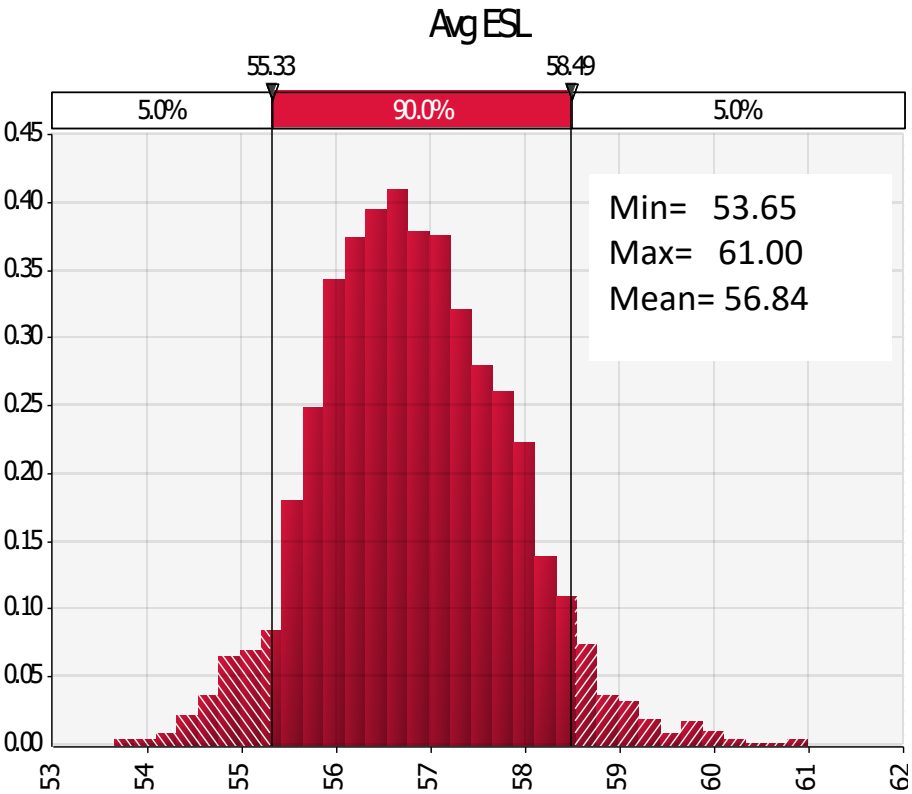
Estimated Service Life



How long does it take to lose 50% of the thickness?



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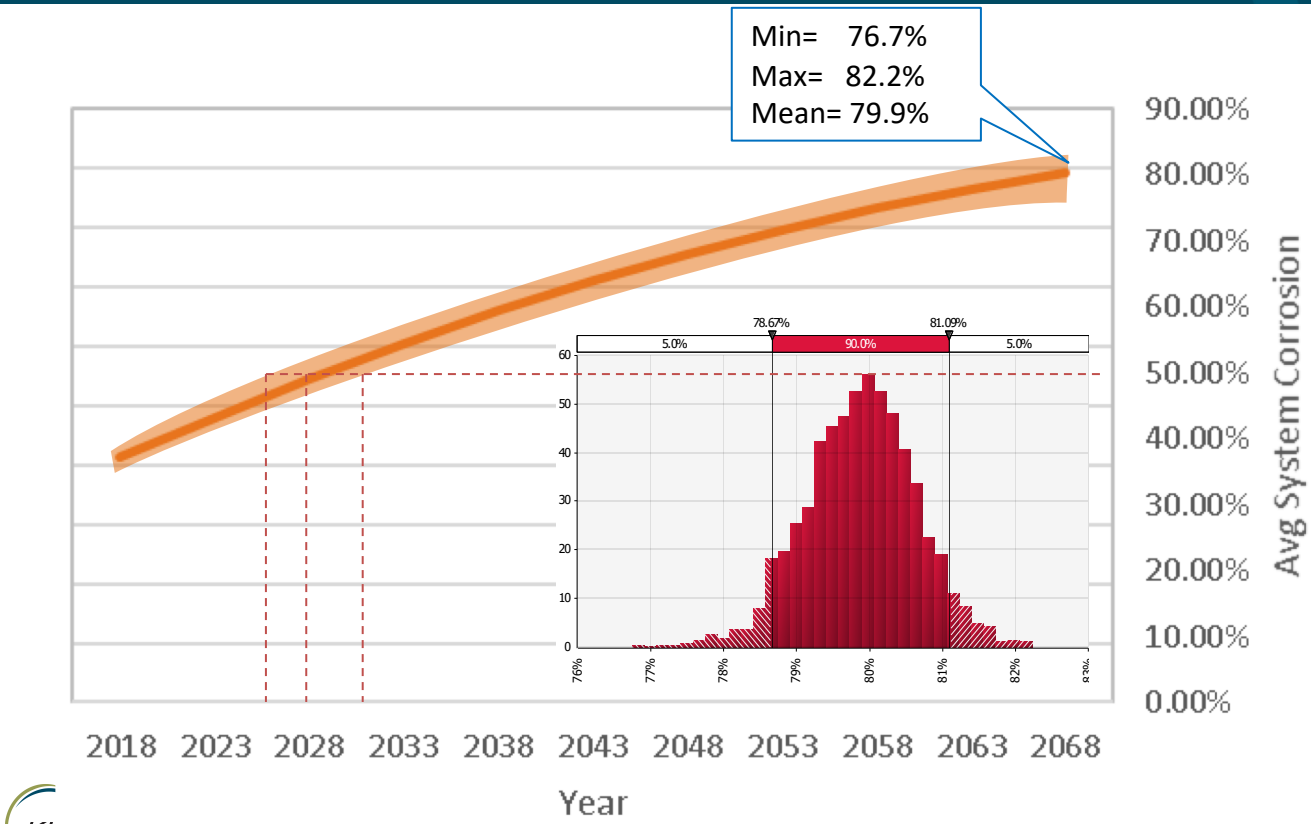
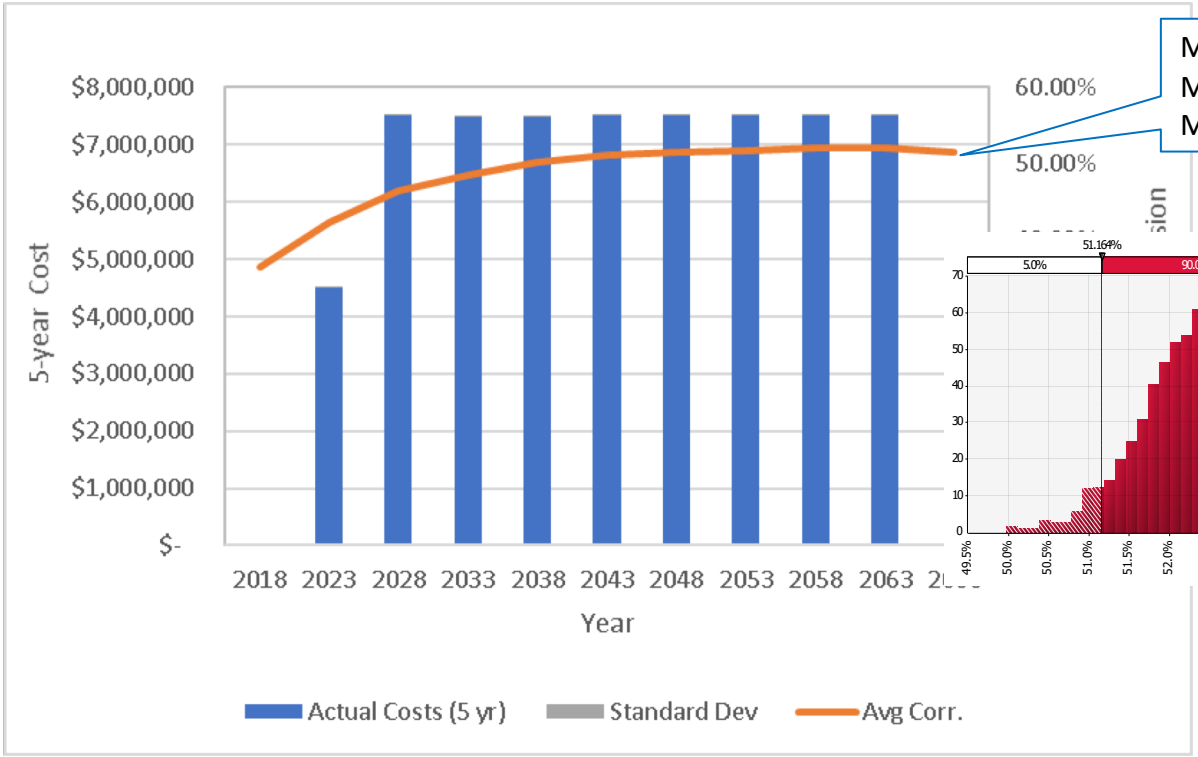
Scenario 1: Budget = $0



Scenario 2: “1.5M /year starting in 2025”



Min= 50.0%
Max= 54.7%
Mean= 52.3%

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Key Findings

- The corrosion rates derived from the Echologic's data result in estimated service life values shorter than what's been traditionally accounted for.
- Soil corrosivity in Wareham could be a concern.
- More corrosivity data should be collected for a more accurate assessment.
- Other failure modes should also be considered.
- This analysis indicates that at least $1.5M per year is needed to maintain the system overtime.

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Questions?

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