Vulnerability Assessment of Southwest Infrastructure to Increased Heat Using a Life Cycle Approach

Emily Bondank
Graduate Student
Civil, Environmental, and Sustainable Engineering
Arizona State University

Mikhail V. Chester
Assistant Professor
Civil, Environmental, and Sustainable Engineering
Arizona State University

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Executive Summary

As average temperatures and occurrences of extreme heat events increase in the Southwest, the water infrastructure that was designed to operate under historical temperature ranges may become increasingly vulnerable to component and operational failures. For each major component along the life cycle of water in an urban water infrastructural system, potential failure events and their semi-quantitative probabilities of occurrence were estimated from interview responses of water industry professionals. These failure events were used to populate event trees to determine the potential pathways to cascading failures in the system. The probabilities of the cascading failure scenarios under future conditions were then calculated and compared to the probabilities of scenarios under current conditions to assess the increased vulnerability of the system. We find that extreme heat events can increase the vulnerability of water systems significantly and that there are ways for water infrastructure managers to proactively mitigate these vulnerabilities before problems occur.

1.0 Introduction

Climate change models predict that the desert regions of the United States will be experiencing a gradual increase in ambient temperatures along with significant increases in frequency, duration, and intensity of extreme heat events (NRDC, n.d.). To water utilities in the Southwest, the increase in air temperature is most significantly a cause of the threat to water supply, but it is also possible that increasing temperatures could pose a threat to other parts of the urban water system. Because the components of water infrastructure are designed to operate under current temperature ranges, those components have the potential to become vulnerable to failure when the temperature exceeds those ranges. This study utilizes event tree analyses to assess whether heat related events could contribute to increased likelihood of system failures in water and wastewater systems in the arid, southwestern state of Arizona. Relationships between system failures and temperature are identified by consulting literature and the opinions of professionals in the industry to get an idea of both how components were designed to operate under increased temperature and how they might actually operate due to the influence of repair and maintenance on their life spans. Ultimate system failures for each of the water systems include waterborne disease outbreaks, interruption in service, and large costs incurred for the deployment of emergency response and maintenance.

It is important to not that while threat or vulnerability is being assessed through the event tree method, traditional risk has not yet been assessed in this particular study because the likelihood of climate events occurring has not been factored into the probability of failure. It has instead been used as an un-quantified initiating stressor of the system.

2.0 Methodology

The following methodology was used to identify failure events, quantify their probabilities for current and future climate scenarios, create event trees to calculate the probability of cascading failure, and assess which heat related failure scenarios pose the greatest threat to overall systems reliability.

2.1 System Boundary

All major manmade systems within the urban water system are included in the analysis. This includes the infrastructure needed for water extraction, treatment, distribution, sewers, and wastewater treatment. The hydrological systems influencing stream flow levels and effluent mixing are excluded from the analysis because they are considered a part of the external natural system. Additionally, pipes distributing water within houses are excluded from the analysis because utilities do not own or manage them. Though the diagram does not depict groundwater or the Central Arizona Project sources of water, the infrastructure needed to extract those sources of water is included in the analysis.

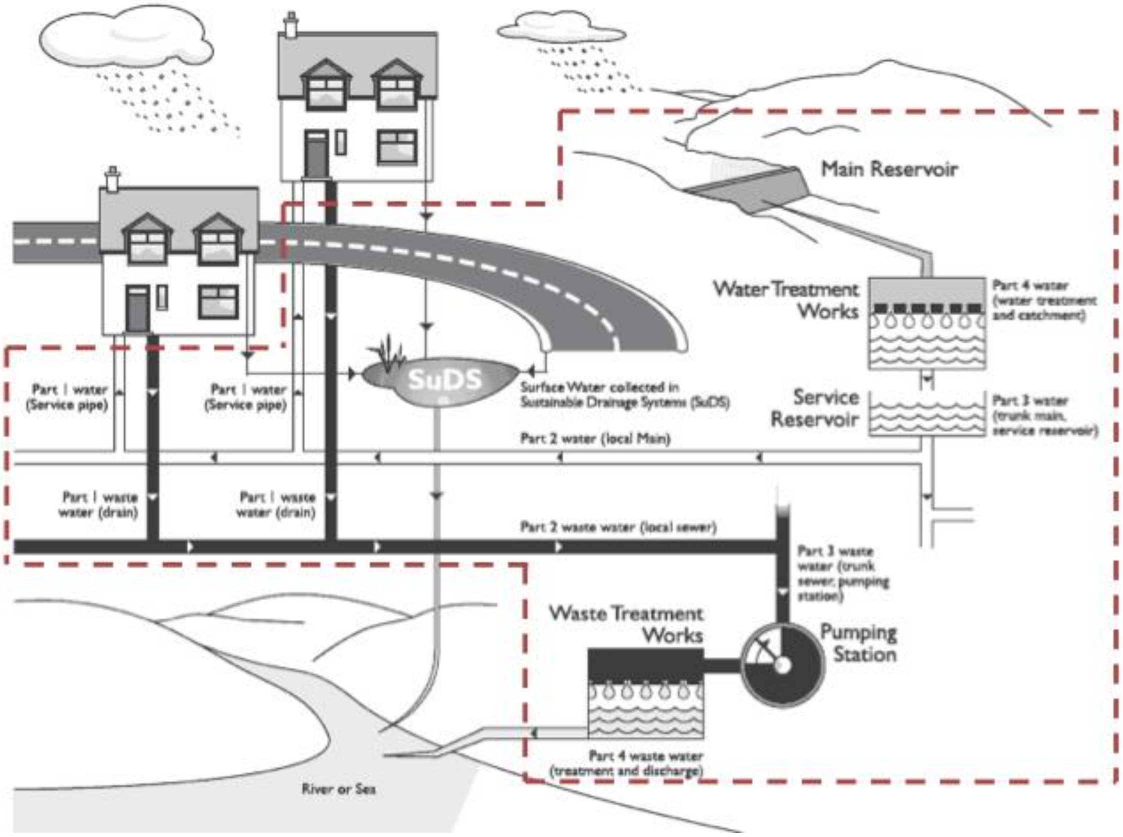


Figure 1 Urban Water System Boundary (adapted from Scottish Government, n.d.)

As shown in Figure 2, each urban water system will be composed of components, subcomponents, and sub-sub components. Using a bottom –up approach, the smallest components will be evaluated first for possible failure modes where there is information available.

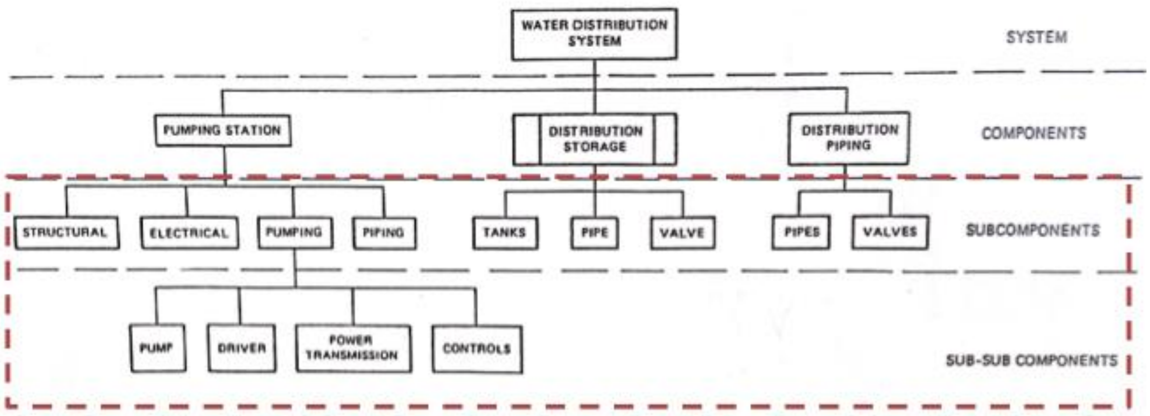


FIGURE 1.15 Hierarchical relationship of components, subcomponents, and sub-subcomponents for a water distribution system (Cullinane, 1989).

Figure 2 Component Boundary (Mays, 2000)

2.1 Formulation of Failure Events along the life cycle of water

Failure events in the infrastructural systems throughout water's life cycle were identified from the *Water Distributions Systems Handbook* (Mays, 2000), interviews and surveys of engineers and operators working in Arizona, and from technical sessions in the conference proceedings of the 88th annual Arizona Water Association conference in Glendale, AZ May 6 -8, 2015.

2.2 Probability of Failure Assessment

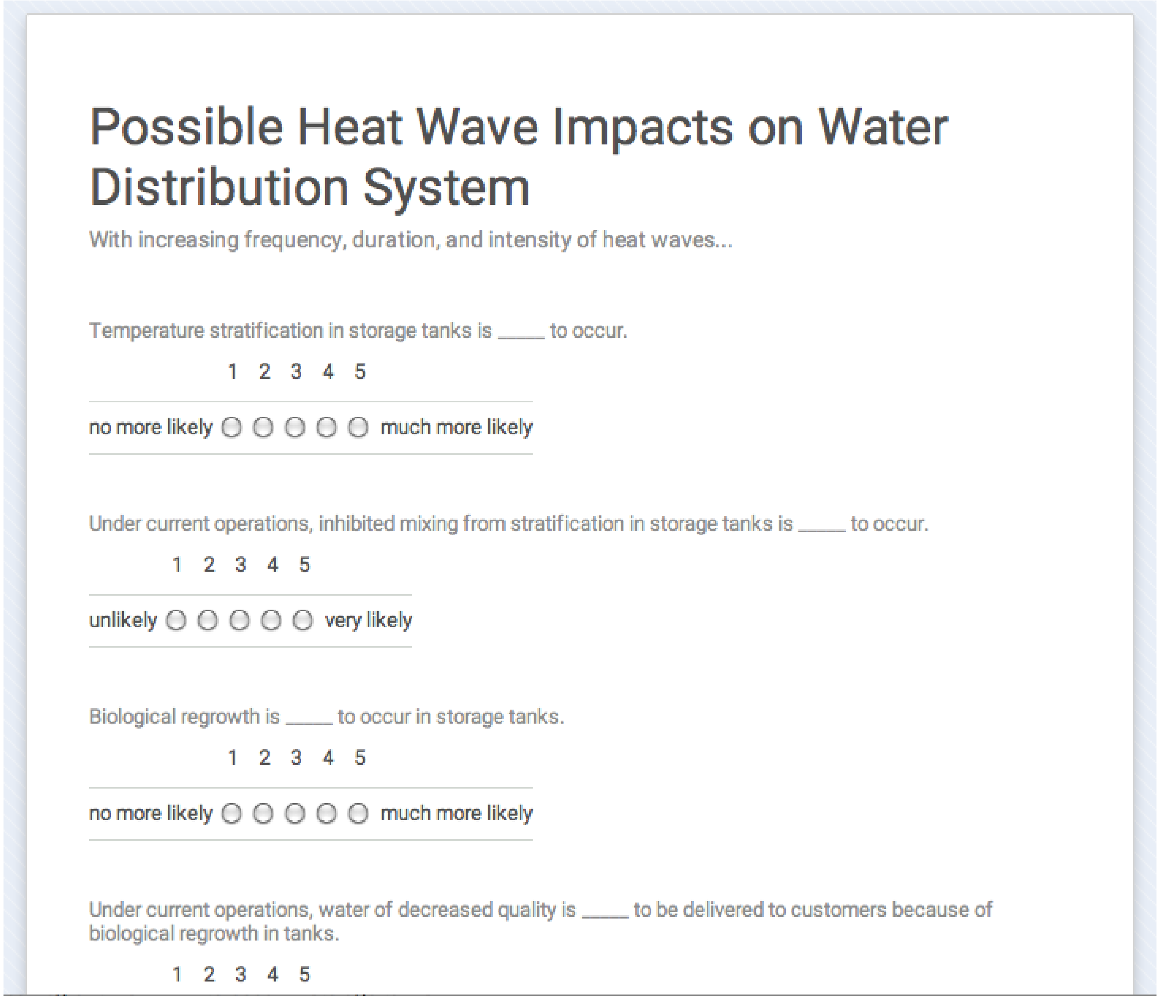
The probability of failure events were evaluated through both engineer estimated and approximated rates of failure and through information provided by manufacturers.

Quantitative Methods:

Some information on the life spans of components and their relationship to temperature is available in manufacturing white papers. Additionally, engineers and operators have sometimes offered this information in interviews.

Mixed Qualitative & Qualitative Method

Interviews and surveys were administered to engineers and operators to assess how likely the specific component would be to fail within certain time frames that were appropriate for each component in the baseline, increasing average temperature, and extreme heat event cases. Interviewees were asked to call upon their experience and knowledge to estimate how likely component failures would be to occur along a likelihood scale from zero to five where zero was no likelihood, one was unlikely and five was very likely.



Possible Heat Wave Impacts on Water Distribution System

With increasing frequency, duration, and intensity of heat waves...

Temperature stratification in storage tanks is _____ to occur.

	1	2	3	4	5	
no more likely	○	○	○	○	○	much more likely

Under current operations, inhibited mixing from stratification in storage tanks is _____ to occur.

	1	2	3	4	5	
unlikely	○	○	○	○	○	very likely

Biological regrowth is _____ to occur in storage tanks.

	1	2	3	4	5	
no more likely	○	○	○	○	○	much more likely

Under current operations, water of decreased quality is _____ to be delivered to customers because of biological regrowth in tanks.

1 2 3 4 5

Figure 3 Portion of likelihood of failure survey administered to engineers and operators

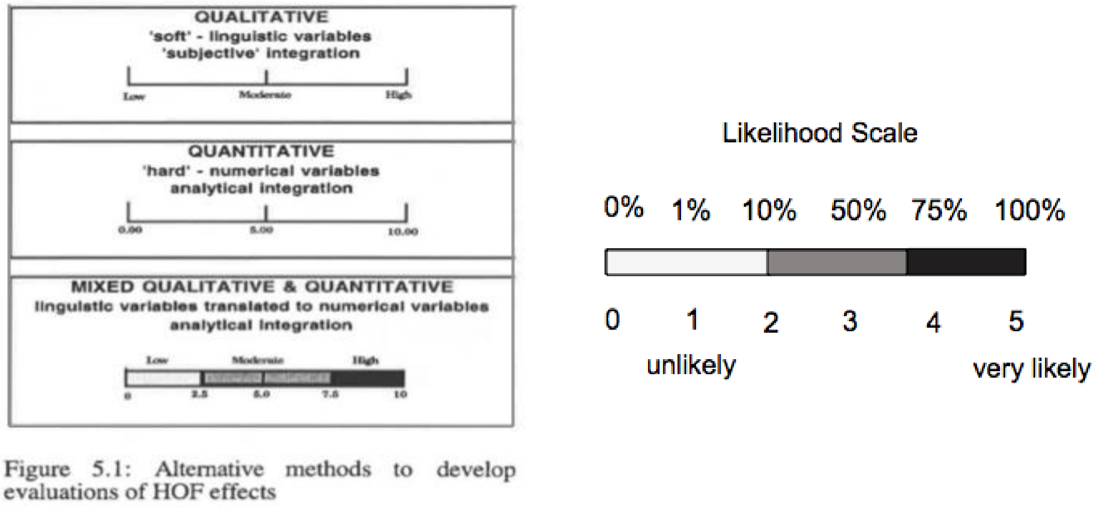


Figure 5.1: Alternative methods to develop evaluations of HOF effects

Figure 4 Left: Mixed Qualitative & Qualitative Scale (Bea, 2005); Right: Likelihood scale used to convert linguistic likelihood to quantitative probability

The mixed qualitative and quantitative likelihood scale provided by Robert Bea was used to translate the baseline, average increasing temperatures, and future extreme heat responses into quantitative probabilities as shown in Figure 4.

2.4 Event trees and system failure scenarios

The method of event tree formation is taken from Bea's work in *Human & Organizational Factors: Quality & Reliability of Engineered Systems* (2005) and Chester's work on *Human and Organizational Factors that Contributed to the US Canadian August 2003 Electricity Grid Blackout* (2013). In this method, event trees are formed by linking failure events together in a sequence of time where each event has the option of being true or false. A probability is assigned to each event being true and the probability that the event is false is simply 100% minus the probability that the event is true. The component failures initiate the tree of events so that a progression of opportunities for operation and management intervention can be seen while the sequence of events progresses towards possibility of catastrophic system failure.

The probabilities of human errors, as defined by Robert Bea, are used to calculate overall probability of failure of the events requiring human action. Figure 4 shows the range of human error values Bea assigns to different types of human tasks.

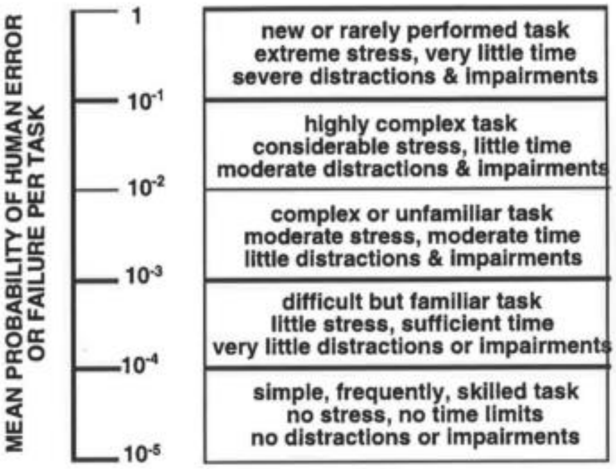


Figure 5 Mean Probability of Human Error or Failure per Task (Bea, 2005)

The probability of failures of each event accounting for human error are then joined in an intersection (multiplication) to form an overall system failure in accordance with Bayesian influence theory (Box & Tiao, 1992).

3.0 Results

The results comprise of the identification and quantification of the probability of failure events along the life cycle of water, two event trees showing two scenarios of a progression of component failures to system failure, and a comparison of scenario probability that points to the significant heat related scenarios.

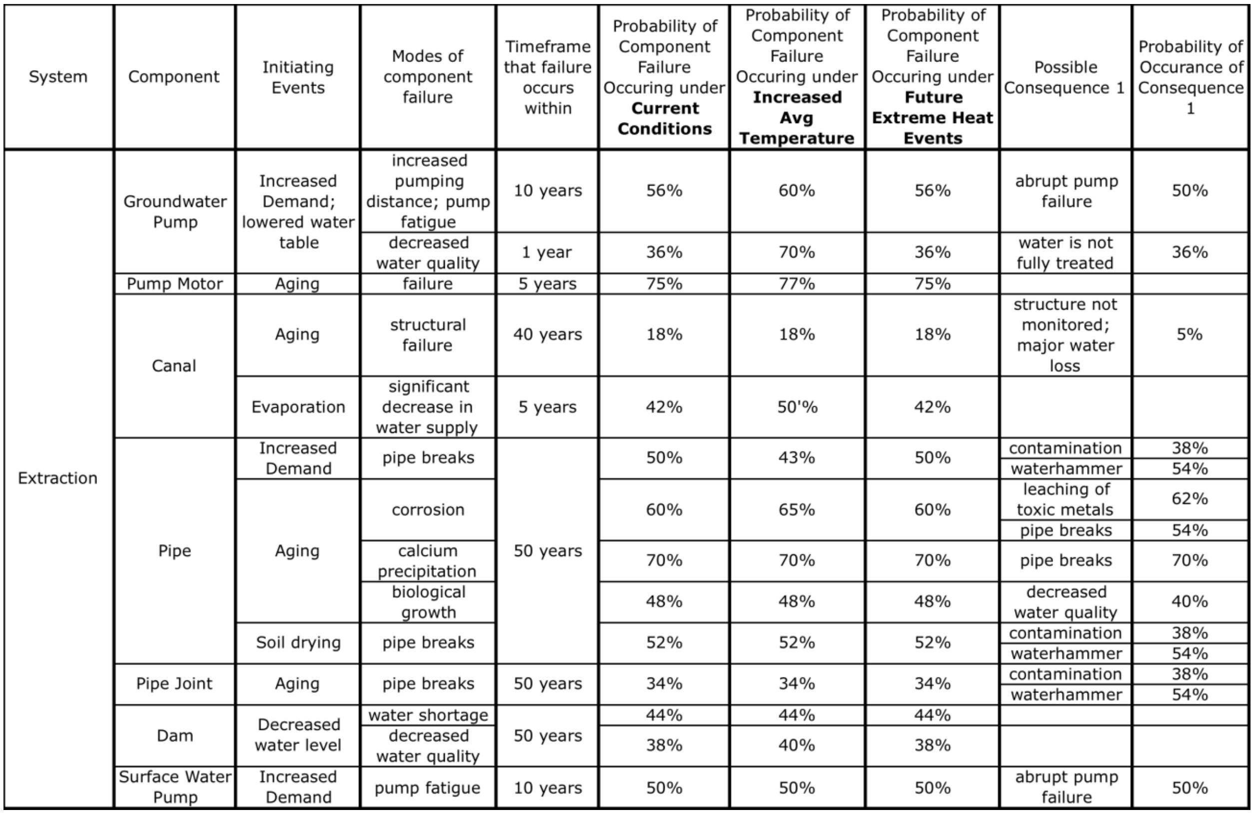
3.1 Failure events along the life cycle of water

Failure events occurring under current conditions, increasing average temperatures, and future extreme heat events that were identified are listed in the following tables for each of the water infrastructural systems. The (dummy) probabilities of occurrence found through surveys are listed as percentages that were found from both quantitative and mixed qualitative and quantitative methods as described in the methodology section.

3.1.1 Water Extraction

A list of the failure events in the water extraction system under current conditions (baseline scenario), increasing average temperatures, and increasing occurrences and intensities of extreme heat events is shown below in Table 1.

Table 1 Water extraction component failures probabilities (dummy data)



System	Component	Initiating Events	Modes of component failure	Timeframe that failure occurs within	Probability of Component Failure Occuring under **Current Conditions**	Probability of Component Failure Occuring under **Increased Avg Temperature**	Probability of Component Failure Occuring under **Future Extreme Heat Events**	Possible Consequence 1	Probability of Occurance of Consequence 1
Extraction	Groundwater Pump	Increased Demand; lowered water table	increased pumping distance; pump fatigue	10 years	56%	60%	56%	abrupt pump failure	50%
			decreased water quality	1 year	36%	70%	36%	water is not fully treated	36%
	Pump Motor	Aging	failure	5 years	75%	77%	75%		
	Canal	Aging	structural failure	40 years	18%	18%	18%	structure not monitored; major water loss	5%
		Evaporation	significant decrease in water supply	5 years	42%	50'%	42%		
	Pipe	Increased Demand	pipe breaks	50 years	50%	43%	50%	contamination	38%
								waterhammer	54%
		Aging	corrosion		60%	65%	60%	leaching of toxic metals	62%
								pipe breaks	54%
			calcium precipitation		70%	70%	70%	pipe breaks	70%
			biological growth		48%	48%	48%	decreased water quality	40%
		Soil drying	pipe breaks		52%	52%	52%	contamination	38%
								waterhammer	54%
	Pipe Joint	Aging	pipe breaks	50 years	34%	34%	34%	contamination	38%
								waterhammer	54%
	Dam	Decreased water level	water shortage	50 years	44%	44%	44%		
			decreased water quality		38%	40%	38%		
	Surface Water Pump	Increased Demand	pump fatigue	10 years	50%	50%	50%	abrupt pump failure	50%

3.1.2 Water Treatment

A list of the failure events in the water treatment system under current conditions (baseline scenario), increasing average temperatures, and increasing occurrences and intensities of extreme heat events is shown below in Table 2.

Table 2 Water treatment component failure probabilities (dummy data)

System	Component	Initiating Events	Modes of component failure	Timeframe that failure occurs within	Probability of Component Failure Occuring under **Current Conditions**	Probability of Component Failure Occuring under **Increased Avg Temperature**	Probability of Component Failure Occuring under **Future Extreme Heat Events**	Possible Consequence 1	Probability of Occurance of Consequence 1	Possible Consequence 2..	Probability of Occurance of Consequence 2
Water Treatment	Bar screen	Increased Demand	clogging	50 years	12%	20%	20%				
	Pump	Increased Demand	pump fatigue	10 years	50%	60%	60%	abrupt pump failure	50%		
	Pump Motor	Aging	malfunctions	5 years	60%	64%	70%				
	Coagulation	Change in inputs	capacity for coagulation decreases	1 year	14%	30%	40%				
	Flocculation	Change inputs	capacity for flocculation decreases	1 year	20%	30%	33%				
	Clarification Basins	Change in inputs	capacity for sedimentation decreases	1 year	24%	25%	33%				
	Mechanical Mixer	Aging	fatigue	10 years	28%	28%	28%	abrupt failure	26%		
	Mixer Motor	Aging	malfunctions	5 years							
	Filter	Aging	fouling	5 years	14%	14%	14%				
	Pipe	Increased Demand	pipe breaks	50 years	50%	50%	50%	contamination	38%		
								waterhammer	54%		
		Aging	corrosion		54%	60%	68%	leaching of toxic metals	62%		
								pipe breaks	54%		
			calcium precipitation		50%	54%	54%	pipe breaks	70%		
			biological growth		12%	40%	30%	decreased water quality	40%		
		Soil drying	pipe breaks		52%	52%	70%	contamination	38%		
								waterhammer	54%		
	Pipe Joint	Aging	pipe breaks	50 years	10%	10%	20%	contamination	38%		
								waterhammer	54%		
	Sensors	Aging	misreadings	1 year	70%	80%	80%				
	SCADA Electronics	Aging	electronic malfunctions	20 years	8%	8%	8%				
	Conveyance channel	Aging	decrease in structural integrity	30 years	6%	6%	6%				
	Chemical disinfection	Aging	chlorine degradation	1 year	40%	60%	70%	need for increased dosing of chlorine	36%	formation of disinfection byproducts	44%
	Chemical Storage Tank	Aging	tank structural integrity	10 years	8%	8%	8%				

3.1.3 Water Distribution

A list of the failure events in the water distribution system under current conditions (baseline scenario), increasing average temperatures, and increasing occurrences and intensities of extreme heat events is shown below in Table 3.

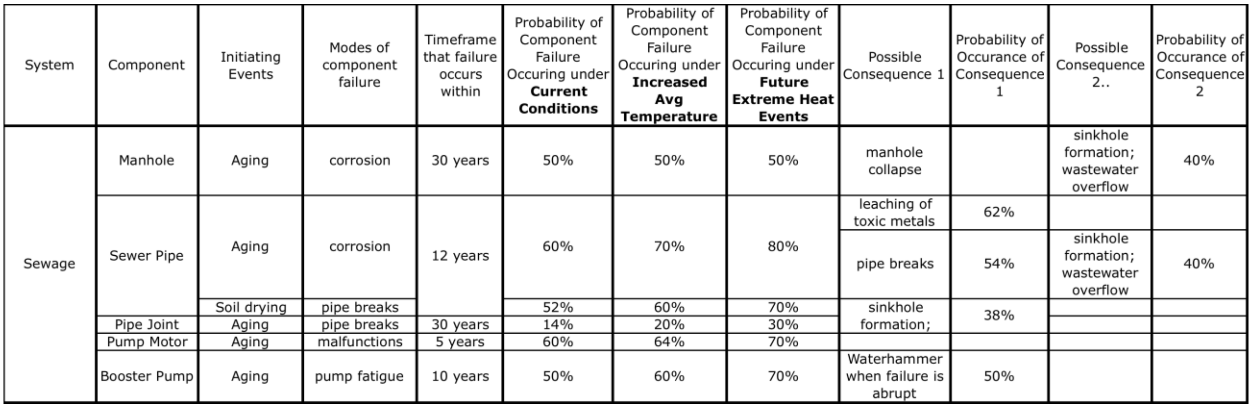
Table 3 Water distribution component failure probabilities (dummy data)

System	Component	Initiating Events	Modes of component failure	Timeframe that failure occurs within	Probability of Component Failure Occuring under **Current Conditions**	Probability of Component Failure Occuring under **Increased Avg Temperature**	Probability of Component Failure Occuring under **Future Extreme Heat Events**	Possible Consequence 1	Probability of Occurance of Consequence 1
Water Distribution	Pump	Aging	pump fatigue	10 years	50%	50%	50%	abrupt failure	50%
	Pump Motor	Aging	malfunctions	5 years	60%	64%	70%		
	Storage Tank	Water Stratification	inhibited mixing	1 year	20%	20%	20%		
		Tank Aging	corrosion	10 years	60%	60%	60%	iron uptake from water	62%
								holes in tank	54%
			biological growth		54%	54%	54%	decreased water quality	26%
		Increased Demand	tank breaks	1 year	6%	6%	6%		
			insufficient mixing		28%	28%	28%		
	Pipe Joint	Aging	pipe breaks	50 years	14%	14%	14%	increased contamination	38%
								waterhammer	38%
	Meters	Aging	misreadings	20 years					
	Sensors	Aging	misreadings	1 year	70%	80%	80%		
	SCADA Electronics	Aging	electronic malfunctions	20 years	8%	8%	8%		
	Valve	Aging	valve breaks	40 years	10%	29%	43%		
	Pipe	Increased Demand	pipe breaks	50 years	50%	50%	50%	increased contamination	38%
								waterhammer	38%
		Aging	corrosion		60%	60%	60%	leaching of toxic metals	62%
								pipe breaks	54%
			calcium precipitation		70%	70%	70%	pipe breaks	50%
			biological growth		58%	58%	58%	decreased water quality	58%
		Soil Drying	pipe breaks		62%	62%	62%	increased contamination	38%
								waterhammer	38%

3.1.4 Wastewater Sewage

A list of the failure events in the wastewater sewage system under current conditions (baseline scenario), increasing average temperatures, and increasing occurrences and intensities of extreme heat events is shown below in Table 4.

Table 4 Wastewater sewage component failure probabilities (dummy data)



System	Component	Initiating Events	Modes of component failure	Timeframe that failure occurs within	Probability of Component Failure Occuring under **Current Conditions**	Probability of Component Failure Occuring under **Increased Avg Temperature**	Probability of Component Failure Occuring under **Future Extreme Heat Events**	Possible Consequence 1	Probability of Occurance of Consequence 1	Possible Consequence 2..	Probability of Occurance of Consequence 2
Sewage	Manhole	Aging	corrosion	30 years	50%	50%	50%	manhole collapse		sinkhole formation; wastewater overflow	40%
	Sewer Pipe	Aging	corrosion	12 years	60%	70%	80%	leaching of toxic metals	62%		
								pipe breaks	54%	sinkhole formation; wastewater overflow	40%
		Soil drying	pipe breaks		52%	60%	70%	sinkhole formation;	38%		
	Pipe Joint	Aging	pipe breaks	30 years	14%	20%	30%				
	Pump Motor	Aging	malfunctions	5 years	60%	64%	70%				
	Booster Pump	Aging	pump fatigue	10 years	50%	60%	70%	Waterhammer when failure is abrupt	50%		

3.1.5 Wastewater Treatment

A list of the failure events in the wastewater treatment system under current conditions (baseline scenario), increasing average temperatures, and increasing occurrences and intensities of extreme heat events is shown below in Table 5.

Table 5 Wastewater treatment component failure probabilities (dummy data)

System	Component	Initiating Events	Modes of component failure	Timeframe that failure occurs within	Probability of Component Failure Occuring under **Current Conditions**	Probability of Component Failure Occuring under **Increased Avg Temperature**	Probability of Component Failure Occuring under **Future Extreme Heat Events**	Possible Consequence 1	Probability of Occurance of Consequence 1
Wastewater Treatment	Bar screens/grit chamber	Aging	clogging	30 years	12%	12%	12%		
	Pumps	Aging	pump fatigue	10 years	50%	50%	50%	abrupt pump failure	50%
	Pump Motor	Aging	malfunctions	5 years					
	Clarification Basin	Change in inputs	decreased capacity for sedimentation	1 year	24%	24%	24%		
		Exposure to air and sunlight	algae blooms	1 year					
	Activated Sludge	Change in inputs	decreased capacity for treatment	1 year	28%	28%	28%		
	Blower	Aging	blower fatigue	5 years	22%	22%	22%	blower failure	26%
		Change in properties of air	decreased efficiency	1 year					
	Filter	Aging	faster fouling	1 year	14%	20%	20%		
	Pipe	Increased Demand	pipe breaks	50 years	50%	50%	50%	increased contamination	38%
								waterhammer	38%
		Aging	increased corrosion		60%	70%	80%	leaching of toxic metals	62%
								pipe breaks	54%
			calcium precipitation		50%	60%	60%	pipe breaks	54%
			biological growth		58%	70%	70%	decreased water quality	58%
		Soil drying	pipe breaks		52%	60%	70%	increased contamination	38%
								waterhammer	38%
	Pipe Joint	Aging	pipe breaks	50 years	14%	20%	20%	increased contamination	38%
								waterhammer	38%
	Sensors	Aging	misreadings	1 year	80%	90%	95%		
	SCADA Electronics	Aging	increased electronic malfunctions	20 years	35%	50%	60%		
	conveyance channel	Aging	decrease in structural integrity	30 years	6%	10%	20%		
	UV Treatment	Aging	decreased capcity	5 years	8%	10%	20%	abrupt failure	13%
	Chemical Storage Tank	Aging	decrease in structural integrity	5 years	10%	10%	10%		

3.2 Failure Event Trees

Some of the possible interconnections between component failures and operation failures were explored in two different event tree analyses. Both of the event trees show the cascading failure in the water provision system to compromised water quality. It should be noted that the progression of events in these event trees are based on time of occurrence and not necessarily on causality of events.

3.2.1 Contamination initiated by corrosion

This event tree is initiated by increased corrosion in storage tanks and bird feces infiltration into the storage tanks. This event tree follows the actual occurrences of the waterborne outbreak of *Salmonella* in Gideon, Missouri in 1994 (Mays, 2000). Probabilities of occurrences of temperature related events reflect the increase in probability of events in the future. In 1994, this cascading failure scenario ultimately resulted in around 500 people being exposed to *Salmonella* (about 40% of town population).

Event Tree Under Current Conditions:

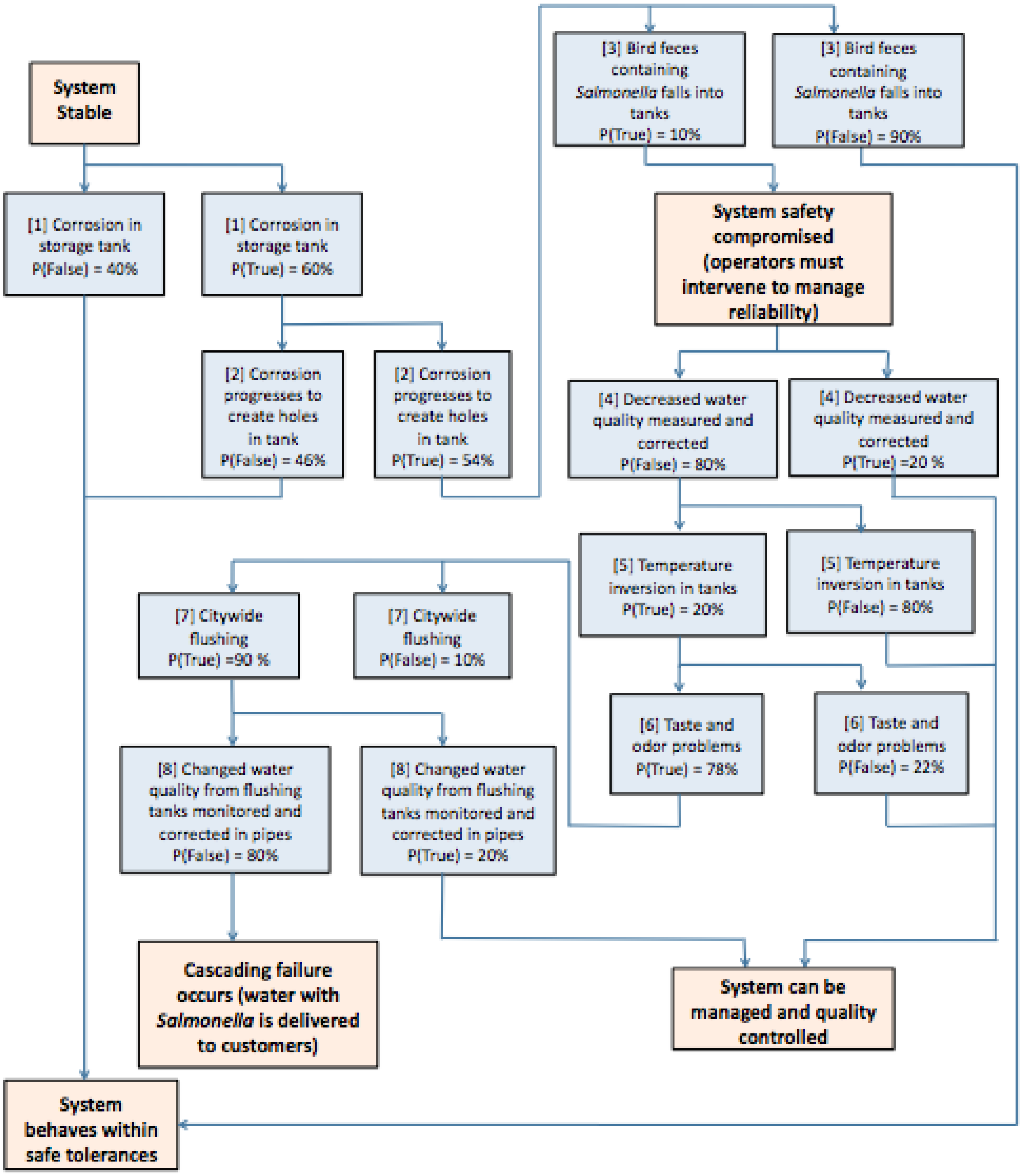


Figure 6 Contamination initiated by corrosion under current conditions

Event Descriptions:

[1] Corrosion occurs in storage tanks. Corrosion is the deterioration of a metal caused by moisture, and presence of air. From the surveys, it was found that the probability of corrosion under current conditions is 60%.

[2] Corrosion progresses to create holes in tanks. If corrosion in tanks is monitored, structural failures due to corrosion can be prevented with the addition of corrosion inhibitors into the water. From the survey it was found that corrosion is normally left unremedied around 54% of the time.

[3] Bird feces containing *Salmonella* falls into tanks. Bird and other animal feces seepage into storage tanks is a concern because the feces can carry harmful pathogens like *Cryptosporidium*, *Giardia*, *Campylobacter*, *Salmonella*, *E.coli,* and viruses. I estimate that the occurrence of pathogenic feces entering storage tanks has a10% likelihood.

[4] Decreased water quality is measured and corrected. Water quality is normally monitored in storage tanks through grab sampling (or manual sampling) rather than continuous monitoring due to the high initial cost associated with installing continuous monitoring devices. I am unsure of the typical frequency with which grab samples are performed but I guess that it is infrequent in some cases. Therefore, I estimate that there is a 20% likelihood of the contamination being detected.

[5] Temperature inversion occurs in tanks. Temperature inversion or stratification is caused by temperature differentials within tanks from either warm or cold temperature shocks. From the survey responses, tank stratification is 20% likely to occur within a one-year time period under current weather conditions.

[6] Taste and odor become a noticeable problem. From the survey responses it was found that taste and odor problems occur after temperature shocks around 78% of the time.

[7] Citywide flushing program instated. Flushing is used often both to remove contaminants and to routinely scour off biofilms from pipes. Therefore I will estimate that there is a 90% chance of flushing being used in this situation. A large fire or power outage might put the system in a similar state because they both would require using water in storage tanks.

[**8] Changed water quality from flushing tanks is monitored and quality is corrected in pipes.** Again, water quality is monitored in storage tanks through grab sampling normally rather than continuous monitoring. I am unsure about the protocol of sampling after large flushes. Therefore, I will estimate that there is a 20% likelihood of the contamination being detected after flushing. In the waterborne outbreak in Gideon, this flushing re-suspended pathogenic solids in the corroded storage tank and caused much of the municipal water to be contaminated thereafter.

Differences in event tree under increased average temperatures:

Increased average temperatures increase the probability that events [1] and [5] are true.

[1] Corrosion occurs in storage tanks. An increase in air and water temperature can cause an increase in corrosion of storage tanks made of steel or steel reinforced concrete. From the surveys, it was found that the probability of corrosion over a 10-year period under increases in average temperatures is 70%.

[5] Temperature inversion occurs in tanks. From the survey responses, tank stratification is 30% likely to occur at least once within a one-year time frame under increased average temperatures.

Differences in event tree under future extreme heat events:

Future occurrences of extreme heat events increase the probability that events [1] and [5] are true as well.

[1] Corrosion occurs in storage tanks. Periods of abnormal increase in air and water temperature can cause an increase in corrosion of storage tanks made of steel or steel reinforced concrete as well. From the surveys, it was found that the probability of corrosion over a 10-year period under future occurrences of extreme heat events is 80%.

[5] Temperature inversion occurs in tanks. From the survey responses, tank stratification is 70% likely to occur at least once within a one-year time frame under future extreme heat events due to the rapid change involved in an extreme heat event.

3.2.2 Contamination from Increased Demand Event Tree

This event tree is initiated by increased demand for potable water that will occur due to population increase, and climate change. This event tree is not guided by historical example, but was made rather from finding connections between possible component failures.

Event Tree Under Current Conditions:

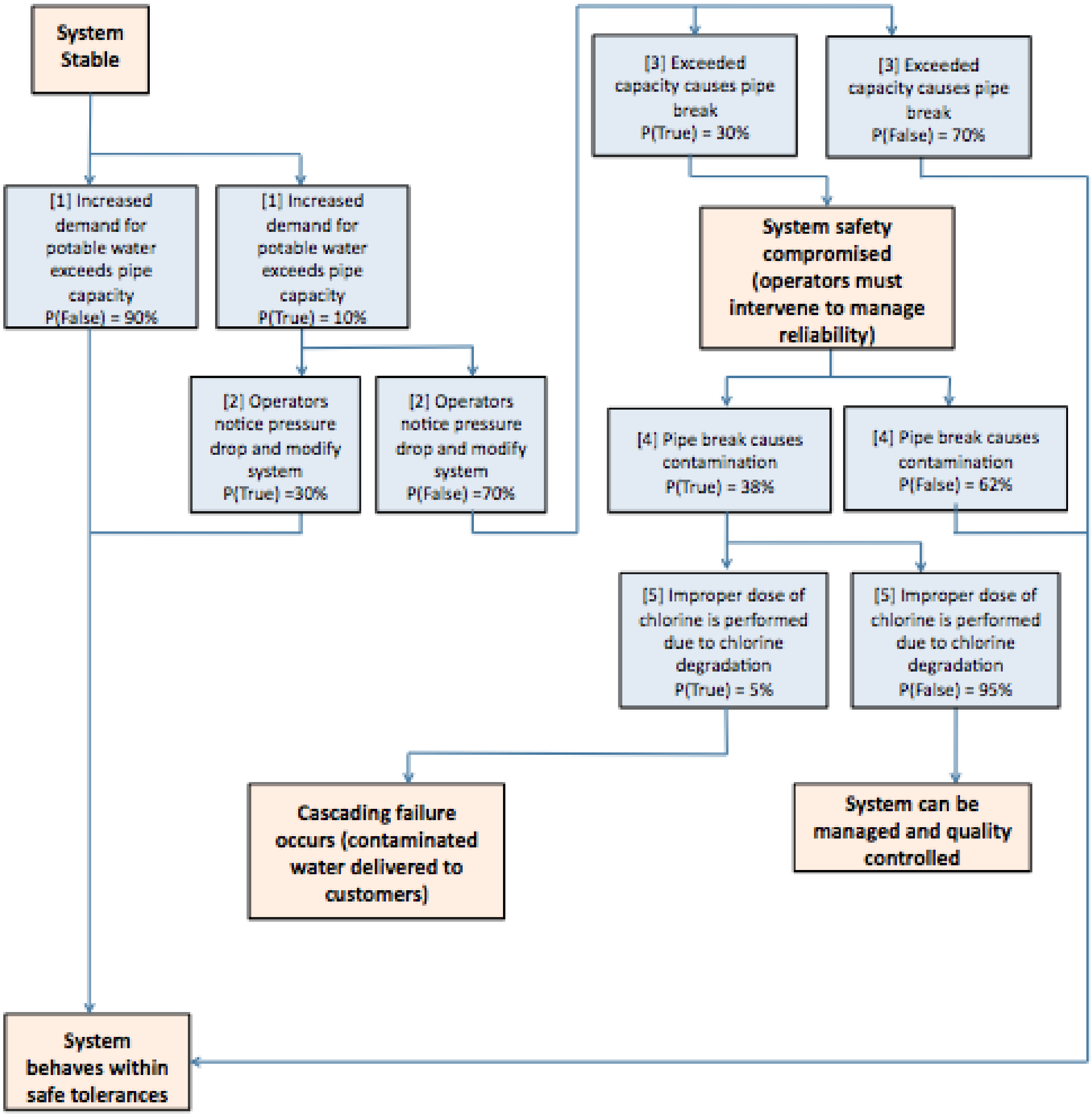


Figure 7 Contamination from increased demand under current conditions

Event Descriptions:

[1] Increased demand for potable water exceeds pipe and pump capacities. It is possible that demand exceeds pipe capacities due to population increase. Because a general decrease in demand has been observed through active and passive conservation, and systems are generally oversized, the likelihood of this occurring is probably close to 5%.

[2] Operators notice pressure drop and modify system. An experienced operator identifies exceedances of capacities through noticing pressure drops in the system. When detected, the problem can be remedied by adding another storage tank or pressure reducing valve to the system or by replacing pipes and pumps (Mays, 2000). I estimate that the likelihood of this happening is 30%.

[3] Exceeded capacity causes pipe break. When excessive loads are present, they are the greatest single cause of water main breaks (Mays, 2000). From survey responses, it is 30% likely that a pipe will break when its capacity is exceeded in a 50-year period.

[4] Pipe break causes contamination. When pipes break, it is possible for water within the pipes to become contaminated if the water is not kept at a high pressure before fixing the pipe. There is a 38% likelihood that this will happen under current conditions.

[5] Improper dose of chlorine is performed due to chlorine degradation. Chlorine can degrade from exposure to high temperatures, light, low pH values, and presence of iron, nickel, copper, or cobalt. For example liquid chlorine looses half of its strength when stored in 100^{o}F for 3 weeks. Because the temperatures we experience are still somewhat expected, it was estimated that the likelihood of inadequate dosing is 5% under current conditions.

<u>Differences in event tree under increased average temperatures:</u>

Increased average temperatures increase the probability that events [1] and [5] will be true.

[1] Increased demand for potable water exceeds pipe and pump capacities. Because there is a large influx of people in some areas of Arizona during the summer, hotter temperatures could indirectly cause large demands in these areas. Additionally, in warmer regions of Arizona, irrigation schedules may be increased when it gets hotter outside. From the survey it is estimated that increased average temperatures would have a 10% likelihood of causing exceedance of pipe capacities.

[5] Improper dose of chlorine is performed due to chlorine degradation. With higher average temperatures, chlorine would degrade even faster. From the surveys it was estimated that it would be 60% likely that chlorine would degrade within 3 weeks.

Differences in event tree under increased occurrences of extreme heat events:

Future occurrences of extreme heat events increase the probabilities that events [1] and [5] will be true as well.

[1] Increased demand for potable water exceeds pipe and pump capacities. Extreme heat events could cause exceedances of pipe capacities for the same reason that increased average temperatures could. Due to the more intense nature of extreme heat events however it was estimated from the surveys that increased extreme heat events would have a 30% likelihood of causing exceedance of pipe capacities.

[5] Improper dose of chlorine is performed due to chlorine degradation. Extreme heat events could also degrade chlorine at a faster rate. From the surveys it was estimated that it would be 70% likely that chlorine would degrade within 3 weeks.

3.3 Cascading Failure Scenario Probabilities

The cascading failure scenarios in the event trees are the series of events that lead to compromised function of the system. In the event trees shown in this report, compromised function is defined as contaminated water reaching the customer. The following tables show the calculation of the probability of failure of the events given estimated human error rates based on estimated levels of task complexity as found in Bea's human error rate scale (Bea, 2005). The overall probability of scenarios is calculated using Bayesian inference by finding the intersection (multiplication) of all event probabilities (Box & Tiao, 1992).

3.3.1 Contamination from Corrosion

Table 6 Scenario probability of contamination initiated by corrosion under current conditions

Event	P(Failure)	Error Rate	P(F|E)
1	60%	1	0.6
2	54%	0.00001	0.0000054
3	10%	1	0.1
4	80%	0.001	0.0008
5	20%	1	0.2
6	78%	1	0.78
7	90%	0.00001	0.000009
8	80%	0.0001	0.00008
		Scenario Probability:	2.91E-20

Table 7 Scenario probability of contamination initiated by corrosion under increasing average temperatures

Event	P(Failure)	Error Rate	P(F|E)
1	70%	1	0.7
2	54%	0.00001	0.0000054
3	10%	1	0.1
4	80%	0.001	0.0008
5	30%	1	0.3
6	78%	1	0.78
7	90%	0.00001	0.000009
8	80%	0.0001	0.00008
		Scenario Probability:	5.09E-20

Table 8 Scenario probability of contamination initiated by corrosion under future extreme heat events

Event	P(Failure)	Error Rate	P(F|E)
1	80%	1	0.8
2	54%	0.00001	0.0000054
3	10%	1	0.1
4	80%	0.001	0.0008
5	70%	1	0.7
6	78%	1	0.78
7	90%	0.00001	0.000009
8	80%	0.0001	0.00008
		Scenario Probability:	1.36E-19

3.3.2 Contamination from Increased Demand

Table 9 Scenario probability of contamination initiated by increased demand under current conditions

Event	P(Failure)	Error Rate	P(F|E)
1	5%	1	0.05
2	70%	0.00001	0.000007
3	30%	1	0.3
4	38%	0.001	0.00038
5	5%	0.0001	0.000005
		Scenario Probability:	2.0 E-16

Table 10 Scenario probability of contamination initiated by increased demand under increasing average temperatures

Event	P(Failure)	Error Rate	P(F|E)
1	10%	1	0.1
2	70%	0.00001	0.000007
3	30%	1	0.3
4	38%	0.001	0.00038
5	60%	0.0001	0.00006
		Scenario Probability:	4.80E-15

Table 11 Scenario probability of contamination initiated by increased demand under future extreme heat events

Event	P(Failure)	Error Rate	P(F|E)
1	30%	1	0.3
2	70%	0.00001	0.000007
3	30%	1	0.3
4	38%	0.001	0.00038
5	70%	0.0001	0.00007
		Scenario Probability:	1.68E-14

3.4 Cascading Failure Scenario Relations to Baseline Scenario

A summary of the differences of impact on scenario probability of the heat related scenarios is shown in Table 12 below.

Table 12 Ratio of baseline scenarios to increased heat scenarios

	Ratio of baseline scenarios to heat related scenarios	
Heat related cascading failure scenario	Increasing Average Temperatures	Future Extreme Heat Events
Corrosion	1.75	2.67
Increased Demand	24	84

The cascading failure scenarios of corrosion causing contamination under increased average temperatures and extreme heat events is only 1.75 and 2.67 times the baseline scenario respectively. The cascading failure scenarios of increased demand causing contamination under increasing average temperatures and extreme heat events were 24 and 84 times the baseline scenario respectively. Therefore, based on the evaluation of these two event tree analyses, it is recommended that if utilities have funds to invest in climate change preparation, they should invest in replacing undersized pipes and predicting future doses of chlorine needed to combat the increasing degradation that will caused by increasing temperatures.

4.0 Discussion and Conclusions

4.1 Uncertainty

A pedigree matrix was not used to assess uncertainty of this study because the goal of the recommendation is to generalize solutions for the state of Arizona while the data comes from specific entities within Arizona. Because this is a large area with many separate utilities with different maintenance procedures and components of different ages, all data is relevant. Whether or not the combination of this select data adequately represents Arizona as a whole is a good question, however. Currently interviews have only been conducted with water providers from cities and towns within the Phoenix metropolitan area. Therefore this reveals an obvious deficiency in the current data. In a few interviews, it was mentioned that pipes break more during the winter season because the water could freeze when stagnant. Therefore, in cities north of Phoenix, warmer temperatures may actually serve as a benefit to the reliability of the system.

Variability of operations:

Though there are regulations set by the American Water Works Association on maintenance operations, there seems to be much freedom left to the individual utilities to decide what additional maintenance and repair programs they would like to instate. Therefore, each utility is run slightly differently according to their different priorities. It may be hard to make estimates of how often tasks should performed generally across AZ or even just within Phoenix because of the existence of so many different utilities.

Variability in treatment systems:

The processes and equipment present in each water system are different as well, depending on the environment the systems are in and where the source water comes from. The surrounding environments are important for the design of wastewater treatment plants because there are different environmental regulations from region to region. For example, wastewater treatment in highly vegetated regions requires more nutrient removal to combat eutrophication in water bodies. In arid regions, water reuse is more of a priority, so wastewater treatment is focused on removing as many harmful constituents as possible through expensive membranes. Additionally, the processes in water treatment systems are dependent on what kind of source water is available. For example, groundwater requires much less treatment than surface water does due to surface water's elevated turbidity and organic content.

Variability in consumers:

Utilities throughout Arizona also differ in levels of demand required from different kinds of consumers. For example, some cities are mostly “bedroom communities” and therefore, most of the water they produce goes to landscape irrigation. For more industrial types of communities, water will be used in different amounts at different times in the day and will be affected by temperature differently as well.

Though this study faces some significant uncertainty, the end goal can still be achieved. The goal is not to say with certainty that planners, engineers, and operators need to invest in infrastructure specific ways to avoid facing certain system failures. It is simply our goal to provide a study to help utilities become aware of effects of climate change, to help assess how much of a threat these effects might pose, and identify some ways utilities can prevent possible failures.

If the investment recommendations are too costly to be desirable, our study will at least provide the useful perspective that things are changing, and that utilities should foster a culture prepared for change. For example, many water planners are starting to view “droughts” differently through the lens of climate change. The idea is that perhaps it is not an abnormal event but a shift to a new norm. The cascading failure events laid out in this study are problems within the water systems that could begin to become less and less abnormal as time goes on. If utilities can decreasingly view the events as individual cases of abnormal behavior, more creative solutions might emerge that could increasingly facilitate adaptation.

4.2 Future Work

The next steps in this study are to

(1) Create more event trees for each water system and to incorporate specific electricity infrastructure failure events into the event trees since the infrastructures systems are heavily coupled.

(2) Include translating failure events into a more dynamic model to depict the interactions between components on a broader scale that is independent of a progression of time.

(3) Use the recommended results from the cascading failure scenarios with significant probabilities to populate decision matrices to determine which group of investments would be financially worthwhile. This could incorporate an analysis of the cost of the infrastructural and operational improvements that would give a better idea of the feasibility and desirability of the implementations suggested.

(4) The study could be taken one step further to incorporate the desirable suggestions for improvement into an asset management program that could be implemented by a utility.

6.0 References

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