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IMPACT ASSESSMENT OF URBAN DECLINE ON COUPLED HUMAN AND WATER SECTOR INFRASTRUCTURE SYSTEMS

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IMPACT ASSESSMENT OF URBAN DECLINE ON COUPLED HUMAN AND WATER SECTOR INFRASTRUCTURE SYSTEMS

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To my mother
Thank you for your unwavering support

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ABSTRACT

Faust, Kasey Mariko. Ph.D., Purdue University, August 2015. Impact Assessment of Urban Decline on Coupled Human and Water Sector Infrastructure Systems. Major Professor: Dulcy M. Abraham.

Urban decline in once vibrant cities has introduced many challenges to managing civil infrastructure. The fixed infrastructure footprint does not contract with the declining population, but remains relatively stable, resulting in underfunded and underutilized infrastructure. The focus of this dissertation is on the assessment of urban decline on the coupled human and water sector infrastructures. Aspects such as the drivers of population decline and transitioning to a smaller city for the current and projected populations in shrinking cities have been well-studied by political and social scientists. However, the repercussions of urban decline on underground infrastructure systems have thus far been underappreciated. Arising from urban decline are water sector infrastructure issues such as, increased water age, operating on reduced personnel, and underutilized impervious services contributing to stormwater runoff. As cities begin to right-size, understanding the impact of the underutilization on underground infrastructures, and the technical viability of retooling alternatives to aid in right-sizing are important to ensure infrastructures continue to provide adequate services to the residents. This dissertation aims to fill the gap in the body of knowledge and the body of practice regarding the impact of urban decline (and underutilization) on the coupled human and water sector infrastructure systems, the technical viability of retooling alternatives, and the public views towards these infrastructure systems and retooling alternatives.

To accomplish the research objective, a mixed-method qualitative and quantitative framework is demonstrated using two case study cities: Flint, Michigan and Saginaw, Michigan. The two case studies demonstrate the applicability of the framework spanning different size classification of cities. Flint is a medium sized city with its population peaking at 196,940 in 1960, whereas Saginaw is classified as a small city with its population peaking at 98,265 in 1960. As of 2010, both cities have since lost over 40% of their population from their peak populations. Qualitative

analyses use data from literature, the water infrastructure data from the case study cities, interviews with subject matter expert, and survey observations from the residents of shrinking cities in the US. First, the dissertation begins with synthesizing the data to identify infrastructure issues typical to shrinking cities, discern possible retooling alternatives, establish relationships between the water infrastructure system, wastewater/stormwater infrastructure system(s), and the types of human-infrastructure interactions relevant to the models. Next, metrics are selected to measure individual water and wastewater/stormwater infrastructure performance in the presence of physical (retooling alternatives) and non-physical (population dynamics, price elasticity, consolidation of demand to more populous areas of the city) disruptors. These metrics include: water infrastructure system pressures, fire flow capabilities, and the reduction of runoff. Following the qualitative analyses, four quantitative analyses were performed using data provided by the case study cities, interviews with subject matter experts, published data, and survey observations from residents of US shrinking cities. Network analyses evaluate the impact of non-physical and physical disrupters on the water infrastructure's ability to provide adequate service. The specific physical disruptor evaluated for the water infrastructure system is decommissioning water pipelines. Hydraulic simulations estimate the impact of decommissioning impervious surfaces, transitioning land uses, and incorporating low-impact development on the generated stormwater runoff entering the wastewater/stormwater infrastructure. After examining the individual infrastructures, survey analyses and statistical modeling is used to evaluate the public views in 21 US shrinking cities towards water and wastewater infrastructure issues and retooling alternatives. Finally, the aforementioned three components are integrated into the interdependency analysis to evaluate the water, wastewater, and stormwater infrastructures and human-infrastructure interaction interdependencies.

This study demonstrates that the retooling alternatives evaluated are technically viable for proactively right-sizing water and wastewater/stormwater infrastructure. The statistical modeling framework estimated the demographic and geographic variables influencing the support (or opposition) of different water retooling alternatives. For instance, the statistical models indicated that residents in Flint, Michigan are more likely to support decommissioning, whereas, residents in Ohio's shrinking cities are more likely to oppose decommissioning. Age of residents is an example of a recurring demographic variable in the statistical models, since the analyses indicates that residents over the age of 50 are more likely to oppose repurposing infrastructure and residents younger than 35 are more like to support maintaining the current infrastructure. The statistical analyses demonstrate a method for incorporating public opinion into the pre-planning

process for potentially reducing public opposition. The interdependency analyses component demonstrates a framework for evaluating the impacts of urban decline on the coupled human-infrastructure systems. The interdependency analysis model can predict future water and wastewater needs based on projected rate increases and population trends, as well as the complex interaction between billing rates, financial return, and water demand. This model can be applied to different size classification of cities, as well as different decline/growth trajectories by updating the parameters in the model to reflect the characteristics of the city. Emergent behavior is captured in this model that is absent from other models in literature, such as the impact of water price elasticity cascading into the wastewater system, impacting the total generated revenues and the systemic interaction of agents to generated desired levels of support. Furthermore, the developed hybrid agent based-system dynamics model enables the estimation of the maximum achievable level of support that may be gained in a time period using market adoption strategies. In conclusion, this dissertation provides a framework for insight into right-sizing water sector infrastructure operations and management in shrinking cities.

CHAPTER 1. INTRODUCTION

"We keep moving forward, opening up new doors and doing new things, because we're curious… and curiosity keeps leading us down new paths."

-Walt Disney

Shrinking cities are cities that have experienced a substantial population decline from their peak populations. Contrary to growth patterns typically assumed by engineers and planners, shrinking cities are plagued by increasing numbers of vacant properties (e.g., homes, businesses, brownfield sites) and decreasing demands for infrastructure services. During these economic contractions, the footprint of built infrastructure does not adjust, but rather remains stable, ultimately creating an excess of underfunded and underutilized infrastructure.

1.1. Motivation

Traditional infrastructure design has been based on the assumption of growing or static populations without future design scenarios that allow for unexpected developments, and flexibility of demand needs. Flexibility of demand needs is defined as the ability of the fixed infrastructure system to handle either significant increases or decreases in demands that differ from the system's designed capacity. Studies have identified challenges within cities arising from the inability to effectively accommodate decreased demands, such as rising per capita infrastructure costs, increased abandoned and vacant areas, decreased aesthetics, or increased crimes (Kabisch et al. 2006; Hollander et al. 2009; Schilling and Logan 2009; USEPA 2014). Previous studies have discussed right-sizing the footprints of shrinking cities by transforming the vacated and abandoned areas to other land uses with minimal attention towards the repercussions of underutilization on the underground infrastructure systems (e.g., Bontje 2004; Armbost et al. 2008; Masi 2008; Pallagst 2009). The performance of individual infrastructures operating at or above design capacity is well understood; however, the impacts of underutilization and how to manage underutilization have not been addressed. Furthermore, retooling alternatives, such as decommissioning excess infrastructure and impervious surfaces, that have been qualitatively discussed in literature have not been evaluated to determine the technically viability of implementing such efforts to right-size a shrinking city's physical infrastructure footprint.

As cities explore right-sizing and implementing various retooling alternatives to transition to sustainable infrastructure management, identifying drivers of opposition and which retooling alternatives the community may support allows for incorporating the community vision and while possibly mitigating opposition. Literature pertaining to public views in the context of urban decline has examined quality of life in the context of perceptions towards abandonment and vacancies, without considering underground water and wastewater infrastructure (e.g., Greenberg and Schneider 1996; Bright 2000; Hollander 2010; Hollander 2011). There is a need to assess the public's knowledge, perceptions, awareness and attitudes towards water and wastewater/stormwater infrastructure alternatives in shrinking cities to identify alternatives that may be implemented within minimal opposition.

The decisions made about above-ground infrastructure may have repercussions on below-ground infrastructure. An example of such a decision is transiting land use from residential to green space, which essentially eliminates demands on the water infrastructure in the area, with the possibility of impacting operations of the fixed water infrastructure network. Conversely, the decisions made about below-ground infrastructure may impact above-ground life. For instance, decommissioning underground water infrastructure can remove or limit the capability of using the particular land parcel for residential purposes due to lack of water service in the area. With the tight coupling of community needs and infrastructure management, decision-makers must consider both the technical viability, as well as the projected needs of the population.

1.2. Key Terminology

Many terms are recurrent throughout this dissertation. Key terminology is defined in this section with relevant examples for each term.

Shrinking city: The term 'shrinking' city in this dissertation refers to a city experiencing chronic decline over many decades that has resulted in a loss of at least 30% of the population from the peak population. Flint, Michigan and Saginaw, Michigan, the cities used as case studies, are example cities that have lost over 40% of their populations since their peak populations in 1960.

Urban decline/shrinkage: Decline of populations within city boundaries is referred to as urban decline or urban shrinkage. Urban decline/shrinkage may also be used to describe decline in economic development, which may contribute to decreasing populations.

Retooling alternative: A physical, managerial, or operational change to the infrastructure that is intended to move the infrastructure system towards right-sizing the infrastructure in the shrinking city.

Decommissioning pipelines: Decommissioning pipelines is a retooling alternative that refers to ceasing to use the pipeline and either cleaning and capping the pipeline or removing the pipeline from underground.

Decommissioning impervious surfaces: Decommissioning impervious surfaces is a retooling alternative that refers to pavement removal of an area and shifting the land to a natural state.

Physical disrupter: A physical disrupter is a tangible change impacting the state of the infrastructure system, such as decommissioning infrastructure components or decreasing the physical quantity of consumed water entering the wastewater system. It is important to note that a disrupter does not necessary cause a disruption in service or a negative impact, but simply causes a change in or to the system. For instance, decommissioning infrastructure components will physically change the fixed network, but may improve operations or save money in maintenance.

Non-physical disrupter: An intangible change impacting the state of the infrastructure is referred to as a non-physical disrupter, such as consumer behavioral changes due to price elasticity, or the decreased number of consumers inherent to urban decline. As mentioned above, the term disrupter does not indicate a disruption to the service or a negative impact, necessarily, but a change to the status quo infrastructure state.

Human-infrastructure interaction: In this dissertation, human-infrastructure interaction is the interface of the public/consumers with the infrastructure system and service (which in the scope of this dissertation is, water, wastewater, and stormwater) provided by the infrastructure system. The difference in daily water use trends based on socioeconomic status is an example of the human interaction with the water infrastructure system. Another interaction between the human-infrastructure in regard to the resource provided is price elasticity. In the context of interactions between the public and the physical infrastructure, an example is the level of support or opposition towards implementing a retooling alternative impacting the implementation time of the alternative. Human-infrastructure interaction may also come in the form of population dynamics, impacting the total infrastructure demands, such as urban decline resulting in decreased water demands citywide, or urban growth leading to built-up areas, resulting in more impervious surfaces generating runoff that enters the wastewater/stormwater system.

Physical Interdependency: Physical interdependencies refer to when the infrastructure is dependent on the material output of another infrastructure. For instance, wastewater infrastructure is dependent on the output of the water demanded that is then entering the wastewater system.

1.3. Research Questions

The dissertation demonstrates an analytical framework to evaluate the impact of underutilization on the water and wastewater/stormwater infrastructures, as well as the public views within shrinking cities towards water and wastewater/stormwater infrastructure issues and retooling alternatives. The research questions answered in this dissertation fall into four categories as follows: water infrastructure, wastewater/stormwater infrastructure, public views, and interdependencies.

Water Infrastructure: What is the impact of continued urban decline and consolidation of demand on the water infrastructure system? What is the impact of retooling alternatives when assessing the individual water infrastructure system? In the context of the decommissioning within each case study, what size pipelines may be decommissioned without compromising the infrastructure's ability to provide services?

Wastewater/Stormwater Infrastructure: What is the impact of implementing retooling alternatives on the generated stormwater runoff? How do these retooling alternatives perform under synthetic storm conditions? Which retooling alternative yields the highest reduction in runoff for financial investment within each case study?

Public Views: What are the public's knowledge, awareness, perceptions, and attitudes toward water and wastewater/stormwater infrastructure issues and retooling alternatives? What are the demographic and location characteristics significant for supporting or opposing various water retooling alternatives?

Interdependencies: What are the emergent behaviors observed due to the interactions between the physical water, wastewater, and stormwater infrastructure systems and the public in shrinking cities? How long does it take to generate the desired level of public support for decommissioning pipelines and decommissioning impervious surfaces?

1.4. Research Objectives

The aim of this research is to fill the gap in the body of knowledge and the body of practice regarding underutilization of infrastructure by exploring the impact of urban decline on the water and wastewater/stormwater infrastructure systems and public views towards these infrastructure systems. Specifically the research objectives for this study are:

1) Identify a set of metrics to analyze the impact of (a) non-physical and physical disruptors on the water infrastructure system and (b) physical disruptors on the wastewater/stormwater infrastructure system.
2) Create and evaluate a model, employing the metrics developed in Objective 1, for evaluating the viability of implementing water and wastewater/stormwater infrastructure retooling alternatives.
3) Assess the impact of the retooling alternatives on: (a) the ability to provide adequate service by the water infrastructure system and (b) the generated stormwater runoff entering the wastewater/stormwater infrastructure system.
4) Quantify the influence of demographics and location parameters on the public perceptions and attitudes towards water and wastewater infrastructure issues and retooling alternatives in shrinking cities.
5) Evaluate the physical interdependencies between the water, wastewater, and stormwater infrastructure systems and the impact of the human-infrastructure interaction on the support/opposition of retooling alternatives, population dynamics, and price elasticity.

1.5. Research Overview

The research methodology (shown in Figure 1.1) employs a mixed method approach, incorporating qualitative and quantitative analyses to accomplish the research objectives (shown in Figure 1.1). The methodology is applied using two shrinking cities as case studies, Flint, Michigan and Saginaw, Michigan, in order to demonstrate the applicability across different size classifications for cities. Flint is a medium-sized city (population peaking at 196,940 in 1960), whereas Saginaw is classified as a small city (population peaking at 98,265 in 1960). Both cities have declined over 40% since there peak population, consequentially resulting in an infrastructure footprint that is larger than necessary for the current population.

Qualitative analyses of the data collected from literature, the case study cities, subject matter expert (SME) interviews, and survey data from residents of US shrinking cities is synthesized to form the foundation of the quantitative analyses. Qualitative analyses were used to identify: (1) the infrastructure issues typical to shrinking cities, (2) possible retooling alternatives to mitigate these issues, (3) relationships between the water infrastructure system, wastewater/stormwater infrastructure system(s), and the types of human-infrastructure interactions relevant to the models, and (4) metrics to measure infrastructure performance under continued urban decline or after the implementation of retooling alternatives.

The quantitative analyses consist of four primary components, shown in Figure 1.1. First, network analyses were conducted to evaluate the impact of non-physical and physical disrupters resulting from urban decline and retooling alternatives on the water infrastructure's ability to provide adequate service. Second, hydraulic simulations were used to estimate the impact of retooling alternatives on generated stormwater runoff entering the wastewater/stormwater infrastructures. After examining the individual water and wastewater/stormwater infrastructures, survey analyses and statistical modeling are used to evaluate the public views in 21 US shrinking cities towards water and wastewater infrastructure issues and retooling alternatives. The final quantitative component of this dissertation ties together the previous three components, evaluating the water, wastewater, and stormwater infrastructures and human-infrastructure interaction interdependencies. The causal loop diagram was used to develop a hybrid agent based-system dynamics model to capture the emergent interdependencies, such as the systemic behavior of the public supporting/opposing alternatives, and the impact of price elasticity, population, and urban decline on revenues generated from utility bills and residential water and wastewater demands.

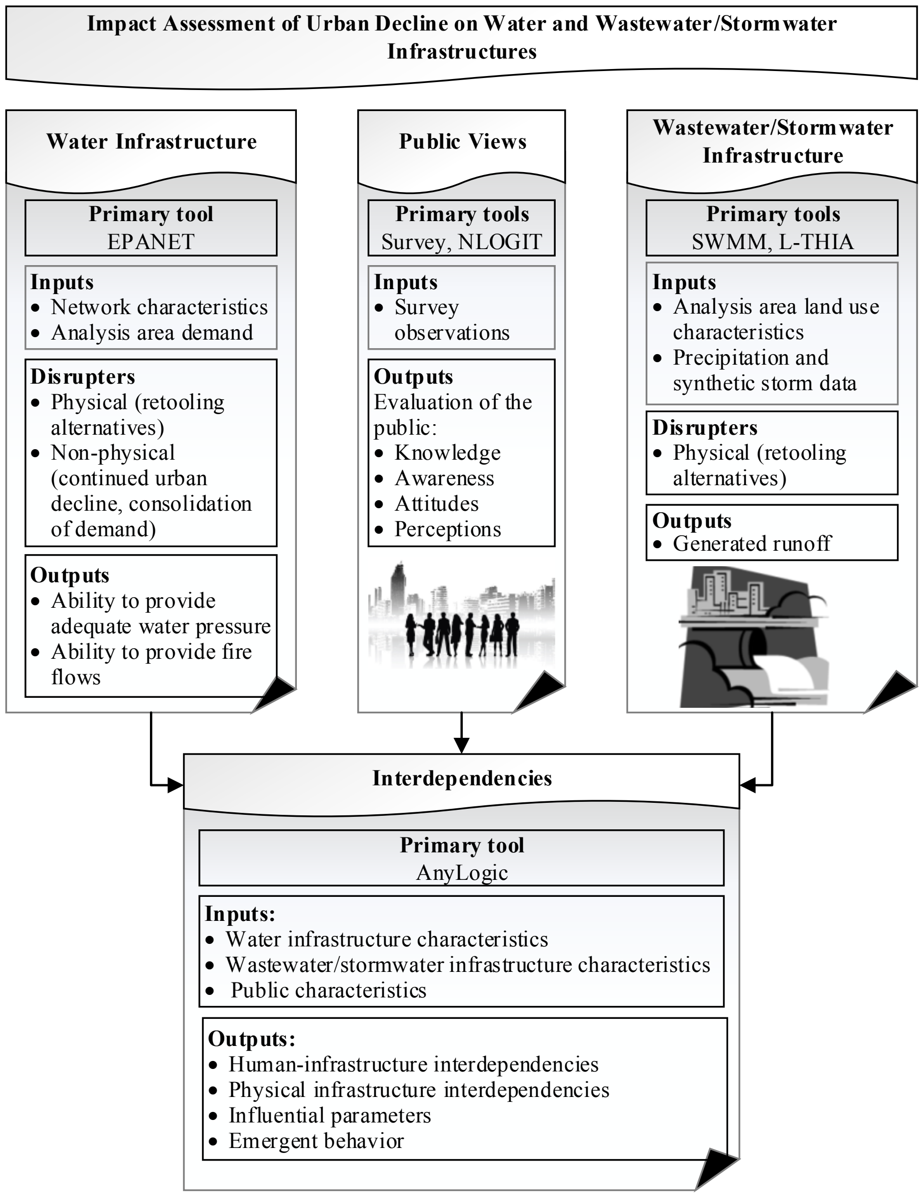

Figure 1.1. Methodology

1.5. Organization

This dissertation is organized into a total of nine chapters. Chapter 1 discusses the motivation, and the research questions, objectives, and overview of the methodology and key terminology. Chapter 2 synthesizes previous research in the domain of critical infrastructure in shrinking cities and infrastructure interdependencies. **Sections from Chapter 2 (indicated as such) are reprinted in part from the Urban Water Journal, 2015, Kasey M. Faust, Fred L. Mannering, and Dulcy M. Abraham, Statistical analysis of public perceptions of water**

infrastructure sustainability in shrinking cities, Copyright (2015), with permission from Taylor & Francis (see Appendix A). Chapter 3 introduces issues typical to the underutilization of water and wastewater infrastructure in cities facing urban decline, as well as potential infrastructure retooling alternatives to mitigate these issues. Chapter 4 describes the methodology used to accomplish the proposed research questions and discusses the case study cities used to demonstrate the proposed methodology. Chapter 5 evaluates the impact of non-physical disruptors (consolidation of and decline of population) and physical disrupters (decommissioning pipelines) on the water infrastructure within the analysis areas of two shrinking cities (Flint and Saginaw). **Sections of Chapter 5 (indicated as such) are reprinted in part from the Construction Research Congress 2014: Construction in a Global Network, 2014, Kasey M. Faust and Dulcy M. Abraham, Evaluating the feasibility of decommissioning residential water infrastructure in cities facing urban decline, Copyright (2014), with permission from the American Society of Civil Engineers (see Appendix B).** Chapter 6 examines the impact of retooling alternatives on the generated stormwater runoff. Chapter 7 examines the public views of residents in shrinking cities towards water and wastewater infrastructure issues and infrastructure retooling alternatives. **Chapter 7 is reprinted in part from the Urban Water Journal, 2015, Kasey M. Faust, Fred L. Mannering, and Dulcy M. Abraham, Statistical analysis of public perceptions of water infrastructure sustainability in shrinking cities, Copyright (2015), with permission from Taylor & Francis. To maintain the format of the dissertation, tables, figures, and captions have been modified (see Appendix A).** Chapter 8 combines the analyses from the Chapters 5, 6, and 7 to evaluate the physical interdependencies between the water infrastructure and wastewater infrastructure system and the impact of human interaction with these infrastructure systems. Chapter 9 concludes the dissertation by presenting a summary of the work, contributions to the body of knowledge and to the body of practice, discusses the limitations of the research and provides recommendations for future research.

CHAPTER 2. PRIOR RESEARCH

"An effective review creates a firm foundation for advancing knowledge."

- *Webster and Watson (2002)*

2.1. Shrinking Cities

The term "shrinking cities" is used to define substantial declines in urban populations (Rybczynski and Linneman 1999; Bontje 2004; Pallagst 2008). The "shrinking cities" phenomenon has been well studied by social and political scientists (e.g., Bontje 2004; Armbost et al. 2008; Masi 2008; Pallagst 2009; Martinez-Fernandez and Wu 2009; Moraes 2009; Wiechmann 2009; Martinez-Fernandez et al. 2012), yet the impacts on engineering and systems management are only beginning to be appreciated (e.g., McDougall 2008; Schillining 2009; Schlör et al. 2009; USEPA 2014).

2.1.1. Drivers of Shrinking Cities and Patterns of Urban Decline

Martinez-Fernandez and Wu (2009) discuss five drivers of shrinking cities (Table 2.1): industrialization, de-industrialization/post-industrialization, globalization, population transition, and climate change. These driving forces causing population decline are the same driving forces (economic, social and political) that cause population growth. It is important to note that a shrinking city may have more than one driver instigating population decline at any given time (Martinez-Fernandez and Wu 2009). Typical to shrinking cities are the increasing numbers of vacant residential areas, which often pose a challenge when/if trying to re-grow the population. Abandoned neighborhoods are seen as blighted areas, associated with higher crime rates (Rybczynski and Linneman 1999; Frazier et al 2013). High vacancies rates are also associated with costly, deteriorating urban infrastructure that must be rehabilitated or rebuilt (Martinez-Fernandez and Wu 2009).

Table 2.1. Drivers of shrinking cities (Martinez-Fernandez and Wu 2009)

Model/ Classification	**Driver**	**Economic/ Social /Environmental Indications**
Industrialization	Concentration of public/private investments and industries that attracts innovations, investments and educated population, periphery (e.g., suburbs, smaller cities, towns) less capable of developing	Rapid development of population centers, industrial zones, pollution
De-industrialization / post-industrialization	Industrial reconstructing, global industrial competition spurring outsourcing, technology changes/development with different labor demands (quantity and skill)	Downtown decline, inner city decline, brownfield sites, increased socio-economic inequality
Globalization	Expansion of export-oriented economies (e.g., Asia), corporatization of cities, global city formation, competition between world city regions, shift towards professional services employment, concentration of innovations and knowledge workers, new mega-city	Global cities (shifting employment structure), decline and/or abandonment of cities or portions of cities, increase in socio-economic inequality
Population Transition	Decline in birth rate, aging population, absolute population decline (e.g., young, educated and/or able populations leaving)	High level of housing vacancy, abandonment of residential areas, underused infrastructure, gentrification, increase in socio-economic inequality
Climate Change	Extreme droughts, floods, natural disasters, changes in climate	Abandoned farms due to prolonged droughts, destroyed infrastructure, changing coast lines, shrinkage of territories, cultural displacement

Other historic attributed causes to shrinking cities include epidemics (Kabisch et al. 2006; Pallagst 2008), agricultural crises (Pallagst 2008) and shifts in political rule (e.g., shift towards post-socialist countries after World War II) (Pallagst 2009). Moraes (2009) argues that in addition to the aforementioned causes, population is also due to historic social inequality.

The locations of shrinking cities and patterns of the urban decline within the city vary from country to country (Pallagst 2008). For instance, in the United States, the Rustbelt cities are the most impacted by declining populations. However, the United Kingdom is experiencing loss of population in the northern regions, while France is losing population in the center, away from inter-country/European transportation networks (Pallagst 2008). Patterns of population loss also differ among international regions (Pallagst 2008). The US is typically seeing a hollowing-out effect of the inner cities experiencing low population (Pallagst 2008). On the contrary, Paris is losing population in its suburban regions, while the inner-city remains stable (Pallagst 2008).

Historically, this shrinking process has been referred to as an “urban crisis” and is a taboo topic (Beauregard 2009; Bernt et al. 2014). Beauregard (2003) refers to shrinking cities as a “stigma” that does not fit the natural thought process of a city’s life or the planning process of the city. Researchers and planners are now emphasizing focusing on stabilizing growth and resizing the city footprint to meet the need of the smaller population and shifting away from population regrowth (shown in Table 2.2). Planning efforts in literature discuss how to transform the excess area to allow the city to reclaim and reinvent itself. Green spaces, parks, pedestrian walkways, and demolition of excess housing are a few of these planning suggestions. With this shift from focusing on stabilizing current population and away from re-growth, comes a shift of attitude, from forcing/attempting re-growth to accepting a smaller city. Table 2.2 presents examples of case studies focused on various regions of the world that place emphasis on urban planning, with a focus on stabilizing the current population of the city, within a shrinking city.

Table 2.2. Examples of published case studies in the context of and right-sizing shrinking cities

Researcher(s) (year)	**Case study**	**Objective/ Argument**	**Conclusion**
Bontje (2004)	Leipzig, East Germany	The author discusses development on the question “how to fight the shrinking city.”	The author proposes shifting focus away from growth and towards stabilizing the city for the ‘shrunk’ population size, similar to Leipzig’s example. Stabilization may be accomplished by adjusting housing stocks, demolishing excess housing and infrastructure for green space and attempting to generate employment to maintain population.
Armbost et al. (2008)	Detroit, Michigan	City planners should embrace the new suburbanism, and accept the fact that the city is smaller.	Presently in shrinking cities like Detroit, Michigan, a ‘new suburbanism’ has developed. Residents are buying vacant lots surrounding their homes, many times demolishing the homes on the lots, and expanding their residences to sit on large properties known as blots. These blots have developed into gardens, expanded garages, playgrounds for children and other uses for the homeowners.
Masi (2008)	Cleveland, OH	Cities may use extra area for agriculture and gardens to provide for a portion of the city’s food.	Cleveland, Ohio is using a portion of its excess space for gardens and agricultural purposes. Lots and paved areas are being converted to gardens and agricultural spaces that are being used for educational purposes, food sources or to gain revenue for individuals, such as selling food at farmers’ markers. By providing for a small portion of the city’s food needs, the city itself may retain more money within the region.

Table 2.2. *(continued)*

Researcher(s) (year)	Case study	Objective/ Argument	Conclusion
Wiechmann (2009)	Dresden, Eastern Germany	Urban planners should shift away from planning for population re-growth, and instead plan for population stabilization.	Dresden, East Germany is used to exemplify that planning strategies for increasing population have been unsuccessful and a negligent use of resources. Through planning for stabilization and allowing flexibility for small increases and declines in population, the city has been able to revitalize and recreate itself in the past decade to maintain a relatively stable population.
Pallagst (2009)	United States	The author presents three case studies in the United States and discusses planning strategies.	The author places emphasis on the positive changes that must occur in shifting from population growth planning to community, smart growth planning. Youngstown, OH is used as an example where the city 'accepted' being a smaller city and aimed at rebuilding the city on a downsized scale, creating new parks and green spaces, and strengthening businesses in the health, education, public administration, and cultural areas.
Domhardt and Troeger-Weiß (2009)	Germany	Small towns in Germany need regional development plans and inter-municipal cooperation.	Strong regional development plans will help to ensure there are equivalent living conditions, services are maintained, and resources are available to the population.
Burkholder (2012)	United States	Underutilized land should be used for ecological benefits.	The author reviews recent literature in urban ecology to identify potential land uses within shrinking cities serving ecological purposes, such as combatting the heat island effect or improving air pollution.
Frazier et al. (2013)	Buffalo, NY	Land use management should be considered in the context of the region.	Attempting to manage shrinkage through methods such as demolition is not removing the crime, but shifting crime to other areas of the city.
Bernt et al. (2014)	Leipzig, Germany; Liverpool, United Kingdom; Genoa, Italy; Bytom, Poland	Shrinkage is not addressed comprehensively, but in a fragmentary fashion due to growth oriented cultural perceptions.	The authors believe that developing analytical frameworks for public policies, with research and scientists is necessary to shift the planning and funding priorities within cities away from growth oriented actions.

2.1.2. Critical Infrastructure in Shrinking Cities

To date, literature related to the domain of critical infrastructure or modeling tools in the context of urban decline is limited. There exists a gap in the body of knowledge in understanding the impact of underutilization on the performance of infrastructure systems and services. Chapter 3 discusses the water sector infrastructure systems in the context of urban decline, specifically covering the issues arising from underutilization, potential retooling infrastructure alternatives, and literature relative to the retooling infrastructure alternatives explored in this study. Table 2.3 highlights select literature focusing on the underutilization of the critical infrastructure systems, irrespective of the infrastructure system. Much of the focus in literature has been on qualitatively discussing infrastructure alternatives, and exploring urban decline's impact on per capita infrastructure service costs.

Table 2.3. Critical infrastructure and modeling tools in the context of shrinking cities found in published

Researcher(s) (Year)	Area of Emphasis	Methodology	Issues/ Metrics Analyzed	Main Findings	Shortcomings and Issues Not Considered
Kabisch et al. (2006)	Urban modeling for shrinking cities	Agent-based modeling is used to examine urban population decline in shrinking cities. The authors also propose predictor variables relevant to urban-decline (e.g., out-migration, age).	Urban modeling for shrinking cities to examine future scenarios and to test theories how to reach desired population goals.	Most urban models focus heavily on growth and are not transferable to urban decline situations. To accomplish this, predictor variables must be established unique to shrinking cities.	It is not clear what data it necessary for this model or what data the author is using for the initial model. There is mention of household surveys, but no elaboration *if* this was done or is a future recommendation.
McDougall (2008)	Energy deficit and urban decline	Case study	Urban decline should be embraced to meet Europe's future energy goals and needs using historical data and trends.	If the population is allowed to decline to a more sustainable level, Europe could reduce its dependency on non-renewable energy, imported from often, unstable countries.	This case study does not consider the impact of urban decline on any other infrastructure from a holistic point of view. Author does not consider interdependencies and issues associated with reducing energy demand in areas of urban decline.

Table 2.3. *(continued)*

Researcher(s) (Year)	Area of Emphasis	Methodology	Issues/ Metrics Analyzed	Main Findings	Shortcomings and Issues Not Considered
Schillining (2009)	Green infra-structure	Regional vacant property policy assessment, funded by Surdna Foundation, for the city of Buffalo, NY completed by five national policy experts and vacant property practitioners during two study visits, which included interviews of individuals (e.g., government officials, developers).	The findings from the report "Blueprint Buffalo" are presented, which recommends changes to re-size the footprint for the current population size.	The author proposes shrinking cities use green infrastructure (i.e., the transformation of vacant properties to green space like parks, conservations lands and landscapes) and land banks (i.e., institutions which merge multiple abandoned properties and legally transfer to a developer for redevelopment).	There is no mention of how successful this initiative has been in NY or PA. In addition, there is no discussion of any infrastructure aside from vacant lots from homes, business etc.
Schlor et al. (2009)	Waste-water infra-structure	This is a cost model running on EXCEL and Visual Basic using the ceteris paribus assumption that the environment/all variables remain static except the demographic structure. Other assumptions include that the infrastructure may not be used for a different purpose, cannot be spatially "thinned out," and maintenance must occur in upcoming years due to aging infrastructure.	Model is intended to analyze the impact of demo-graphic changes on wastewater costs to a German federal state.	The per-capita wastewater costs will escalate between183.4 percent and 282 percent, depending on the scenario and region of Germany. However, the regions of Germany that have the lowest, average, disposable incomes have the highest wastewater cost escalation.	This tool functions under the assumption that the infrastructure may only be used for the city population's wastewater needs. This is contradictory to Hoornbeek and Schwarz's study (2009), which suggests using excess to generate revenue. The model is not made flexible to allow the infrastructure to be used in alternative ways to reflect and/or test this theory.

Table 2.3. *(continued)*

Researcher(s) (Year)	Area of Emphasis	Methodology	Issues/ Metrics Analyzed	Main Findings	Shortcomings and Issues Not Considered
Hendrickson (2009)	Identifying urban ecology potential in shrinking cities	A developed GIS–based framework is used.	This tool is used to examine the urban ecology potential within Pittsburg, as well as score vacant parcels based on the potential.	The model generates scoring layers within GIS for the predetermined attributes. Model users can individually score parcels based on the ability of the parcel to contribute to the urban ecology of the region. Scoring is accomplished by overlaying parcels with scoring layers. The scores allow for a way to prioritize parcels based on urban ecology potential.	This study assumes that a small percentage of the parcels will be redeveloped in the near-term for residential development, and does not consider community involvement, which is crucial for the success of a project. Additionally, the model's scoring system was developed by the author using a method that has been criticized in literature.
Hoornbeek and Schwarz (2009)	Sustainable infra-structure in shrinking cities	Review of recent literature regarding infrastructure management in shrinking cities, interviews with infrastructure management professionals from mainly NE Ohio.	The potential for decommissioning infrastructure in Cleveland, OH, as well as other infrastructure management strategies in shrinking cities.	Many aspects must be considered when decommissioning infrastructure. There is potential to use excess infrastructure for other uses (e.g., stormwater retention, redundancy in network).	This study is purely qualitative and applies only to Cleveland/NE, Ohio. Although transferability is suggested, it has not been tested on shrinking cities in other regions/areas.

Table 2.3. *(continued)*

Researcher(s) (Year)	**Area of Emphasis**	**Methodology**	**Issues/Metrics Analyzed**	**Main Findings**	**Shortcomings and Issues Not Considered**
Lauf et al. (2010)	Housing preference and housing space	System dynamics is used to examine nonlinear dynamics and feedbacks between residential housing and demographics.	The impact of demographics and population changes, both growth and decline, on the housing stock in East Germany.	Albeit urban decline, an increase number of single households yields a total residential demand in the central parts of the study area. In addition, there is a negative net-demand of flats as the percentage of low-income households increases. The results also indicate that the population needs during growth and decline are vastly different, and thus, this information may help planners made appropriate decisions.	Internal factors regarding each household and population trends are considered. However, no external factors are modeled outside of the residential sector and populations (e.g., services, infrastructure condition).
Butts and Gasteyer (2011)	Social equity of water rates in the Michigan's shrinking cities	A literature review and econometric and statistical modeling (bivariate and multivariate model) using census data for 83 counties in Michigan.	Examine the social inequity between races (white and non-white) in different regions of Michigan in regard to the prices paid for water.	Due to the patterns of urban decline, many urban areas are disproportionally high with non-white populations. These areas carry a larger financial burden when considering the cost of water. These high prices infringe on the quality of life of the community. This study highlights the social inequity occurring across Michigan.	This study considers race, income and whether the region is inner-city. There are likely other factors (e.g., age, number of people in each household, % subsidized by government) that should be considered, as well. In addition, the overall fit of the model is poor, indicating that other variables should be considered to explain the variation in the data.
USEPA (2014)	Exploring methods to reuse vacant properties in Saginaw, MI	Interviews and engagement with the city decision-makers	This report evaluated possible alternatives for a largely vacated area in Saginaw.	Saginaw should work with local stakeholders to establish a long-term vision of the infrastructure. Revising current codes, identifying historic properties, and exploring green infrastructure are the main USEPA suggestions for moving forward.	The research is a qualitative discussion of management alternatives that does not look at the technical viability of implementing the retooling alternatives in specific areas.

2.2. Critical Infrastructure Interdependency Analyses

Critical infrastructure is the lifeline providing goods and services to our cities, regions, and nation, which the *"…incapacity or destruction would have a debilitating impact on our defense and economic security."* (PCCIP 1997). Over its service life, infrastructures may experience many stresses and threats, such as fluctuating demands, natural disasters, and targeted attacks. Consequences from these stresses and threats may include significantly decreasing the service life of an infrastructure system, debilitation of the infrastructure, or infrastructure failure. Zimmerman (2004, p.3) states that "*[i]nfrastructure interdependencies are now recognized as both opportunities as well as points of vulnerability."* Interdependency analyses approaches examine infrastructures to identify vulnerabilities, increase sustainability, increase resilience, provide insight into the infrastructure and infrastructure environment, and to attempt to ensure efficient, constant flow of goods and services.

The occurrences of critical infrastructure failing or their inability to function efficiently and effectively threatens the stability of the city, state, region or nation. A failure in one infrastructure may potentially cause failures in multiple infrastructures with severe consequences, such as decreased service life or the inability to provide services (Rinaldi et al. 2001; Church et al. 2004; Hoyt 2004; Oliva and Setola 2015). Interdependencies among infrastructures increase the risk of these failures (Rinaldi et al. 2001; Pederson et al. 2006; Oliva and Setola 2015). These interdependencies that are not well understood range in types and are a result of the multiple connections between infrastructures, in which the state of one infrastructure is influenced or impacted by the state of another infrastructure (Rinaldi et al. 2001; Dudenhoeffer et al. 2006; Oliva and Setola 2015).

2.2.1. Qualitative Analysis

The results from the qualitative analyses can often be discussed or shown visually, such as through causal loop diagrams, indicating the relationships between the infrastructure systems. Throughout the qualitative analyses, many relationships and factors necessary for the quantitative interdependency analysis are uncovered. This section discusses factors evaluated in the qualitative analysis. Data for interdependencies analyses approaches are typically obtained through interviews with or questionnaires distributed to experts (in addition to literature and operations data), which may lead to missing hidden elements if complete information/data is not gathered (Panzieri et al. 2004; Panzieri et al. 2005).

In the context of interdependencies, coupling refers to the degree of dependency between two infrastructures (Rinaldi et al. 2001; Perrow 2007; Oliva and Setola 2015). *Tight* coupling indicates that the infrastructures are highly dependent on one another and a disruption in one infrastructure impacts and propagates quickly to another infrastructure (Rinaldi et al. 2001; Perrow 2007). On the contrary, *loose* coupling is indicative of a low-degree dependence between two infrastructures (Rinaldi et al. 2001; Perrow 2007; Oliva and Setola 2015). There is typically a time delay when disturbances in one infrastructure impact another loose-coupled infrastructure.

The scale of the infrastructure interdependencies analyses may vary from a very granular, local leveled, to a high level, such as regional. If the objective of the analysis is to examine a facility or city, a higher level of granularity is required then necessary for examining national infrastructure networks, altering the spatial scale to accomplish various objectives (Pederson et al. 2006). Other scales that are often examined in infrastructure analysis are geographical and temporal. Geographical scales refer to the physical spaces under analysis, such as the cities, regions, national or international (Rinaldi et al. 2001). Temporal scales consider different time scales that may be of interest, such as milliseconds in power system operations to years for infrastructure upgrades (Rinaldi et al. 2001).

An infrastructure's environment is defined by the owners and operators who establish objectives, delineate the businesses, examine operations, and make the decisions, which directly impact the infrastructure's architecture and operations (Rinaldi et al. 2001). When considering the business aspect of infrastructure, economic and business goals may impact the evolution and operation of an infrastructure. Heavily regulated infrastructures are more constrained in this aspect (Rinaldi et al. 2001). Policy may also impact the environment an infrastructure is operating within, as policy may regulate operations for both private and public infrastructures (Rinaldi et al. 2001). Technical advances in infrastructures also force the infrastructure to evolve. Technology may improve efficiency while creating more interdependencies (Rinaldi et al. 2001).

The state of operation indicates the operating state of the infrastructure. This may include normal, stressed, disrupted, restored, or repaired. This state may range, abstractly, from the design-operational state, which is the optimal state the infrastructure is designed to operate, to a failure state with no services available via the infrastructure under analysis.

2.2.2. Quantitative Methods

Quantitative methods for examining infrastructure typically use computer simulations to generate predictive information and to uncover hidden interdependencies (Panzieri et al. 2004; Panzieri et al. 2005). Pederson et al. (2006) categorizes quantitative analyses into two classes: integrated system modeling and coupling individual infrastructure models. An integrated system modeling approach models multiple infrastructures and infrastructure interdependencies in one network (such as is the case in Chapter 8). The latter approach simulates infrastructure networks individually and couples the simulations together to identify the dependencies between the networks.

The complexity of many models from the numerous networks and components, however, poses difficulty in creating models that have the ability to predict interdependencies accurately, as well as obtaining data necessary for the model to run, such as sensitive data like financial infrastructure or large quantities of data (Panzieri et al. 2005; Dunn and Mauer 2006). Furthermore, Dunn and Mauer (2006) stated that this complexity and subjective inputs has the potential to obscure the underlying assumptions of the modeling procedure, which ultimately may lead to inaccurate results.

Emphasis has been placed on the importance of infrastructure interdependencies and critical infrastructure analysis since the mid-1990s, spurring the development of numerous modeling tools. A synopsis of modeling tools under development and developed, which are used for system analysis is provided in the following section.

2.2.3. Current Research and Modeling Examining Critical Infrastructure

Events worldwide, such as hurricanes Katrina and Rita, 9/11, and the London Bombings, have brought awareness to the importance of protecting and improving the resilience and sustainability of our critical infrastructure (Pederson et al. 2006). In addition to safety, national security, and the ability to provide services, Heller (2001) briefly discusses the immense costs associated with failures due to critical infrastructure interdependencies. Cascading failures due to power blackouts in the United States during two months in 1996 cost approximately $1.4 billion dollars to both infrastructures and the environment (Amin 2000). The cost of earthquakes averages $4.4 billion per year (FEMA 1999). Recognizing the importance of maintaining and protecting critical infrastructure to provide goods, services, and resources throughout the nation (and world) has motivated researchers and modelers internationally to develop innovative models and frameworks to examine critical infrastructure and critical infrastructure interdependencies.

These approaches employing a wide array of tools include, but are not limited to, agent-based modeling, Fuzzy Logic, game theory, system dynamics, and GIS to model infrastructures, such as transportation, water, power, natural gas, telecommunications, financial, and oil (Pederson et al. 2006; Oliva and Setola 2015). In 2006, the Idaho National Laboratory published a review of current (as of 2006) research and models developed and under development for analyzing critical infrastructure and critical infrastructure interdependencies. This survey includes both national models as well as international models with the goal of compiling a single source for critical infrastructure interdependency modeling tools (Pederson et al. 2006). In Table 2.4, Peralta (2009) divides the models surveyed by Pederson et al. (2006) on the basis of metrics used in the models for interdependency analysis. Metrics for examining critical infrastructure interdependencies and critical infrastructure will differ depending on the modeling goal, infrastructure being examined and variables being measured. The metrics considered are grouped into four categories: economic, risk, time and environmental and human effects. A fifth category is shown below, which was proposed in Peralta (2009) for examining the operating states of infrastructure in developing countries. For each metric, Peralta (2009) summarizes examples of these models, metric, infrastructure systems analyzed, and possible scenarios simulated.

Table 2.4. Metrics used in models for the analysis of interdependencies (Peralta 2009)

Type	**Example of models and/or authors that use the metrics**	**Example of metrics**	**Infrastructure Systems Analyzed**	**Disruptors/ scenarios simulated**
Economic metrics	• COMM- ASPEN • N-ABLE • Critical Infrastructure Protection (CIP) Modeling and Analysis (CIPMA)	• Changes in segments in the economy: banks, households, industries, and Federal Reserve • Cost of restoration • Repair priorities (budget allocation)	Electric power, water supply, gas and oil supply, telecommunications, banking and finance, highway networks	• Natural disaster events • Terrorist attacks • Policies and regulations regarding infrastructures.
Risk metrics	• CARVER 2 TM • NGtools • Fort Future	• Criticalities of nodes and linkages • Rank of priorities of potential terrorist targets	Electric power, water supply, gas and oil supply, telecommunications	• Natural disaster events • Terrorist attacks • Response plans

Table 2.4. *(continued)*

Type	Example of models and/or authors that use the metrics	Example of metrics	Infrastructure Systems Analyzed	Disruptors/ scenarios simulated
Time metrics	• CI ^{3} - Critical Infrastructure Interdependencies Integrator • MUNICIPAL • NEXUS Fusion Framework ^{TM}	• Time for repairs	Electric power, water supply, gas and oil supply, telecommunications, banking and finance	• Response plans • Natural disaster events • Terrorist attacks
Environ-mental and human effects metrics	• TRANSIM • CIP/DSS – The Critical Infrastructure Protection Decision Support System • TRAGIS	• Effects on populations and human health • Environmental impacts: noise, traffic congestion, threat to endangered species	Emergency services, electric power, water supply, airport facilities, transportation	• Natural disaster events • Terrorist attacks
Operating States of Critical Infrastruc-ture in Developing Countries	• Peralta (2009)	• Travel time • Volume to capacity ratio • Capacity Margin • Unsatisfied demand	Transportation, electric power	• Growth in number of vehicle trips • Addition of high- rise buildings • Demand changes

To date, the research efforts for critical infrastructure interdependencies have largely focused on natural disasters, terrorist/intentional attacks, response plans to major failures, or policies pertaining to infrastructure (e.g., Pederson et al. 2006; Brown et al. 2004; Wijnia and Herder 2004; McDaniels et al. 2007; Zhang and Peeta 2010; Chou and Tseng 2010; Chang et al. 2014; Ehlen and Vargas 2013; Atef and Moselhi et al. 2014). This study examines critical infrastructure interdependencies in the context of underutilization and the impact of physical and non-physical disrupters.

A set of metrics used for examining infrastructure interdependencies and infrastructure in shrinking cities is defined in Chapter 4. The current categories of metrics used for analyzing infrastructure and measuring various variables, are not appropriate or directly applicable in their current form for examining interdependencies in shrinking cities. These categories of metrics shown in Table 2.4, with the exception of the type of metric proposed by Peralta (2009), are used to measure reactive scenarios, such as natural disaster or terrorist attacks, as opposed to the nondisrupters occurring during the status quo. Through defining a metric set tailored for shrinking cities, variables may be measured that give insight into the operating state of infrastructure in shrinking cities and the impacts of underutilization on users and managers of the infrastructures. For example, the criticality of links in water systems indicated by pressures may allow for identification of potential infrastructure that may be removed or indicate the necessity of the link or node. The operating states of critical infrastructure in shrinking cities will be examined, under the status quo and infrastructure retooling alternatives (e.g., razing of infrastructure, decommissioning portions of the city) to gain insight into how the different scenarios affect the resiliency of the city or the ability to provide services.

2.4. Summary and Departure Point

Critical infrastructure systems provide products and services essential to the health, security, and economic well-being of society. These infrastructure systems are constantly increasing in complexity and mutual independence, which poses potential new vulnerabilities, such as cascading failures when a disruptor, either physical (e.g., removing components of the infrastructure system) or non-physical (e.g., changes in demand), alters the infrastructure. The current methods for examining critical infrastructure and infrastructure interdependencies are primarily reactive in nature and focus on the response time for emergencies, terrorist attacks, or natural disasters.

As previously mentioned, when the population declines in shrinking cities, the number and size of infrastructures systems (e.g., roads, wastewater systems) remain the same. Approximately 75-80 percent of the costs associated with these infrastructures are fixed costs, unchanging with the population, resulting in a higher per capita cost for the individuals residing in the city (Herz 2006; Schlör et al. 2009). The higher per capita cost contributes to further migration from the already shrinking city (Rybczynski and Linneman 1999; Herz 2006). In addition, many times the areas affected by the increase in per capita costs are regions that are low-income and cannot afford the increase in costs (Schlör et al. 2009; Moraes 2009; Butts and Gasteyer 2011). Razing or decommissioning infrastructure have been proposed in order to address the excess infrastructure issues (Hoornbeek and Schwarz 2009; Martinez-Fernandez and Wu 2009; USEPA 2014). These measures are intended to lower the per capita cost to maintain the infrastructure, regulate crime, or improve its aesthetic appeal in an attempt to stimulate re-growth (Rybczynski and Linneman 1999; Martinez-Fernandez and Wu 2009; Hoornbeek and Schwarz 2009).

To date, research in the context of shrinking cities has focused on a) methods to stabilize a shrinking city and to resize the footprint of the city to meet the needs of the *new*, smaller population, and b) causes and experiences of urban decline internationally. Presently, a need exists to comprehensively understand the impact of underutilization on infrastructure systems and interdependencies, and the technical viability of retooling infrastructure alternatives. In conjunction with identifying viable retooling alternatives, the public views in shrinking cities in the context of infrastructure issues and retooling alternatives should be evaluated. Gauging and incorporating the community's attitudes and perceptions into infrastructure decision-making, and understanding the elements of public concern, may allow for sustainable, implementable alternatives that aid in transitioning shrinking cities towards right-sizing their infrastructure for a smaller population. The remaining chapters in this dissertation fill these gaps in the body of knowledge and the body of practice to understand the impacts of underutilization of water sector infrastructure, water sector infrastructure interdependencies, and public views regarding water sector issues arising from urban decline and water sector retooling alternatives.

CHAPTER 3. WATER AND WASTEWATER INFRASTRUCTURE IN THE CONTEXT OF SHRINKING CITIES

"Safe drinking water and properly treated wastewater are critical to modern life. The former is a prerequisite for all human activity—physical, economic, and cultural. Wastewater treatment is important for preventing disease and protecting the environment."

-Department of Homeland Security 2012

Contrary to growth patterns typically assumed by engineers and planners, shrinking cities are plagued by increasing numbers of vacant properties (e.g., homes, businesses, brownfield sites) and decreasing demands for infrastructure services. During economic contractions, the footprint of built infrastructure does not adjust, but rather remains stable, ultimately creating an excess of underfunded and underutilized infrastructure. Current infrastructure life-cycle considerations do not include the costs or planning associated with the end of the useful life of infrastructure, when the infrastructure is degraded to the point that it can no longer provide service or that the infrastructure is no longer needed to meet the population demands.

Chapter 3 provides context for water and wastewater/stormwater infrastructure retooling alternatives and interdependencies evaluated in this dissertation, as well as the motivation for exploring this underappreciated area of infrastructure management. This chapter (1) identifies and discusses common challenges for infrastructure management within shrinking cities; (2) suggests possible infrastructure management alternatives that may mitigate these challenges; and (3) provides a departure point for these alternatives.

3.1. Water and Wastewater Infrastructure Issues Characteristic to Shrinking Cities

Water and wastewater infrastructures have unique characteristics that constrain their responses to the dynamics present in shrinking cities. First, because these systems are underground and unseen, the residents lack the same level of awareness about operations and conditions of these systems as compared to other infrastructure systems, such as roads and bridges. Second, these systems provide services that have major public health and environmental implications. Providing potable water to communities and conveying wastewater to treatment plants prevents the spread of disease while simultaneously protecting the environment.

The declining service quality resulting from decreased demands and aging infrastructure, along with high service costs, may exacerbate deindustrialization, thereby, continuing a cycle that may decrease the quality of the water and the efficiency of operations while increasing the per capita costs of the infrastructure system. Nonetheless, shrinking cities have the potential to implement alternatives in operations and management, such as reductions in the physical footprint, which may stabilize or reduce costs, while improving the water quality by decreasing stagnant water and the age of the water delivered through the system. As shrinking cities attempt to right-size the city's footprint to meet the needs of the current and projected populations, efforts must be focused on how to retool these buried infrastructures while considering issues affecting shrinking cities.

Socioeconomic data (income, population, etc.) collected from the 2010 census (US Census Bureau 2011) were used to identify shrinking cities in the Midwestern US for follow-up interviews with subject matter experts (SMEs) to fill in the knowledge gaps about current water infrastructure management. Personnel from Gary, IN; Akron, OH; Saginaw, MI; and Flint, MI were selected for additional interviews, as these four cities use different, yet representative, water infrastructure management approaches typical to cities throughout the US. Three to four phone calls were conducted with city officials from these cities between August 2012 and September 2013. Up to four face-to-face follow-up meetings that included more detailed questions and discussions were also conducted in Gary, Flint, and Saginaw between October 2012 and October 2014.

A private water supply company that employs a regional service approach manages Gary's water system, while its wastewater system is municipal and managed within the city. On the other hand, Akron has municipal wastewater and water supply providers that manage both of their systems from a regional approach. Saginaw and Flint have different providers for their municipal wastewater treatment and their water systems. The contrasts in management approaches provide insight into issues that are unique to each approach, as well as issues that are common across the different organizational and management structures of the systems (e.g., privately managed vs. publicly managed).

3.1.1. Issues Spanning the Water and Wastewater Infrastructures

Although each infrastructure system has unique challenges, many issues, such as fiscal distress, number of personnel, and aging infrastructure affect the management of both water and wastewater infrastructure.

3.1.1.1. Financial Issues

In shrinking cities, the cost of maintaining the aging infrastructure intended for use by larger populations remains constant or increases, while the tax base declines (Rybczynski and Linneman 1999; Beazley et al. 2011; Butt and Gasteyer 2011). For instance, Detroit has an excess of aging water infrastructure, some of which are over two centuries old and were originally intended to support over twice the present population and a water-intensive manufacturing industry. However, since the 1950s, Detroit's population and manufacturing industry have been shrinking, leaving the city with far fewer people who utilize the water infrastructure and fewer water-rate-payers. Yet, the infrastructure must be maintained to provide services for the current population (Southeast Michigan Council of Governments 2011).

The four cities investigated in this study (Akron, Flint, Gary, and Saginaw) indicated that water and wastewater systems need to be self-sustaining, and the current financial challenges were going to be met by decreasing their operation and maintenance costs or by increasing rates to consumers. Approximately 75-80% of the water sector infrastructure costs are fixed (e.g., capital, operations) (Herz 2006; Hummel and Lux 2007; Schlör et al. 2009); and the financial burden of capital replacements, in conjunction with the heightened costs of treatment and regulatory compliance therefore, falls upon the residents of the community. The recovery of costs in the event of shrinking city populations (i.e., reduced number of customers) results in municipal services becoming more expensive per capita (Herz 2006; Rybczynski and Linneman 1999; Beazley et al. 2011; Butts and Gasteyer 2011).

However, rate increases to meet financial challenges may not be uniform across all water users as different classes of consumers may be billed differently, due to wholesale agreements between utilities and municipalities. For instance, in Akron, the water rates for suburban customers are higher than those for residents within the city boundaries. In Saginaw, the rates for both residential and wholesale customers are derived based on the distance required to transport the water. Gary's regional rates are derived based on a "cost of service study," to determine the appropriate billing for wholesale and residential customers. Previous studies (Schlör et al. 2009; Butts and Gasteyer 2011) indicate these increased costs for both water and wastewater are not insignificant, impacting regions in Michigan and Germany, where population decline has been the highest and the incomes are the lowest, highlighting the social inequity occurring due to population decline patterns.

Income inequity in shrinking cities is illustrated in Table 3.1. These cities are representative of classes of cities that use different water supply infrastructure management approaches typical to cities throughout the U.S., and span multiple states, illustrating that the income inequity challenges are not isolated to select states or management approaches. The values in parentheses compare the income of a shrinking city with the income for a city in the same state with a typical growth pattern (identified in that table by italics), as well as the average income for the state where the shrinking city is located. These shrinking cities have a per capita annual income that is between $3,954 and $8,659 lower than the average annual income for the associated state's cities with a typical growth pattern, and between $5,954 and $11,325 less than the average per capita annual income for the state (US Census Bureau 2011). The median household income for each shrinking city was $4,269 to $19,634 lower than the average median household income for a city with a typical growth pattern in the same state, and $13,712 to $21,618 less than the associated state average. Due to this income inequity, shrinking cities not only face a decline in customers, but the inability of the existing customers to afford drastically increasing rates, as the cost of services is a higher percentage of the residents' average income. For other infrastructure services, which rely largely on tax bases, the lower average income results in a tax base that is not only decreasing due to urban decline but also due to lower incomes of the existing residents.

Table 3.1. Comparisons of incomes between select shrinking cities, cities with typical growth patterns, and state averages (Data based on 2010 census (US Census Bureau 2011))

	2010 Population	**Per capita money income in past 12 months (2010 dollars) 2006-2010**	**Median household income 2006-2010**
Flint, MI	102,434	$14,910 (City: -$7,906) (State: -$10,572)	$27,199 (City: -$19,486) (State: -$21,618)
Saginaw, MI	51,508	$14,157 (City: -$8,659) (State: -$11,325)	$27,051 (City: -$19,634) (State: -$21,618)
Dearborn, MI	98,153	$22,816	$46,685
Michigan		$25,482	$48,669
Gary, In	80,294	$15,383 (City: -$7,917) (State: -$9,114)	$27,846 (City: -$16,751) (State: -$20,547)
Fort Wayne, IN	253,691	$23,300	$44,597
Indiana		$24,497	$48,393
Akron, OH	199,110	$19,664 (City: -$3,954) (State: -$5,954)	$34,359 (City: -$4,269) (State: -$13,712)
Columbus, OH	787,033	$23,618	$43,348
Ohio		$25,618	$48,071

3.1.1.2. Personnel

Due to the dramatic decrease in available funds within shrinking cities, one of the common cost saving strategies indicated by SMEs in Flint, Saginaw, and Akron was a reduction in personnel. However, completing non-urgent repairs, providing system upgrades, and pursuing long-term planning is difficult with a reduced level of staffing so performing all the necessary maintenance then may not be feasible with the existing personnel resources. For instance, one city recruits the public to flush the neighborhood hydrants annually.

Further straining the fiscal operations of these systems is the retirement of personnel and the ensuing obligations to pay retirement benefits. For example, one city was paying retirement benefits to approximately four times more people than were currently working. Additionally, Detroit's Chapter 9 bankruptcy filing in July 2013 included the fiscal burdens associated with retired personnel across municipal departments (Helms and Guillen 2013).

The private, regional water provider in Gary did not cite personnel reductions due to declining funds within shrinking cities as a major problem. Contrary to municipal systems, the private water supply provider reported needing to dedicate personnel resources to more instances of disconnecting and reconnecting services due to nonpayment of utility bills in the shrinking city than in other cities within the region. This expense for the increased personnel is distributed throughout the region served by the water provider and drives up operation costs for the entire system.

3.1.1.3. Aging Infrastructure and Maintenance

Water and wastewater infrastructure systems have finite lives, with their condition deteriorating over time that result in failures, decreased performance, or decreased service. Maintenance and reinvestment in infrastructure is necessary to extend their service lives (NAE 2009). ASCE (2013) predicts a nationwide funding gap of $84 billion by 2020 between investment needs and available funds, resulting in "…*higher costs to businesses and households as a consequence of less efficient and more costly infrastructure services*." Underinvesting in infrastructure is occurring nationwide (ASCE 2013). Many cities, although currently maintaining water and wastewater infrastructure reactively, are attempting to transition to proactive approaches (e.g., Durrans et al. 2004; USEPA 2013), which is a difficult task to accomplish in fiscally strained, shrinking cities.

Interviews with personnel in shrinking cities indicated that due to fiscal constraints and reduced personnel, proactive maintenance is difficult and largely occurs on an as-needed basis. Typically, in these cities, water mains receive attention when they fail and are only replaced when absolutely necessary due to the costs associated with replacing these major components. Based on both the published literature and our interviews, very few shrinking cities appear to have shifted to proactive attempts to identify solutions to manage and maintain excess infrastructure. The personnel interviewed from one shrinking city indicated that their municipal department has spent time and resources to explore addressing infrastructure issues through decommissioning and are actively looking for ways to resize their infrastructure for the current population. However, our interviews with SMEs indicate that this strategy appeared to be the exception rather than common practice.

3.1.1.4. Increasingly Stringent Regulatory Requirements

Water and wastewater providers must constantly meet increasing standards set by the state and federal government. These standards, put in place for consumer safety, have become increasingly stringent throughout the years (Roberson 2011). In order to maintain the safety of the public and continue to meet the federal and state requirements, investments and regular maintenance that require financial capital are necessary. The cost of meeting more stringent regulations is increasingly difficult for water and wastewater systems within shrinking cities due to the declining tax base and being fiscally strained. For instance, in order to obtain a National Pollutant Discharge Elimination System (NPDES) permit, the U.S. Environmental Protection Agency (USEPA) requires any municipality with a population greater than 100,000 to have separate storm sewer systems (USEPA 2013). However, since many shrinking cities have combined sewer systems, creating a separate storm water management program requires extensive financial resources, which is beyond the reach of cities experiencing population decline.

3.1.2. Issues Specific to Water Infrastructure

Water infrastructure is a critical infrastructure providing irreplaceable services necessary for the health and livelihood of the community as well as maintaining a sustainable, diverse environment. Underutilization has created challenges in delivering high quality potable water throughout shrinking communities.

3.1.2.1. Quality Issues

Decreased demand may reduce the flow through the pipeline system, causing the pipelines to degrade faster. This deterioration and low flows may reduce the quality of the water reaching the residents due to stagnant water or the interaction between the pipeline wall and the water. Additionally, the age of water within the distribution system is a major consideration in water quality deterioration due to the interaction between the pipeline wall and water, as well as the reaction within the bulk water. Lower demands in cities with systems intended to operate at higher demands may increase the water age. Based on a survey of 800 utilities, the average distribution system retention time is 1.3 days, and the average maximum time is three days (AWWA and AwwaRF 1992). Although the average water age across shrinking cities is not specifically published, Rink et al. (2010), Barr (2013) and Cubillo and Ibanez (2014) discuss that water age has increased due to declining demands, creating water quality challenges and changes to water treatment plant operations. Cruickshank (2010) and Barr (2013) suggest flushing, increasing tank turnover, optimizing the pumps, using control valves, closing valves changing storage volumes, and changing operational methods as ways to reduce water age. Of interest to shrinking cities, Barr (2013) suggests abandoning or reducing piping to reduce water age, a retooling alternative referred throughout this document as decommissioning. Reducing tank volumes is another alternative that may apply to many shrinking cities as the decline in population, and additional changes in water demand due to water use changes, have significantly reduced demands on a system intended for a much larger population. Table 3.2 summarizes water quality problems associated with water age and long detentions times.

Table 3.2. Water quality issues associated with water age

Chemical Issues	**Biological Issues**	**Physical Issues**
Disinfection by-product formation	Nitrification	Temperature increases
Corrosion control effectiveness	Microbial regrowth	Sediment deposition
Taste and odor		Color

3.1.3. Issues Specific to Wastewater Infrastructure

Methods of collection and treatment of wastewater systems vary both within and across communities. Wastewater may be treated in a decentralized system near the origin (e.g., septic tanks, biofilters, aerobic treatment systems) or transported to a treatment plant for treatment or disposal. Systems that convey the greywater and blackwater from the point of origin to a treatment plant fall into two main categories: (1) combined sewer systems that transport stormwater, greywater, and blackwater together and (2) sanitary sewer systems, which do not transport stormwater, and solely transport greywater and blackwater. Sanitary sewers are operated independently from storm drains that transport rain and runoff from streets and other impervious surfaces. (USEPA 2008).

3.1.3.1. Quality Issues

Combined sewer systems serve approximately 770 communities containing approximately 40 million people, largely concentrated in the Pacific Northwest, Northeast, and the Great Lakes Region (USEPA 2008). Combined sewer systems are characteristic of older communities (USEPA 2008), including many shrinking cities in the Midwest. During wet weather, the systems may exceed their storage capacity or the capacity of the treatment plant, discharging untreated wastewater into surrounding streams, rivers, lakes, and oceans. Depending on the capacity of the combined sewer system, precipitation as little as 0.1 inches may result in overflows (Lijklema and Tyson 1993). This untreated wastewater degrades the quality of the water and can present a public health threat, environmental degradation, and lead to discoloration of the water, as the overflows introduce a source of pathogens and pollutants into the receiving water. The National Combined Sewer Overflow (CSO) Control Policy (USEPA 1994) states:

> *"CSOs consist of mixtures of domestic sewage, industrial and commercial wastewater, and storm runoff. CSOs often contain high levels of suspended solids, pathogenic microorganisms, toxic pollutants, floatables, nutrients, oxygen-demanding compounds, oil and grease, and other pollutants. CSOs can cause exceedances of water quality standards. Such exceedances may pose risk to human health, threaten aquatic life and its habitat, and impair the use and enjoyment of the Nation's waterways."*

Further exasperating the issues posed by combined sewer systems is during dry periods, wastewater solids may settle within the system due to low flows, and are subsequently discharged during wet weather events. During wet weather, generated runoff travels across the land, amassing non-point source pollutants and debris, further contributing to the pollutant challenge present.

The Clean Water Act, a federal law, which established environmental programs such as the National Pollutant Discharge Elimination permit program, regulates pollutant discharges in waters, significantly improving water quality since the early 1970's (USEPA 2009). Suggested methods to mitigate overflows include increasing the capacity of the CSS, and implementing stormwater management alternatives to reduce the regenerated runoff entering the CSS.

The application of stormwater management to reduce generated runoff has been explored recent decades. Carter and Jackson (2007) consider implementing stormwater management in urbanized areas, evaluating the most effective practices in densely populated areas. Using spatial analysis of an urban watershed in Athens, Georgia between 2003 and 2004, they identified green roofs as significantly reducing stormwater runoff. Montalto et al. (2007) presents a low impact development rapid assessment tool to estimate the cost-effectiveness of various forms of LID practices. Similar to Carter and Jackson (2007), Montalto et al. (2007) considered densely, urbanized areas where lot-level investments are viable. Montalto et al. (2007) state that their model is intended to provide more general information for planners than that provided by more complicated hydraulic models, such as SWMM. Jia et al. (2015) proposes a decision-making tool using ArcGIS and optimization, to aid in low-impact development (LID) design practices. This tool evaluates both the highest performing (in terms of quantity of runoff and water quality), and the most cost-effective low-impact development alternative. Many of the alternatives explore lot-level practices, such as rain gardens, and rain barrels. The tool does not replace existing, zoned parcels with LID practices or consider decommissioning existing structures/pavements, but optimizes the potential LID alternative to coexist with the proposed or existing development. Carter and Jackson (2007), Montalto et al. (2007), and Jai et al. (2015) explore integrating LID practices in urban areas, with dense populations. However, this study explores integrating stormwater management within shrinking cities where there is an abundance of underutilized, vacant land and limited opportunity for lot-level investment due to the high vacancy rates.

One alternative, widely studied in literature is the impact of permeable pavements on water quality and runoff quantities (Rushton 2001; Brattebo and Booth 2003; Bean et al. 2007; Scholz and Grabowiecki 2007; Collins et al. 2008). This low-impact development (LID) alternative is unlikely to be implemented in a fiscally strained, shrinking city due to the large-scale repaving effort necessary in the severely declining areas.

Philadelphia, PA is an example of a city that is operating on a CSS. The city is attempting to combat overflows by investing in management methods to treat stormwater onsite using green infrastructure, such as bioswales and rain gardens (*Green City, Clean Waters* plan) (PWD, 2015; McRandle 2012; Baker 2011). The Philadelphia Water Department (2015) states that meeting wastewater and stormwater needs *"... requires either a significant new investment in "grey" infrastructure (underground storage tanks and pipes) or a paradigm shift in our approach to urban water resources"* Prior to investing in such grey water infrastructure, Philadelphia is attempting to treat stormwater using green infrastructure (PWD 2015). The *Green City, Clean Waters* effort not only avoids large hikes in rate increases as seen when Portland, OR invested in an overflow tunnel, but also creates jobs and improves aesthetics of the neighborhoods in Philadelphia (Baker 2011).

It should be noted that in the presence of extensive impervious surfaces, it is difficult to reduce stormwater runoff with solely green infrastructure (Baker 2011). One SME interviewed identified similar concerns in regard to green infrastructure, stating that underutilized impervious surfaces create challenges in effectively reducing large quantities of runoff, and in order to decommission these surfaces, the city must commit to rezoning or transitioning portions of the city's land. A separate option may be to repave the underutilized area with porous pavement, an alternative that SMEs interviewed stated is often infeasible in sparsely populated areas within fiscally strained cities. Thus, a combination of strategies may be appropriate depending on the severity of the overflow problem in the city.

3.1.3.2. Impervious Surfaces

Further contributing to the problem of capacity within wastewater systems is the number of impervious surfaces in shrinking cities. Many vacant properties and brownfields leave concrete and asphalt foundations, vast parking lots, and other surfaces that hinder the ability of water to enter the groundwater system during rainfall. These surfaces create runoff that enters the stormwater or combined sewer systems, which ultimately contributes to increasing the quantity and volume of discharges as the systems reach and exceed capacity.

3.2. Technical and Managerial Water and Wastewater/Stormwater Infrastructure Management Alternatives

Engineers, researchers, planners, and decision-makers are now beginning to emphasize stabilizing growth and resizing the city footprint to meet the need of the smaller population, thereby moving away from the attitude of awaiting population regrowth. Planning efforts in the literature (e.g., Bontje 2004; Armbost et al. 2008; Wiechmann 2009; Cunningham-Sabot and Fol 2009; Pallagst 2009) discuss how to transform the excess area to allow the city to reclaim and reinvent itself, which would be a shift from focusing on stabilizing current population.

As shrinking cities in the US begin to explore the options of right-sizing their infrastructure to meet the projected population needs, technical and management alternatives need to be explored. The feasibility of such alternatives to provide essential water and wastewater services to the community in a cost-effective manner should be considered. Changes to the systems, whether physical, operational, or managerial, may have the potential to reduce or stabilize the cost or increase the level of service of the systems. Various alternatives may be more viable in different locations due to factors such as population decline patterns, financial and personnel resources available, structure of the management of the infrastructure system (e.g., private vs. public, regional vs. city), and state and city laws, regulations, and ordinances.

Reducing the physical footprint of the aging infrastructure, either through the removal or abandonment of infrastructure, is considered as an option for retooling underutilized or 'extra' infrastructure (discussed in Table 3.3). However, there are also physical constraints that downsizing infrastructure networks pose. Infrastructure components, such as sewers or power lines often link portions of cities through areas of severe population decline, and the redundancy poses a benefit for aging infrastructure, such as providing back up to maintain service when a water main fails (Hoornbeek and Schwarz 2009; USEPA 2014). Additionally, the immediate cost of removing or shutting down infrastructures has a high initial capital cost, while the costs to maintain existing infrastructure may be lower (Hoornbeek and Schwarz 2009; USEPA 2014).

Water infrastructure systems traditionally are designed based on deterministic water demand projections with the assumption that the system's operational capability and capacity will be able to provide service to the consumers for the infrastructure's design life (Basupi and Kapelin 2015). Flexible design of water infrastructure systems, specifically, the ability of the system to alter the infrastructure topology as new information becomes known (such as changing population dynamics as seen in shrinking cities), has not been widely explored in literature (Spiller et al. 2015). Previous studies (e.g., Kapelan et al. 2005; Babayan et al. 2005; Huang et al. 2010) in general, consider the flexibility of *new* system designs by incorporating stochastic future demand projections as opposed to *existing*, in-place systems. Specifically of interest to this study are those systems that have become underutilized due to population dynamics.

Kapelan et al. (2005) and Babayan et al. (2005) explored designing pipes within the network using a RNSGAII optimization approach based on genetic algorithms, and genetic algorithms, respectively. Using Pareto optimal solutions, Kapelan et al. (2005) and Babayan et al. (2005) identified the tradeoff between cost and robustness of a new system or rehabilitation. However, the analysis does not consider alternative demand patterns or fire flow capabilities, or discuss possible reconfigurations of the existing systems. Huang et al. (2010) proposed modeling different system scenarios for uncertain future water demand using a scenario tree and applying genetic algorithms to minimize the life cycle cost. In Huang et al. (2010) flexibility refers to the development and expansion of the physical system and capacity. The existing, in-place infrastructure in the model is rigid, with defined topology *additions* to the existing system based on varying increased in demand, and does not consider fire flow capabilities. Using decision trees, Marques et al. (2014) applied a real options approach to consider uncertainties regarding water distribution network that represents future strategies, in attempt to minimize 60-year planning horizon costs. Marques et al. (2014) acknowledges the possibility of depopulation in one of eight scenarios and addresses this through altering the pumps and required energy costs, leaving the network in place. Basupi and Kapelan (2015) combined genetic algorithms and sampling techniques, such as Monte Carlo simulation, to provide design solutions for unexpected demands that vary from the deterministic demand assumptions made during the design phase of new infrastructure. In this study, the planning horizon occurs in stages, delaying the physical changes made to the water infrastructure system (e.g., additional pipelines, increased capacity) until increased capacity is needed. However, this study considered that no changes may be made to the in-place infrastructure, only additional components may be added to expand the infrastructure system.

In April 2012, USEPA Region 5 hosted a workshop with SMEs spanning a variety of disciplines and professions to gain insight into potential methods for managing infrastructure in shrinking cities and developing tools to aid shrinking cities in reconfiguring infrastructure for the current populations. Other options proposed at the USEPA workshop included alternatives that have the potential to generate revenues, such as contracting out the excess capacity of existing infrastructure systems. In addition to discussing alternatives, potential consequences and barriers to these alternatives were further developed by the USEPA Region 5 post workshop. Tables 3.3 and 3.4 show potential water and wastewater/stormwater infrastructure retooling alternatives which were developed from the review of the published literature, interviews with city managers from five Midwestern shrinking cities, the USEPA retooling workshop, and discussions with academics with expertise in infrastructure or issues related to shrinking cities.

Table 3.3. Water infrastructure retooling alternatives

<table>
<tr><th>ALTERNATIVES</th><th>CONSIDERATIONS</th><th>POSSIBLE CONSEQUENCES OR BARRIERS</th></tr>
<tr><td colspan="3">Status Quo Physical Network</td></tr>
<tr><td>Consolidate demand (e.g., residences, businesses) to certain city blocks while maintaining status quo physical network
*This alternative may be appropriate if the city stops services to an area, such as, garbage collection or lighting</td><td rowspan="3">• Maintenance cost
• Intended purpose for future land use
• Impact on the water quality, capacity of the system, and operational integrity of the existing pipes
• Relocating sparsely populated areas
• Vacancies and vacancy patterns within potential area
• Ability to maintain fire flows
• Existing establishments (e.g., churches, business, schools)
• Environmental impact</td><td>• Cost of relocating residents and stopping service to the area
• May have to implement eminent domain to relocate resistant customers</td></tr>
<tr><td>Do not fix system component failures: do nothing, allow to function until end of useful life</td><td>• Cost of deferring maintenance until absolutely necessary
• Decreased water quality
• Increased number of failures
• Increased number of complaints
• Environment impact from failures
• Impact on bond rating
• Nuisance liability</td></tr>
<tr><td>Have residents absorb costs to fix failures if failures occur in a sparsely populated area of city</td><td>• Cost of altering billing structure
• Increased number of complaints
• Nuisance liability
• Legal barriers for different pricing structures based on vacancy patterns</td></tr>
<tr><td colspan="3">Alternative ways of providing services or improve efficiency</td></tr>
<tr><td>Trucking water in
*Remove residents from the network and bring in water separately</td><td>• Cost(s)
• Logistical feasibility and available resources (e.g., trucks)
• Adequate supply for emergency services</td><td>• Cost of trucking in water
• Further straining limited personnel resources if regulated by the municipality
• Difficulty maintaining flows to hydrants</td></tr>
<tr><td>Water ATM
*Remove residents from the network and have a stand-alone system</td><td>• Cost(s)
• Logistical feasibility and available resources (e.g., trucks)
• Adequate supply for emergency services</td><td>• Costs of installing ATMs
• Further straining limited personnel resources if maintained, operated, or regulated by the municipality
• Impact on bond rating
• Difficulty maintaining flows to hydrants</td></tr>
<tr><td>Wells (New, currently used, out of service)
*Water drawn from a structure built to access groundwater</td><td>• Availability and quality of ground water
• Installation and maintenance costs
• Environmental impacts
• Treatment required of water
• USEPA does not regulate privately owned wells</td><td>• Costs of installing or reopening wells
• Further straining limited personnel resources if maintained or regulated by the municipality
• Impact on bond rating
• Difficulty maintaining flows to hydrants</td></tr>
</table>

Table 3.3. *(continued)*

<table>
<tr><th>ALTERNATIVES</th><th>CONSIDERATIONS</th><th>POSSIBLE CONSEQUENCES OR BARRIERS</th></tr>
<tr><td>Water loss programs

*Decrease water loss in the system to lessen water withdrawals and operation and maintenance costs (USEPA 2010)</td><td>• Cost(s)
• Logistical feasibility and available resources</td><td>• Cost of implementing program
• Further straining limited personnel resources</td></tr>
<tr><td>Energy management conservation program

*Identify cost savings available through energy management via technology as 25-30% of operation and maintenance costs are linked of energy usage for water treatment and distribution (USEPA 2012)</td><td>• Cost(s)
• Logistical feasibility and available resources</td><td>• Cost of implementing program
• Further straining limited personnel resources</td></tr>
<tr><td colspan="3">Decommissioning Options</td></tr>
<tr><td>Decommissioning pipes, while maintaining redundancies in the network
*By maintaining redundancy loops, the system is able to provide service during a failure</td><td rowspan="4">• Cost
• Intended purpose for future land use
• Impact on the water quality, capacity of the system, and operational integrity of the existing pipes
• Criticality of pipes (e.g., are they connecting two densely populated regions?)
• Vacancies and vacancy patterns within potential area
• Risk of main system failure
• Length of time it would take to fix a main system failure
• Ability to maintain fire flows with retooling configuration.
• Current zoning of the area
• Existing establishments (e.g., churches, business, community centers, schools)
• Environmental impact</td><td rowspan="4">• Cost of capping decommissioned pipes
• Legal implications of downsizing infrastructure
• Difficulty maintaining flows to hydrants if critical pipelines are removed
• Nuisance liability
• Barriers that may require negotiation for decommissioning pipelines on private property</td></tr>
<tr><td>Decommissioning pipes from periphery of city</td></tr>
<tr><td>Scale back the redundancy within the system by decommissioning excess pipes, including redundancy loops
*By removing all pipelines, there is an increased chance of service disruption during a failure</td></tr>
<tr><td>Consolidate residences and services along a main service corridor, decommission excess infrastructure
*This option considers multiple neighborhoods and large areas with a high number of vacancies</td></tr>
</table>

Table 3.4. Wastewater/Stormwater infrastructure retooling alternatives

ALTERNATIVES	CONSIDERATIONS	POSSIBLE CONSEQUENCES OR BARRIERS
Alternatives Impacting Wastewater		
Removing impervious, abandoned surfaces **Repaving/renovating parking lots and sidewalks with permeable paving and pervious concrete*	• Cost and benefits • Intended purpose for land in vision • Soil type in area • Impact on the water quality, • Environmental impact	• Cost of modeling and decommissioning • Further straining limited personnel resources for design and maintenance • Impact on watershed and environment
Rainwater harvesting **Storage of rainwater for reuse for purposes such as irrigation*	• Cost and benefits • Intended purpose for land in vision • Regulations by city or state regarding use or ownership of rainwater • Environmental impact	• Cost of modeling • Further straining limited personnel resources for design and maintenance • Impact on watershed and environment
Greywater collection and on site use **Wastewater generated from household activities that may be reused onsite for applications like irrigation*	• Cost and benefits • Regulations by city or state regarding use of grey water • Chemicals used in the generation of grey water (e.g., detergents) • Environmental impact	• Cost of modeling • Further straining limited personnel resources for design and maintenance • Impact on watershed and environment • Legal barriers for use of greywater
Install green infrastructure to offset stormwater flows and to help existing system meet current demands **e.g., stormwater wetland, bioretention options, permeable pavements, green roofs*	• Costs and Benefits • Long-term land use vision • System's capacity-is system near or above capacity during wet weather • Soils in proposed area • Maintenance costs • Environmental impact	• Cost of modeling • Further straining limited personnel resources for design and maintenance • Impact on watershed and environment • Legal restrictions on type and size of green infrastructure, as well as aesthetic city ordinances
Individual septic systems or septage hauler, Onsite sewage facility	• Costs and benefits • Maintenance and regular cleaning • Water quality • Ground water availability • Environmental issues resulting from leaks • Public health risks • Logistical feasibility • Homeowner responsibility to maintain system	• Cost of implementing program • Further straining limited personnel resources • Impact on watershed and environment • Meeting federal, state, and city public health standards

Table 3.4. *(continued)*

ALTERNATIVES	CONSIDERATIONS	POSSIBLE CONSEQUENCES OR BARRIERS
Energy management conservation program ** Identify cost savings available through energy management via technology as 25-30% of operation and maintenance costs are linked of energy usage for water treatment and distribution (USEPA 2012*	• Cost and benefits • Logistical feasibility and available resources	• Cost of implementing program • Further straining limited personnel resources
Repurpose Infrastructure		
Contract out excess capacity of sewer system to neighboring communities	• Benefit if contracting to the shrinking city • Amount of excess capacity • Projected needs of community • Cost to tie pipes into surrounding communities • Environmental impact	• Cost of negotiations for contacts • Further straining limited personnel resources for negotiations • Further straining limited personnel resources for operating a system with higher demands
Contract excess wastewater treatment plant space to surrounding communities **If a city has a wastewater treatment plant, excess capacity may be used as a revenue generating option.*	• Benefit if contracting to the shrinking city • Amount of excess capacity • Projected needs of community • City/town has local waste water treatment plant • Cost to tie pipes into surrounding communities • Cost of trucking in wastewater • Environmental Impact	

It should be noted that community vision is often overlooked when discussing infrastructure alternatives. Aside from the technical viability of these infrastructure alternatives, there have not been any studies, to the author's knowledge, that gauge public perceptions and attitudes towards possible infrastructure retooling alternatives. Prior studies pertaining to the public's stance in the context of declining urban populations have examined quality of life, and perceptions towards abandonment and vacancies, without considering infrastructure related issues (e.g., Greenberg and Schneider 1996; Bright 2000; Hollander 2010; Hollander 2011). Understanding public perception is critical for the success of any infrastructure project because making infrastructure decisions that do not have adequate public support may pose risks such as inefficient or unsuccessful implementation, or unsustainable solutions due to public opposition (Susskind and Cruikshank 1987; Global Water Partnership Technical Advisory Committee 2000, Gerasidi et al. 2009, Nancarrow et al. 2010, Faust et al. 2013). Gauging and incorporating public opinion into infrastructure decision-making, and understanding the elements of public concern, may allow for sustainable, implementable alternatives that aid in transitioning shrinking cities towards right-sizing their infrastructure for a smaller population. [1]

3.3. Summary and Departure Point for Evaluated Infrastructure Retooling Alternatives

Shrinking cities face a multitude of infrastructure issues, exasperated by the city's current economic condition. Although this dissertation focuses on water and wastewater, similar issues may span other infrastructure services, such as roads or power. Faced with a declining tax base, further diminished by the income inequity occurring within the city, and reduced numbers of customers, utility providers are challenged with providing adequate service, while meeting increasingly stringent legal and environmental regulations. Operating with minimal personnel and the loss of institutional knowledge due to retirements and staff reductions further challenges these utilities in maintaining consistent and efficient services.

Underutilized infrastructure may result in reduced water quality and wastewater infrastructure performance. Decreased demands can result in increased water age and stagnant water throughout the system. Unused impervious surfaces generate runoff, which enters the combined sewer systems in many older, Midwestern communities, contributing to the volume of each sewer overflow and the number of sewer overflows, worsening the quality of water and the source.

By identifying challenges associated with water and wastewater infrastructure and existing interdependencies between the infrastructure systems, technical and managerial management strategies can be examined to facilitate the transition to sustainable services. Considerations, such as technical feasibility, existing condition of the infrastructure, and declining patterns must be assessed within each city. Decommissioning water infrastructure and consolidating demands are the two retooling alternatives evaluated in Chapter 5. Impacts of decommissioning impervious surfaces that generate runoff, transitioning land uses, and incorporating low-impact development alternatives are evaluated in Chapter 6. The impact of urban decline and implementing new management alternatives on the interdependencies between water and wastewater infrastructures are evaluated in Chapter 8.

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[1] Paragraph adapted from Faust et al. (2015b)

Each community must not only assess the viability of different management alternatives in the context of technical feasibility, but also frame these alternatives within the context of community vision. To mitigate potential opposition, the utility provider should incorporate participatory processes when implementing infrastructure retooling alternatives. The decisions made about infrastructure below ground may have implications for the above ground life of the community, such as shifting land uses or consolidating neighborhoods to more populous areas. This dissertation provides a framework to evaluate the (1) technical viability of select water and wastewater/stormwater retooling alternatives and (2) public views towards water and wastewater infrastructure issues and stormwater management to aid in participatory processes.

SMEs identified a need for understanding the technical and operational infrastructure issues that are spanning shrinking cities and not unique to one city. Many issues common to urban decline were identified via literature and interviews with four Midwestern shrinking cities, such as rising per capita costs, fulfilling obligations to retired personnel, increased water age, and runoff from vacant land entering the combined sewer systems present in many of these cities. Previous work has focused on a limited scope of issues, such as the financial burden of water and wastewater utilities falling on the consumer (Schlor et al. 2009; Butts and Gasteyer 2011) or water age (Barr 2013), without holistically looking at multiple problems arising from urban decline. Select issues spanning shrinking cities were characteristic to the type of provider. For instance, drastic personnel reductions were found in public water utilities, whereas private utilities did not face the challenge of operating on minimal personnel. Instead, private utilities highlighted the issue of dedicating more resources to connecting/disconnecting water service in shrinking cities than other cities served. Beyond the technical and operational issues spanning shrinking cities, interview with SMEs indicated that they were not aware of many alternatives that were being discussed or could be considered for the underutilization of infrastructure. Additionally, due to limited work force, shrinking cities cannot typically afford the resources to explore and identify plausible management alternatives.

Challenges faced when synthesizing the information presented in this chapter include the lack of published literature pertaining to underground infrastructure in shrinking cities and the underutilization of infrastructure. Additionally, there was no indication that shrinking cities shared information or had knowledge of how other cities were managing infrastructure in the context the urban decline. Typically, the end of life-cycle for infrastructure refers to the end of the functional life, as opposed to the end of useful life in terms of necessity to meet population demands. This chapter compiled not only the issues in shrinking cities, but provided a list of potential retooling alternatives, including applicable scenarios and barriers that can be explored, depending on the future land use and decline patterns of the city, to shift towards managing infrastructure in this new paradigm for the end of the life-cycle of infrastructure.

CHAPTER 4. METHODOLOGY

"Research is formalized curiosity. It's poking and prying with a purpose."

-Zora Neale Hurston

This chapter describes the methodology to accomplish the research goals presented in Chapter 1 and the departure point in Chapter 2. This dissertation has four related, yet independent components, shown in Figure 4.1: 1) analysis of the performance of the water infrastructure system under different retooling alternatives; 2) evaluation of the runoff generated for different retooling alternatives; 3) quantifying the public views towards water and wastewater infrastructure issues and retooling infrastructure alternatives; and 4) examining the interdependencies between water, wastewater, and stormwater infrastructure and human-infrastructure interactions.

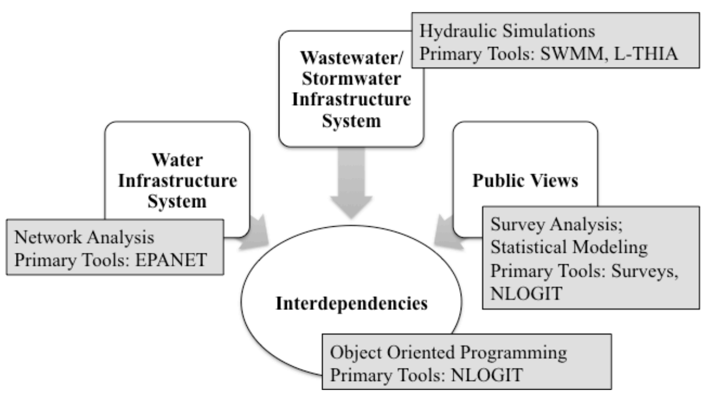


Figure 4.1. Methodology Components

4.1. Case Study Cities

Two US cities serve as test beds to demonstrate the proposed methodology: 1) Flint, Michigan and 2) Saginaw, Michigan. Flint is a medium-sized city, peaking at over 100,000, with a population of 196,940 in 1960. Saginaw is classified as a small city with its population peaking below 100,000 at 98,265 people in 1960.

4.1.1. Case Study Cities

According to the US Census Bureau data from 1940 to 2010, Flint and Saginaw have experienced a decline in population of 43.4% and 47.5%, respectively, since each city's peak population (US Census Bureau 2011). As illustrated in Figures 4.2, their population decline is not tied solely to the economic cycle that follows a trend of rise and fall in the short term (e.g., the US economic downturn since 2007), but rather has been a chronic decline over multiple decades. The populations in these cities peaked in the 1960s when industries such as automotive, steel and manufacturing brought jobs and growth. However, due to industrial decline, these cities, as well as other US industrial cities, began a steady decline from the 1960s until present day, in some instances, losing over half of their population. Juxtaposed with four shrinking cities in Figure 4.2 are three cities (Fort Wayne, Indiana; Dearborn, Michigan; and Hamilton, Ohio) that follow the typical city growth trends, shown by grey-dashed lines, to illustrate the chronic decline seen in shrinking cities.

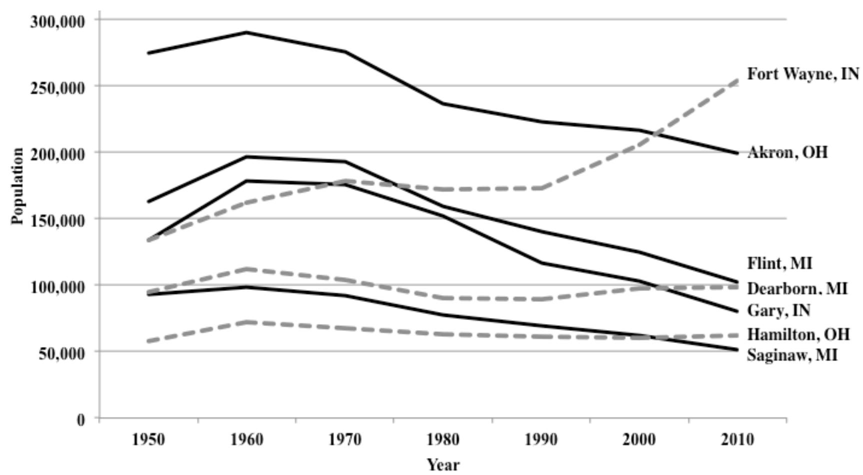


Figure 4.2. Population dynamics: Cities experiencing urban shrinkage juxtaposed with "typical" city growth trends

Figures 4.3 (a) and (b) depict the "urban crisis" occurring in Michigan, which was the only state in the US to lose total population in the past decade, according to the US Census Bureau (2011). Shrinking cities are experiencing increased vacancies and abandonment, disinvestment in the neighborhoods, and increased per capita costs for infrastructure operation and maintenance. The USEPA (2014) describes the impact this decline on Saginaw's community as having approximately 5,500 vacant or abandoned properties comprising 25% of Saginaw's land area.

(a)

(b)

Figure 4.3. Michigan's urban crisis: (a) Flint and (b) Saginaw

Often times, shrinking cities, especially those resulting from industrial decline, are plagued by a decrease in the average incomes of residents. Individuals with the means, skills, and abilities often leave the city in pursuit of opportunities. This inequity is present in the case study cities where median income for Flint is $27,199 with 36.6% of the population below poverty. Similarly, Saginaw's median income is $27,051 with 37.4% of the population below poverty. This information indicates that a given neighborhood may or may not be low-income. When evaluating the performance of the water infrastructure system, water use demand patterns that vary due to socioeconomic status (discussed in Section 4.2.2.1) must be considered to ensure that the appropriate water usage patterns are applied and this income inequity is captured.

In the context of water and wastewater infrastructures, the management and operational aspects vary between cities, as shown in Table 4.1. One important difference between the two case study cities is that Saginaw is attempting to transition towards proactive management styles, whereas Flint remains primarily reactionary. To the author's knowledge, as of March 2015, Flint has not performed formal analyses for the cost and benefits of retooling alternatives nor have areas been formally selected by city officials to examine the feasibility of retooling alternatives. However, discussions with representatives from Flint's water utility (in May 2013) revealed that the city is open to exploring retooling alternatives to lower infrastructure costs, and they are currently developing a future land use plan for the city. Saginaw has considered decommissioning infrastructure and has developed a vision for future land use.

Table 4.1. Water and wastewater infrastructure management and operational characteristics

Parameter	Saginaw, MI	Flint, MI
WATER INFRASTRUCTURE SYSTEM		
Ownership/management	Municipal	Municipal
Asset management strategies	Proactive	Reactionary
Age	Approximately 80 years	• Major upgrades occurred in the 1980s • Some pipe in place and functioning from the 1800s
Material issues highlighted in conference calls and discussions	Internal corrosion, tuberculation	• High failure of galvanized pipe • Copper pipe theft on vacant properties
Demand	Citywide, 600 million gallons per month on average	-
Water source	Lake Huron	City of Detroit
Maintenance and replacement	Replace as necessary, maintenance investment is determined on an annual basis	Replace as necessary
Percentage of failures causing service disruptions	10%	-
Average service disruption	8 hours total	-
Number of households impacted	Approximately 20-30 households	-
Rate increase	3-year rotation to re-evaluate rates	Annual evaluation occurs; 25% increase in 2012 (previously no changes in the last decade)
Financial components	Self-sustaining	Self-sustaining
Personnel issues	Supporting a significant number of retired workers	Reduced personnel considerably
WASTERWATER/STORMWATER INFRASTRUCTURE SYSTEM		
Ownership/management	Public	Public
Type	Combined sewer system	Separate stormwater systems
Issues Highlighted	• Would like to transition to green infrastructure to capture and clean stormwater onsite wherever deemed appropriate to reduce the quantity of water entering the system • Stormwater contributes approximately 30% of the daily wastewater	• 40% of water into sanitary system comes from footing drains (15mgd during dry weather, over 100 mgd in wet weather entered the system) • Collection system is old, ground water table is rising, sewers and interceptors are located along river banks (river is coming into the treatment system) • Could close one part of the plant if the wet weather issues were not present

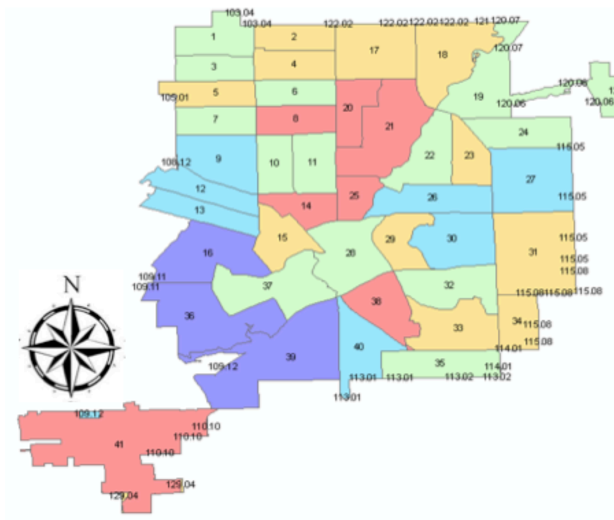
4.1.1. City of Flint Analysis Area

To observe the population decline patterns throughout Flint and to identify appropriate locations to test the methodology, maps of Flint were divided into sections aligning with the 2000 census tracts. Census tracts are used to bound geographical regions of a city into comparatively homogeneous areas with regard to population characteristics, economic status, and living conditions (US Census Bureau 2011). The boundaries of census tracts may change every ten years with each census in an attempt to maintain homogeneity among the tracts within the city and to accommodate geographic changes to the city. The 2000 census tracts were used as the defining boundaries within each city to allow for the comparison between the 2000 and 2010 populations in the same defined area. The 2010 census data are available for both the 2000 and 2010 tracts, whereas the 2000 census data are available for the 1990 and 2000 tracts.

These thematic maps use both "Equal" breaks and "Jenks"/"Natural" breaks (referred to as "Jenks" throughout the thematic maps). Equal breaks take the range of data and breaks down the data into categories that all have the same length (e.g., 1-10 broken into two equal categories yields 1-5 and 6-10). "Jenks" defines the breaks by clusters of data. The number of categories is the number of clusters. Jenks minimizes the variability within a cluster while maximizing the variability between each cluster.

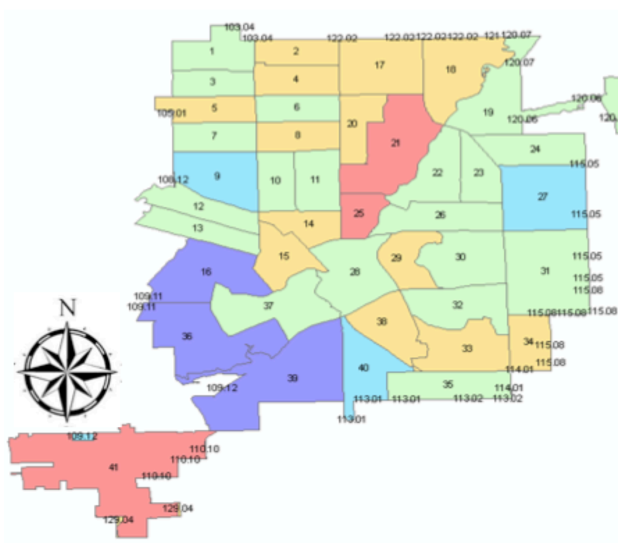
Categories (depicted by various colors) are used to divide the population and population decline (growth) by tracts that exhibit similar patterns. Decline (growth) is represented by the ratio of the 2010 population to the 2000 population in an individual tract. If the population reported for 2010 in a particular tract is less than that reported for the same tract in 2000, the ratio yields a value that is less than one. Conversely, if the population reported for 2010 in a particular tract is greater than reported for the same tract in 2000, the ratio yields a value that is greater than 1, indicating growth within the boundaries of that particular tract. The Equal and Jenks breaks have been slightly modified to ensure that 1.0 is the boundary for two of the levels to distinguish between growth and decline.

As shown in Figures 4.4-4.7, Flint appears to have low population pockets amidst larger population pockets, showing a pattern coined as a Swiss cheese appearance. The lowest area of population appears to be in the center of the city, and the highest areas of population are in the southwest portion of the city. When observing the population decline between 2000 and 2010, the west portion of the Flint is shown to have experienced higher declines and the eastern portion is shown to have experienced growth. The tracts experiencing growth, however, are among pockets experiencing decline. Interestingly enough, two of the tracts, Tracts 21 and 25, with the lowest population, have experienced growth since 2000. By increasing the population in Tract 21 by a mere 20 people, Tract 21 has the appearance of growth, due to the tract's low population.



Color	Population (people)
	43-1388
	1389-2323
	2324-2997
	2998-3936
	3937-5683

Figure 4.4. 2010 Population (Jenks Breaks)



Color	Population (people)
	43-1171
	1171-2299
	2299-3427
	3427-4555
	4555-5683

Figure 4.5. 2010 Population (Equal Breaks)

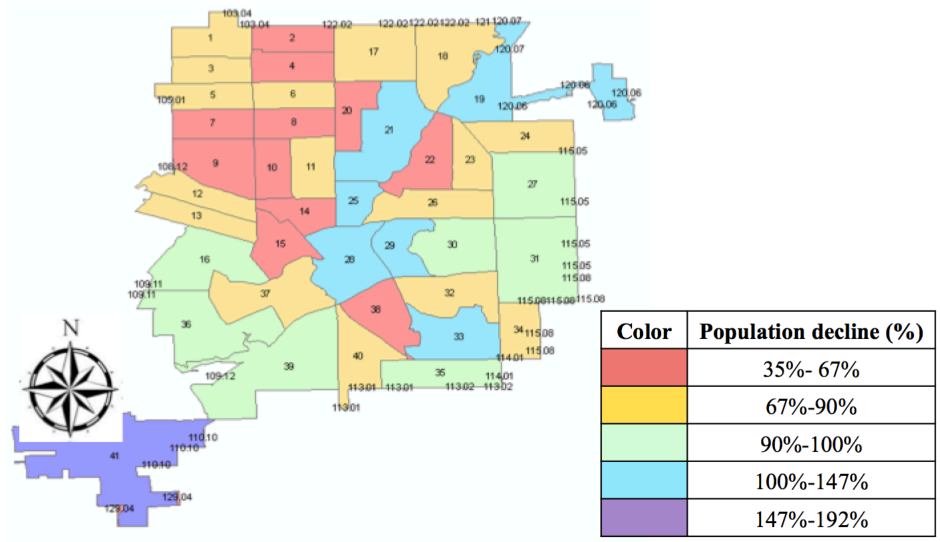


Figure 4.6. Population decline between the 2000 census and 2010 census (Jenks Breaks)

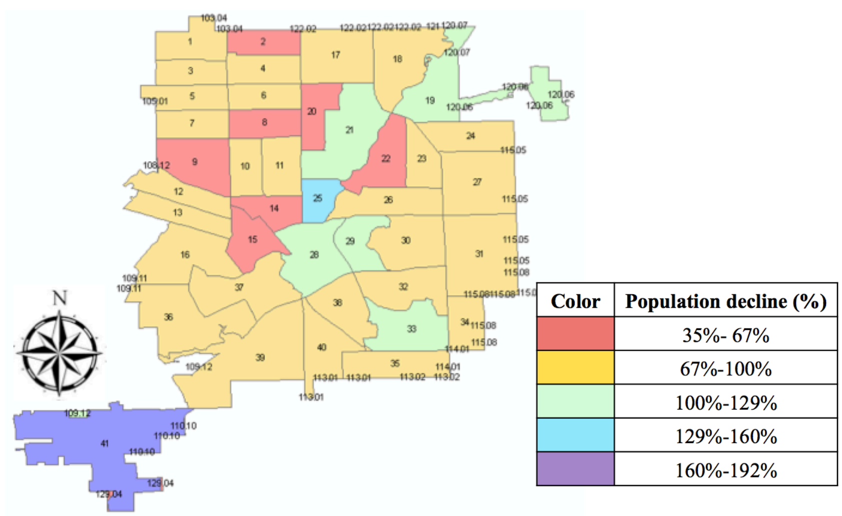


Figure 4.7. Population decline between the 2000 census and 2010 census (Equal Breaks)

The city blocks used in the analyses for this study are located in Tract 20. This area of the city is among the lowest populated and is amidst the tracts experiencing the highest population decline. In addition, this area is zoned primarily for residential parcels, many of which are owned by the Genesee County Land Bank. Figure 4.8 shows the specific area used to test the methodology. The dark blue parcels indicate privately owned residential parcels. The green parcels indicate Genesee County Land Bank owned parcels, as of January 2012, as indicated by the Genesee County Land Bank GIS layer, provided by the Genesee County Land Bank.

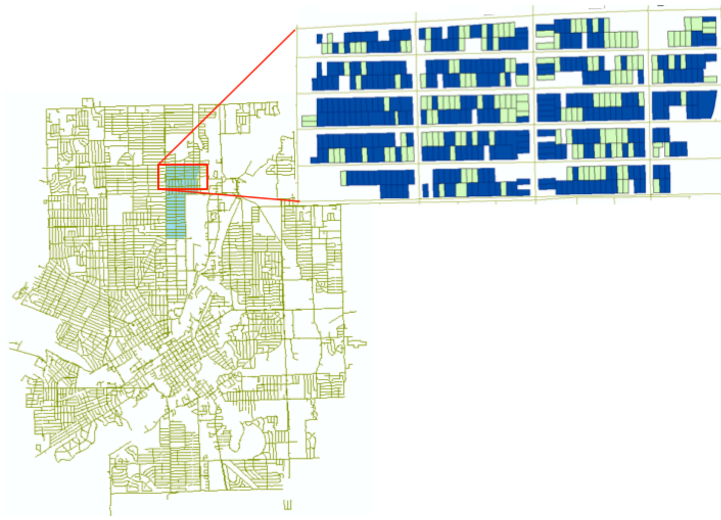


Figure 4.8. Analysis area in Flint

4.1.2. City of Saginaw Analysis Area

The Green Zone (Figure 4.9) is a primarily residential zone within Saginaw that was identified as a candidate by the city for retooling alternatives, specifically incorporating green infrastructure and recreating the area. This Green Zone is bounded by I-675 to the south, the Saginaw River to the west, North Washington Avenue to the north, and a rail yard to the east. Approximately 70% of the land is considered vacant, with the Saginaw County Land Bank owning approximately 370 of the 800 properties in the area (USEPA 2014). The green parcels in Figure 4.9 are known, vacant parcels, many of which are owned by the Saginaw County Land Bank as 2011.

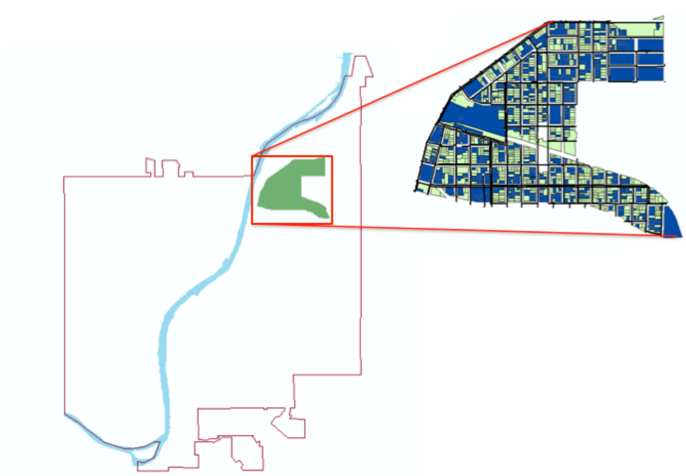


Figure 4.9. Location of the Green Zone within Saginaw's city boundaries

This area is referred to as the "Green Zone" for its potential candidacy for installing green infrastructure, thereby reducing the amount of impervious surfaces that flood during wet weather and making the area more aesthetically appealing (USEPA 2014). Due to the high vacancy rates and pre-identified potential for retooling this area by Saginaw, analyses will take place in the neighborhoods within the Green Zone. The Green Zone is primarily residentially zoned as R-2 or two-family residential, which typically allows for up to two family dwellings. The future land use plan for this area in Saginaw will not include residences in these areas and is intended to transition to green opportunity areas. The specific analysis area for this study within the Green Zone is depicted in Figure 4.10.

Figure 4.10. Analysis area in Saginaw's Green Zone

4.2. Water and Wastewater/Stormwater Infrastructure Analyses

The metrics and tools used to evaluate the performance of water and wastewater/stormwater infrastructures in Flint and Saginaw are described in Sections 4.2.1 and 4.2.2, respectively. Model development specific to each city is presented in Chapters 5 and 6 with the analysis results.

4.2.1. Metrics Used in Water and Stormwater Analyses

A set of metrics was defined and applied to evaluate the performance of the infrastructure systems. Performance metrics are used to evaluate whether a specific function is accomplished in a desired manner (Sinha and Labi 2007) and may be expressed either qualitatively or quantitatively, as well as applied for varying spatial scales. According to Sinha and Labi (2007), a well-defined performance measure should exhibit the following characteristics:

- Appropriateness. The metric should represent one or more of the system's goals.
- Measurability. The metric should be easily evaluated in an unbiased, objective manner.
- Dimensionality. The metric should be applicable for the appropriate scale (e.g., temporal, spatial, geographic) of the analysis.
- Realistic. Data necessary for the metric should be accessible without extensive time or resources.
- Defensible. The metric should be clear, concise, and easily interpretable.
- Forecastable: The metric should be applicable for future use.

To identify appropriate metrics for the analysis of infrastructures in shrinking cities, it is useful to review the metrics that are applied in current infrastructure analysis models. Previously discussed in Chapter 2's Table 2.4, Peralta (2009) categorized the models surveyed by Pederson et al. (2006) into four groups of metrics: economic, risk, time, and environmental and human effects. A fifth category, which was proposed in Peralta (2009) for examining the operating states of infrastructure in developing countries, is also included in Table 2.4. These metrics used in previous models were not capable of measuring the impact of both physical and non-physical disruptors on the infrastructure systems, and were primarily used to measure physical disruptors, such as intentional attacks or natural disasters. Different from previous studies, this study examines critical infrastructure and infrastructure interdependencies in the context of shrinking cities (that is the presence of non-physical disruptors in the form of urban decline), and retooling alternatives (physical disruptors due to reconfiguring existing infrastructure). Table 4.2 summarizes the metrics used in this study.

Table 4.2. Metric justification

	Water Infrastructure	**Wastewater/Stormwater Infrastructure**
Metric(s)	Pressures at nodes are between 20-80 psi (ideally above 35 psi) and the system has the ability to provide adequate fire flows, defined as 250 gpm for two consecutive hours	Change in generated runoff due to the removal of impervious surfaces
Relevance	Evaluates the system's ability to function and operate at an acceptable level	Examines the changes runoff entering the wastewater/stormwater system,

Table 4.2. *(continued)*

	Water Infrastructure	Wastewater/Stormwater Infrastructure
Data Sets	The data necessary include the characteristics of the system's components (e.g., elevations, diameters, pipeline material, and average demands)	The data necessary include the characteristics of the area and infrastructure zoning (e.g., elevations, impervious surfaces, current land use, intended land use, soil), water demand, and wet weather events
Comparison	Functionality of the system can be examined and compared under various retooling scenarios	Functionality of the system can be examined and compared under various retooling scenarios
Adequate Measurement of Goals	Metric reflects the system's operation under various demands, capacities, and scenarios	Metric reflects the generated runoff entering the system
Measurability	Pressures and fire flow scenarios may be calculated using EPANET	The generated runoff (and characteristics of that runoff such as, non-point source pollutants) may be estimated using L-THIA and SWMM
Realistic in terms of data availability	Data are available from the city GIS layer and published material	Data are available from the city GIS layers and published material
Dimensionality: comparable across time and geography	Metrics can be calculated at various times, days, months, etc., as well as in various locations of the city	This metric can be calculated for various locations of the city, as well as times and storm intensities
Defensible in terms of calculation	The values are characteristic of the system (e.g., pipeline diameter, pipeline materials, location of junctions) or from published material	The values are characteristic of the area and wet weather events in the area
Forecastable	Historic trends in demand decline (or growth) may be used to predict future conditions of the neighborhood(s)	Historic trends in demand decline (or growth) may be used to predict future potential for retooling impervious surfaces and incorporating green infrastructure
Appropriate for modeling and validation	EPANET is used to estimate these metrics, and the pressures and fire flows are verified by the city as reasonable values	L-THIA and SWMM have the capability to model this metric and the results of the stormwater produced, and wet weather events may be verified by local weather station data

4.2.2. Water Infrastructure Retooling Alternatives Analyses

EPANET was used for network analysis. This network model provides a representation of the physical network as a set of links and nodes with the information about the location, the direction of flows, and the connectivity. Specifically, it allows for editing network data, running hydraulic and water quality simulations, and viewing the results in various formats like color-coded network maps, data tables, time series graphs, or contour plots. EPANET was used in this study to evaluate the pressure changes in the system as a result of retooling the infrastructure, and assess the system's ability to provide adequate fire flow under various retooling alternatives.

The specific inputs used for the EPANET are shown in Table 4.3. The inputs were based on the availability of data and the published literature. Data for the pipelines, consisting of the relative location, length, and diameter and the geographic location of the nodes, were imported directly from each city's water distribution system GIS layer for use in the EPANET models. Since the water distribution GIS layer did not include elevation or slope data for the pipelines throughout the city, the relative elevations of the nodes and reservoir were determined from US Geological Survey (USGS) topographic maps. In the analyses, water entered the water infrastructure distribution system via the pipelines located nearest to the reservoir located on a USGS topographic map.

Table 4.3. EPANET inputs and sources

Inputs	Source
Pipeline Characteristics • Material • Length • Diameter • Intersecting pipelines • Relative location	GIS layer from each city
Node locations	GIS layer from each city
Elevation of Nodes	US topographic map
Reservoir location and Elevation	US topographic map
Pump curve	Determined as a typical pump used in EPANET examples
Water use trends	Aquacraft, Inc. (2011) (discussed in Section 3.2)
Water Demand	AWWA (1999)

4.2.2.1. Water Use Trends and Demands Used In EPANET

The estimated daily demand patterns, accounting for the variations of water demand throughout the day, as developed by Aquacraft, Inc. (2011), were used in this study as an input for EPANET. Usage variations throughout the day are an important consideration to ensure that water demands are met during peak periods. Aquacraft Inc. (2011) developed two demand patterns based on household incomes: 1) Single Family Homes and 2) Single Low-Income Family Homes. These demand patterns were created for the California Public Utilities Commission Energy Division to obtain more accurate water use profiles than previously available. Single Family Homes are those that are occupied by one family as opposed to a multi-unit apartment complex. The total water consumption did not vary significantly for total demand, but water usage varied throughout the day across socioeconomic boundaries, as shown in the demand patterns in Figure 4.11. Therefore, the time of or the number of peak demands in a community may differ if the socioeconomic status of the area is predominately middle/upper-income versus low-income.

While evaluating the impact of physical changes on the water system in shrinking cities, these cities need to determine which water use trends are appropriate for their analyses. In cities experiencing urban decline, the financial burden of maintaining the water infrastructure often falls on those who cannot afford increased service charges and may likely be in the low-income bracket (Rybczynski and Linneman 1999; Beazley et al. 2011; Butt and Gasteyer 2011). Thus, single low-income family water use trends may be more applicable for such analyses. The average income of a city may be obtained from census data to identify the demand pattern that is most appropriate for the area.

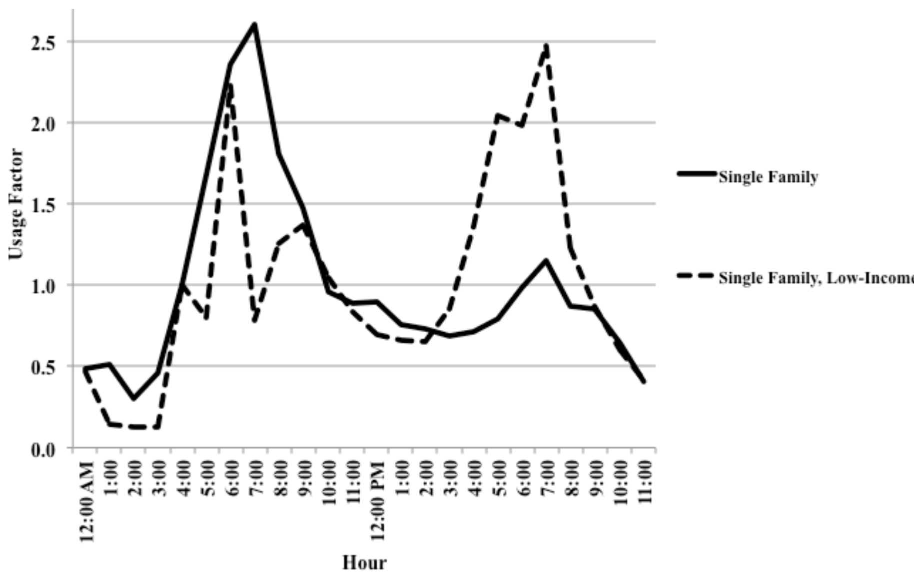


Figure 4.11. Socioeconomic daily water use demand pattern

4.2.2.2. Fire Flow Analyses

Providing adequate fire flow to the area during peak times is critical for the safety of the residents in the area. Hickey (2008) stated that for a fire hydrant to be recognized by the city, it must be able to maintain a flow of 250 gpm for two consecutive hours without reducing the pressure of any node below 20 psi. Fire Flow 2.1, a tool developed by Optiwater used with EPANET, modeled the increase in the flow at each node individually until the established pressure threshold for any node in the network was violated. The fire flow ability of the network was analyzed by determining the maximum flow available for two consecutive hours and the maximum flow available for any instantaneous moment in time. The maximum flow available was determined for peak times using the Single Family Homes and Low-Income Single Family Homes demand patterns to examine if the difference in peak demands significantly impacts the fire flow capabilities of the network. Additionally, each fire flow analysis was performed under further decline (termed demand alternative in Chapter 5) to evaluate the impact that further urban decline may have on the ability to provide fire flows.

4.2.3. Stormwater Infrastructure Retooling Alternatives Analyses

Long-Term Hydrologic Impact Assessment (L-THIA), and Storm Water Management Model (SWMM) were the primary tools used for the stormwater runoff analysis. Purdue University, the USEPA, the Local Government Environmental Assistance Network (LGEAN), and the International City/County Management Association for the states of Indiana, Illinois, Wisconsin, Michigan, and Ohio jointly developed L-THIA. L-THIA has a user interface in which the area of land, current land use, changes in land use, soil type, and incorporation of low-impact development (LID) practices are selected by the user. L-THIA estimates runoff with curve number analysis, which incorporates the Natural Resource Conservation Service's (NRCS) classification system of four hydraulic soil groups, Groups A through D. Group A has the lowest potential for runoff and D has the greatest potential for runoff.

SWMM, a tool developed by the USEPA, is a dynamic simulation model for estimating runoff quality and quantity based on precipitation. For this analysis, base models of the status quo candidate areas were developed in SWMM. The base models were altered by changing land uses at a subcatchment level or incorporating LID practices. The runoff estimates from SWMM used the curve number analysis approach (one of three available infiltration methods available in SWMM), allowing for uniform infiltrate estimation methods between tools.

The two tools, L-THIA and SWMM, were used for comparison of estimated changes in runoff and infiltration for the candidate area, to understand the impacts various alternatives would have on the area, and more specifically the wastewater/stormwater system. Both tools estimate the quantity of runoff, based on historical rainfall data and soil types in the candidate area. The effects of development and urbanization on the naturally categorized soil group was considered due to activities such as heavy equipment during construction or daily activity on the land (Town of Bluffton 2011). Thus, all alternatives were evaluated under the assumption that development has caused the soil to compact to Category D (in addition to the soil categories characteristic to the area), resulting in the soil having the greatest runoff potential. Specific inputs and sources are for these analyses are shown in Table 4.4.

Table 4.4. L-THIA and SWMM inputs and sources

Inputs	**Source**
Size of changing land use	GoogleEarthPro
Soil type	USDA: NCRS (2013) and GIS layers
Current land use	City provided GIS layers
Status quo percent impervious	USDA (1986)
Precipitation data	National Climate Data Center (NCDC) (2014)
Land use scenarios and BMPs	L-THIA: Pre-defined, based on literature SWMM: USDA (1986), SEMCOG (2008)
Underground infrastructure in candidate area	City provided GIS layers

4.2.3.1. Using L-THIA to Model Retooling Alternatives

In L-THIA, land use was divided into individual cells, with hydraulic soil groups assigned to each cell. Each cell had a curve number assigned based on the land use, and either contributed to the total runoff or infiltrated the land. Runoff was then estimated using Eqns. 4.1- 4.3 (USDA 1986):

$$Q= ((P-Ia)^2)/(P-Ia+S) \qquad \text{[Eqn. 4.1]}$$

$$S= 100/CN-10 \qquad \text{[Eqn. 4.2]}$$

$$Ia = 0.2S \qquad \text{[Eqn. 4.3]}$$

where, Q was the total runoff, P was the rainfall, S was the soil moisture, Ia was the initial abstraction (i.e., amount of water prior to runoff), and CN was the assigned curve number. The runoff depth over the area is then converted to a volume (by multiplying by the area of the cell). Figure 4.12 summarizes L-THIA's methodology.

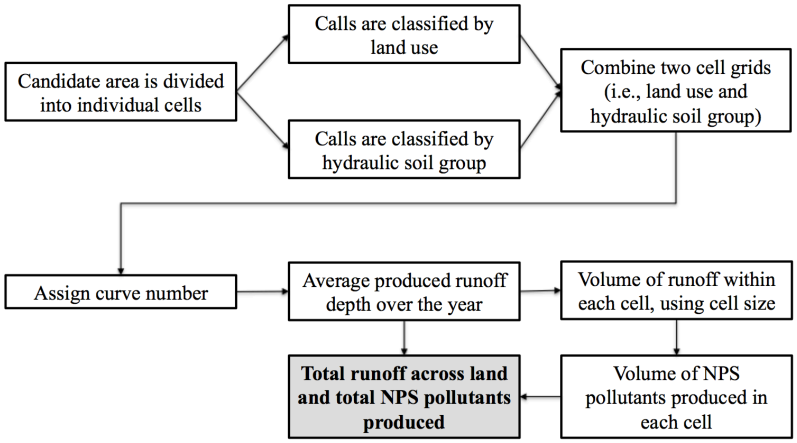


Figure 4.12. L-THIA methodology summary (adapted from Lim et al. 1999)

L-THIA assumes that the water flowing across a surface is equally distributed across the landscape (i.e., there is no routing of the water), and there is not subsurface drainage system. Additionally, the rainfall is evenly spread across the county, as historical precipitation data is determined on a county-by-county basis, L-THIA does not account for rainfall duration or intensity, and the accuracy in predicting runoff is not high when the runoff is less than 0.5 inches.

4.2.3.2. Using SWMM to Model Retooling Alternatives

SWMM models the drainage systems as subcatchments (where precipitation and runoff are generated) and routes the runoff through a conveyance system. Subcatchments account for variations in land uses, allows for assigning the percentage of pervious and impervious surface, and is the location for the incorporation of LID practices. The conveyance system has the ability to transport external flows (e.g., runoff, base flows in pipelines, household wastewater) to model the performance of the underground infrastructure and drainage systems. The simulation is a discrete-time model, based on conservation of mass, energy, or momentum, by conceptual representing the surface (e.g., natural infiltration, LID alternatives) and sub-surface drainage system (e.g., wastewater infrastructure, stormwater infrastructure). For this analysis, SWMM was used to model the change in runoff by decommissioning impervious surfaces (e.g., driveways, sidewalks, foundations), changing land uses, and incorporating LID practices.

Data for the pipelines, consisting of the relative location, length, and diameter and the geographic location of the nodes, were determined from each city's stormwater/wastewater system GIS layer. As the GIS layer obtained from the case study cities did not include elevation or slope data for the pipelines throughout the city, the relative elevations of the land/subcatchments were determined using GoogleEarthPro, and the sewer slopes were based on published design recommendations from the Wastewater Committee of the Great Lakes (2004). In the analyses, runoff from each subcatchment was assumed to enter the conveyance system via the pipelines located within the proximity and transported to a single outfall.

The SWMM models developed in this study assumed that the conveyance system was in good condition. If the design diameter is no longer correct (or there is change in ovality of the pipe), the roughness coefficient is considerably different from published estimates, or there are many breaks in the underground pipelines, the SWMM results may not accurately represent the runoff entering the system. Breaks in the pipelines cause infiltration into the conveyance system, underestimating the quantity of stormwater entering the conveyance system during each simulation.

4.2.3.3. Precipitation and Storm Data

Precipitation data varied across source and geographical scale (i.e., city versus county), impacting the total runoff estimated (discussed in Chapter 6). Countywide data is used to estimate runoff in L-THIA. SWMM allows for the incorporation of local weather station data or user defined data. Due to the availability of National Climate Data Center (NCDC) weather station data, Vassar, MI, a neighboring city to Saginaw, which has a more extensive database, was used. Similarly for Flint, L-THIA used Genesee county averages, whereas the SWMM model incorporated city specific precipitation data, reducing the variation that may occur over the county.

Contrary to L-THIA that simulated the alternatives using daily precipitation averages, SWMM simulated the alternatives using precipitation data in 30-minute increments, providing more accurate time steps that were a closer reflection of the intensity and duration of the storm. Additionally, SWMM's capabilities allowed for incorporating the wastewater/stormwater infrastructure system, topography of the land, and LID alternatives. L-THIA incorporated 30 years of countywide precipitation data, whereas this SWMM results were estimated using the most recent 10 years of city-specific precipitation data.

Following the simulations based on historic precipitation specific to that country/city, all alternatives were simulated using a 2-year and 10-year, 24-hour design storm in SWMM.

Additionally, the performance of different alternatives in Saginaw was evaluated for a 2-year and a 10-year, 10-minute design storm, due to the combined sewer system (CSS) in the city. The 10-minute storms measured the effectiveness of the retooling alternatives to manage stormwater during short duration, high intensity storms, as this is a challenge for CSS due to the risk of overflows from the abrupt volume of runoff entering the system in a short period of time. As of October 2014, L-THIA did not have the capability to model storms or user defined rainfall data. The precipitation depths of the storms were from NOAA (2014) and relative to the location of Flint and Saginaw. The storm's intensity was determined using National Resource Conservation Service developed distributions using National Weather Service duration-frequency data or storm data. Michigan is categorized as Type II design storms, with the most intense storms of the four distributions (USDA 1986).

4.3. Survey Analyses of Public Views in Shrinking Cities

A survey was deployed to residents of US shrinking cities with the purpose of gaining insight into the perceptions, knowledge, awareness, and attitudes concerning water and wastewater infrastructure issues and infrastructure retooling alternatives. Information gained from this survey may serve as a jumping block for further assessing viable infrastructure retooling alternatives with public opinion considered, as well as provide framework for estimating the drivers of attitudes and perceptions towards retooling alternatives in shrinking cities.

4.3.1 Survey development and deployment[2]

Qualtrics, a web-based survey software, was used to format and deploy the survey. Responses were voluntary, and all respondents were over the age of 18. The survey's validity was determined through content review by 11 SMEs with backgrounds in issues inherent to shrinking cities, water and wastewater infrastructure management, or in the development and deployment of public perception surveys. Following content validation, the survey was pre-deployed to 25 people with limited knowledge of water sector infrastructure issues to ensure that a population with limited knowledge could easily respond to, and understand the survey (the responses from the pre-deployment were not included in the final sample pool). Prior to pre-deployment, the survey underwent IRB review at Purdue University (see Appendix E). The feedback from the SMEs and pre-deployment was incorporated in the final survey instrument, to ensure that the survey gathered the desired data.

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[2] Section adapted from Faust et al. (2015a; 2015b)

The respondent pool consisted of residents from 21 US shrinking cities (listed in Table 4.5) that are classified as medium or large cities, had a peak population greater than 100,000, and have experienced a decline of at least 30% of their population (with the exception of Saginaw, Michigan which peaked just under 100,000). As of the 2010 census, the total population of targeted cities was approximately 4.6 million (US Census Bureau 2011). To obtain a confidence level of 95% with a confidence interval of 5%, more than 450 complete surveys comprised the sample population, with a minimum of 10 responses from each city. Responses were sought from cities in multiple states to: a) reduce the potential that responses only reflect specific state, regional, or city policies, and b) allow comparison of the public perceptions, knowledge, awareness, and attitudes across cities/states. It should be noted that due to dynamic changes in perceptions and attitude for reasons such as, imperfect information, increase in awareness, and media coverage, perceptions and attitudes may evolve over time.

Table 4.5. Targeted cities comprising survey response pool (Faust et al. 2015b)

City	**Percent decline from peak population**	**Peak Population (Year)**	**2010 Population** (US Census Bureau)
Akron, Ohio	34.5%	290,351 (1960)	199,110
Baltimore, Maryland	34.6%	949,708 (1950)	620,961
Birmingham, Alabama	37.7%	340,887 (1950)	212,237
Buffalo, New York	53.4%	580,132 (1950)	270,240
Camden, New Jersey	37.9%	124,555 (1950)	77,344
Canton, Ohio	37.6%	116,912 (1950)	73,007
Cincinnati, Ohio	41.1%	503,998 (1950)	296,943
Cleveland, Ohio	56.6%	914,808 (1950)	396,815
Dayton, Ohio	46.1%	262,332 (1960)	141,527
Detroit, Michigan	61.4%	1,849,568 (1950)	713,777
Flint, Michigan	43.4%	196,940 (1960)	84,465
Gary, Indiana	55.0%	178,320 (1960)	98,026
Niagara Falls, New York	51.0%	102,394 (1960)	52,200
Pittsburgh, Pennsylvania	54.8%	676,806 (1950)	371,102
Rochester, New York	36.7%	332,488 (1950)	121,923
Saginaw, Michigan	47.5%	98,265 (1960)	51,508
Scranton, Pennsylvania	46.9%	143,333 (1930)	67,244
St. Louis, Missouri	62.7%	856,796 (1950)	537,502
Syracuse, New York	34.2%	220,583 (1950)	75,413
Trenton, New Jersey	33.7%	128,009 (1950)	43,096
Youngstown, Ohio	60.6%	170,002 (1930)	103,020

4.3.2. Statistical Models

Survey questions were modeled using binary probit and binary logit models with random parameters, depending on the model type that was the best fit. Marginal effects are used to interpret the results of each model.

4.3.2.1. Binary Probit [3]

The binary probit models were estimated with the standard maximum likelihood method and assumed normally distributed error terms (ε) with a mean of zero. The binary probit model equation:

$$P_i(YES) = \phi\left(\frac{\beta_{YES}X_{YESi}}{\sigma}\right) \qquad \text{[Eqn. 4.4]}$$

estimates the probability of outcome 1 for observation i. Phi (Φ) is the standardized cumulative normal distribution, β_1 are the estimable parameters for outcome i, and X_{1i} are the vectors of the observable characteristics (e.g., respondent demographics, cities, states) that determine if "1" is the suggested outcome of observation i (Washington et al. 2011).

4.3.2.2. Binary Logit with Random Parameters [4]

For the binary logit with random-parameters models, a function that determines the probability of opposing an option is defined as,

$$O_i = \beta X_i + \varepsilon_{i,} \qquad \text{[Eqn. 4.5]}$$

where O_i is a function determining the probability that respondent i will oppose the sustainability option, X_i is a vector of explanatory variables that affect the likelihood that respondent i will oppose the sustainability option, β_i is a vector of estimable parameters for, and ε_i is an error term which is assumed to be generalized extreme value distributed (McFadden 1981). To arrive at the random-parameters binary logit model, random parameters are introduced with $f(\beta_i|\varphi)$, where φ is a vector of parameters of the chosen density function (mean and variance). The resulting binary logit with random parameters opposition probabilities are (McFadden and Train 2000; Train 2009):

[3] Section adapted from Faust et al. (2015a)
[4] Section adapted from Faust et al. (2015b)

$$P_i(o|\varphi)\int \frac{1}{1+e^{-\beta X_i}} f(\beta_i|\varphi)d\beta_i \qquad \text{[Eqn. 4.6]}$$

where, $P_i(o|\varphi)$ is the probability of respondent i opposing (o) conditional on $f(\beta_{in}|\varphi)$. If the variance in φ is determined to be significantly different from zero, there will be respondent-specific variations of the effect of X on the probability of opposing, with the density function $f(\beta_i|\varphi)$ used to determine the values of β_i across respondents (Train 2009).

Simulated maximum likelihood is used to estimate random-parameters logit models with logit probabilities approximated by drawing values of β_i from $f(\beta_i|\varphi)$ for given values of φ. Research by Bhat (2003) has shown that an efficient way of drawing values of β_i from $f(\beta_i|\varphi)$ to compute logit probabilities is to use a Halton sequence approach (Bhat 2003; Train 2009). 500 Halton draws were used for accurate parameter estimation (this number of Halton draws will be used in forthcoming model estimations). For the functional form of the parameter density functions, consideration is given to normal, lognormal, triangular, uniform and weibull distributions. With the functional forms of the parameter density functions specified, values of β_i are drawn from $f(\beta_i|\varphi)$, logit probabilities are computed, and the simulated likelihood function is maximized.

To assess the effect of individual parameter estimates on injury-severity outcome probabilities, marginal effects can be readily computed (Washington et al. 2011) from the partial derivative for each respondent i (i subscripting omitted for simplicity) as:

$$ME^{P(o|\varphi)} = \frac{\partial P(o|\varphi)}{\partial x_k} \qquad \text{[Eqn. 4.7]}$$

where x_k is the k^{th} included variable and other terms are as previously defined.

4.3.2.3. Marginal Effects

Marginal effects are used to interpret the results, with each variable's marginal effect being the average of the individual marginal effect for all observations. The marginal effect yields the average change in probability yielded from a one-unit change in the independent variable (Washington et al. 2011). The marginal effects of indicator variables (i.e., variables that have a value of zero or one) indicate the change when the indicator variable changes from zero to one (Washington et al. 2011).

4.3.2.4. Akaike Information Criterion and the Bayesian Information Criterion

For model selection, the Akaike information criterion (*AIC*) and the Bayesian information criterion (*BIC*) were used. Both criterion incorporate the same goodness- of-fit term and, with k equal to the number of parameters in the model and log-likelihood function $f\ (y|.)$, the is $AIC = -2\ln f(y|\widehat{\beta_k}) + 2k$ and $BIC = -2\ln f(y|\widehat{\beta_k}) + k\ln n$ (Cavanaugh 2012). Although both terms are partially based on the log-likelihood function, *BIC* penalizes over fitting to a greater degree than *AIC*, therefore favoring parsimonious models. *AIC* yields an unbiased estimator of the Kullback-Leiber divergence between the candidate model and the true model, whereas *BIC* yields an estimator of the Bayesian posterior probability. *AIC* is asymptotically efficient, selecting the model that minimizes the mean square error, and thus, is appropriate as a predictive criterion (identifying via a pairwise comparison which model via a pairwise comparison, most efficiently predicts the outcomes). *BIC* is consistent, identifying the model with the factors that are the most influential, and thus is appropriate as a descriptive criterion (Cavanaugh 2012). When selecting models, the smallest *AIC* and *BIC* are indicative of the best fitted models (Schneider and Schneider 2009).

4.4. Interdependency Analyses

Object oriented programming, using the tool AnyLogic, was used to model water, wastewater, and stormwater interdependencies while incorporating the human interaction with the infrastructure systems and retooling alternatives. AnyLogic allows for modeling different simulation types, specifically agent based modeling, discrete event simulation, and system dynamics, in a single interface. AnyLogic capabilities used for this analysis include integrating agent based and system dynamics (AB-SD) modeling methods into a hybrid model, to capture the dynamic behavior of these infrastructure systems and human-infrastructure interactions under parameter variations, such as price elasticity, declining populations, levels of support for different alternatives, and decreasing impervious surfaces. The system dynamics portion of the model focused on the stocks and flow of resources (such as, water demand, wastewater produced, runoff generated), under different conditions. The agent based model centered on the public perception of the residents towards retooling alternatives impacting these infrastructure systems. Within the agent based model, each individual agent maintained his/her own level of support or opposition, which in real-time impacts the implementation of the retooling alternatives in the system dynamics model. The model development and data inputs for Flint and Saginaw is discussed in depth in Chapter 8.

4.4.1 Causal Loop Diagrams

After identifying the scope of the analysis, which in this case is the water, wastewater, and stormwater infrastructure systems, and human-infrastructure interactions, primarily at the neighborhood level, a causal loop diagram was developed. The casual loop diagram conceptualized the system(s) modeled into the components relevant and quantifiable for the analysis, as well as depicted the relationship between variables. The signs (+/-) within the influence diagrams indicate whether the beginning node/variable will have a positive or negative impact on the end node/variable. A complete loop within the influence diagram is termed a feedback loop, which is the algebraic product of the sum of the links (Kirkwoord 1998). Positive feedback loops yield reinforced change within a model, where as a negative loop, balances the system, converging the system towards a goal (Kirkwood 1998). The individual causal loop diagrams for Flint and Saginaw are presented in Chapter 8. Separate influence diagrams are necessary as the two cities differ in wastewater system, with Flint operating a separate stormwater system and Saginaw having a combine sewer overflow system.

4.4.2. System Dynamics Modeling

System dynamic models represent the complex system as a series of stocks, flows, and feedback loops. Stocks are the level/accumulations of the variables, and flows are the rates at which the stocks change. Variables and parameters are used to contain the information necessary to change the stocks, flows, and feedback loops (Kirkwood 1998). The user may vary variables and parameters to observe the system under varying circumstances and to assess feedback loops within the system. System dynamics allows users to control the variables within the systems and examine the system under various circumstances. Winz and Brierly (2007) states that a model's *"…usefulness lies in the fact that they allow us to test real world behavior in an artificial setting, thus being easy and inexpensive to perform in repetition."* Forrester (1987) discusses that people can accurately understand the structure of the system, but cannot predict the behavior of complex systems. System dynamics allows for evaluating and viewing the complex interaction and the behavior between the behavior to capture patterns and relationships that may otherwise not be seen. Of interest to system dynamics modeling was these patterns of behavior over time and the relationships between parameters that may not otherwise been seen, not necessarily a singular output.

4.4.3. Agent Based Modeling

Agent based modeling allows for modeling the actions and interactions of autonomous agents, while viewing the agents functioning within their environment. This individual-centric methodology allows the user to define the agents, agents' behavior, connections or transitions between states the agents exist within, and the overarching environment. Resulting from the interactions between agents and the transitions between states, global behavior emerges between the agents, within the environment. The agent based portion of the AB-SD hybrid model focused on the support and opposition of various retooling alternatives. Each agent is assigned a level of support for a retooling alternative evaluated in the AB-SD model, based on the survey data discussed in Chapter 7. Agents have the ability to move between the support and opposition states as well as exit the agent-based model based on the city's historic decline patterns. When the desired number of agents has moved to the support state, the retooling infrastructure alternatives transitions into the infrastructure budget in the system dynamics model.

4.5. Summary

This chapter provides an overview of the methodology used to accomplish the research goals presented in Chapter 1 and the departure point in Chapter 2. Water sector infrastructure systems in Flint and Saginaw, two cities in Michigan, were used to demonstrate the methodology, assess the viability of different retooling alternatives, and evaluate the water, wastewater, stormwater, and human interaction interdependencies. These cities represent two classes of cities, with Flint being a medium shrinking city and Saginaw representing a small shrinking city. Within each city, in Section 4.1, the analysis areas used in Chapters 5, 6, and 8 are identified.

EPANET, the tool used to evaluate the impact of urban decline and retooling alternatives on the individual water infrastructure system, is described this chapter. EPANET was used specifically to evaluate the pressure changes to the system as a result of retooling alternatives, and assess the system's ability to provide adequate fire flows under various retooling alternatives.

Chapter 6 used L-THIA and SWMM to assess how retooling alternatives may reduce generated stormwater runoff in shrinking cities. The curve number approach was the infiltration estimation method used for both tools. The retooling alternatives evaluated were considered under soil conditions native to the area (identified using NRCS (2013)), as well as fully compact, Category D soils, resulting from the areas' land development.

A survey was deployed to 21 US shrinking cities to gain insight into the residential public views concerning water and wastewater infrastructure issues and infrastructure retooling alternatives. Responses were gathered from cities in multiple states to mitigate the potential that responses only reflect specific state, regional, or city policies, as well as allow comparison of the public perceptions attitudes across different cities and states. Binary probit models and binary logit models with random parameters, were used to assess the perceptions and attitudes of the residents towards select water retooling alternatives.

AnyLogic, an object-oriented tool, was used to develop a hybrid agent based-system dynamics model to evaluate water, wastewater, and stormwater interdependencies, and human behavior interaction with the infrastructure systems and retooling alternatives in Chapter 8. The system dynamics component of the model focused on the stocks and flow of resources, while the agent based component centered on the public support towards retooling alternatives. The agent based component of the model interacts in 'real-time' with the system dynamics component of the model throughout the simulation.

CHAPTER 5. ANALYSIS OF WATER INFRASTRUCTURE RETOOLING ALTERNATIVES

"*Although the challenge to our water infrastructure has been less visible than other infrastructure concerns, it's no less important. Our water treatment and delivery systems provide public health protection, fire protection, economic prosperity and the high quality of life we enjoy.*"

-AWWA (2012)

In shrinking cities, the per capita cost for infrastructure increases due to the reduced population maintaining an infrastructure footprint designed for a larger population. Water retooling alternatives may potentially reduce costs and improve a community's public health by decreasing the presence of stagnant water or slowing pipeline deterioration rates that result from reduced flows. However, retooling alternatives present challenges, such as maintaining adequate services and emergency demands. Additionally, criteria such as future land use and network connectivity must be considered to determine if the retooling alternatives is feasible. Chapter 5 evaluates the viability of two categories of retooling alternatives for water infrastructure in shrinking cities: (1) consolidating demand, and (2) decommissioning water pipelines. Retooling alternatives are examined in the context of the water infrastructure in Flint and Saginaw using water network models developed using EPANET. As discussed in Section 4.2, much of the excess capacity lies in the piped network due to the high number of vacancies throughout the city that no longer require water service. Discussions with SMEs indicated that pipelines up to 12 inches in diameter are the underused components of the water infrastructure system that would tend not to alter the pressures of the system upon decommissioning. The impact of decommissioning two categories of water pipelines was evaluated considering:

1) Small diameter pipelines: those less than 12 inches in diameter.
2) Large diameter pipelines: those equal to or greater than 12 inches in diameter.[5]

[5] Paragraph adapted from Faust and Abraham (2014)

5.1. Small Diameter Pipeline Network Analysis

The small diameter pipeline analyses tests the hypothesis that pipelines less than 12 inches in diameter may be removed from the network in vacant areas of the city without significantly altering the water pressures or fire flow capabilities. Additionally, Section 5.1.1 evaluates the impact of consolidating demand to certain sections of the analysis area. Consolidating demand is an applicable alternative if the city wishes to stop services to the area, such as mail delivery, garbage collection, street maintenance, lighting, or water. The network remains in place and fully functional, but homes on vacant blocks are not tied to the water system.

5.1.1. Model Development and Results for Flint's Small Diameter Pipeline Analysis

The pipeline network in a selected section of Flint was used to demonstrate the methodology, test that the hypotheses for the small diameter analysis, and evaluate the impact of consolidating demand. The description of the model and the analyses results are discussed in this section.

5.1.1.1. Pipeline Diameters

As discussed in Section 4.1 a 20-block portion of a primarily residentially zoned area in Flint is used within the EPANET model. The analysis area has a high number of vacancies, with many of the pipelines having diameters of less than 12 inches. The diameters of pipes within the bounded area of interest are shown in Figure 5.1.

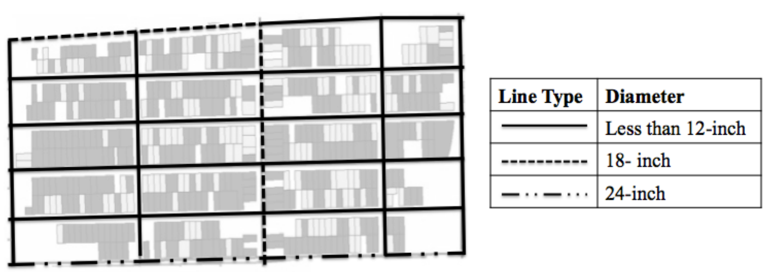

Figure 5.1. Diameter of water infrastructure pipelines within analysis area

5.1.1.2. Assessing Demand

The demand for the analysis area was loaded on the nodes located at the pipeline junctions, represented by black dots in Figure 5.2. The area containing the parcels contributing to the water demand to each node is delineated by dashed lines, with the numerical identifier of the node within each delineated area. For example, 33977 is the node in the uppermost left-hand corner. Houses privately owned were assumed to be occupied and houses owned by the Genesee County

Land Bank were assumed to be vacant. A vacant home contributes no demand to the respective node. Daily demand was approximated for each parcel, by multiplying the average household size by the per capita indoor and outdoor daily water use. The average household size used for Flint is 2.48, as determined by the 2010 US Census (US Census Bureau 2011). AWWA (1999) estimated water use to be, on average, 69.3 gallons per capita per day and 101 gallons per capita per day, for indoor and outdoor water use, respectively.

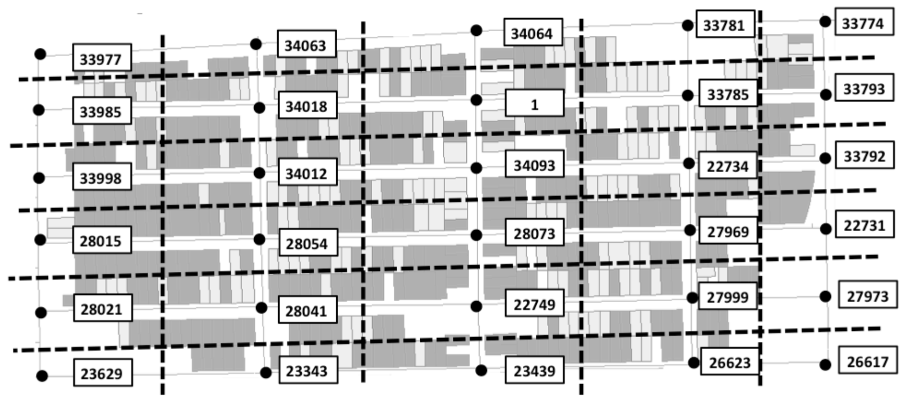

Figure 5.2. Demand nodes and contributing areas

5.1.1.3. Retooling Alternatives

The infrastructure network within the analysis area was examined under different retooling scenarios, discussed in Table 5.1. Specific considerations for each retooling scenario are summarized in Table 5.2. Scenarios (1), 2(a), and 2(b) assume that the total demand in the analysis area remains the same but is reallocated *within the analysis area*. I.e., when a housing swap occurs, a resident moves from a sparsely populated area to a more densely populated area within the analysis area. All scenarios were simulated under normal operations, using the typical daily residential demand, as well as under fire flow/emergency conditions. Simulations were also performed to examine if fire flows and pressures remain adequate under reduced demand within the area, which may represent residents moving away from the neighborhood, continued population decline, or changing water use behavior.

Table 5.1. Retooling scenarios evaluated (Faust and Abraham 2014)

<table>
<tr><th>Description</th><th>Demand</th><th>Rationale</th></tr>
<tr><td>BASE CASE: The status quo bounded distribution network and demand</td><td>Demand is based on per capita averages and the average household size in the city</td><td>This case represents the status quo of the system within the analysis area</td></tr>
<tr><td>SCENARIO 1: The status quo bounded distribution network with consolidated demand</td><td rowspan="3">Demand was consolidated west of the 18-inch diameter pipeline, running north to south in the center of the bounded region

Demand was consolidated to the western portion of the network as the residential area to the east was more sparsely populated

This assumes that housing swaps have occurred within the bounded network of interest in this study, and the total number of residents is static</td><td>Applicable scenario if the city wishes to stop services to the area, such as mail delivery, garbage collection, street maintenance, lighting, or water

The network remains in place and fully functional, but does not have homes on vacant blocks tied to the water system</td></tr>
<tr><td>SCENARIO 2 (a): Decommissioning of all of pipelines (i.e., there is no redundancy loop) in the vacant area, east of the 18-inch diameter pipeline</td><td>By removing all pipelines east of the 18-inch diameter pipeline, including the redundancy loop, there is an increased chance of service disruption as there is no alternative path to provide service</td></tr>
<tr><td>SCENARIO 2 (b): Redundancy loop left in place to provide service to the western portion of the network in the instance of failure

Decommissioning of all pipelines in the vacant area within the redundancy loop, east of the 18-inch diameter pipeline</td><td>Scenario 2(b) has a redundancy loop within the network to address possible pipeline failures, thereby ensuring a more resilient system</td></tr>
</table>

Table 5.2. Incorporation of considerations for each modeled retooling scenario

<table>
<tr><th>Scenario</th><th>Consideration</th><th>Addressing Consideration</th></tr>
<tr><td rowspan="3">SCENARIO 1: The status quo bounded distribution network with consolidated demand</td><td>Maintenance cost</td><td>There will be no change in maintenance costs for this option as the network remains the same and only the demand is relocated</td></tr>
<tr><td>Intended purpose for land in vision</td><td>As of October 2014, Flint does not have a future land use plan for the analysis area</td></tr>
<tr><td>Impact on the water quality (e.g., is water age increased beyond an acceptable range), capacity of the system (i.e., can the system meet the current and projected demands with fewer pipes), and operational integrity (e.g., is adequate pressure within the system maintained with the retooling option) of the existing pipes</td><td>Water Quality: Since the analysis area is limited to the neighborhood level, water age was not considered

During the simulation, there is not the presence of stagnant water in the pipelines due to the granular, neighborhood level of the analysis and the constant water demand throughout the simulation time (the capacity of the water treatment plant and the water age at the water treatment plant is not considered)

Capacity of system and operational integrity: Pressure is used as a metric to determine the impact of the scenario on the system</td></tr>
</table>

Table 5.2. *(continued)*

Scenario	Consideration	Addressing Consideration
SCENARIO 1: The status quo bounded distribution network with consolidated demand	Relocating sparsely populated areas	Assumes that relocation has occurred
	Vacancies and vacancy patterns within potential area	The analysis area was determined based on the number and density of vacant residences as well as historic decline patterns using US census data
	Ability to maintain fire flows	A fire flow analysis examines the ability of the system to maintain adequate, emergency flows under each configuration
	Existing establishments (e.g., churches, businesses, schools)	Neighborhoods which are zoned residential, are the subject of this analysis
SCENARIO 2 (a): Decommissioning of all of pipelines in the non-populated area, east of the secondary feeder Pipelines less than 12 inches in diameter are eligible for decommissioning	Cost	Saginaw is the only shrinking city known to the author to have estimated costs for decommissioning infrastructure and maintenance savings in the US The water utility in Saginaw estimated that decommissioning pipelines with diameters less than 12 inches would save approximately $375 per block in fixed costs per year
	Intended purpose for land in vision	As of June 2014, Flint does not have a future land use plan for the analysis area
	Impact on the water quality (e.g., is water age increased beyond an acceptable range), capacity of the system (i.e., can the system meet the current and projected demands with fewer pipes), and operational integrity (e.g., is adequate pressure within the system maintained with the retooling option) of the existing pipes	Water Quality: Since the analysis area is limited to the neighborhood level, water age was not considered During the simulation, there was no evidence of stagnant water in the pipelines due to the granular, neighborhood level of the analysis and the constant water demand throughout the simulation time (the capacity of the water treatment plant and the water age at the water treatment plant is not considered) Capacity of system and operational integrity: Pressure is used as a metric to determine the impact of the scenario on the system
	Relocating sparsely populated areas	Assumes that relocation has occurred
	Vacancies and vacancy patterns within potential area	The analysis area was determined based on the number and density of vacant residences as well as historic decline patterns using US census data
	Ability to maintain fire flows	A fire flow analysis examines the ability of the system to maintain adequate, emergency flows under each configuration
	Existing establishments (e.g., churches, businesses, schools)	Neighborhoods which are zoned residential, are the subject of this analysis
	Risk of main system failure Length of time it would take to fix a main system failure	This is not considered in the scope of the study Based on discussion with SMEs from Saginaw, Michigan; Akron, Ohio; Gary, Indiana; Lafayette, Indiana; and Indianapolis, Indiana when a failure occurs, service disruptions may be up to eight hours

Table 5.2. *(continued)*

<table>
<tr><th>Scenario</th><th>Consideration</th><th>Addressing Consideration</th></tr>
<tr><td>SCENARIO 2 (a): Decommissioning of all of pipelines in the non-populated area, east of the secondary feeder

Pipelines less than 12 inches in diameter are eligible for decommissioning</td><td>Presence of and location of pipes with diameters less than 12 inches that are eligible for decommissioning</td><td>Residential areas with pipelines smaller than12-inch diameter pipelines were considered for this analysis</td></tr>
<tr><td rowspan="8">SCENARIO 2 (b): Redundancy loop pipelines left in place to provide service to the western portion of the network in the instance of failure

Decommissioning of all of pipeline in the non-populated area within the redundancy loop, east of the secondary feeder

Select pipelines less than 12-inch in diameter are eligible for decommissioning</td><td>Cost</td><td>Saginaw is the only shrinking city known to the author to have estimated costs for decommissioning infrastructure and maintenance savings in the US

The water utility in Saginaw estimated that decommissioning pipelines with diameters less than 12 inches would save approximately $375 per block in fixed costs per year</td></tr>
<tr><td>Intended purpose for land in vision</td><td>As of June 2014, Flint does not have a future land use plan for the analysis area</td></tr>
<tr><td>Impact on the water quality (e.g., water age), capacity of the system (i.e., can the system meet the current and projected demands with fewer pipes), and operational integrity (e.g., is adequate pressure within the system maintained with the retooling option) of the existing pipes</td><td>Water Quality: Since the analysis area is limited to the neighborhood level, water age was not considered

During the simulation, there was no evidence of stagnant water in the pipelines due to the granular, neighborhood level of the analysis and the constant water demand throughout the simulation time (the capacity of the water treatment plant and the water age at the water treatment plant is not considered)

Capacity of system and operational integrity: Pressures at the nodes of the pipeline network is used as a metric to determine the impact of the scenario on the system</td></tr>
<tr><td>Relocating sparsely populated areas</td><td>Assumes that relocation has occurred</td></tr>
<tr><td>Vacancies and vacancy patterns within potential area</td><td>The analysis area was determined based on the number and density of vacant residences as well as historic decline patterns using US census data</td></tr>
<tr><td>Ability to maintain fire flows</td><td>A fire flow analysis examines the ability of the system to maintain adequate, emergency flows</td></tr>
<tr><td>Existing establishments (e.g., businesses, schools)</td><td>Neighborhoods which are zoned residential, are the subject of this analysis</td></tr>
<tr><td>Presence of and location of pipes with diameters less than 12 inches that are eligible for decommissioning</td><td>Residential areas with pipelines smaller than12-inch diameter pipelines were considered for this analysis</td></tr>
</table>

Figures 5.3-5.4 show the different decommissioning configurations of this network. Acceptable operating ranges for pressure throughout the water system vary from 20 psi to above 80 psi (e.g., LVVWD 2012; City of Brentwood Public Works 2012; City of College Station 2012). Hickey (2008) stated that the minimal working pressure in the distribution system should be no less than 35 psi, which was confirmed by two SMEs from Indiana, each with over 10 years of experience in water system modeling.

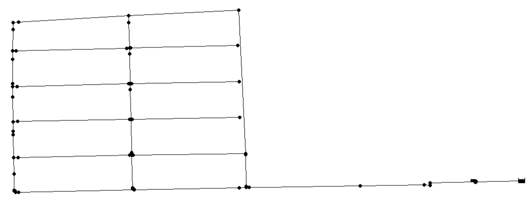

Figure 5.3. Scenario 2(a): Decommissioning of small diameter pipelines east of the secondary feeder, demand consolidated west of secondary feeder

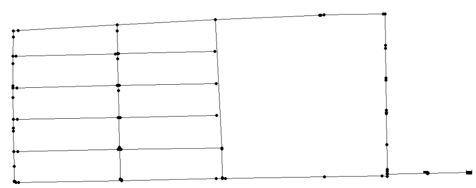

Figure 5.4. Scenario 2(b): Decommissioning of small diameter pipelines east of the secondary feeder, demand consolidated west of secondary feeder with redundancy loop in place

5.1.1.4. Metric 1: Pressures at Nodes

One metric to examine the operational capability of the system under various configurations used in this study is the pressure at each node in the network. The number of nodes for any scenario varies from 57 to 95; however, the base demand is loaded on the 24 intersecting nodes illustrated in Figure 5.2. The remaining 33 to 71 nodes (dependent on the retooling scenario being modeled) connect pipelines in a linear fashion, run along each block, or connect the reservoir to the piped network. These remaining nodes have a base demand of 0 gallons per minute (gpm) as they are not located at pipeline intersections.

The scenarios are simulated for a seven-day period in EPANET. However, the graphs illustrate 24-hours, since the demand patterns (i.e., the Single Family Demand Pattern and the Low-Income Single Family Demand Pattern described in Section 4.1.2.) developed by Aquacraft, Inc. (2011)

are for a 24-hour/1-day cycle, and the demand is based on a daily per capita average over the calendar year. Thus, during each 24-hour period, the pressure patterns at each node repeat. Depicting 24-hour periods along the graph also allows for viewing the pressure changes throughout each day at a higher level of detail.

Different daily total demands are modeled for each scenario, which are referred to as "*demand alternatives*," to provide insight about the impact of further urban decline on the system at a neighborhood level, under each retooling scenario. The difference in daily demand may not only represent population decline, but may be interpreted as decline due to behavioral changes, such as reduced usage due to increased water rates, and technological advances, such as the use of water conserving toilets or showers. The demand alternatives analyzed are as follows:

- The base demand, which is the total daily demand for the analysis region for the current number of occupied residences.
- The total expected daily demand after 10 years of urban decline. The population decline (14.6%) in the analysis was determined from historical US census data with the assumption that the per capita daily water demand established by AWWA (1999) remained constant over the 10-year period and that the decrease in demand within the analysis region was due to urban decline.
- The total expected daily demand after 20 years of urban decline. The population decline (29.2%) in the analysis area was determined from historical US census data with the assumption that the per capita daily water demand established by AWWA (1999) remained constant over the 20-year period and that the decrease in demand within the analysis region was due to urban decline.

The trends of the pressures at the nodes vary between the Single Family Demand Pattern and the Low-Income Single Family Demand Pattern for each demand alternative, but do not vary significantly between retooling scenarios. The pressure drops illustrated in Figures 5.5 and 5.6, as expected, mimic the peak demand hours of each demand pattern. For instance, the Low-Income Single Family Demand Pattern has two peak demand periods each day, one in the morning and one in the evening, reflected in Figure 5.6 as drops in the pressures. These drops in the node pressure become less pronounced as the demand declines for the different demand alternatives. The pressures decreases in correlation with the nodes located further northwest, away from the pump and in the direction of increasing elevation. Many of the nodes within the same region of the network have very similar pressures and thus, the nodes appear to essentially overlap in the graphs, leaving indistinguishable pressure trend lines.

For the retooling alternatives examined, regardless of demand pattern or demand alternative, all nodes fell within the acceptable range of 20-80 psi. Furthermore, the pressures of all nodes, for each scenario were greater than the ideal minimum pressure of 35 psi. These results indicate that each alternative is able to provide service at an acceptable level for normal operating conditions. Table 5.3 is a summary of all of the retooling scenarios, demand patterns, and demand alternatives evaluated, totaling 24 models. To highlight the results from the models, two graphs illustrating the node pressures from the *Status Quo Network with Consolidated Demand* models are shown in Figures 5.5 and 5.6. The remaining node pressure graphs may be found in Appendix C. Section 5.1.1.5 evaluates the ability of each scenario, demand pattern, and demand alternative to operate under emergency fire flow conditions.

Table 5.3. Summary of all modeled scenarios for Flint

Retooling Scenario	**Demand Pattern**	**Demand Alternative**
Base Case: Status Quo Network	Single Family	Baseline demand
		10 year population decline in demand
		20 year population decline in demand
	Low-Income Single Family	Baseline demand
		10 year population decline in demand
		20 year population decline in demand
Scenario 1: Status Quo Network with Consolidated Demand	Single Family	Baseline demand
		10 year population decline in demand
		20 year population decline in demand
	Low-Income Single Family	Baseline demand
		10 year population decline in demand
		20 year population decline in demand
Scenario 2(a): Decommissioning Scenario with Redundancy Loop	Single Family	Baseline demand
		10 year population decline in demand
		20 year population decline in demand
	Low-Income Single Family	Baseline demand
		10 year population decline in demand
		20 year population decline in demand
Scenario 2(b): Decommissioning Scenario with No Redundancy Loop	Single Family	Baseline demand
		10 year population decline in demand
		20 year population decline in demand
	Low-Income Single Family	Baseline demand
		10 year population decline in demand
		20 year population decline in demand

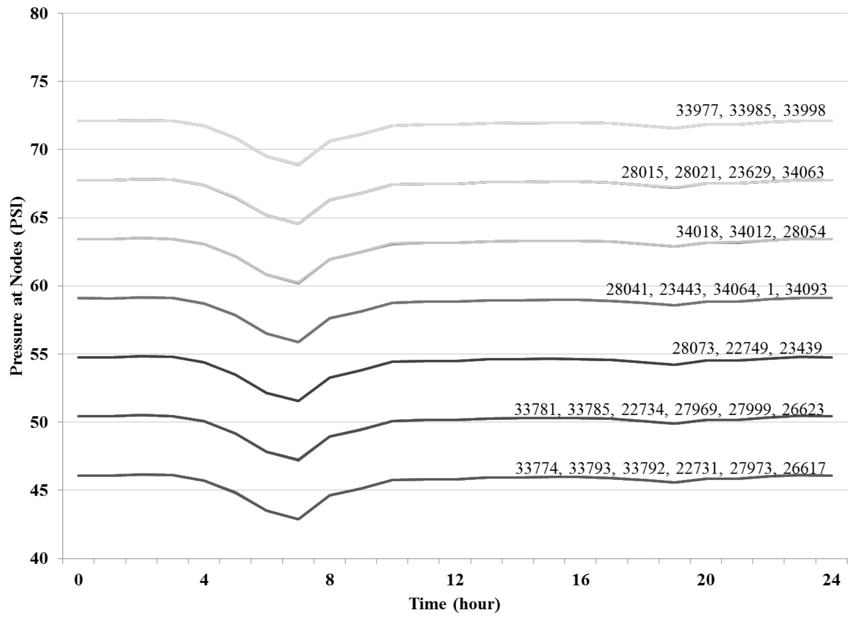

Figure 5.5. Node pressures (psi) for Scenario 1: Single Family Demand Pattern, base demand alternative over 24 hours *(each graph is labeled with the nodes corresponding with Figure 5.2)*

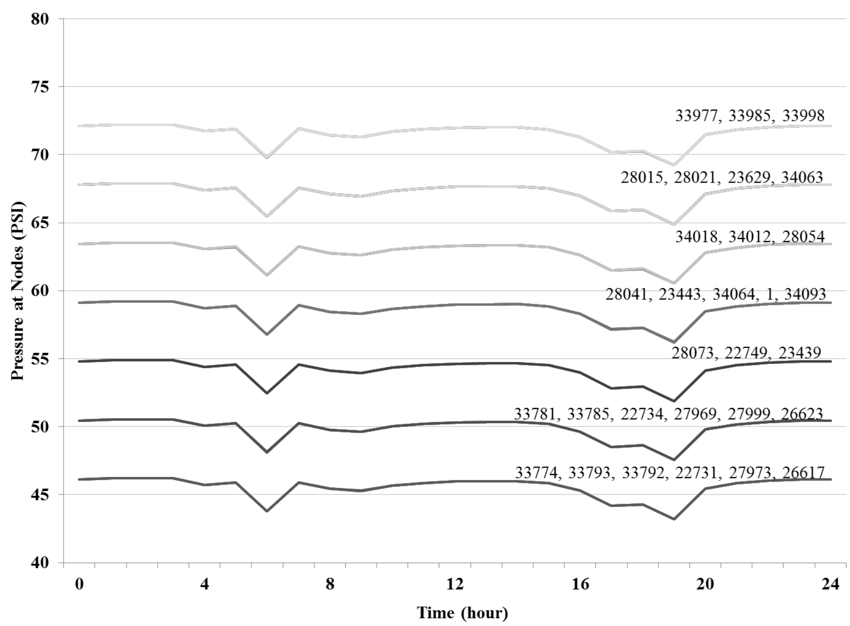

Figure 5.6. Node pressures (psi) for Scenario 1: Low-Income Single Family Demand Pattern, base demand alternative over 24 hours *(each graph is labeled with the nodes corresponding with Figure 5.2)*

5.1.1.4. Metric 2: Fire Flow Capability

There are up to 95 nodes in each of the scenarios, although only the 24 nodes identified in Figure 5.2 are illustrated in the figures due to space constraints. The nodes not explicitly identified exceed the minimum, required flows (i.e., 250 gpm for two hours); and fall within the fire flow ranges depicted in each figure. All the nodes for each scenario, demand pattern, and demand alternative have the ability to provide between 610-690 gpm flow for two hours, exceeding the minimum threshold for fire hydrants to be recognized by a city (i.e., 250 gpm for two hours). When determining the maximum flow available at each node for an instantaneous moment of time (as opposed to the available flow for two consecutive hours), each node has the ability to provide between 10 and 20 gpm more flow. The flow available at the individual nodes differs up to 60 gpm for the various retooling scenarios evaluated.

As the total demand declined between the base demand alternative through the 20-year decline in demand alternative within the analysis area, the system has the ability to provide greater fire flows, as expected. Nodes 34093 and 1 consistently provided the lowest fire flows, ranging between 610-630 gpm. The lower flows at nodes 34093 and 1 are due to dead ends created at these nodes in Scenario 2(a) and 2(b). In the figure of the infrastructure network (such as, Figure 5.1), nodes 34093 and 1 falsely appear to connect to the secondary feeder that runs north-south, when in fact the nodes solely connect the pipeline, running east-west that does not connect to the north-south secondary feeder in a grid fashion. One method to ensure circulation of water, avoid sedimentation and maintain higher pressures at these nodes would be to connect the east-west pipeline to the secondary feeder at these nodes.

The fire flow analyses demonstrate that retooling the infrastructure at a neighborhood level allows for adequate fire flows in emergency situations. Consolidating demand by moving residents to more densely populated locations and leaving the infrastructure functional also allows for adequate fire flows at this neighborhood level. To highlight the results obtained from the models, two graphs illustrating the fire flows for all retooling scenarios from the Single Family Demand Pattern with the base demand alternative are shown in Figures 5.7 and 5.8. The remaining graphs may be found in Appendix C.

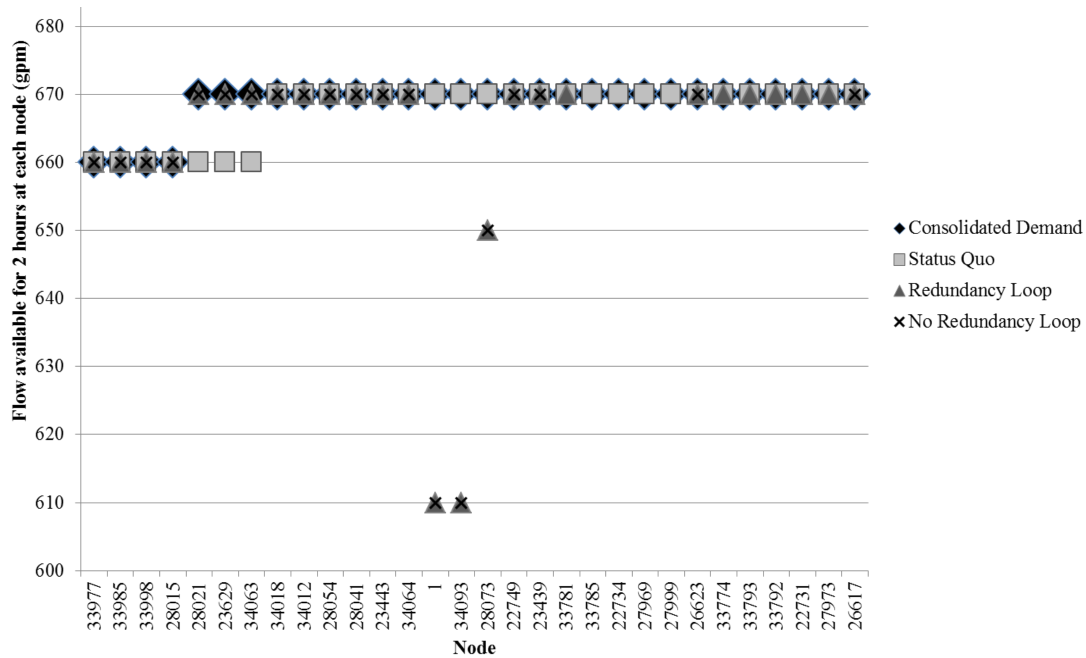

Figure 5.7. Maximum flow available at each node for a two-hour duration while maintaining all nodes at 20 psi minimum: Single Family Demand Pattern, base demand alternative

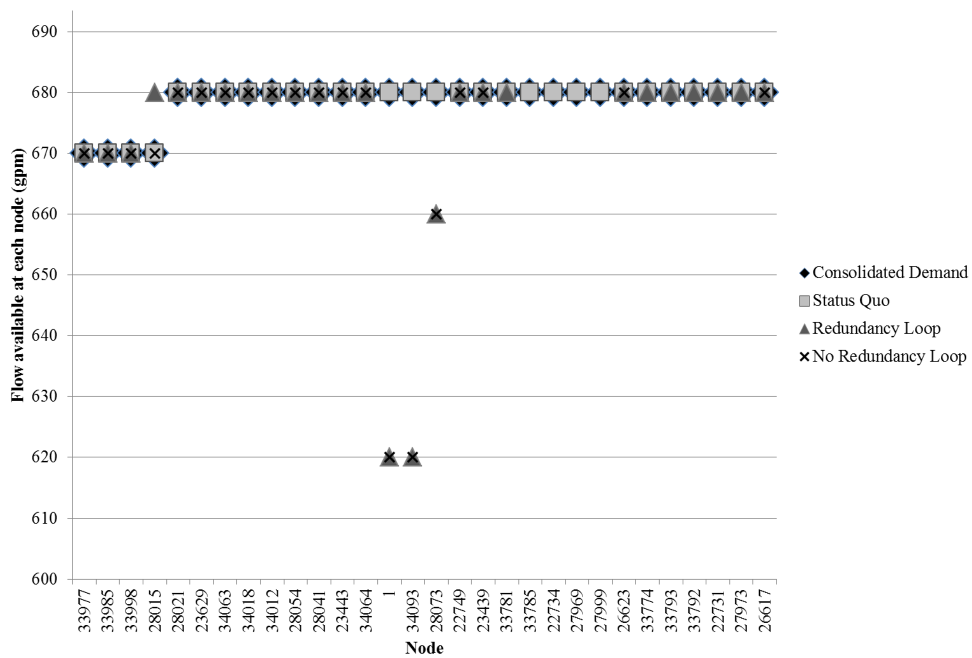

Figure 5.8. Maximum flow available at each node for an instantaneous moment of time while maintaining a 20 psi minimum: Single Family Demand Pattern, base demand alternative

5.1.2. Model Development and Results for Saginaw's Small Diameter Pipeline Analysis

The pipeline network in a selected section of Saginaw was used to demonstrate the methodology, and test that the hypotheses for the small diameter analysis. A brief description of the model (as its development is similar to that of Flint) and the analyses results are discussed in this section.

5.1.2.1. Pipeline Diameters and Assessing Demand

Similar to the analysis area for Flint, the analysis area in Saginaw has a high number of vacancies, with many of the pipelines having diameters of less than 12 inches. The demand for the analysis area was loaded on the nodes located at the pipeline junctions. A GIS layer provided by Saginaw indicated which homes were vacant. A vacant home contributes no demand. Analogous to Flint, daily demand was approximated for each occupied parcel by multiplying the average household size by the per capita indoor and outdoor daily water use. The average household size used for Saginaw was 2.59, based on the 2010 US census (US Census Bureau 2011). AWWA (1999) estimated that the water use would be, on average, 69.3 gallons per capita per day and 101 gallons per capita per day, for indoor and outdoor water use, respectively.

5.1.2.2. Retooling Alternatives

The infrastructure network within the analysis area was examined under different retooling scenarios, discussed in Table 5.4, and Figure 5.9. Specific considerations for each retooling scenario are summarized in Table 5.5. Scenarios 1(a), 1(b), and 2 have been tested under normal operations, using the typical daily residential demand, as well as under fire flow conditions. Each retooling scenario represents residents moving away from the neighborhood in the area where pipelines are decommissioned. As discussed in Chapter 4, the analysis area has a future land use plan of transitioning to green reserve opportunity areas, implying that the future land use plan for Saginaw will not include residences in these areas, altering the considered retooling options from that of Flint. Demand will not be consolidated or rearranged within the analysis area in Saginaw, as was done in Flint. Additionally, reduced demand over time (i.e., different demand alternatives) will not be considered as the Green Zone is transitioning away from residential zoning and long-term residential alternatives are not within Saginaw's future land use plan. The water demand will be removed and not reallocated within the analysis area, representing that the families leave the Green Zone entirely.

Table 5.4. Retooling scenarios evaluated (Faust and Abraham 2014)

Description	Demand	Rationale
BASE CASE: The status quo network and demand	Demand is based on per capita averages and the average household size in Saginaw A GIS layer provided by Saginaw was used to identify the vacant and occupied residences	This case represents the status quo of the system within the analysis area
SCENARIO 1 (a): The eastern side of the network is decommissioned		By removing small diameter pipelines, maintenance costs will be reduced
SCENARIO 1 (b): The center and eastern side of the network are decommissioned		
SCENARIO 2: All pipelines less than 12 inches in diameter are eligible for decommissioning		

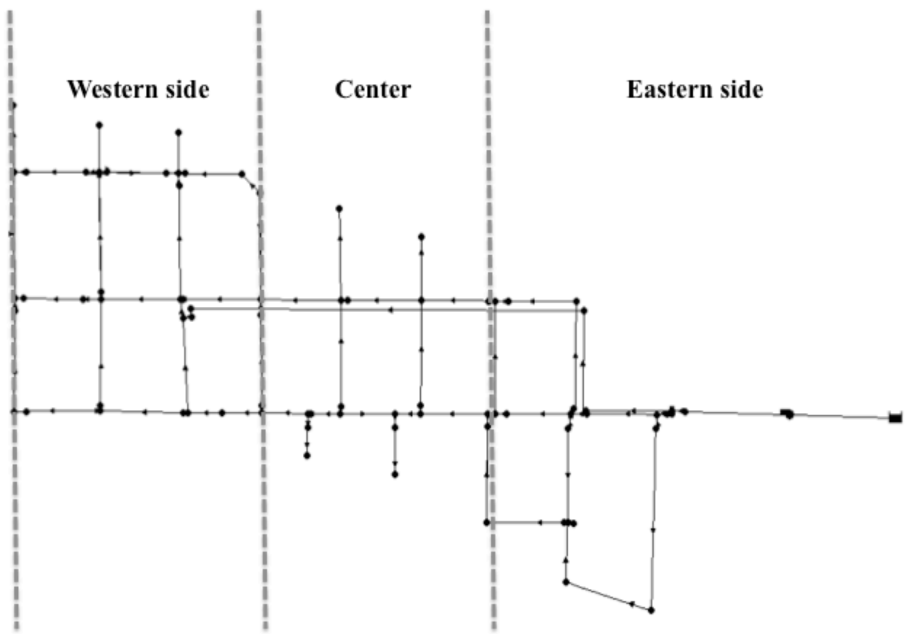

Figure 5.9. Decommissioning scenarios (Faust and Abraham 2014)

Table 5.5. Incorporation of considerations for each modeled retooling scenario

Scenario	Consideration	Addressing Consideration
SCENARIO 1(a), 1(b), and (2): Decommissioning of all of sections pipelines that are less than 12 inches in diameter are eligible for decommissioning.	Cost	The water utility in Saginaw estimated that decommissioning pipelines with diameters less than 12 inches would save approximately $375 per block in fixed costs per year
	Intended purpose for land in vision	The analysis area has been selected for green opportunities, thus, zoning will no longer be residential, and the remaining residents will transition out of the area
	Impact on the water quality (e.g., is water age increased beyond an acceptable range), capacity of the system (i.e., can the system meet the current and projected demands with fewer pipes), and operational integrity (e.g., is adequate pressure within the system maintained with the retooling option) of the existing pipes	Water Quality: Since the analysis area is limited to the neighborhood level, water age was not considered During the simulation, there is not the presence of stagnant water in the pipelines due to the granular, neighborhood level of the analysis and the constant water demand throughout the simulation time (the capacity of the water treatment plant and the water age at the water treatment plant are not considered) Capacity of system and operational integrity: Pressure is used as a metric to determine the impact of the scenario on the system
	Relocating sparsely populated areas	Assumes that relocation has occurred
	Vacancies and vacancy patterns within potential area	The analysis area was identified by Saginaw as a candidate area for retooling, due to the high number of vacancies
	Ability to maintain fire flows	A fire flow analysis examines the ability of the system to maintain adequate, emergency flows under each configuration
	Existing establishments (e.g., churches, businesses, schools)	Neighborhoods which are zoned for residential use, are the subject of this analysis
	Risk of main system failure	This is not considered in the scope of the study
	Length of time it would take to fix a main system failure	Based on discussion with SMEs from Saginaw, Michigan; Akron, Ohio; Gary, Indiana; Lafayette, Indiana; and Indianapolis, Indiana, when a failure occurs, service disruptions may be up to eight hours
	Presence of and location of pipes with diameters less than 12 inches that are eligible for decommissioning	Residential areas with pipelines smaller than12-inch diameter pipelines were considered for this analysis

Figures 5.10-5.12 show the different decommissioning configurations of this network. Similar to Flint, acceptable operating ranges for pressure throughout the water system varied from 20 psi to

above 80 psi (e.g., LVVWD 2012; City of Brentwood Public Works 2012; City of College Station 2012).

Figure 5.10 shows the base case (i.e., the status quo network). For each retooling scenario, it was assumed that approximately one-third of the residential area was decomissioned at a time. The decommissioned regions were removed in logical full blocks to represent decommisioning neighborhoods over time, as opposed to decommissioning all neighborhoods at once.

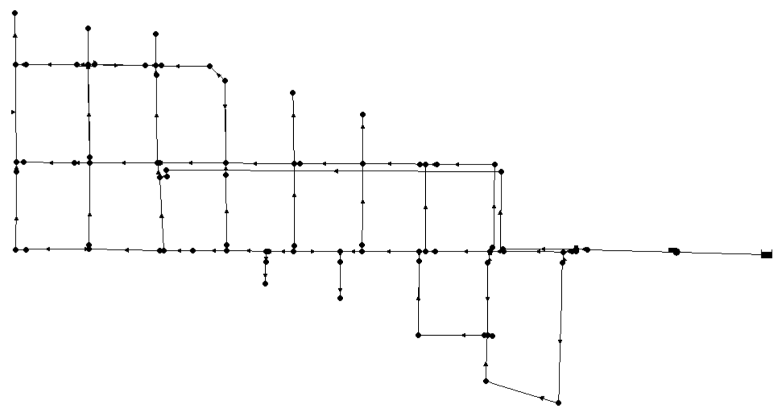

Figure 5.10. Status quo network

Figure 5.11 depicts Scenario 1(a), which is the infrastructure network with the eastern side decommissioned. This scenario assumes this land has been vacated of all residences and pipelines are no longer necessary for the green reserve area.

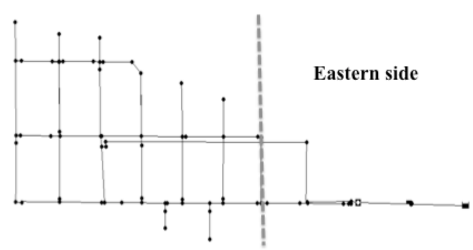

Figure 5.11. Scenario 1(a): Eastern side decommissioned

Figure 5.12 shows Scenario 1(b), which is the network with the center and eastern side decommissioned.

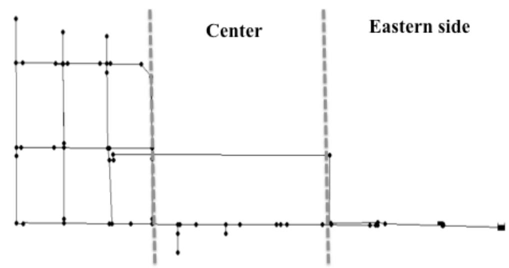

Figure 5.12. Scenario 1(b): Center and Eastern side decommissioned

In Scenario 2 (Figure 5.13), all small diameter pipelines within the analysis area are decommissioned. This scenario assumes that the land has been vacated of all residences and the pipelines are no longer necessary for the green reserve area. Water demand was placed on the westernmost node of the secondary feeders (located in the Western side), to ensure that water flow is capable of being transported to areas of the network outside of the analysis area.

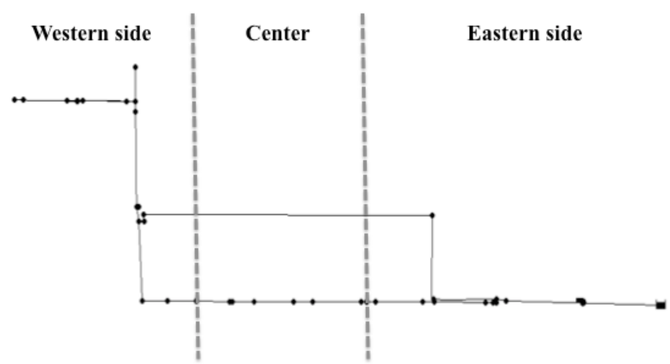

Figure 5.13. Scenario 2: All small diameter pipelines decommissioned

5.1.2.3. Metric 1: Pressures at Nodes

Similar to analysis performed for the small diameter pipeline analysis in Flint, Saginaw's analysis area was examined using pressure as one metric to evaluate the operational capability of the system under various decommissioning configurations. The nodes' pressures vary between the Single Family Demand Pattern and the Low-Income Single Family Demand Pattern, but they do not vary significantly between the decommissioning scenarios. The pressures decreases in correlation with the nodes located further northwest, away from the pump and in the direction of increasing elevation. Many of the nodes within the same region of the network have very similar pressures and thus, the nodes appear to essentially overlap in the graphs, leaving indistinguishable pressure trend lines.

For all modeled scenarios (summarized in Table 5.6), the nodes' pressures fell within the acceptable range of 20-80 psi, and were greater than the ideal minimum pressure of 35 psi, providing service at an acceptable level for normal operating conditions. Figures 5.14 and 5.15 illustrate node pressures in the network with Scenario 1(a) incorporating the Single Family Demand Pattern and the Low-Income Single Family Demand Pattern, respectively. The pressures for all nodes are within 57-60 psi throughout the 24-hour day. The remaining graphs for Metric 1 may be found in Appendix D.

Table 5.6. Summary of all modeled scenarios for Saginaw

Retooling alternative	**Demand Pattern**
Base Case: Status Quo Network	Single Family
	Low-Income Single Family
Scenario 1 (a): The western side decommissioned	Single Family
	Low-Income Single Family
Scenario 1 (b): Center and eastern side decommissioned	Single Family
	Low-Income Single Family
Scenario 2: All pipelines less than 12 inches in diameter are eligible for decommissioning	Single Family
	Low-Income Single Family

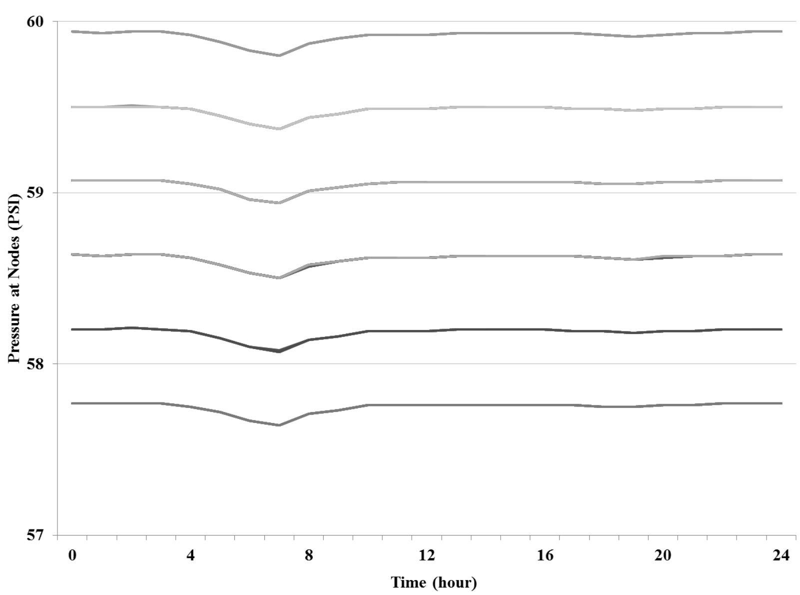

Figure 5.14. Scenario 1(a): Single Family Demand Pattern pressures (psi) over 24 hours

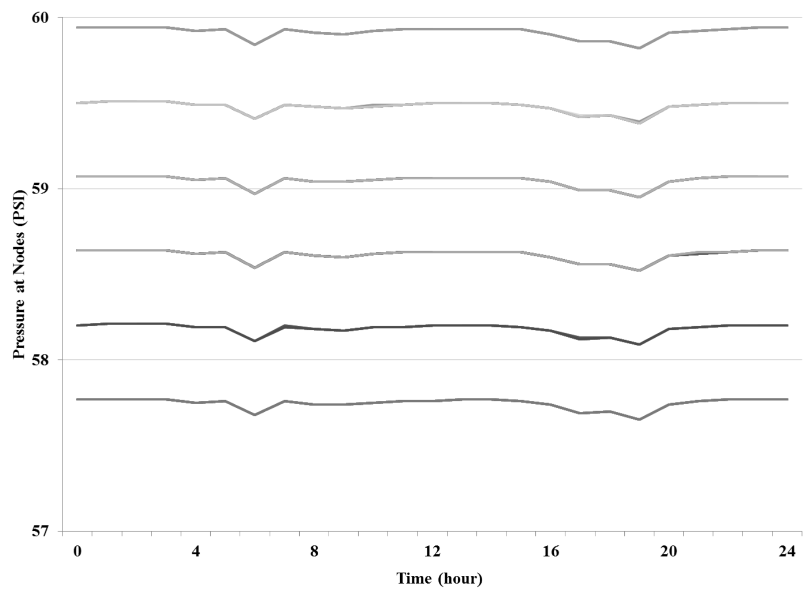

Figure 5.15. Scenario 1(a): Low-Income Single Family Demand Pattern pressures (psi) over 24 hours

5.1.2.4. Metric 2: Fire Flow Capability

The fire flow analysis shows that all the nodes, for each decommissioning scenario and demand pattern, have the ability to provide between 840-960 gpm flows for two hours, exceeding the minimum threshold for fire hydrants to be recognized by a city. When determining the maximum flow available at each node for an instantaneous moment of time, each node has the ability of providing an additional 10-20 gpm. The fire flow analysis demonstrates that retooling the infrastructure at a neighborhood level allows for adequate fire flows in emergency situations. Figures 5.16 and 5.17 illustrate the fire flows for the Single Family Demand Pattern. The remaining graphs may be found in Appendix D.

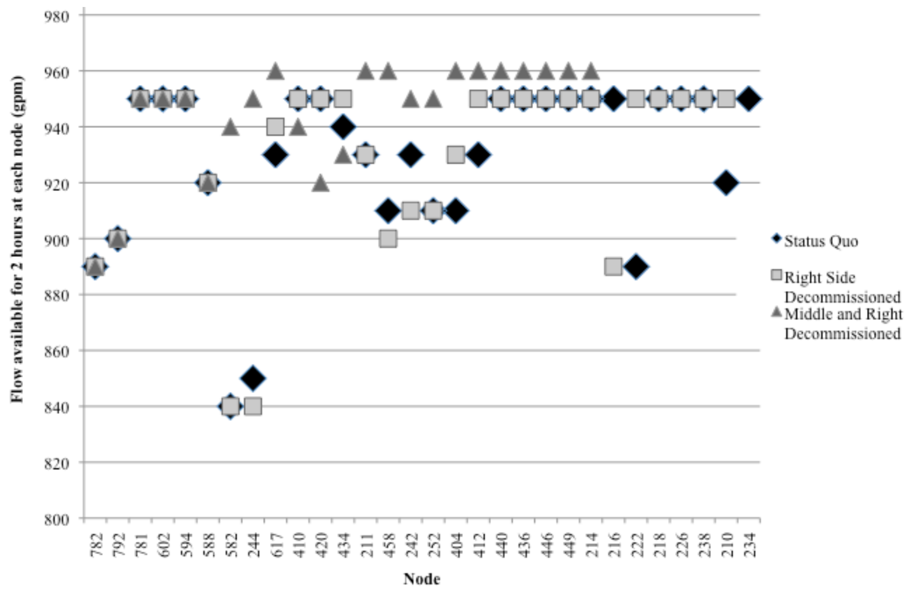

Figure 5.16. Maximum flow available at each intersecting node for two-hour duration while maintaining all nodes at a 20 psi minimum: Single Family Demand Pattern

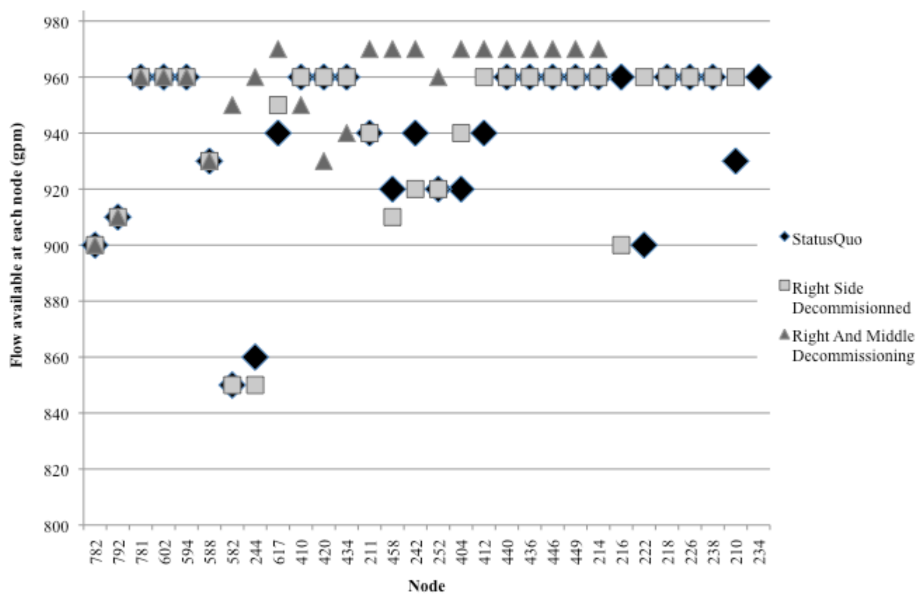

Figure 5.17. Maximum flow available at each intersecting node while maintaining all nodes at a 20 psi minimum: Single Family Demand Pattern

5.2. Large Pipeline Diameter Network Analysis

As discussed in Section 4.1.2, the distribution and secondary lines, up to 12-inch diameter, were the most likely underused components of the water infrastructure system and were thus considered for decommissioning. Furthermore, SMEs confirmed that pipelines with diameters of less than 12 inches are those pipelines that are likely to be eligible candidates for decommissioning as these pipelines are underused and, theoretically, should not significantly alter the flows, pressures, connectivity, or fire flow capabilities of the water infrastructure network serving customers throughout the city. Section 5.1 tested the hypothesis that pipelines less than 12 inches in diameter may be decommissioned without significantly altering the pressures or fire flow capabilities. This section extends the analysis to include the hypothesis that large diameter pipelines may not be decommissioned without impacting service, and uses the same metrics: (1) system pressures and (2) fire flow capability.

5.2.1. Analysis Area

The water network in Flint was used to evaluate the impact of decommissioning large diamter pipelines. Flint was appropriate for this portion of the analysis because the location of Tract 20 (i.e., the original analysis area) is in the center of the city where large diamater pipelines travel through to provide connectivity throughout the city. The original analysis area within Tract 20 (described in Section 4.2) that was used in the small diameter pipeline network analysis was extended to include the surroudning tracts, as illustrated in Figure 5.18, to include a sufficient number of large diameter pipelines. The tract to the east of Tract 20, Tract 21, was not included in this analysis since this tract is primarily composed of industrial areas, most of which are vacant due to the decline in the automotive industry in the area.

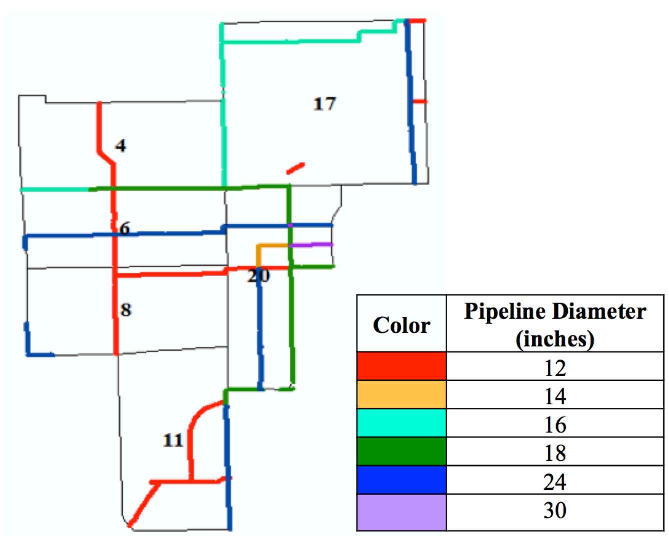

Figure 5.18. Large diameter pipelines in the analysis area

5.2.2. Demand for Analysis Area

Similar to the small diameter pipeline network analysis, the demand was determined at each of the nodes located at the pipeline junctions, represented by black dots in Figure 5.19. The area contributing demand to each node is delineated by hashed lines with the node's numerical identifier. Residential demand was considered in the analysis due to the primarily residential zoning within the analysis area. Privately owned houses were assumed occupied and houses owned by the Genesee County Land Bank were assumed to be vacant, contributing no demand to its respective node. Daily demand was approximated for each parcel by multiplying the average household size by the per capita indoor and outdoor daily water use. The average household size used for Flint was 2.48, as determined by the 2010 US Census (US Census Bureau 2011). AWWA (1999) estimated the water use to be, on average, 69.3 gallons per capita per day and 101 gallons per capita per day, for indoor and outdoor water use, respectively.

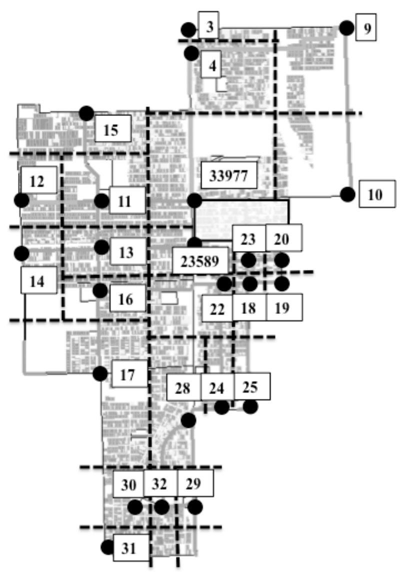

Figure 5.19. Demand nodes and contributing areas

5.2.3. Retooling Alternatives

Figure 5.20 depicts the status quo model developed in EPANET and the retooling scenarios evaluated. Table 5.7 discusses each retooling scenario and the rationale for the scenario. All scenarios were tested under normal operations, as well as under fire flow/emergency conditions.

Table 5.7. Decommissioning scenarios evaluated (Faust and Abraham 2014)

Description	Rationale
BASE CASE: The status quo bounded distribution network and demand	This case represents the status quo of the network within the analysis area, and is used as a basis for comparison for all other scenarios
SCENARIO 1: Decommission 18-inch pipelines running north-south	Scenarios 1 and 2 examine the impact of removing large diameter (12 inches or greater in diameter) pipelines from the analysis and surrounding areas
SCENARIO 2: Decommission 18-inch pipelines running north-south, and northern 18-inch pipeline running west-east	
SCENARIO 3: Decommission 18-inch pipelines running north-south and select 6-inch pipelines	Scenarios 3 and 4 build upon Scenarios 1 and 2 to evaluate whether decommissioning additional small diameter (less than 12 inches in diameter) pipelines further alters the pressures or fire flow capabilities within the analysis area
SCENARIO 4: Decommission 18-inch pipelines running north-south, northern 18-inch pipeline running west-east, and select 6-inch pipelines	

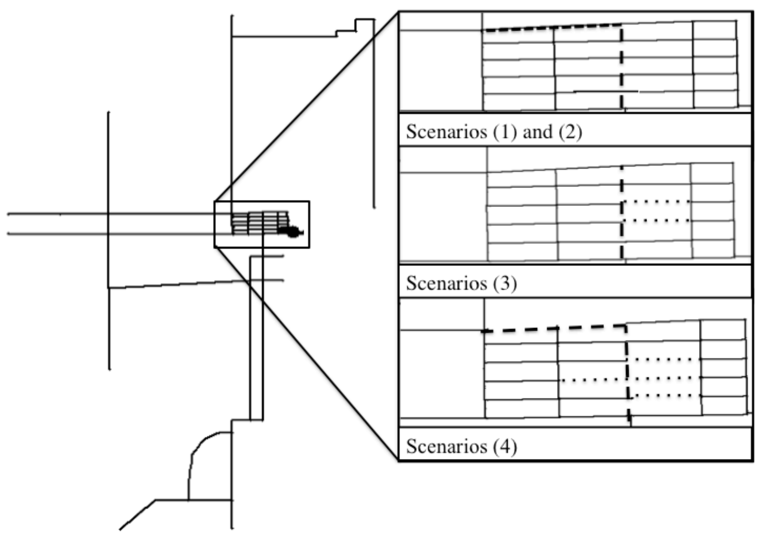

Figure 5.20. Retooling scenarios considered (Scenario numbers correspond to Table 5.7) (Faust and Abraham 2014)

5.2.4. Metric 1: Pressures at Nodes and Metric 2: Fire Flow Capability

Analogous to the small diameter pipeline network analysis, the decommissioning scenarios in Table 5.7 and were simulated for seven days in EPANET, and the figures depicting pressure throughout the system illustrate a 24-hour period (Figures 5.21-5.30). Removing pipelines greater than or equal to 12 inches in diameter from the network altered the system's pressure significantly such that the pressures of select nodes within the analysis area fell below the acceptable operating range of 20-80 psi. This result indicates that the large diameter pipelines are integral for providing connectivity and sufficient pressure throughout the network. Removing the small diameter pipelines in conjunction with the large diameter pipelines caused negligible change in the water pressure within the analysis area, beyond the pressure changes caused by removing the large pipelines. I.e., the removal of the small diameter pipelines in Scenarios 3 and 4 did not *further* lower the pressures significantly within the network from the pressure changes cause by Scenarios 1 and 2. Conversely, when only the small diameter pipelines were removed and the large diameter pipelines were left in place, the network was able to provide sufficient pressures to all nodes, which supports the previous findings that small diameter pipelines may be decommissioned in vacant areas of the city or areas with changing land uses.

The nodes most impacted by the removal of large pipelines are those with connectivity to the large pipelines in the northern portion of the network. The 18-inch diameter pipelines were integral, in this configuration, to supply water for the demand at these nodes at an acceptable pressure. Their removal reduced the water pressure during typical peak demand periods, hindering the ability to provide emergency fire flows. Thus, connectivity of the network's large diameter pipelines to populated or high demand areas of the city, outside of the vacant regions, is an important factor to be considered in decommissioning decisions.

When the scenarios were modeled using the Single Family Demand Pattern, the nodes within the analysis area north of the decommissioned 18-inch diameter pipelines experienced pressures below the acceptable pressure range during peak periods. However, when the same scenarios were modeled using the Low-Income Single Family Demand Pattern, the pressures at these nodes approached the lower bound of the acceptable pressure range, but they did not fall out of the acceptable pressure range. This result is linked to the two smaller demand peak periods in a 24-hour time frame, as opposed to one larger peak period at hour "7" for the Single Family Demand Pattern.

The different patterns in daily use exhibited by varying socioeconomic statuses may change the ability to provide emergency fire flows to the city. Fire flow needs were not met during peak hours for the Single Family Demand Pattern when the large diameter pipelines were decommissioned. When modeling the scenarios using the Low-Income Single Family Demand Pattern, fire flow needs were met for Scenarios (1) and (3), but were NOT met for Scenarios (2) and (4). Scenarios (1) and (3) removed only one large diameter pipeline, as opposed to Scenarios

(2) and (4), which removed multiple large diameter pipelines. This result indicates that the two small peak demands throughout the day associated with the Low-Income Single Family Demand Pattern, allows for decommissioning select large diameter pipelines. Furthermore, it illustrates that considering the socioeconomic status of an area is important for determining the eligibility of decommissioning scenarios.

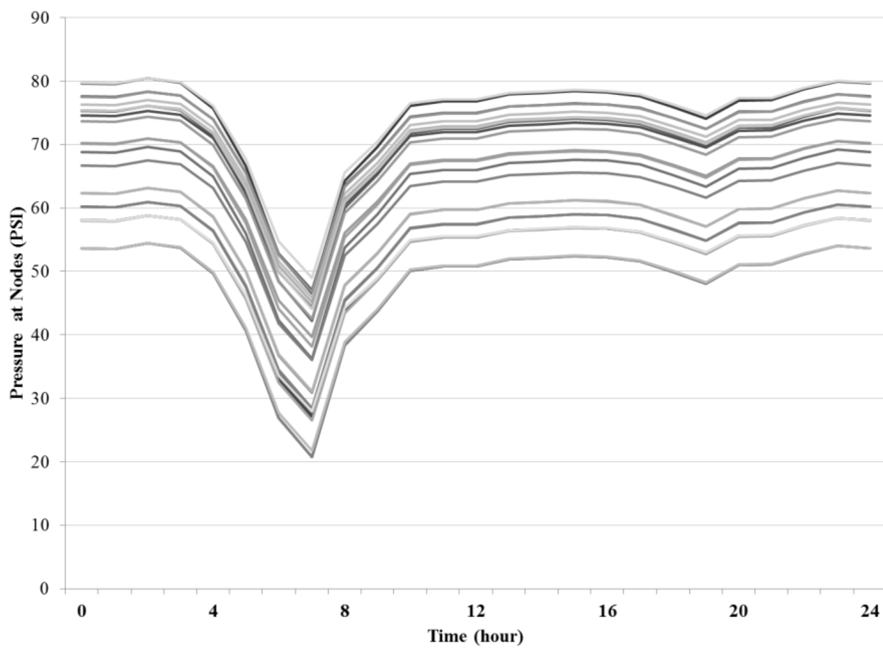

Figure 5.21. Status quo network: Single Family Demand Pattern

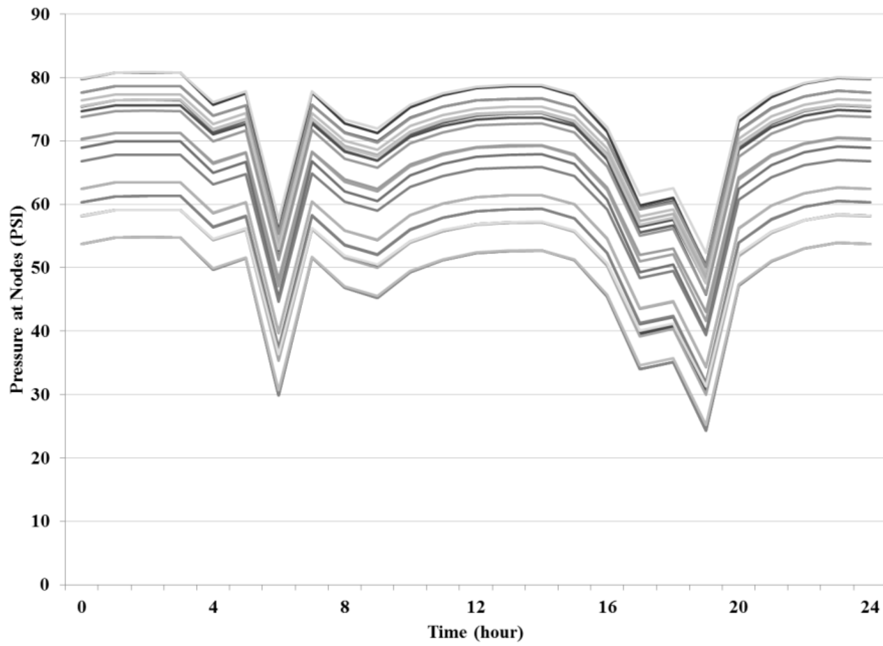

Figure 5.22. Status quo network: Low-Income Single Family Demand Pattern

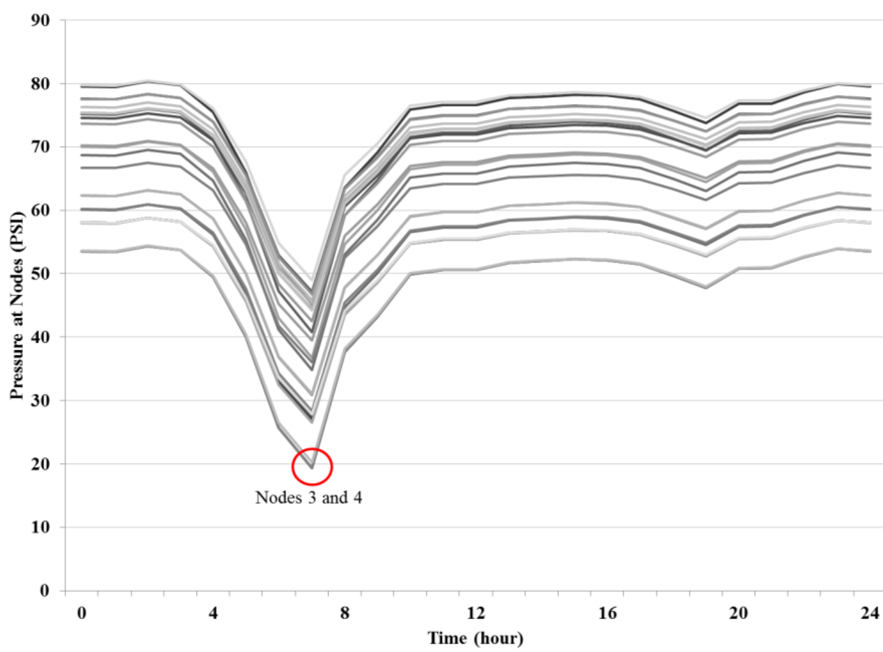

Figure 5.23. Scenario (1): Single Family Demand Pattern

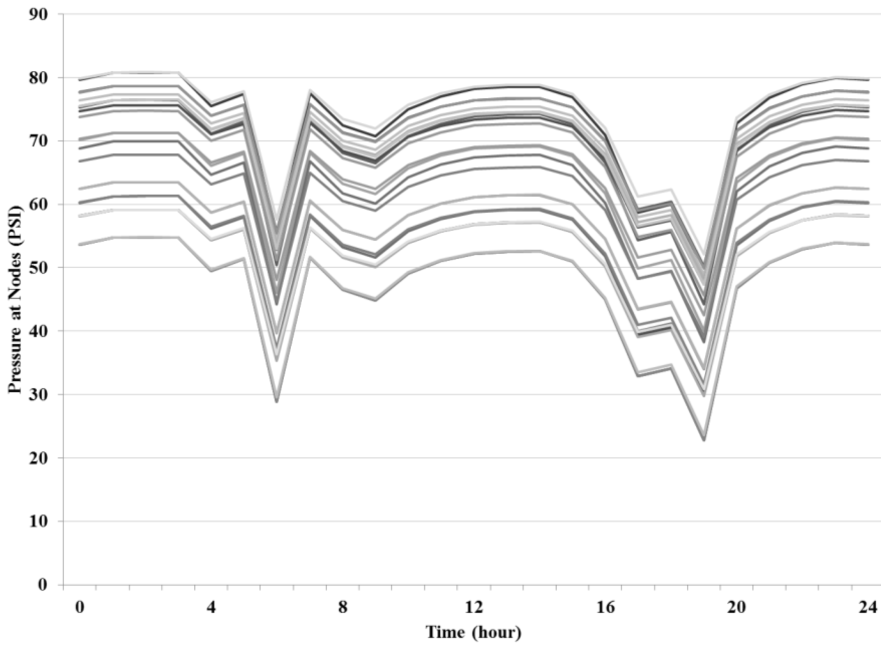

Figure 5.24. Scenario (1): Low-Income Single Family Demand Pattern

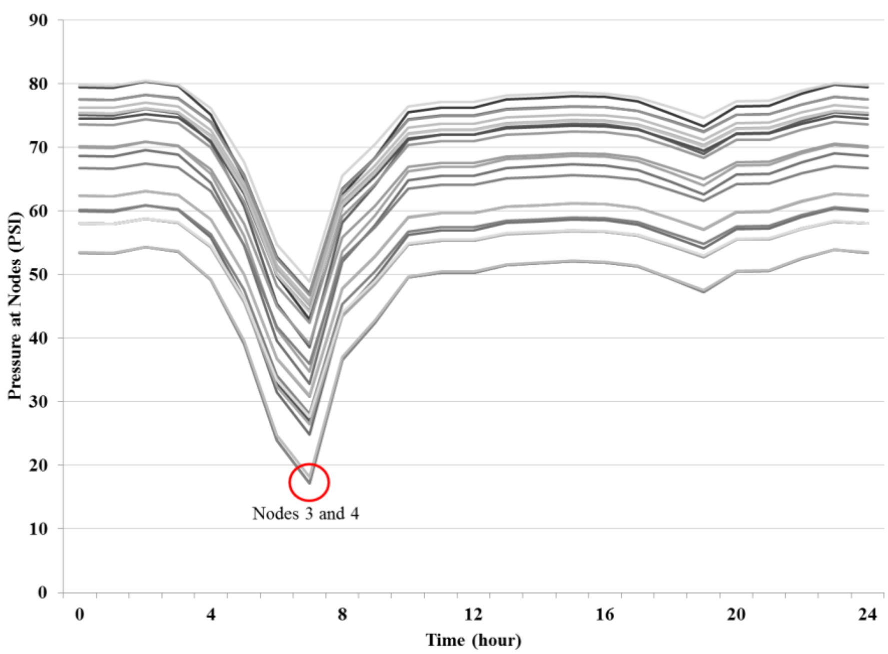

Figure 5.25. Scenario (2): Single Family Demand Pattern

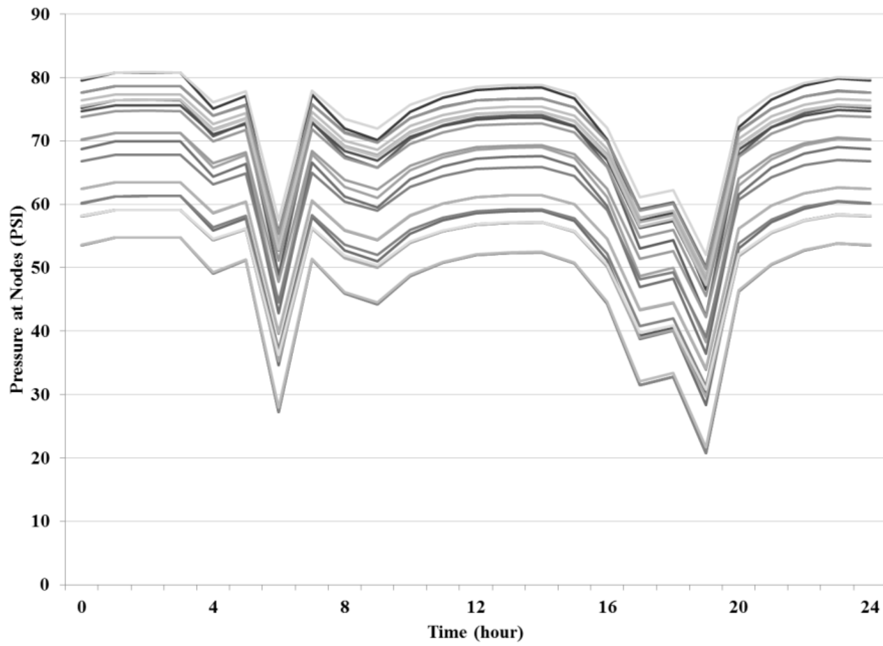

Figure 5.26. Scenario (2): Low-Income Single Family Demand Pattern

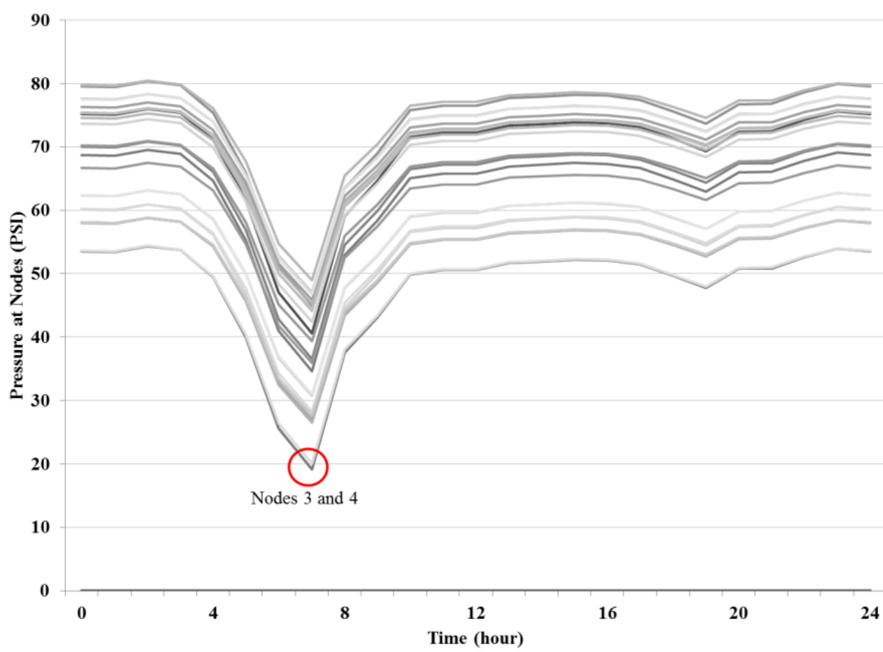

Figure 5.27. Scenario (3): Single Family Demand Pattern

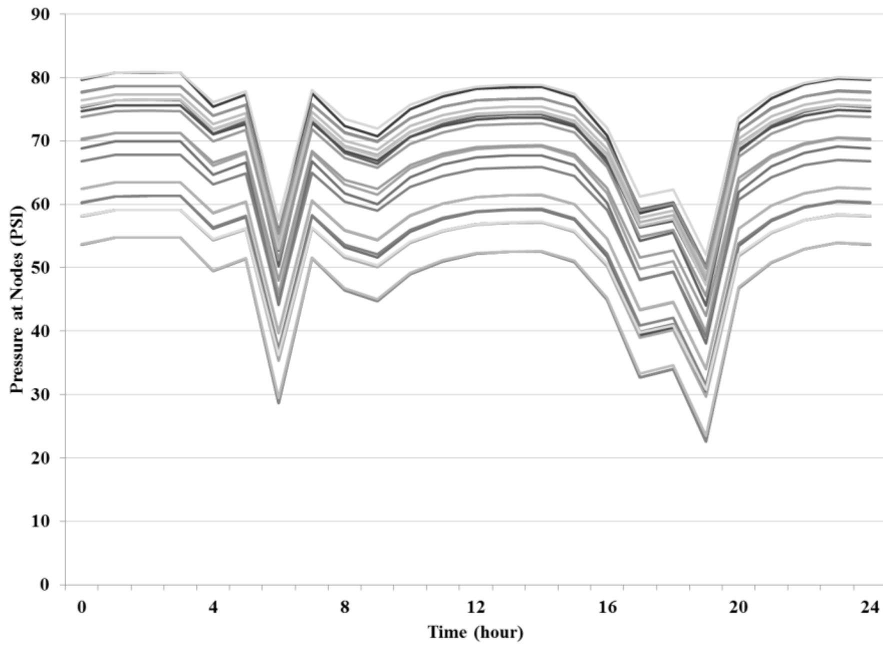

Figure 5.28. Scenario (3): Low-Income Single Family Demand Pattern

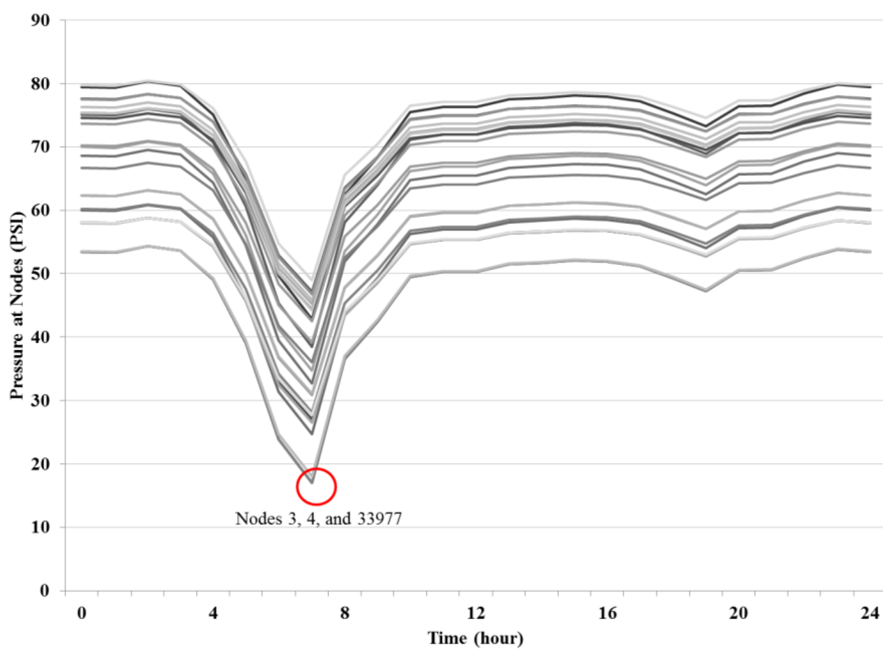

Figure 5.29. Scenario (4): Single Family Demand Pattern

Pressure at nodes 3, 4, and 33977 drops below 20 psi to 17 psi, 17 psi, and 18 psi, respectively, during peak demand times. A third node, 33977, drops below 20 psi due to the location. In this particular configuration, connectivity to node 33977 is critical for providing water to the northern and western areas of the network. The removal of small diameter pipelines altered the available paths for water to reach this node, decreasing the pressure below the 20 psi threshold, with the pressure decreasing further as water travels past this node (node 32977) to nodes 3 and 4.

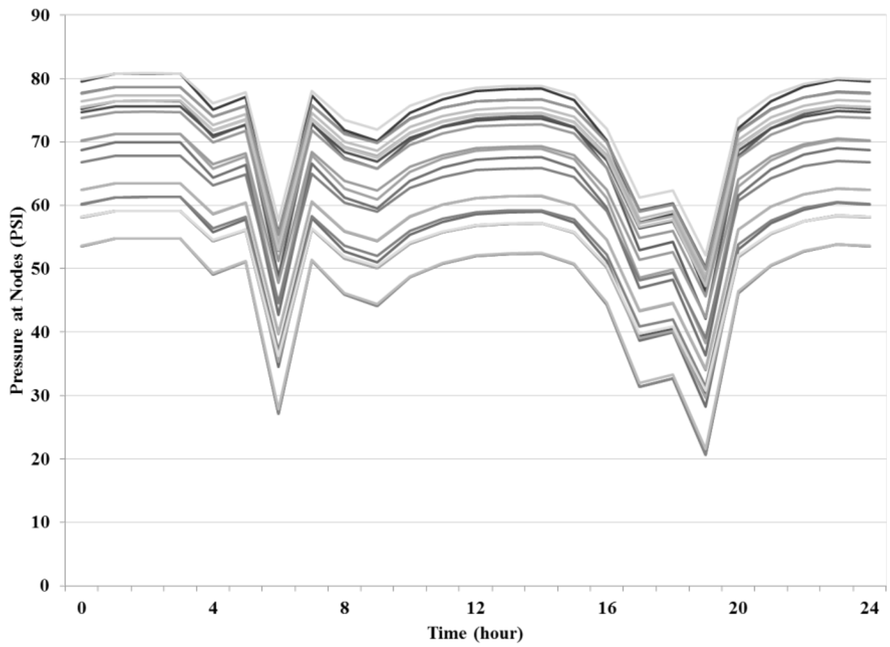

Figure 5.30. Scenario (4): Low-Income Single Family Demand Pattern

5.3. Validation and Verification

This model was validated and verified using four primary steps (Sargent 2004) outlined in Table 5.8. The model, the assumptions made, the data used as input, and the initial outputs were validated as technically correct and reasonable by five SMEs from Indiana and Michigan, each with over 10 years of water system modeling or management experience during the model development. Post development and results 4 SMEs (1 of which was involved in the development process) were asked to provide quantitative feedback on difference aspects of the stormwater infrastructure analysis in the October 2014, of which the average of the quantitative values for different model components are shown in Table 5.9. The SMEs providing quantified scores to validate this model have had a minimum of 15 years experience working with the city water or wastewater utilities from the operations or management side.

Table 5.8. Validation and verification steps

Validation and Verification Components	Justification
Data Validity (Sargent 2004) Data is correct, reliable, and able to sufficiently represent system or population	Data used is provided by the cities, and published literature from reliable sources (e.g., AWWA 1999, US Topographic Maps)
Conceptual Model Validation (Sargent 2004) The theories, assumptions, and representations of the problem are accurate	During the model development, the model, assumptions, data, and initial outputs were validated as technically correct by 5 SMES from Indiana and Michigan. The final model was validated for assumptions and representation by 4 SMEs from Flint and Saginaw (1 SME was involved in the model development process).
Computerized Model (Sargent 2004) The computer model accurately represents the conceptual model	The results obtained by applying the model were consistent across the two case studies 4 SMEs from Flint and Saginaw reviewed the final models and indicated that they accurately represent the water infrastructure system.
Operational Validity (Sargent 2004) The behavior of the model accurately represents the system	The behavior of the model is deemed reasonable by 4 SMEs from Flint and Saginaw in terms of pressures at the pipeline nodes throughout the water infrastructure system, demands, and fire flow capabilities.
Operational Validity (Sargent 2004)**:** **Degenerate Tests** Behavior of model responds appropriately to changes in parameters	Different retooling alternatives (decommissioning pipelines and consolidating demand) were evaluated. The changes in pressures and fire flow capabilities in these alternatives were expected when compared to the results of the status quo/base alternative.
Operational Validity (Sargent 2004)**:** **Extreme Condition Tests** The model behaves appropriately when the extreme ends of parameter ranges are used	As population decline occurs throughout the analysis area, the model responded appropriately by decreasing the pressures throughout the system at the peak demand times.
Operational Validity (Sargent 2004)**:** **Internal Validation** Multiple run replications occur to ensure consistency	Multiple runs using different demands occurred prior to the retooling alternative analysis to ensure model stability.

Table 5.9. Quantitative feedback from SMEs for validation and verification purposes

Aspect of the Stormwater Model	Averages*
The components of the model represent the most critical aspects of the system needed for modeling the goal.	**4.5**
The behavior of the model is reasonable.	**5**
The theories and assumptions underlying the model are correct.	**4.75**
The model's representation of the system is reasonable.	**4.75**
The assumptions regarding the model's parameters and variables are reasonable.	**4.75**
The level of detail used for the model is appropriate for the intended purpose of providing information regarding the impact of decommissioning water pipelines on the system performance.	**4.75**
The output of the model has the accuracy required for the model's intended purpose.	**4.5**
The model could be helpful for water management and produces useful results.	**5**

(1: poor, 2: needs significant improvements, 3: needs modifications to be useful, 4: good enough, 5: excellent)

5.4. Summary

Chapter 5 evaluates the impact of two retooling alternatives, decommissioning pipelines and consolidating demand, using EPANET to examine how altering the topology of and changing demands within the infrastructure network impacts the water infrastructure's performance. The infrastructure's performance is evaluated using the following metrics: (1) the ability to provide operational pressures throughout the system during typical daily demands, and (2) the ability to provide adequate fire flows during emergency demands. Decommissioning two categories of water pipelines was evaluated: small diameter pipelines (less than 12 inches in diameter) and large diameter pipelines (greater or equal to 12 inches in diameter). The model development and assumptions were verified by five SMEs, each with more than 10 years of experience in hydraulic modeling or management. The most current data (as of May 2013) provided by the cities were used in this study, and the results of the status quo/base case models (e.g., fire flows, typical operating pressures) were confirmed as reasonable values for what is observed within the water distribution networks in Flint and Saginaw.

This study demonstrates that consolidating demands and decommissioning small diameter pipelines are viable retooling scenarios in cities experiencing urban decline. Pipelines less than 12 inches in diameter that were removed from the network did not hinder the ability of the system to provide adequate pressures during typical daily demands or to address emergency fire flow demands. Decommissioning large diameter pipelines is a case-dependent alternative. The viability of decommissioning large diameter pipelines, based on the metrics used in this study, depends on the location/connectivity of the particular pipeline, as well as the socioeconomic status of the area. Decommissioning scenarios using the Single Family Demand Pattern were not able to provide adequate pressures for typical daily use or fire flows. However, when using the Low-Income Single Family Demand Pattern, certain decommissioning alternatives provided adequate services and may be feasible alternatives for consideration. Other considerations to determine the feasibility of reconfiguring each infrastructure system by decommissioning includes, but is not limited to, examining the necessary changes to the pumps and valves, as well as the possibility of surge or hammer effect, sedimentation, or stagnant water occurring at possible dead ends resulting from the decommissioning scenarios.[6]

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[6] Paragraph adapted from Faust and Abraham (2014)

Decommissioning scenarios that result in dead-end pipelines, such as Scenario 2(a) in the Flint case study may result in surge or hammer effect at nodes 34093 and 1, as these nodes are not tied to the secondary feeder running north-south. Tying these nodes to the secondary feeder may mitigate this possibility, as well as make the remaining system more resilient, providing alternate paths to reach nodes 34093 and 1 in the instance of failure. However, as the depth of the nodes with reference to the secondary feeder is not known, the possibility of tying pipelines to the secondary feeder may not be viable. Other issues that may occur at these dead ends may include sedimentation and stagnant water from reduced flows reaches the end of the pipeline with no circulation. Although, surge and hammer effects were not seen during simulations, if a drastic change in demand occurs at a dead-end or if the network configuration is changed temporarily due to repairs or maintenance, surge or hammer effect is a possibility that may be exasperated due to decommissioning.

Extensive reconfiguration of the city water networks may require making changes to the pumps or valves to regulate flows and pressures. If technical upgrades are required for these components or if the components are nearing the end of their lifecycle, changing pumps or valves may be an additional cost already required by the city. However, if these infrastructure components are not near the end of their lifecycle, the costs required for altering other system components should be incorporated in the cost feasibility consideration of the alternative. No changes were necessary to the pumps or pump curves incorporated in EPANET between the base case or retooling scenarios considered in this chapter to maintain adequate pressure for normal operations or emergency flows for the small pipeline diameter network analysis. As demonstrated in the decommissioning large diameter pipeline analysis for the Single Family Demand Pattern, changes to the pumps and valves may be necessary to provide adequate pressures, dependent on the socioeconomic status of the area.

Decreased demand may reduce the flow through the pipeline network, causing the pipelines to degrade faster. This deterioration, as well as low flow rates, may reduce the quality of the water reaching the residents, which could have impacts on the health of the residents due to stagnant water or water reacting to the deteriorating walls of the pipelines. Although stagnant water was not observed during the simulations, local conditions could cause such risks. The water use trends incorporated into EPANET are based on average behavior associated with socioeconomic status (as discussed in Chapter 4). In the instance that daily use trends differ significantly, or demands unique to a particular neighborhood are reduced drastically from factors such as higher than anticipated decline rates or behavior changes from drastic increases in costs, there is a possibility for the occurrence of stagnant water.

Decommissioning infrastructure may potentially improve the water quality for both drinking water and surface water. By decommissioning decaying infrastructure, the city is reducing the footprint of aging pipes that are internally corroded, failing, leaking, and sometimes vandalized by thieves to recover and resell the metal. Additionally, as discussed in Chapter 3, lower demands in cities with systems intended to operate at higher demands may increase the water age, especially if the water treatment plant is drastically oversized for the current population, causing chemical (e.g., disinfection by-product formation), biological (e.g., nitrification, microbial regrowth), and physical issues in the system (e.g., sediment deposition, color). SMEs from 2 shrinking cities conjectured that the removal of excess infrastructure may reduce the risk of stagnant water and improve the age of the water in the system, thereby, further improving the water quality beyond solely reducing the number of corroding and deteriorating pipelines.[7]

Previous studies have discussed resizing the footprints of cities facing urban decline by transforming the area to other land uses with minimal attention towards the repercussions of underutilization of the underground infrastructure systems and methods to resize the underground infrastructure systems. The performance of individual infrastructure systems operating at or above design capacity is well understood; however, the impacts of underutilization and how to manage underutilization is not addressed in practice or in literature. Using network analysis, this study provides a framework for evaluating the impact of applying retooling alternatives by evaluating the capability of the water network to provide adequate pressures and fire flows to the remaining residents. By retooling decaying infrastructure, the city is able to reduce the built infrastructure footprint of aging pipes that are internally corroded, failing, leaking, and sometimes vandalized by thieves to recover and resell the metal. Additionally, retooling alternatives have the potential to stabilize or reduce per capita costs by reducing the fixed costs associated with the water infrastructure system, such as maintenance costs.

Different daily use patterns of infrastructure services by individuals of varying socioeconomic statuses changes the viability of retooling alternatives. The coupling of human interaction with

[7] Paragraph adapted from Faust and Abraham (2014)

water infrastructure performance is demonstrated by the inability of the system to provide adequate water pressures and fire flows when retooling alternatives, such as decommissioning large diameter pipelines are applied. Furthermore, this human-infrastructure coupling impacts which management alternatives may be implemented to retool the infrastructure system for a smaller population. Having knowledge of the intended future needs of the area can assist decision makers in ensuring that retooling alternatives do not impede the performance of the system for the current *or* projected population.

CHAPTER 6. ANALYSIS OF STORMWATER INFRASTRUCTURE RETOOLING ALTERNATIVES

"The association between watercourse degradation and landscape alteration in general, and urban development in particular, seems inexorable. The scientific and regulatory challenge of the last three decades has been to decouple this relationship..."

-National Research Council (2009)

In shrinking cities, the number of abandoned and vacant properties increases as the population declines. These impervious surfaces and compacted soils from urbanization impact the hydrology of developed areas, generating runoff during precipitation. The runoff picks up non-point source (NPS) pollutants while traveling across impervious surfaces, and impacts the performance of the stormwater/wastewater system by contributing to the number of and volume of overflows as the system reaches and exceeds its capacity. Cities experiencing drastic urban decline have the potential to shift land uses, selectively transition excess land from impervious to pervious surfaces, or implement low impact development (LID) practices that treat stormwater onsite, to reduce the quantity of runoff and pollutants entering the stormwater/wastewater system. This chapter analyzes the impact of three categories of stormwater retooling alternatives:

1) **Decommissioning impervious surfaces.** This retooling alternative decommissions vacant or abandoned impervious surfaces to allow onsite infiltration.
2) **Transitioning land uses.** Post removal of impervious surfaces, the city may wish to transition the land use for community or aesthetic purposes, such as a wooded or grass area for the residents.
3) **Incorporating bioretention cells at the neighborhood level**, with runoff from the candidate area diverted to the bioretention cells. Bioretention cells, the LID practice evaluated in this chapter, may be installed onsite to avoid removal of impervious surfaces by redirecting the water to the bioretention cell using methods such as, the natural topography or creating channels, to allow the water to infiltrate onsite.

6.1. Model Development

The model inputs and the retooling alternatives are described in this section. L-THIA and SWMM are used for comparison of estimated changes in runoff for the analysis areas in Flint and Saginaw to evaluate the impact of various retooling alternatives on the stormwater/wastewater system.

6.1.1. Retooling Alternatives in Flint

The input for retooling alternatives for the Flint study are shown in Table 6.1. L-THIA utilizes a graphical user interface (GUI) with little flexibility for customization of characteristics specific to an area. Figure 6.1 shows the SWMM model used for simulating retooling alternatives impacting stormwater runoff generation in analysis area chosen for the Flint case study (as discussed in Section 4.1). The separate stormwater system is illustrated as arcs and nodes between the subcatchments. Each subcatchment has an area of one city-block.

Table 6.1. Data inputs for Flint

	Data	**Source**
Location	Genesee, Flint, MI	N/A
Analysis area size	0.14 square miles (defined in Section 4.1)	GoogleEarthPro
Soil type	Urban land-Crosier-Williamstown complex, 0.0974 square miles | Hydraulic group B Crosier loam, 0.0476 square miles | Hydraulic group C	USDA: NCRS 2013 and GIS layers to identify location of candidate area with reference to the soil surveys
Current land use	Dense residential, approximately 1/8 acre parcels	City provided GIS layers
Status quo impervious area	65% Impervious	USDA 1986
Future land use	Unknown as of October 2014	N/A
Precipitation data	L-THIA: 30 years of county-averaged data SWMM: Local weather station	National Climate Data Center (NCDC)
Synthetic storm depths	2-year, 24-hour storm: 2.32 inches 10-year 24-hour storm: 3.29 inches	NOAA 2014
Curve numbers and LID designs	L-THIA: Pre-defined curve numbers associated with each LID alternative and land use SWMM: Land use curve numbers (USDA 1986), LID designs (SEMCOG 2008)	L-THIA: Pre-defined, based on literature SWMM: USDA 1986; SEMCOG 2008
Infrastructure	Separate stormwater system	City provided GIS layers
Slope	Varies by subcatchment	US Topographic Maps

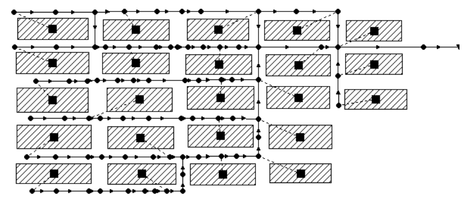


Figure 6.1. SWMM model for analysis area in in Flint

Lot- level investments, such as rain gardens or rain barrels, are not included in this analysis as the investment into vacant or abandoned properties is improbable in fiscally strained, shrinking cities. Additionally, when the models were simulated with lot-level LID alternatives in SWMM for the sparsely located, occupied residences within the analysis area, the reductions in runoff were negligible. Since fiscally strained cities are already having difficulty maintaining existing infrastructure, porous pavements were not considered in the analysis as this options required additional financial investment necessary for repaving. In areas of the city experiencing severe decline, the likelihood of investing in a massive re-pavement effort is low, and more likely in new developed areas. Tables 6.2 and 6.3 summarize the retooling options for Flint discussed in this study and the considerations for each retooling scenario.

Table 6.2. Flint's retooling alternatives analyzed in study

Alternatives	**Rationale**
Status quo (65% impervious, high density residential area)	Represents the status quo of the analysis area (base model)
Reduction in impervious surfaces (simulations ranged from 60% impervious to 5% impervious in 5% increments)	Applicable if the city wishes to decommission impervious surfaces (e.g., driveways, foundations, sidewalks, roads) Decommissioned surfaces assumed to transition to grass in "good" condition
Transitioning land uses ((1) grass and pasture, (2) brush, (3) woods, (4) meadow)	Applicable if the city wishes to rezone the area for other land uses post decommissioning surfaces
Bioretention cells[1, 2, 3]	Assumes 65% impervious area Applicable if the city wishes to reduce stormwater runoff throughout the neighborhood without investing in the removal of impervious surfaces

[1]Size is 15% of the impervious area (Atchison et al. 2006, SEMCOG 2008). [2]L-THIA does not allow user to route a percentage of the runoff. In SWMM, the percentages of the generated runoff routed are 50%, 75%, and 100%. [3]L-THIA does not allow user to change the storage depth or density of vegetation. In SWMM, user defined storage depths of the bioretention cell are 12-inch and 6-inch, as suggested in SEMCOG (2008), evaluated with both minimal (0%) and dense (50%) vegetation.

Table 6.3. Incorporation of considerations for each modeled retooling scenario in Flint

Scenario	Consideration	Addressing Consideration
Reduction in impervious surfaces	Cost and benefits	Costs include decommissioning surfaces, removal of pavement from site, and erosion seeding Benefits include reduction of runoff and NPS pollutants, possible aesthetic improvement to the area
	Intended purpose for land in vision	As of October 2014 Flint did not have a future land use plan for the analysis area
	Soil type in area	Incorporates area specific soil types and land use curve numbers corresponding to specific soil types
	Impact on the water quality Environmental impact	Reduction in impervious surfaces reduces the nonpoint source pollutants entering the waterways via overflows since runoff is reduced and soil infiltration is increased
Transitioning land uses	Cost and benefits	Costs include decommissioning surfaces, removal of pavement from site, erosion seeding, and planting for future land uses Benefits include reduction of runoff and NPS pollutants, possible aesthetic improvement to the area and ability to enhance the community via parks or recreational areas
	Intended purpose for land in vision	As of October 2014 Flint does not have a future land use plan for the analysis area
	Soil type in area	Incorporates area specific soil types and land use curve numbers corresponding to specific soil types
	Impact on the water quality Environmental impact	Reduction in impervious surfaces reduces the nonpoint source pollutants entering the waterways via overflows since runoff is reduced and soil infiltration is increased
Bioretention cells	Cost and benefits	Costs include the construction and maintenance of the bioretention cell(s) Benefits include reduction of runoff and NPS pollutants
	Intended purpose for land in vision	As of October 2014 Flint does not have a future land use plan for the analysis area
	Soil type in area	Incorporates area specific soil types and land use curve numbers corresponding to specific soil types
	Impact on the water quality Environmental impact	Routing water to bioretention cell reduces source pollutants entering the waterways via overflows due to decreased runoff and increased infiltration

6.1.2. Retooling Alternatives in Saginaw

The inputs for retooling alternatives for the Saginaw study are shown in Table 6.4. The SWMM model used for simulating retooling alternatives in Saginaw's analysis area (analysis area discussed in Section 4.1) is shown in Figure 6.2. The combined sewer system is depicted as arcs and nodes between the subcatchments. Each subcatchment has an area of one city-block.

Table 6.4. Data inputs for Saginaw

Data	Saginaw, MI	Source
Location	Genesee	N/A
Analysis area size	0.16 square miles (defined in Section 4.1)	GoogleEarthPro
Soil type	(0-12 inches) loam, (12-16 inches) clay loam, (16-80 inches) silty clay loam | Hydraulic group B	USDA: NCRS 2013 and GIS layers to identify location of candidate area with reference to the soil surveys
Current land use	Dense residential, approximately 1/4 acre parcels	City provided GIS layers
Status quo impervious area	38% Impervious	USDA 1986
Future land use	Green opportunity (i.e., shifting land use from residential towards performing in its natural state via green infrastructure, and land use transitions)	N/A
Precipitation data	L-THIA: 30 years of county-averaged data SWMM: Local weather station	National Climate Data Center (NCDC)
Synthetic storm depths	2-year, 24-hour storm: 2.35 inches 10-year, 24-hour storm: 3.46 inches 2-year, 10-minute storm: 0.495 inches 10-year, 10-minute storm: 0.738 inches	NOAA 2014
Curve numbers and LID designs	L-THIA: Pre-defined curve numbers associated with each LID alternative and land use SWMM: Land use curve numbers (USDA 1986), LID designs (SEMCOG 2008)	L-THIA: Pre-defined, based on literature SWMM: USDA 1986; SEMCOG 2008
Infrastructure	Combined sewer system	City provided GIS layers
Slope	Varies by subcatchment	US Topographic Maps

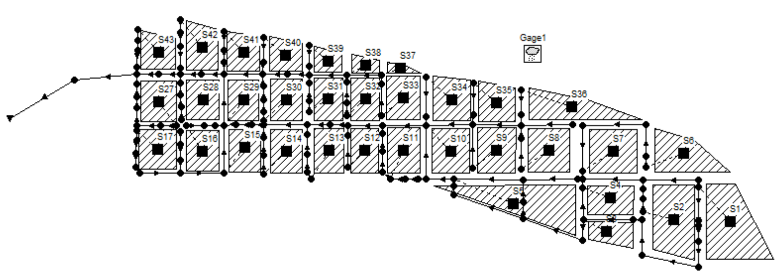


Figure 6.2. SWMM model for analysis area in in Saginaw

Similar to Flint, the LID alternatives considered did not include lot-level investments, such as rain gardens or porous pavements. The analysis area, known as the Green Zone is in an area of Saginaw that is considered approximately 70% vacant (USEPA 2014) and has a future land use to transition towards green opportunity. The likelihood of lot-level investments or capital-intensive infrastructure investment, such as porous pavements, is unlikely in area transitioning away from residential zoning towards green space. Tables 6.5 and 6.6 summarize the retooling alternatives for Saginaw discussed in this study and the considerations for each retooling scenario.

Table 6.5. Saginaw's retooling alternatives analyzed in study

Strategy	**Rationale**
Status quo (38% impervious, high density residential area)	Represents the status quo of the analysis area (base model)
Reduction in impervious surfaces (simulations ranged from 33% impervious to 3% impervious in 5% increments)	Applicable if the city wishes to decommission and raze impervious surfaces (e.g., driveways, foundations, sidewalks, roads) Decommissioned surfaces assumed to transition to grass in "good" condition
Transitioning land uses ((1) grass, (2) brush, (3) woods, (4) meadow)	Applicable if the city wishes to rezone the area for parks or wooded areas post decommissioning impervious surfaces
Bioretention cells[1, 2, 3]	Assumes 38% impervious area Applicable if the city wishes to reduce stormwater runoff throughout the neighborhood without investing in the removal of impervious surfaces

[1]*Size is 15% of the impervious area (Atchison et al. 2006, SEMCOG 2008).* [2]*L-THIA does not allow user to route a percentage of the runoff. In SWMM, the percentages of the generated runoff routed are 50%, 75%, and 100%.* [3]*L-THIA does not allow user to change the storage depth or density of vegetation. In SWMM, user defined storage depths of the bioretention cell are 12-inch and 6-inch, as suggested in SEMCOG (2008), evaluated with both minimal (0%) and dense (50%) vegetation.*

Table 6.6. Incorporation of considerations for each modeled retooling scenario in Saginaw

Scenario	**Consideration**	**Addressing Consideration**
Reduction in impervious surfaces	Cost and benefits	Costs include decommissioning surfaces, removal of pavement from site, and erosion seeding Benefits include reduction of runoff and NPS pollutants, possible aesthetic improvement to the area
	Intended purpose for land in vision	The analysis area has been selected for green opportunities, thus, zoning will no longer be residential, and the remaining residents will transition out of the area
	Soil type in area	Incorporates area specific soil types and land use curve numbers corresponding to specific soil types
	Impact on the water quality	Reduction in impervious surfaces reduces the nonpoint source pollutants entering the waterways via overflows since runoff is reduced and soil infiltration is increased
	Environmental impact	

Table 6.6 (*continued*).

Scenario	Consideration	Addressing Consideration
Transitioning land uses	Cost and benefits	Costs include decommissioning surfaces, removal of pavement from site, erosion seeding, and planting for future land uses Benefits include reduction of runoff and NPS pollutants, possible aesthetic improvement to the area and ability to enhance the community via parks or recreational areas
	Intended purpose for land in vision	The analysis area has been selected for green opportunities, thus, zoning will no longer be residential, and the remaining residents will transition out of the area
	Soil type in area	Incorporates area specific soil types and land use curve numbers corresponding to specific soil types
	Impact on the water quality	Reduction in impervious surfaces reduces the nonpoint source pollutants entering the waterways via overflows since runoff is reduced and soil infiltration is increased
	Environmental impact	
Bioretention cells	Cost and benefits	Costs include the construction and maintenance of the bioretention cell(s) Benefits include reduction of runoff and NPS pollutants
	Intended purpose for land in vision	The analysis area has been selected for green opportunities, thus, zoning will no longer be residential, and the remaining residents will transition out of the area
	Soil type in area	Incorporates area specific soil types and land use curve numbers corresponding to specific soil types
	Impact on the water quality	Routing water to bioretention cell reduces source pollutants entering the waterways via overflows due to decreased runoff and increased soil infiltration
	Environmental impact	

6.2 Decommissioning Impervious Surfaces Analysis

The results from decommissioning impervious surfaces are presented in this section. Within each subsection, the results for the B/C soils are presented, followed by the results for the D/compacted soils. After displaying the results of decommissioning impervious surfaces based on historical precipitation data specific to the case study city, the impact of decommissioning impervious surfaces during a 2-year and a 10-year, 24-hour storm are presented to evaluate the performance of the retooling alternatives during large volume precipitations events. The analyses area is evaluated for a 2-year and a 10-year, 10-minute storm, as well, due to the presence of a combined sewer system (CSS) in Saginaw. The 10-minute storms measure the effectiveness of the retooling alternatives to manage stormwater during high intensity precipitation events. High intensity precipitation events increase the risk of overflows due to the abrupt volume of runoff entering the system over a short duration. The storm analyses are only performed in SWMM since L-THIA does not allow for user-defined precipitation. When viewing the graphs depicting the reduction in runoff, the percent change is relative to the status quo/base scenario for that precipitation event. For instance, the change in runoff from decommissioning impervious surfaces during a 10-year, 24-hour storm is compared to runoff generated during that same storm over the status quo/base scenario.

6.2.1. Decommissioning Impervious Surfaces in Flint

The base case in the Flint case study consists of approximately 65% impervious surfaces. These impervious surfaces were decommissioned in 5% increments, until all impervious surfaces were decommissioned (0%), to examine the impact of varying pavement removal efforts. Grass/pasture represents 0% impervious surfaces. Post removal of all impervious surfaces, different land uses were simulated to view the generated runoff.

6.2.1.1. Generated Runoff Using Historical Precipitation Data in Flint

Each retooling alternative was evaluated in L-THIA for B/C soils and D soils using daily precipitation averages across Genesee County, and in SWMM using local weather station data at 30-minute increments. The results (Figures 6.3-6.6) indicate that the runoff in the analysis area can be reduced by over 85% when all impervious surfaces are reduced for B/C soils. Brush had the greatest reduction in runoff, reducing the runoff in the area by over 95% for B/C soils and over 85% for D soils. Brush could not be verified by L-THIA as the use of brush as a land use was not available in this tool. L-THIA yielded transitioning the land area to a wooded area as having the greatest impact on the runoff reduction for both B/C soils and D soils. L-THIA and SWMM yielded a runoff reduction of over 70% and 65% when all surfaces were decommissioned, for B/C soils and D soils, respectively.

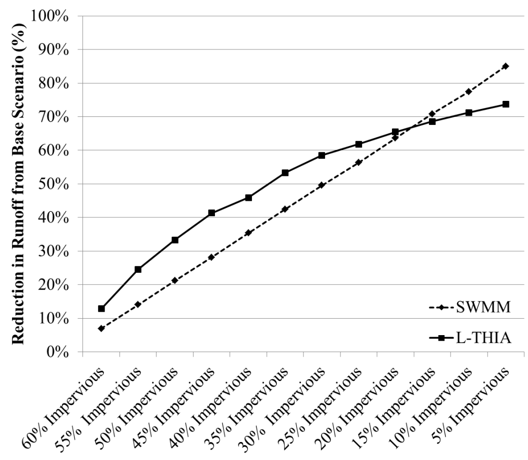


Figure 6.3. Impact of decommissioning impervious surfaces based on historical data (B/C soils)

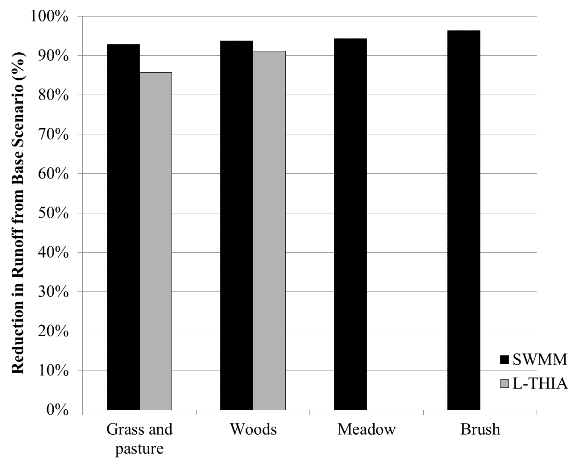


Figure 6.4. Impact of transitioning land uses based on historical data (B/C soils)

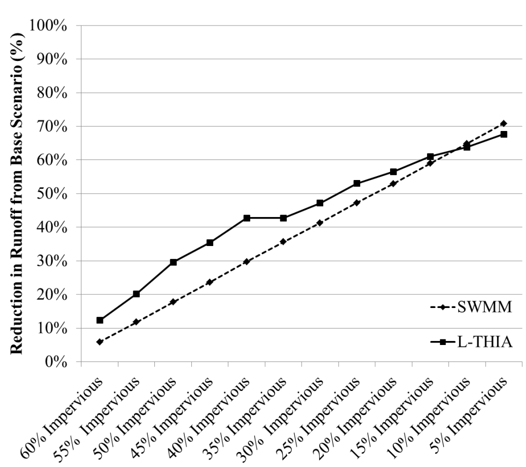


Figure 6.5. Impact of decommissioning impervious surfaces based on historical data (D soils)

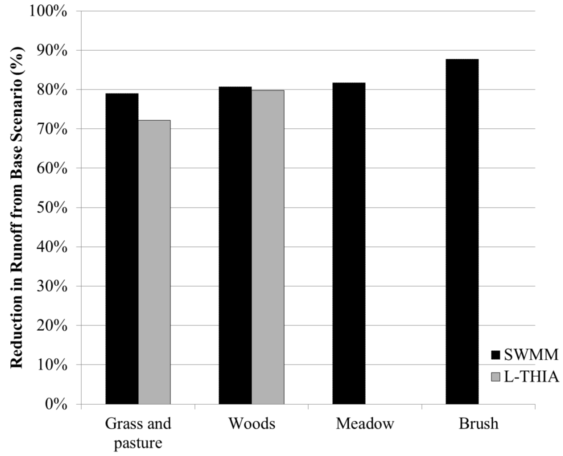


Figure 6.6. Impact of transitioning land uses based on historical data (D soils)

6.2.1.2. Generated Runoff During a 2-year and 10-year, 24-hour Storm in Flint

Each retooling alternative was evaluated for B/C soils and D soils in SWMM for a 2-year and a 10-year, 24-hour storm, simulating a large volume precipitation event (Figures 6.7-6.10). Decommissioning all impervious surfaces reduces the runoff for the 2-year storm by over 70% and 50% for B/C soils and D soils, respectively. For the 10-year storm, the runoff is reduced by approximately 60% and over 40% for B/C soils and D soils, respectively. Similar to the analysis based on historic precipitation, brush reduces the runoff the most for both B/C soils and D soils.

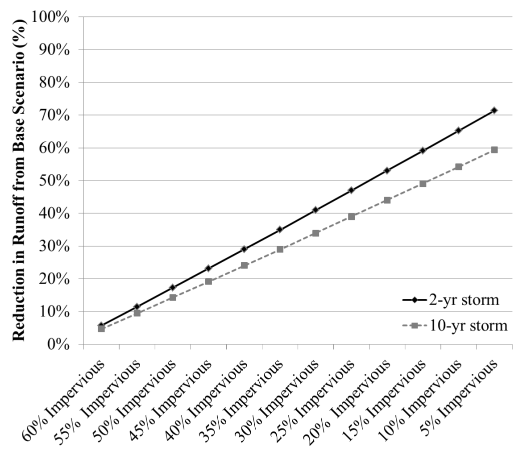


Figure 6.7. Impact of decommissioning impervious surfaces during a 2-year and 10-year, 24-hour storm (B/C soils)

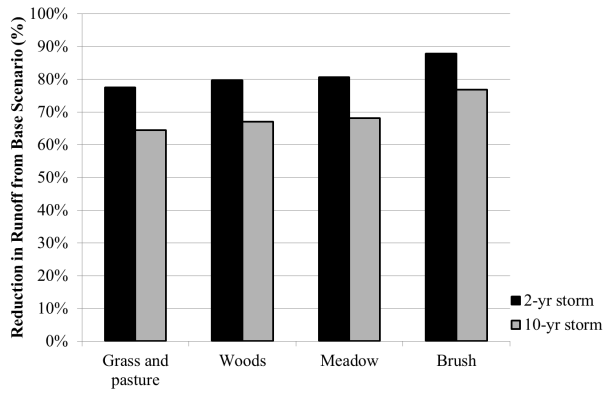


Figure 6.8. Impact of transitioning land uses during a 2-year and 10-year, 24-hour storm (B/C soils)

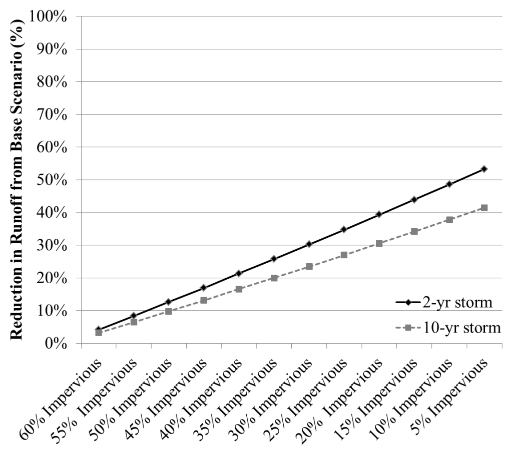


Figure 6.9. Impact of decommissioning impervious surfaces during a 2-year and 10-year, 24-hour storm (D soil)

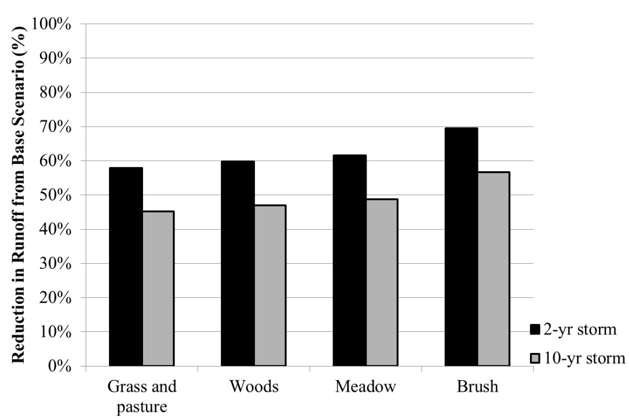


Figure 6.10. Impact of transitioning land uses during a 2-year and 10-year, 24-hour storm (D soil)

6.2.2. Decommissioning Impervious Surfaces in Saginaw

The base case in the Saginaw case study consists of approximately 38% impervious surfaces. These impervious surfaces were decommissioned in 5% increments (38% through 3%, and 0%/grass and pasture) to assess the impact of pavement removal efforts. After decommissioning all impervious surfaces, different land uses were simulated to view the generated runoff. Similar to Flint, the quantity of runoff in Saginaw was evaluated for a 2-year and a 10-year, 24-hour storm to assess the performance during a high volume precipitation event. In addition to the 24-hour storm, Saginaw's analysis area was evaluated for the quantity of runoff for a 10-minute storm due to the CSS in the city, to estimate the effectiveness during high intensity precipitation events.

6.2.2.1. Generated Runoff Using Historical Precipitation Data in Saginaw

Each retooling alternative was evaluated in L-THIA for B soils and D soils using daily precipitation averages across Saginaw County, and in SWMM using local weather station data at 30-minute increments. When all but 3% of impervious surfaces are decommissioned the runoff generated in the analysis area, for B soils, can be reduced by over 65% and 85%, in L-THIA and SWMM, respectively (Figure 6.11). The reduction in runoff for D soils differed drastically in L-THIA and SWMM when all impervious surfaces were decommissioned (Figure 6.13). L-THIA estimates a reduction in runoff just over 40%, whereas SWMM estimates a reduction in runoff of approximately 70%. The status quo/base values for SWMM are in line with literature (discussed in Section 6.2.3) and thus, more reliable.

Similar to Flint, the land use brush had the greatest reduction of runoff, reducing the runoff in the area by over 95%, assuming B soils, and by over 80% assuming D soils (Figures 6.12 and 6.14). L-THIA indicated that transitioning the land area to a wooded area had the greatest impact on the runoff reduction, reducing the runoff by over 80% for B soils and by over 60% for D soils.

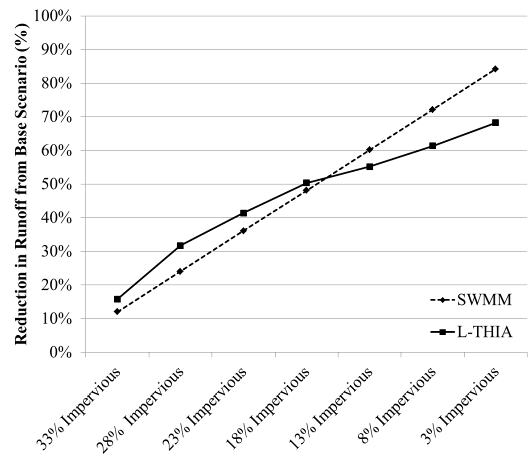


Figure 6.11. Impact of decommissioning impervious surfaces based on historical data (B soils)

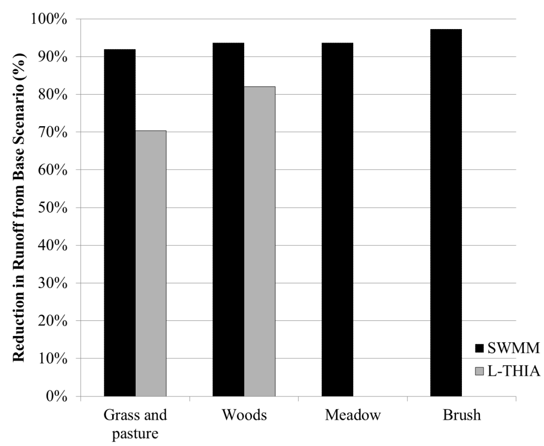


Figure 6.12. Impact of transitioning land uses based on historical data (B soils)

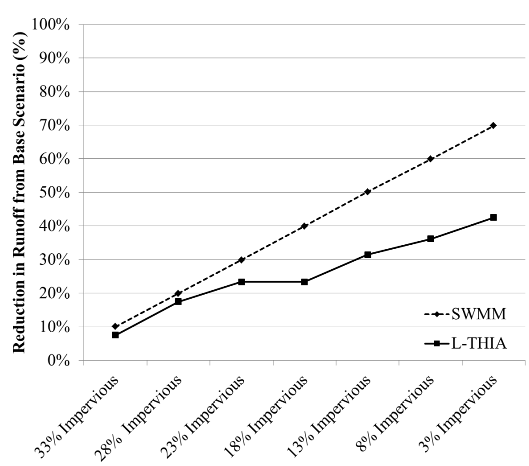


Figure 6.13. Impact of decommissioning impervious surfaces based on historical data (D soils)

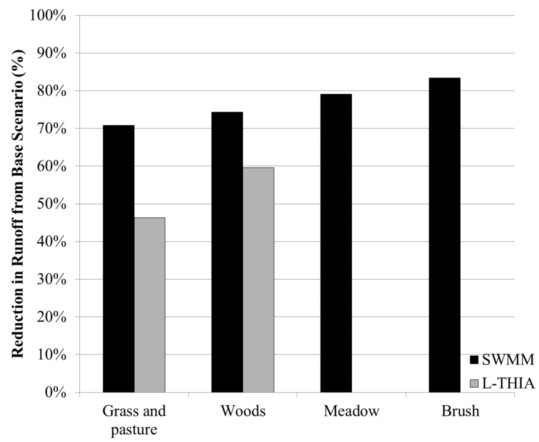


Figure 6.14. Impact of transitioning land uses based on historical data (D soils)

6.2.2.2. Generated Runoff During a 2-year and 10-year, 24-hour Storm in Saginaw

Each retooling alternative was evaluated for B soils and D soils in SWMM for a 2-year and a 10-year, 24-hour storm to simulate the performance of the retooling alternative during large volume precipitation events. Decommissioning all but 3% of the impervious surfaces reduces the runoff for the 2-year storm by approximately 65% for both B soils and D soils. For the 10-year storm, the runoff is reduced by approximately 50% for both B soils and D soils. Similar to the results shown for Flint, brush is the land use that reduced runoff the most for both soils.

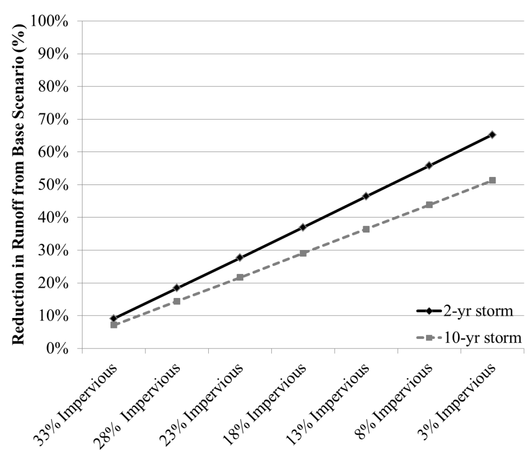


Figure 6.15. Impact of decommissioning impervious surfaces during a 2-year and a 10-year, 24-hour storm (B soils)

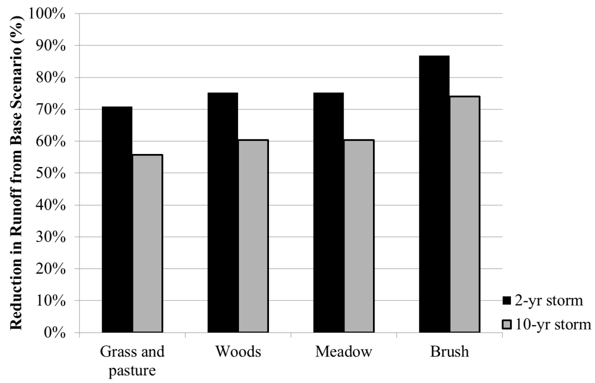


Figure 6.16. Impact of transitioning land uses during a 2-year and a 10-year, 24-hour storm (D soils)

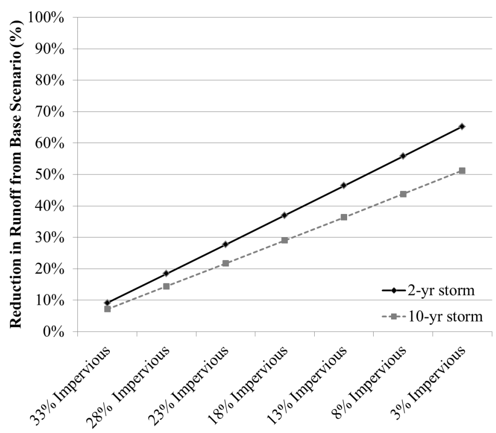


Figure 6.17. Impact of decommissioning impervious surfaces during a 2-year and a 10-year, 24-hour storm (D soils)

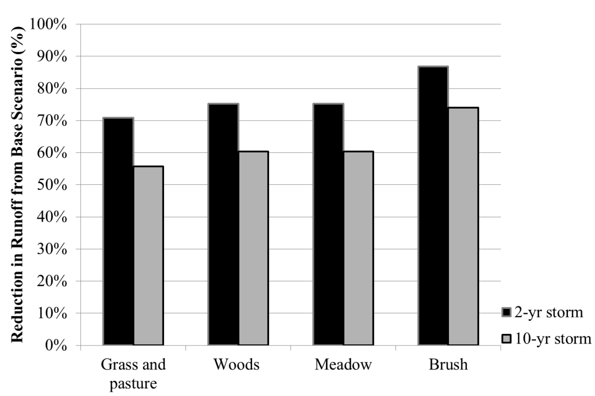


Figure 6.18. Impact of transitioning land uses during a 2-year and a 10-year, 24-hour storm (D soils)

6.2.2.3. Generated Runoff During a 2-year and 10-year, 10-minute Storm in Saginaw

Each retooling alternative was evaluated during a 2-year and a 10-year, 10-minute storm to estimate the effectiveness of the retooling alternative during high intensity precipitation events. The findings from this analysis provided interesting results. It should be re-noted here that the comparison for the change in runoff is relative to the status/quo base scenario for that particular precipitation pattern. This is important to note because the reduction in runoff for the 2-year and 10-year storm are within 1% and thus, appear to be overlapping in Figures 6.19 and 6.21. By decommissioning the impervious surface up to 3% the runoff typically generated during the storms can be reduced by over 90%, for both soils types, thus providing a significant reduction in stormwater entering the underground infrastructure during the high intensity precipitation events. Transitioning land uses, for both soil types, was able to reduce the runoff by over 97% during these high intensity storms.

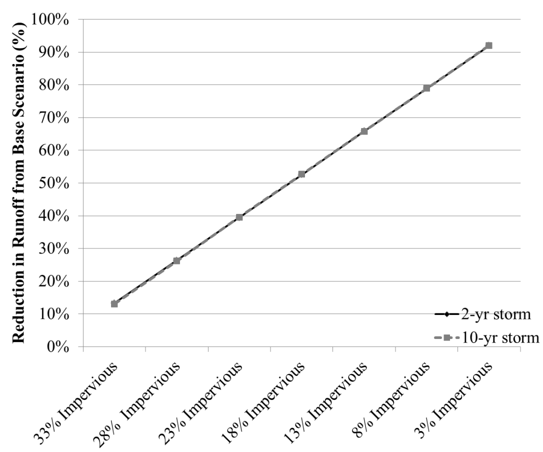


Figure 6.19. Impact of decommissioning impervious surfaces during a 2-year and 10-year, 10-minute storm (B soils)

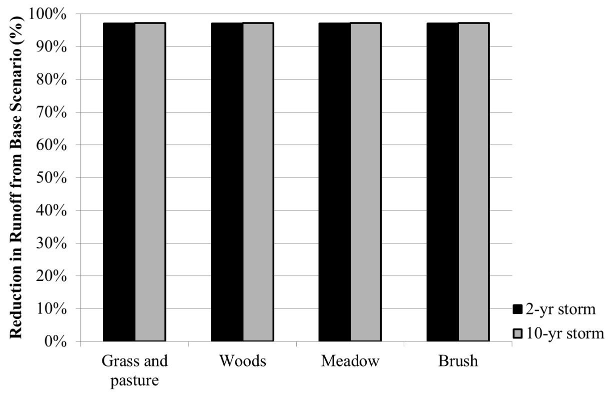


Figure 6.20. Impact of transitioning land uses during a 2-year and 10-year, 10-minute storm (B soils)

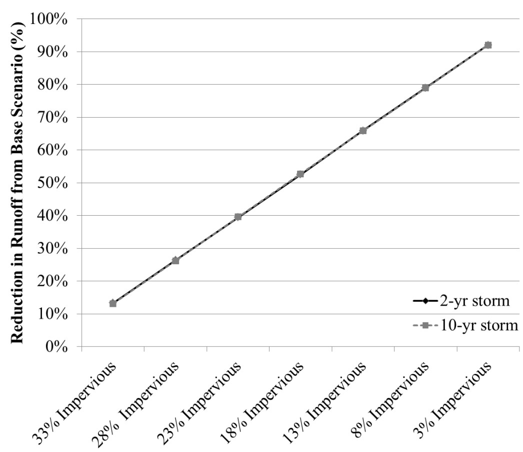


Figure 6.21. Impact of decommissioning impervious surfaces during a 2-year and 10-year, 10-minute storm (D soils)

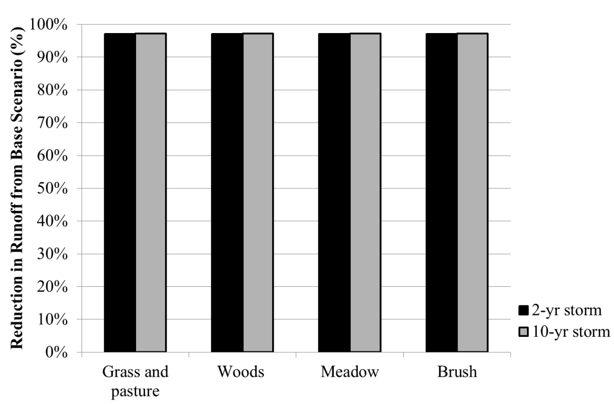


Figure 6.22. Impact of transitioning land uses during a 2-year and 10-year, 10-minute storm (D soils)

6.2.3. Implications of the Decommissioning Impervious Surfaces Analyses

Figures 6.3-6.22 depict the results of the reduction of impervious surfaces and changing land uses (post-removal of impervious surfaces), for B/C soils and D soils, in Flint and Saginaw. L-THIA estimates less total runoff for the status quo/base model considerably percent changes in the runoff. In some instances, L-THIA estimates the same runoff to precipitation ratio for different retooling alternatives. For example, the retooling alternatives for decommissioning 15% and 20% of the impervious area in Saginaw yield the same runoff to precipitation ratio for D soils, resulting in an inconsistent downward trend of the decrease in runoff corresponding to decommissioning impervious surfaces. However, SWMM estimated a consistent decrease in runoff correlated with a decrease in the percentage of impervious surfaces. Additionally, SWMM estimates higher quantities of runoff for all retooling alternatives evaluated when compared to L-THIA. However, SWMM's estimated runoff is comparable to published values from residential land uses for 1/4-acre and 1/8-acre residential parcels (Gironás et al. 2009; MDOT 2006). Although, the runoff magnitude between the two tools varies, the percentage change between the status quo/base model and different alternatives are comparable. Thus, while the models differ for average depth of runoff, due to difference in assumptions and models, we can generalize that the impact *between* alternatives is similar.

The land use transformations assume that all impervious surfaces have been decommissioned and the land use has undergone transition. As expected, the greater the reduction in impervious surfaces across the analysis area, the greater the reduction in runoff. Between the land transformation retooling alternatives of grass/pasture and woods (the two options evaluated using both tools), transitioning the land to forest or woods has the greatest potential for reduction in runoff. The land use options meadow and brush were also evaluated in SWMM, with brush yielding the highest reduction of runoff for all land uses. In Saginaw, due to the future land use designation to transition to the "Green Zone," grass/pasture may be more desirable, and does have a high reduction in runoff, as well.

The impact on generated runoff for the different soil types becomes more pronounced when the 2-year and 10-year, 24-hour storms are simulated. The soils in the analysis area that have been compacted to D soils have the lowest infiltration capabilities, reaching saturation before category A-C soils, thus, generating more runoff. The B/C soils, with high infiltration capabilities, are able to infiltrate a larger percentage of the precipitation of the 2-year and 10-year storms. For transitioning land uses, the change to brush had the greatest reduction in runoff for the storms evaluated, consistent with the results using historical precipitation data, and grass/pasture performed the worst. This indicates that between the best-case (brush) and worst-case land use (grass/pasture), the worst-case produces approximately 15% more total runoff (depending on the soil type).

The runoff resulting from the 2-year and 10-year, 10-minute storm demonstrated that the decommissioning impervious surfaces and transitioning land uses perform very well during high intensity, short duration storms. Decommissioning the impervious surfaces in Saginaw, regardless of soil type, was able to reduce the runoff typically generated during the storm by over 90%. Transitioning land uses yielded a runoff reduction of over 97%, irrespective of soil type. These results indicate that these retooling alternatives are technically viable to aid in reducing overflows during high intensity, short duration storms.

6.3. Low-Impact Development Analysis

The results from the low-impact development analyses are presented in this section. Within each subsection, the results for the B/C soils are presented, followed by the results for the D soils. After displaying the results based on historical precipitation runoff generated during a 2-year and a 10-year, 24-hour storm are presented. Similar to Section 6.2, Saginaw's analysis area was also evaluated for generated runoff during a 2-year and a 10-year, 10-minute storm, in addition to the 24-hour duration storms.

6.3.1. Low-Impact Development in Flint

The LID analysis performed in Flint assumed that no impervious surface decommissioning has occurred. The bioretention cells serve as another retooling alternative aside from decommissioning the impervious surfaces, by routing generated runoff to the cells for onsite infiltration. The size of the bioretention cells (one for each subcatchment in SWMM) is 15% of the impervious area (0.0137 square miles in total) as suggested by Atchison et al. (2006) and aligning with SEMCOG (2008) recommendations. In Flint's analysis area, the bioretention cell is slightly more than three lots per block (assuming 1/8 acre lots). L-THIA does not allow user defined designs for the bioretention cell as a standard curve number is applied to the area of the bioretention cell in L-THIA's simulation. The bioretention cells in SWMM were evaluated for

12-inch and 6-inch storage depths with both minimal and dense vegetation, based on design recommendations by SEMCOG (2008).

6.3.1.1. Generated Runoff Using Historical Precipitation Data in Flint

For B/C soils and D soils, L-THIA estimates an approximate 10% and 35% reduction in the runoff, respectively. Due to L-THIA's inability to customize the bioretention cells, a constant value is shown for the reduction in runoff across all bioretention cells assessed in SWMM (Figures 6.23-6.26). In SWMM, the storage volume and the percentage of runoff routed to the bioretention cell influences the reduction of runoff. A bioretention cell receiving 100% of the runoff generated by impervious surfaces with the largest storage area (12-inch and minimal vegetation) was capable of reducing the runoff in the analysis area by almost 100% for B/C soils and D soils. The storage area for 12-inches, dense vegetation and 6-inches, minimal vegetation has negligible differences and appears equivalent in Figures 6.23-6.26. The flat line spanning the alternatives with 50% of the runoff routed indicates that all design alternatives were capable of capturing and treating the runoff routed to the bioretention cell onsite.

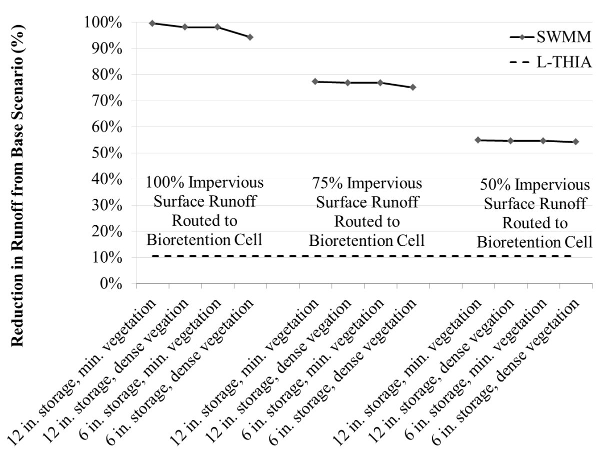


Figure 6.23. Impact of bioretention cells based on historical data (B/C soils)

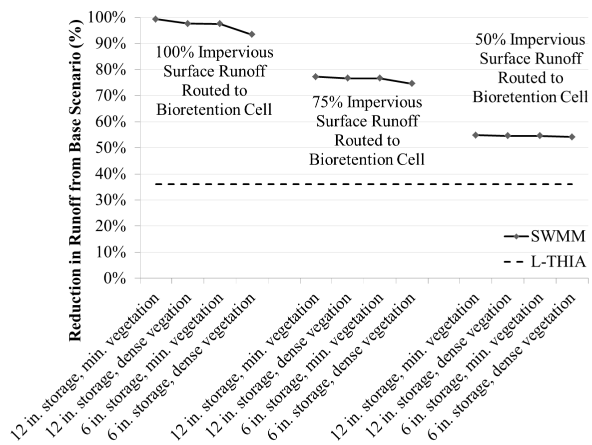


Figure 6.24. Impact of bioretention cells based on historical data (D soils)

6.3.1.2. Generated Runoff During a 2-year and a 10-year, 24-hour Storm in Flint

The bioretention cells were evaluated for B/C soils and D soils using a 2-year and 10-year, 24-hour storm in SWMM. The ability to treat runoff onsite varies considerably between the 2-year and 10-year storm, as well as across the different percentages of runoff that is routed to the bioretention cell from the impervious surfaces in the analysis area.

The results (Figures 6.25-6.26) indicate that when 50% of the runoff from the impervious areas is routed to the bioretention cell, the runoff from the 2-year storm for all storage designs, except the 6-inch storage with dense vegetation, may be treated onsite for both soil types. For the 10-year storm, only the 12-inch storage design and minimal vegetation is capable of treating the volume of runoff for both soil types.

In the instances that 75% of the runoff is routed to the bioretention cell during the 2-year storm, all storage designs, except the 6-inch storage and dense vegetation, are capable of treating the precipitation onsite for all soils evaluated. During the 10-year storm with 75% of the runoff routed to the bioretention cell, the 12-inch storage and minimal vegetation is capable of treating the volume of runoff onsite for B/C soils and D soils.

The bioretention cell that routes 100% of the runoff generated across the analysis area's impervious surfaces is only capable of treating the volume of runoff during the 2-year storm, for B/C soils, when the storage design is at its maximum capacity of 12-inch storage and minimal vegetation. However, although the bioretention cells reach capacity during the storms for most designs assessed, the bioretention cells are still capable of considerably reducing the runoff during these synthetic storms. For instance, during the 10-year storm runoff is reduced by at least 30% for bioretention cells assessed, irrespective of soil type. When the bioretention cell reaches capacity, excess water routed to the cell continues to Flint's separate stormwater system.

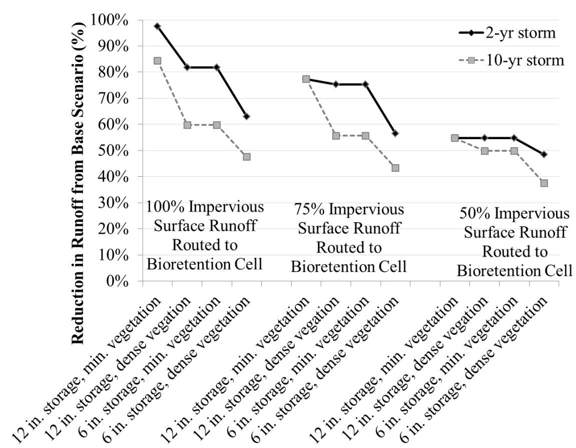


Figure 6.25. Impact of bioretention cells during a 2-year and a 10-year, 24-hour storm (B/C soils)

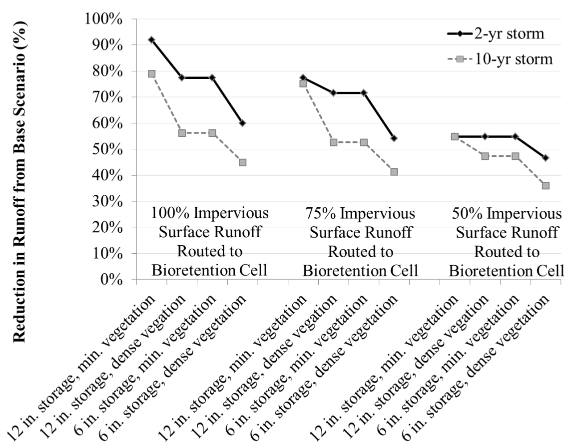


Figure 6.26. Impact of bioretention cells during a 2-year and a 10-year, 24-hour storm (D soils)

6.3.2. Low-Impact Development in Saginaw

Analogous to Flint, the LID analysis performed in Saginaw assumes that no impervious surface decommissioning has occurred. The size of the bioretention cells (one for each subcatchment in SWMM) is 15% of the impervious area (0.0156 square miles in total across the analysis area) as suggested by Atchison et al. (2006) and aligning with SEMCOG (2008) recommendations. The average size of the bioretention cells is slightly less than one lot per block in Saginaw's analysis area (assuming 1/4 acre lots).

6.3.2.1. Generated Runoff Using Historical Precipitation Data in Saginaw

Each bioretention cell was evaluated for B soils and D soils using the similar approach as outline above for Flint. Consistent with the SWMM analysis performed in Flint, the reduction of the runoff was influenced primarily by the storage area and the percentage of runoff routed to the bioretention cell. The bioretention cell that all 100% of the runoff generated was routed to with the largest storage area (12-inch storage and minimal vegetation) was capable of reducing the runoff by over 95% for B soils and D soils. The alternatives with 50% of the runoff routed (for all storage design alternatives) were capable of capturing the volume of runoff routed to the bioretention cells and treating the runoff onsite.

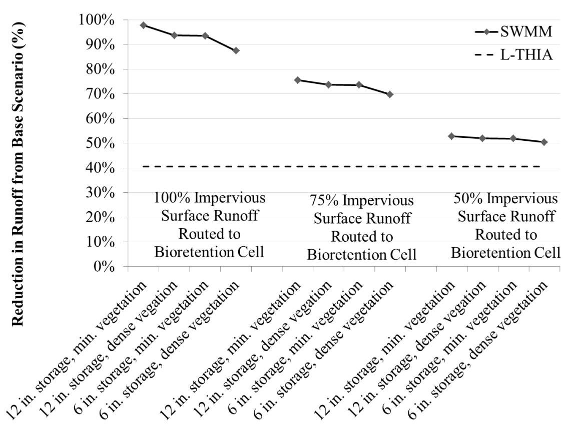


Figure 6.27. Impact of bioretention cells based on historical data (B soils)

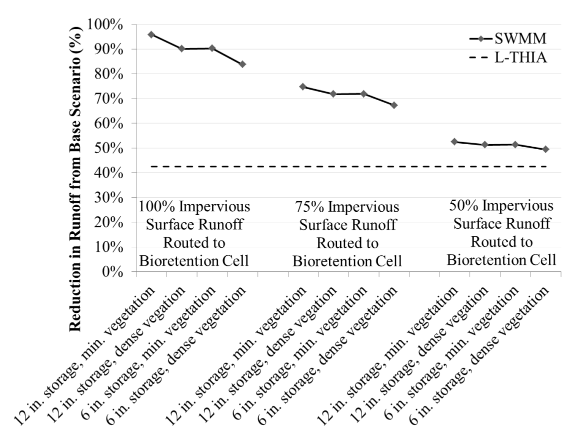


Figure 6.28. Impact of bioretention cells based on historical data (D soils)

6.3.2.2. Generated Runoff During a 2-year and a 10-year, 24-hour Storm in Saginaw

The bioretention cells were evaluated for B soils and D soils using a 2-year and 10-year, 24-hour storm, to evaluate the bioretention cell performance during high volume precipitation events. All findings for the 24-hour storms were consistent with the analysis performed for Flint. The results (Figures 6.29-6.30) indicate that when 50% of the runoff is routed to the bioretention cell, the runoff generated during a 2-year storm for all storage designs, except the 6-inch storage with dense vegetation, may be treated onsite for both B soils and D soils. For the 10-year storm, only the 12-inch storage design and minimal vegetation is capable of treating the volume of runoff generated during the storm onsite for all soils evaluated.

When 75% of the runoff is routed to the bioretention cell, the runoff from the 2-year storm may be treated onsite for all storage designs, except the 6-inch storage and dense vegetation, for both soil types. During the 10-year storm, when 75% of the runoff is routed to the bioretention cell, the 12-inch storage and minimal vegetation is the only design capable of treating the volume of runoff onsite.

The designs that route 100% of the runoff generated are capable of treating the volume of runoff during the 2-year storm, for B soils, when the storage design is at its maximum capacity of 12-inch storage with minimal vegetation. Although all bioretention cell designs are not capable of treating all runoff during the synthetic storms onsite, the bioretention cells considerably reduce the runoff entering the infrastructure system. For all bioretention cell designs, the 10-year storm runoff was reduced by over 30%. When the bioretention cell reaches capacity, excess water routed to the cell continues to Saginaw's CSS.

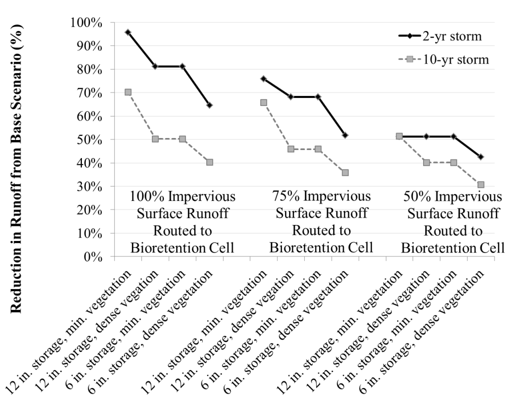


Figure 6.29. Impact of bioretention cells during a 2-year and a 10-year, 24-hour storm (B soils)

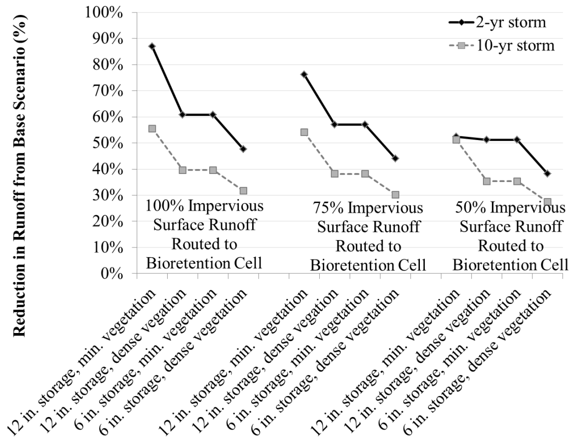


Figure 6.30. Impact of bioretention cells during a 2-year and a 10-year, 24-hour storm (D soils)

6.3.2.3. Generated Runoff During a 2-year and a 10-year, 10-minute Storm in Saginaw

The bioretention cells performed very well during the high intensity, short duration storms. All bioretention cells were capable of treating the runoff generated and routed to the bioretention cell during the 2-year and 10-year, 10-minute storms, with the exception of one design. When 100% of the runoff is routed to the bioretention cell, the smallest storage design, 6-inch storage with dense vegetation, was not capable of treating all runoff onsite, but still reduced the runoff by 80%, a considerable reduction from the status quo. For the assessed synthetic storms, soil types, and storage designs, the runoff was reduced by at least 55%. The runoff reduction is slightly higher for D soils as the infiltration capacity of the soil is characteristically less than B soils, thus, during status quo conditions more runoff is generated.

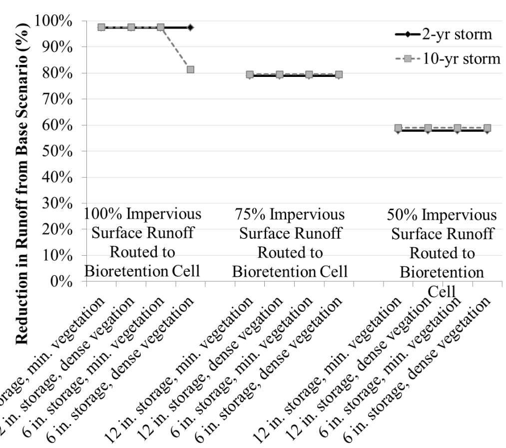


Figure 6.31. Impact of bioretention cells during a 2-year and a 10-year, 10-minute storm (B soils)

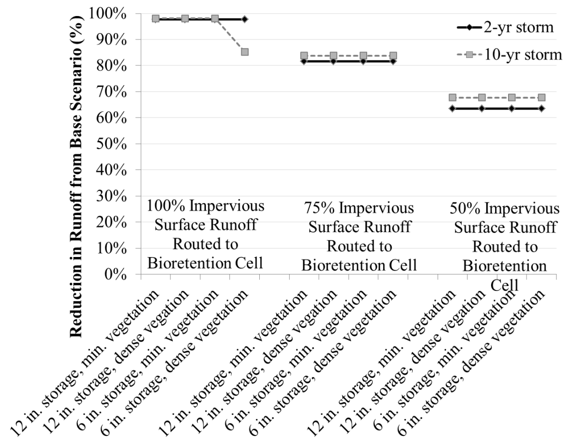


Figure 6.32. Impact of bioretention cells during a 2-year and a 10-year, 10-minute storm (D soils)

6.3.3. Implications of the Low-Impact Development Analysis

The use of bioretention cells as a retooling alternative was examined as this option aligned most closely with the transition to green space for Saginaw, did not require lot-level investment for Flint, and is appropriate for the topography of both candidate areas. The L-THIA model uses a pre-defined bioretention cell, whereas SWMM allows for customizable bioretention cell designs. The values of the design parameters for the planting soil depth, void ratio of soil were assume to be the average of the suggested implementable range identified for Michigan LID alternatives in SEMCOG (2008). The approximate size of the bioretention cell is slightly less than one lot per block in Saginaw's analysis area (with 1/4 acre lots), and slightly more than three lots per block in Flint's analysis area (with 1/8 acre lots). The different in the number of lots is due to Flint having a greater percentage of impervious surfaces and smaller lot sizes than Saginaw.

Figures 6.23-6.32 illustrate percent reduction in the runoff between the alternatives and status quo conditions/base model. The x-axis states the bioretention cell designs assessed for different storage sizes, sparse/dense vegetation, and percentage of the runoff generated in the impervious surface within the analysis area that was routed to the bioretention cell.

The L-THIA ratios of runoff to precipitation most closely align with bioretention cells in SWMM that routed between 50%-75% of the runoff in the Flint analysis. In the Saginaw analysis, L-THIA's ratio of runoff to precipitation most closely aligned with the alternative simulated in SWMM that routed 100% of the generated stormwater runoff to the bioretention cell. When viewing the percent change in runoff from the status quo, L-THIA consistently estimated a much smaller impact than SWMM for both cities. The discrepancies in the volume of runoff between L-THIA and SWMM may be a result of the differing precipitation data, or the tools' methodological approach. These values estimated in L-THIA are based on changing the curve number in the area designated as a bioretention cell, whereas SWMM allows for the customization of the LID alternatives, the incorporation of the land's topography, and local precipitation data.

The minimal change in runoff estimated by L-THIA was a 10% reduction in the runoff, estimated for B/C soils in Flint. The maximum reduction of runoff estimated by L-THIA was a 43% reduction in runoff for D soils in Saginaw. When modeling in SWMM, the largest impact occurred when all runoff within the analysis area was routed to a bioretention cell with a storage depth of 12-inches and minimal vegetation, reducing the runoff by approximately 100% during historic precipitation patterns. The different bioretention cell designs presented in this section (runoff routing percentages, storage sizing, presence of vegetation) allows a decision-maker to design the bioretention cell within the financial and physical constraints of the area. For instance, vegetation may be a choice that reduces the storage volume but could function as a potential erosion control. Additionally, routing all runoff may be challenging and require financial investment due to the urbanization of the areas, resulting in curbs or land with minimal slopes.

Across all designs evaluated within SWMM, the bioretention cells are capable of reducing the runoff by at least 50% for historic precipitation patterns. During the 24-hour storms, the bioretention cells evaluated in this section are capable of reducing runoff by at least 38% and at least 28% for the 2-year and 10-year storm. During in the 10-minute storms, the generated runoff was reduced by at least 55% for all storage designs.

6.4. Reduction of Runoff for Investment

The percent decrease in runoff from the base model, indicating the impact of implementing the alternative as compared to the status quo, is shown alongside the conceptual costs for each alternative in Figures 6.33-6.36. The costs are estimated using published conceptual cost data for each shown in Table 6.7. These costs are not specific to the area, but provide a general comparison. Each alternative is represented by letter(s), A-AC, corresponding to entries in the tables following the graphs, with the corresponding tool in parenthesis that was use to estimate the reduction in the runoff; S for SWMM and L for L-THIA. More extensive cost analysis of labor, materials, and expected maintenance expenses, would be needed to assess the financial viability of these alternatives.

Table 6.7. Conceptual costs

Conceptual Cost Item	Value		Source
Pavement decommissioning (values based on one-city block)	Pavement removal	$14,667	USEPA (2014)
	Roadway excavation	$3,911	
	Curb removal	$800	
	Sidewalk removal	$5,867	
	Driveway removal	$2,800	
	Fill Placement and compaction	$38,499	
	Erosion control seeding	$4,848	
	Total per city block	**$71,392**	
Transitioning land use to forest	Total per acre	$300	Lambrecht (1994)
	Total per acre	$513	Gorte (2009)
	Total per acre	$230	Piedmont Land & Timber (2010)
	Average	**$348**	
Transitioning land use to grass, meadow, or brush	Cost contained in erosion and control seeding		
Bioretention cells	Cost= $7.3*(volume)^{0.99}$		Brown and Schueler (1997)

6.4.1. Runoff Reduction Versus Investment in Flint

The reduction of runoff from the status quo/base model is graphed against the conceptual costs for each retooling alternative shown in Table 6.8 and Figure 6.33. For B/C soils and D soils, transitioning land use post decommissioning consistently provided the highest ratio of reduction in stormwater runoff to conceptual costs for the L-THIA and SWMM estimations. Of the four land uses evaluated, all of which yielded high runoff reductions for the investment, brush performed the best for all soil types as indicated by the letter AB in Figures 6.33 and 6.34. The bioretention cell providing the highest return (based on estimates from the SWMM analysis) was the 6-inch storage, with dense vegetation and 100% of the runoff routed to the cell, indicated by the letter Y. The y-axis is based on the reduction of the runoff during historic precipitation patterns. However, the designs storms are consistent with the historic data in that the highest performing alternative for historic precipitation was the highest performing retooling alternative during the 2-year and 10-year, 24-hour storm. All land uses performed equally well during the 2-year and 10-year, 10-minute storms.

Table 6.8. Conceptual costs of retooling alternatives for Flint key for Figures 6.33 and 6.34

	B/ C Soils					
	(L)	L-THIA		**(S)**	SWMM	
65% Impervious: Base Model		**% Change from Base**	**Costs (M)**		**% Change from Base**	**Costs (M)**
60% Impervious	**A(L)**	13%	$0.05	**A(S)**	7%	$0.05
55% Impervious	**B(L)**	25%	$0.11	**B(S)**	14%	$0.11
50% Impervious	**C(L)**	33%	$0.16	**C(S)**	21%	$0.16
45% Impervious	**D(L)**	41%	$0.22	**D(S)**	28%	$0.22
40% Impervious	**E(L)**	46%	$0.27	**E(S)**	35%	$0.27
35% Impervious	**F(L)**	53%	$0.33	**F(S)**	42%	$0.33
30% Impervious	**G(L)**	58%	$0.38	**G(S)**	50%	$0.38
25% Impervious	**H(L)**	62%	$0.44	**H(S)**	56%	$0.44
20% Impervious	**I(L)**	65%	$0.49	**I(S)**	64%	$0.49
15% Impervious	**J(L)**	69%	$0.55	**J(S)**	71%	$0.55
10% Impervious	**K(L)**	71%	$0.60	**K(S)**	77%	$0.60
5% Impervious	**L(L)**	74%	$0.66	**L(S)**	85%	$0.66
Grass and pasture	**M(L)**	86%	$0.71	**M(S)**	93%	$0.71
12", no veg., 75% routed	**N(L)**	-	-	**N(S)**	77%	$1.95
6", no veg., 75% routed	**O(L)**	-	-	**O(S)**	77%	$0.98
12 ", 50% veg., 75% routed	**P(L)**	-	-	**P(S)**	77%	$0.98
6 ", 50% veg., 75% routed	**Q(L)**	-	-	**Q(S)**	75%	$0.49
12", no veg., 50% routed	**R(L)**	-	-	**R(S)**	55%	$1.95
6", no veg., 50% routed	**S(L)**	-	-	**S(S)**	55%	$0.98
12 ", 50% veg., 50 routed	**T(L)**	-	-	**T(S)**	55%	$0.98
6 ", 50% veg., 50% routed	**U(L)**	-	-	**U(S)**	54%	$0.49
12", no veg., 100% routed	**V(L)**	-	-	**V(S)**	100%	$1.95
6", no veg., 100% routed	**W(L)**	-	-	**W(S)**	98%	$0.98
12 ", 50% veg., 100% routed	**X(L)**	-	-	**X(S)**	98%	$0.98
6 ", 50% veg., 100% routed	**Y(L)**	-	-	**Y(S)**	94%	$0.49
Woods	**Z(L)**	91%	$0.73	**Z(S)**	94%	$0.73
Meadow	**AA(L)**	-	-	**AA(S)**	94%	$0.71
Brush	**AB(L)**	-	-	**AB(S)**	96%	$0.71
Bioretention Cell	**AC(L)**	10%	$1.14	**AC(S)**		

Table 6.8. (*continued)*

	D Soils					
	(L)	L-THIA		**(S)**	SWMM	
65% Impervious: Base Model		**% Change from Base**	**Costs (M)**		**% Change from Base**	**Costs (M)**
60% Impervious	**A(L)**	12%	$0.05	**A(S)**	6%	$0.05
55% Impervious	**B(L)**	20%	$0.11	**B(S)**	12%	$0.11
50% Impervious	**C(L)**	30%	$0.16	**C(S)**	18%	$0.16
45% Impervious	**D(L)**	35%	$0.22	**D(S)**	24%	$0.22
40% Impervious	**E(L)**	43%	$0.27	**E(S)**	30%	$0.27
35% Impervious	**F(L)**	43%	$0.33	**F(S)**	36%	$0.33
30% Impervious	**G(L)**	47%	$0.38	**G(S)**	41%	$0.38
25% Impervious	**H(L)**	53%	$0.44	**H(S)**	47%	$0.44
20% Impervious	**I(L)**	57%	$0.49	**I(S)**	53%	$0.49
15% Impervious	**J(L)**	61%	$0.55	**J(S)**	59%	$0.55
10% Impervious	**K(L)**	64%	$0.60	**K(S)**	65%	$0.60
5% Impervious	**L(L)**	68%	$0.66	**L(S)**	71%	$0.66
Grass and pasture	**M(L)**	72%	$0.71	**M(S)**	79%	$0.71
12", no veg., 75% routed	**N(L)**	-	-	**N(S)**	77%	$1.95
6", no veg., 75% routed	**O(L)**	-	-	**O(S)**	77%	$0.98
12 ", 50% veg., 75% routed	**P(L)**	-	-	**P(S)**	77%	$0.98
6 ", 50% veg., 75% routed	**Q(L)**	-	-	**Q(S)**	75%	$0.49
12", no veg., 50% routed	**R(L)**	-	-	**R(S)**	55%	$1.95
6", no veg., 50% routed	**S(L)**	-	-	**S(S)**	55%	$0.98
12 ", 50% veg., 50% routed	**T(L)**	-	-	**T(S)**	55%	$0.98
6 ", 50% veg., 50% routed	**U(L)**	-	-	**U(S)**	54%	$0.49
12", no veg., 100% routed	**V(L)**	-	-	**V(S)**	99%	$1.95
6", no veg., 100% routed	**W(L)**	-	-	**W(S)**	98%	$0.98
12 ", 50% veg., 100% routed	**X(L)**	-	-	**X(S)**	98%	$0.98
6 ", 50% veg., 100% routed	**Y(L)**	-	-	**Y(S)**	75%	$0.49
Woods	**Z(L)**	80%	$0.73	**Z(S)**	81%	$0.73
Meadow	**AA(L)**	-	-	**AA(S)**	82%	$0.71
Brush	**AB(L)**	-	-	**AB(S)**	88%	$0.71
Bioretention Cell	**AC(L)**	36%	$1.14	**AC(S)**		

In Flint, when historic precipitation data is considered, transitioning the land use to brush in the analysis area would reduce the runoff in the analysis area by 96% and 88% for B/C soils and D soils, respectively, as estimated in SWMM. For the same estimated conceptual costs, transitioning the land use to a meadow would reduce the runoff by 94% and 82% for B/C soils and D soils, respectively (estimated in SWMM). Transitioning the land use to wooded area is estimated by

SWMM to reduce runoff by or 94% for B/C soils and 81% for D soils, and 91% for B/C soils and 80% for D soils in L-THIA. Transitioning the land use to grass (cost of $710,00 for the 0.14 square mile area) is estimated in SWMM to reduce runoff by 93% for B/C soils and 79% for D soils, and 86% for B/C soils and 72% for D soils in L-THIA. The bioretention cell evaluated in SWMM with a 6-inch storage, dense vegetation, and 100% of water routed to the bioretention cell (cost of $490,000) is estimated to reduce the runoff by 94% and 75% for B soils and D soils, respectively.

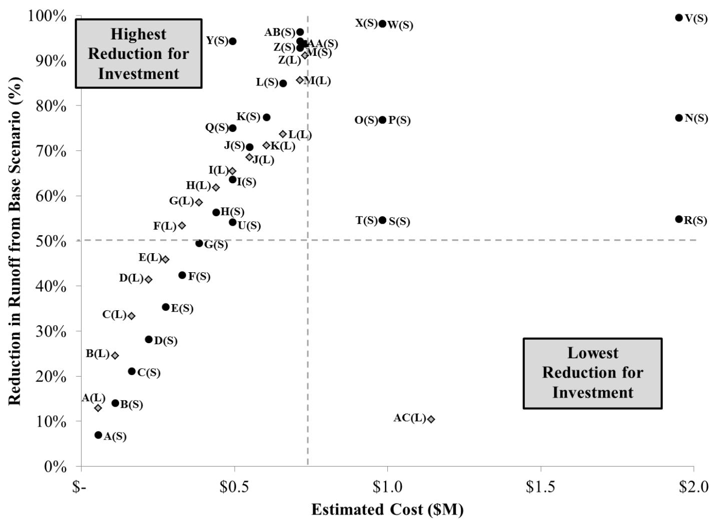


Figure 6.33 Runoff reduction versus financial investment for Flint (B/C soils)

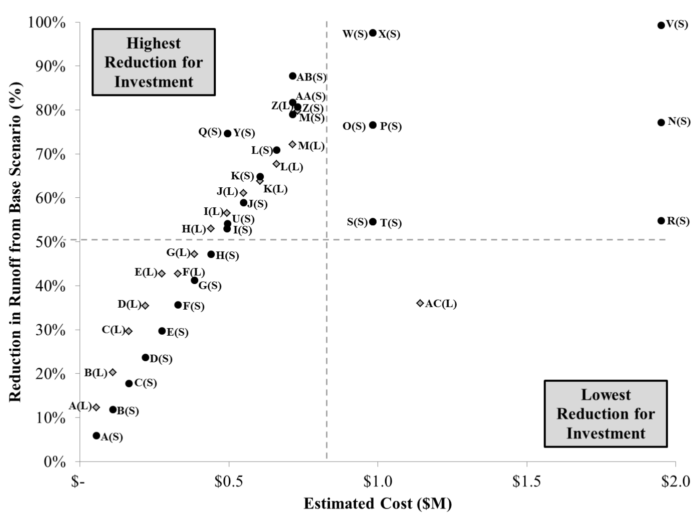


Figure 6.34 Runoff reduction versus financial investment for Flint (D soils)

6.5.2. Runoff Reduction Versus Investment in Saginaw

The reduction of runoff from the status quo/base model is graphed against the conceptual costs (see Table 6.9) for each retooling alternative for Saginaw in Figures 6.27 and 6.28. For both B soils and D soils, transitioning land use post decommissioning consistently provided the highest reduction in runoff to the conceptual costs, with brush having the highest reduction in runoff for the cost, indicated by W. Consistent with the analysis performed for Flint, the bioretention cell providing the highest return is the 6-inch storage with dense vegetation and 100% of the runoff routed, indicated by the letter T for all soils.

Table 6.9. Conceptual costs of retooling alternatives for Saginaw and key for Figures 6.35 and 6.36

	B Soil					
	(L)	L-THIA		(S)	SWMM	
38% Impervious: Base Model		**% Change from Base**	**Costs (M)**		**% Change from Base**	**Costs (M)**
33% Impervious	A(L)	16%	$0.15	A(S)	12%	$0.15
28% Impervious	B(L)	33%	$0.30	B(S)	24%	$0.30
23% Impervious	C(L)	43%	$0.45	C(S)	36%	$0.45
18% Impervious	D(L)	51%	$0.60	D(S)	48%	$0.60
13% Impervious	E(L)	56%	$0.75	E(S)	60%	$0.75
8% Impervious	F(L)	62%	$0.90	F(S)	72%	$0.90
3% Impervious	G(L)	69%	$1.05	G(S)	84%	$1.05
Grass and pasture	H(L)	71%	$1.14	H(S)	92%	$1.14
12", no veg., 75% routed	I(L)	-	-	I(S)	76%	$4.27
6", no veg., 75% routed	J(L)	-	-	J(S)	74%	$2.15
12 ", 50% veg., 75% routed	K(L)	-	-	K(S)	74%	$2.15
6 ", 50% veg., 75% routed	L(L)	-	-	L(S)	70%	$1.08
12", no veg., 50% routed	M(L)	-	-	M(S)	53%	$4.27
6", no veg., 50% routed	N(L)	-	-	N(S)	52%	$2.15
12 ", 50% veg., 50% routed	O(L)	-	-	O(S)	52%	$2.15
6 ", 50% veg., 50% routed	P(L)	-	-	P(S)	50%	$1.08
12", no veg., 100% routed	Q(L)	-	-	Q(S)	98%	$4.27
6", no veg., 100% routed	R(L)	-	-	R(S)	94%	$2.15
12 ", 50% veg., 100% routed	S(L)	-	-	S(S)	94%	$2.15
6 ", 50% veg., 100% routed	T(L)	-	-	T(S)	87%	$1.08
Woods	U(L)	83%	$1.18	U(S)	94%	$1.178
Meadow	V(L)	-	-	V(S)	94%	$1.17
Brush	W(L)	-	-	W(S)	97%	$1.17
Bioretention Cell	X(L)	43%	$2.41	X(S)	-	-

Table 6.9. *(continued)*

	D Soil					
38% Impervious: Base Model	(L)	**% Change from Base**	**Costs (M)**	(S)	**% Change from Base**	**Costs (M)**
33% Impervious		9%	$0.15		10%	$0.15
28% Impervious	B(L)	20%	$0.30	B(S)	20%	$0.30
23% Impervious	C(L)	27%	$0.45	C(S)	30%	$0.45
18% Impervious	D(L)	27%	$0.60	D(S)	40%	$0.60
13% Impervious	E(L)	35%	$0.75	E(S)	50%	$0.75
8% Impervious	F(L)	40%	$0.90	F(S)	60%	$0.90
3% Impervious	G(L)	47%	$1.05	G(S)	70%	$1.05
Grass and pasture	H(L)	51%	$1.14	H(S)	71%	$1.14
12", no veg., 75% routed	I(L)	-	-	I(S)	75%	$4.27
6", no veg., 75% routed	J(L)	-	-	J(S)	72%	$2.15
12 ", 50% veg., 75% routed	K(L)	-	-	K(S)	72%	$2.15
6 ", 50% veg., 75% routed	L(L)	-	-	L(S)	67%	$1.08
12", no veg., 50% routed	M(L)	-	-	M(S)	53%	$4.27
6", no veg., 50% routed	N(L)	-	-	N(S)	51%	$2.15
12 ", 50% veg., 50% routed	O(L)	-	-	O(S)	51%	$2.15
6 ", 50% veg., 50% routed	P(L)	-	-	P(S)	49%	$1.08
12", no veg., 100% routed	Q(L)	-	-	Q(S)	96%	$4.27
6", no veg., 100% routed	R(L)	-	-	R(S)	90%	$2.15
12 ", 50% veg., 100% routed	S(L)	-	-	S(S)	90%	$2.15
6 ", 50% veg., 100% routed	T(L)	-	-	T(S)	84%	$1.08
Woods	U(L)	64%	$1.18	U(S)	74%	$1.18
Meadow	V(L)	-	-	V(S)	79%	$1.17
Brush	W(L)	-	-	W(S)	83%	$1.17
Bioretention Cell	X(L)	47%	$2.41	X(S)	-	-

In Saginaw, when historic precipitation data is considered, transitioning the land use to brush (cost of $1,170,000) is estimated by SWMM reduce the runoff by 97% and 83% for B soils and D soils, respectively. For the same estimated conceptual costs, the SWMM model estimated that transitioning the land use to a meadow would reduce the runoff by 94% and 79% for B soils and D soils, respectively. Transitioning the land use to wooded area (cost of $1,178,000) is estimated to in SWMM reduce runoff by 94% for B soils and 74% for D soils, and by 83% for B soils and 64% for D soils in L-THIA. Transitioning the land use to grass (cost of $1,140,000 for an area of 0.16 square miles) is estimated in SWMM to reduce runoff by 92% for B soils and 71% for D soils, and by 71% for B soils and 51% for D soils in L-THIA. The bioretention cell with a 6-inch storage, dense vegetation, and 100% of water routed to the bioretention cell (cost of $1,083,000) is estimated in SWMM to reduce the runoff by 87% and 84% for B soils and D soils, respectively.

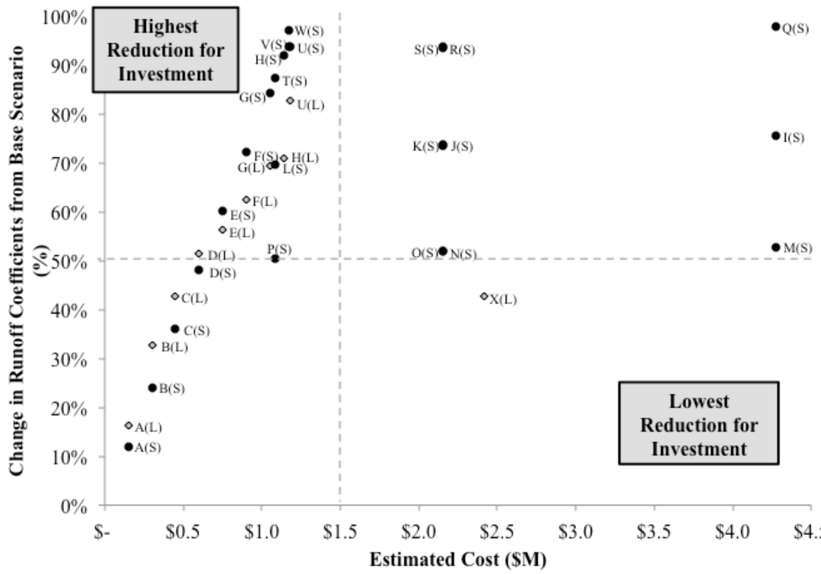


Figure 6.35. Runoff reduction versus financial investment for Saginaw (B soils)

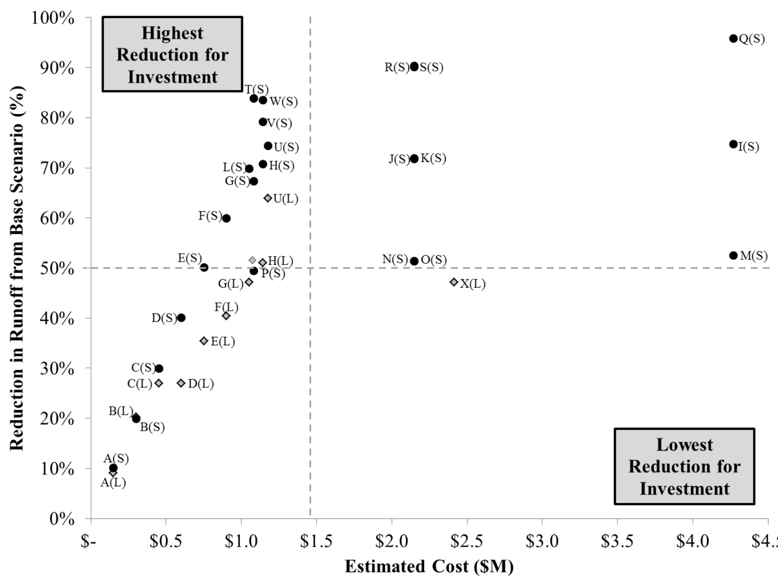


Figure 6.36. Runoff reduction versus financial investment for Saginaw (D soils)

6.5.3. Implications of the Return on Investment Analyses

The return on investment analyses for Flint and Saginaw produced consistent results in terms of the ratio of the alternatives' reduction of runoff to the conceptual costs. In general, decommissioning all impervious surfaces and transitioning land uses from residential to natural landscapes is the most effective retooling alternative for reducing runoff per dollar spent, regardless of soil type. Brush landscape had the highest return on investment for transitioning land uses, followed by meadow, woods and grass/pasture. For B/C soils, all transitioning land use alternatives were within a 5% range for reduction of runoff in Flint and Saginaw. For D soils, all transitioning land use alternatives were within a 10% range for reduction of runoff in both case studies.

Due to the low, initial runoff estimate and the inability to design individual bioretention cells for the area, the percent change in runoff is understated in L-THIA, as compared to percent change in runoff estimates in SWMM. Based on SWMM estimates, the bioretention cell providing the highest return is the 6-inch storage, with dense vegetation, and 100% of the runoff routed to the cell, for both Saginaw and Flint, regardless of soil type.

Depending on the goals of the city one retooling alternative may be more appropriate/appealing than another. For instance, if the goal is solely reducing the runoff, bioretention cell may be the ideal alternative. Whereas, if the city plans to transition the vacant land to a community green space or to improve aesthetics, decommissioning all impervious surfaces and transitioning to grass may be the alternative that accomplishes the goals.

6.6. Validation and Verification

This model was validated and verified using three steps: conceptual model validation, computerized model verification, operational validation (see Table 6.10). The first meetings for validation and verification occurred in October 2014 with five subject matter experts (SMEs) from Flint and Saginaw who were asked to provide feedback on difference aspects of the stormwater infrastructure analysis. The average of the quantitative values for the assessment of different model components are shown in Table 6.11. The experts had a minimum of 15 years experience working with the city water or wastewater utilities in operations or management roles. In March 2015, the validation and verification process was repeated with 4 subject matter experts from the same two cities, with SMEs that had a minimum of 10 years working with urban planning or city water or wastewater utilities in operations or management roles. The SMEs validated the conceptual model for the assumptions and representation of the underground infrastructure and topology of the land. The operational validation was accomplished by confirming that results were consistent across case studies and with published literature (see

Table 6.12). Furthermore, the SMEs confirmed that the reductions of runoff were confirmed to be reasonable.

Table 6.10. Validation and verification steps

Validation and Verification Components	Justification
Data Validity (Sargent 2004) Data is correct, reliable, and able to sufficiently represent system or population	Data used is provided by the cities, and published literature from reliable sources (e.g., NCDC 2014; USDA: NRCS 2013, Baird and Jennings 1996).
Conceptual Model Validation (Sargent 2004) The theories, assumptions, and representations of the problem are accurate	The final model was validated for the assumptions and representation of the infrastructure by 5 SMEs in Flint and Saginaw. Specific quantitative scores for the validation of the final model may be found in Table 6.11.
Computerized Model (Sargent 2004) The computer model accurately represents the conceptual model	The results were consistent across case studies, the final model was validated that is accurately represents infrastructure system discussed conceptually by 5 SMEs in Flint and Saginaw. Specific quantitative scores for the validation of the final model may be found in Table 6.11.
Operational Validity (Sargent 2004) The behavior of the model accurately represents the system	The model's results were consistent across case studies and the status quo alternative was verified by published literature. The final model was validated that the behavior of the model, in terms of the reductions of runoff, is reasonable by 5 SMEs in Flint and Saginaw. Specific quantitative scores for the validation of the final model may be found in Table 6.11.
Operational Validity (Sargent 2004)**:** **Degenerate Tests** Behavior of model responds appropriately to changes in parameters	Three types of retooling alternatives were evaluated, namely, decommissioning impervious surfaces, transitioning land uses, and incorporating bioretention cells. The results from the retooling alternatives were reasonable in comparison to the status quo/base alternative.
Operational Validity (Sargent 2004)**:** **Extreme Condition Tests** The model behaves appropriately when the extreme ends of ranges for parameters is used	The model estimated the quantity of runoff appropriately when all impervious surfaces were decommissioned, as well as when the synthetic storms were incorporated into the model.
Operational Validity (Sargent 2004)**:** **Internal Validation** Multiple run replications occur to ensure consistency	Multiple simulations with the base model were performed to ensure model stability.

Table 6.11. Quantitative feedback from SMEs for validation and verification purposes

Aspect of the Stormwater Model	Averages*
The components of the model represent the most critical aspects of the system needed for modeling the goal.	**4.6**
The behavior of the model is reasonable.	**4.6**
The theories and assumptions underlying the model are correct.	**4.6**
The model's representation of the system is reasonable.	**5**
The assumptions regarding the model's parameters and variables are reasonable.	**4.4**

Table 6.11. *(continued)*

Aspect of the Stormwater Model	Averages*
The level of detail used for the model is appropriate for the intended purpose of providing information regarding the impact of decommissioning and LID alternatives on generated runoff.	**4.4**
The output of the model has the accuracy required for the model's intended purpose.	**4.6**
The model could be helpful for stormwater management and produces useful results.	**5**

**(1: poor, 2: needs significant improvements, 3: needs modifications to be useful, 4: good enough, 5: excellent)*

Table 6.12. External validation

Relevant findings	Study
Status quo/base model runoff comparable for land use and percentage of impervious surfaces	Gironás et al. (2009); MDOT (2006)
Decommissioning impervious surfaces can reduce the generated runoff	USEPA (2014)
Percentage of reduced runoff in bioretention cells (45-99% dependent on study) aligns with estimated runoff reductions post bioretention cell implementation	Davis (2008); Hunt et al. (2008); Chapman and Horner (2010); DeBusk and Wynn (2011)
During small precipitation events, bioretention cells modeled were capable of capturing inflows, consistent with the findings for 10 minute storms from this study	Davis (2008)
Sizing of and density/choice of vegetation impact the performance of the bioretention cell, consistent with findings in this study	Davis et al. (2009); Brown and Hunt (2012)

6.7. Summary

Chapter 6 evaluates the impact of retooling scenarios using SWMM and L-THIA to examine how retooling alternatives may impact the generated stormwater runoff based on: (1) historic county/local data, (2) 2-year, 24-hour storm, (3) 10-year, 24-hour, storm, (4) 2-year, 10-minute storm (Saginaw only), and (5) 10-year, 10-minute, storm (Saginaw only). Three categories of retooling alternatives for stormwater decommissioning were evaluated:

1) Decommissioning impervious surfaces.
2) Transitioning land uses.
3) Incorporating bioretention cells at the neighborhood/lot level, with runoff from the candidate area diverted to the bioretention cell.

As expected, all retooling alternatives did reduce the generated runoff within the analysis area. L-THIA understated the total generated runoff considerably in comparison to SWMM. The ratio of runoff to precipitation estimated in SWMM for the residential zoning aligned with literature, whereas L-THIA's estimated ratios of runoff to precipitation were much lower. The lower ratios of runoff to precipitation in L-THIA may be a result of the generalized assumptions of the region, as opposed to area specific models, the precipitation data based on daily averages as opposed to more granular 30-minute increments, or the inability of the tool to incorporate local subsurface drainage systems (i.e., stormwater/wastewater infrastructures). Although, the magnitude of runoff varied between the two tools, the percentage change between the status quo/base model and different retooling alternatives are comparable. Therefore, while the SWMM and L-THIA differ in estimates of the total runoff, we can generalize that the impact *between* alternatives is similar.

In the context of decommissioning pavement and transitioning land uses, the higher the percentage of impervious surfaces that were decommissioned, the greater the reduction in the runoff for local precipitation data, for all storms evaluated. The land use transformations assume that all impervious surfaces have been decommissioned and the land is undergoing transition. Between the land transformation alternatives of grass/pasture and woods (the two options evaluated using both tools), transitioning the land to forest or woods has the greatest potential for reduction in runoff. The land use options meadow and brush were also evaluated in SWMM, with brush yielding the highest reduction of runoff for all land uses, across both tools. Brush and meadow land uses were not assessed in L-THIA since L-THIA does not include these options. In Saginaw, due to the future land use designation of transition to the "Green Zone", grass/pasture may be more desirable, and does have a high reduction in runoff, as well. .

Both LTHIA and SWMM assumed that decommissioning had not occurred prior to implementing the bioretention cell. The bioretention cells evaluated using SWMM were customized based on different percent routing of runoff, storage depth, and presence of vegetation. The bioretention cell modeled using L-THIA could not be customized. The results of the analysis using L-THIA consistently estimated a lower impact due to incorporating a bioretention cell on the generated runoff in comparison to SWMM. In SWMM, the storage area and percentage of runoff routed to the cell were the most influential factors determining the bioretention cell's effectiveness of reducing runoff. The greater the percentage of runoff routed to the cell, as well as the greater the storage area, the better the bioretention cell performed during typical precipitation patterns, as well as, during the storms. When viewing the percent change in runoff from the status quo, L-THIA consistently estimated a much smaller impact than SWMM for both cities. The minimal change in runoff estimated by L-THIA was a 10% reduction in the runoff, estimated for B/C soils in Flint. The maximum change in Flint was a 43% change in the runoff for D soils in Saginaw.

In general, decommissioning all impervious surfaces and transitioning land uses from residential to natural landscapes is the most effective retooling alternative for reducing runoff per dollar spent, regardless of soil type. Brush landscape had the highest return on investment for transitioning land uses, followed by meadow, woods, and finally, grass/pasture. Based on SWMM estimates and conceptual costs, the bioretention cell providing the highest return is the 6-inch storage, with dense vegetation, and 100% of the runoff routed to the cell. Depending on the goals of the city one retooling alternative may be more appropriate/appealing than another.

This study demonstrates that retooling alternatives are a viable method for reducing the generated stormwater runoff and allow for infiltration or treatment onsite. Within shrinking cities, there is potential to transition land uses and incorporate these retooling alternatives to improve the aesthetics of the area and to aid in decreasing the number of overflows and volume of each overflows occurring in the city. By reducing the generated runoff, the strain on the wastewater treatment plant served by the city during wet weather events can be reduced, to mitigate the necessity of expanding the plant or underground infrastructure to comply with the Clean Water Act. For instance, 7.5 million gallons per day of stormwater enters Saginaw's wastewater treatment plant. During wet weather the plant may reach capacity, causing combined sewer overflows that may be mitigated through reducing the generated runoff from vacant and abandoned land.

The effectiveness of re-zoning and transforming land, as well as incorporating bioretention cells to proactively manage underutilized infrastructure was analyzed in this study. Previous literature discusses the impact of decommissioning underutilized impervious surfaces in shrinking cities (e.g., Hendrickson 2009; Burkholder 2012; USEPA 2014) without quantifying the impacts of such retooling alternatives. This study presents an approach for quantifying the impact of retooling alternatives on the generated runoff. This approach can assist cities on combined sewer systems to analyze possible methods to reduce the runoff entering the infrastructure systems, possibly reducing the volume of or frequency of overflows. When cities cannot afford the financial investment to separate combined sewers, implementing retooling alternatives may be a cost effective method for reducing the strain on the wastewater treatment plant.

The findings from this study can assist cities operating on separate sewer systems by providing strategies for reducing the runoff and non-point source pollutants from entering the stormwater system, thereby improving the water source quality. The viability of retooling alternatives was analyzed using open-source software, thus providing fiscally strained cities an economical option for analyses. Furthermore, quantifying the area needed for bioretention cells in terms of vacant lots provides a reference to the relative area necessary per city block to accomplish the reductions in runoff.

CHAPTER 7. GAUGING PUBLIC VIEWS TOWARDS WATER AND WASTEWATER ISSUES AND RETOOLING ALTERNATIVES

"Water management is constrained by physical characteristics, regulation, contracts, and politics. Thus, integral water management needs to be pluralistic, involving multiple stakeholders who represent multiple perspectives."

-van der Brugge et al. 2005

Local governing agencies responsible for making decisions regarding public utilities often face the difficult task of acquiring and maintaining stakeholder support for their decisions. To better understand the views of the general public in shrinking cities, a survey was deployed to assess the perceptions, knowledge, awareness, and attitudes regarding water and wastewater infrastructure issues and infrastructure retooling alternatives in shrinking cities. Sudarmadi et al. (2001) defines the concepts explored via this survey as follows:

(1) Perception: the ability to perceive issues in the real world, based on memory and influenced by prior experience (e.g., "I have water quality issues in my neighborhood").
(2) Knowledge: the understanding of the body of facts and principles concerning the issues (e.g., "I know the cause of the water quality issue").
(3) Awareness of issues: the attention, concern, and sensitivity to the issue (e.g., "I think water quality in my neighborhood is a serious problem").
(4) Attitude towards the issues: the values and feelings of concern and the motivation for actively participating in support or opposition (e.g., "I think water quality requires attention").

The results of the qualitative and quantitative analyses are presented in this chapter. The IRB approval, full survey, and specific statistics that are not shown in Section 7.1 accompanying respective graphs may be found in Appendices E, F, and G. Many of the graphs shown in Section 7.1 are composed of two parts. The first graph depicts the break down of the responses on a five-point scale (*strongly disagree/oppose, disagree/oppose, neutral, agree/support, strongly agree/support*) with a sixth option being "*I do not know*." The option *"I do not know"* allowed for respondents who did not feel confident in responding to the question or were undergoing decision paralysis, to opt out of answering without skipping the question or skewing the results. The second graph shows the same results, collapsed from a scale spanning *strongly oppose* to *strongly agree*, to binary responses, illustrating *strongly oppose/disagree*, *oppose/disagree*, and *I do not know* and *strongly agree/support*, *agree/support*, and *neutral*. Often of interest for discussion with policy and decision-makers are those individuals who may pose opposition (easily viewed in the collapsed, binary graphs) and how to potentially mitigate that opposition.

Statistical modeling was used to identify significant parameters influencing the support or opposition towards different water infrastructure retooling alternatives (discussed in Sections 7.2 and 7.3). Understanding the sources of opposition and identifying retooling alternatives that have an increased likelihood of support may facilitate the incorporation of the community's vision and public participation in the selection of retooling alternatives.

7.1. Descriptive Survey Statistics

Four hundred and fifty-five (455) complete surveys were collected from the 21 US shrinking cities. Of the respondents, approximately 60% were male and approximately half were over the age of 50 years old. A majority of respondents had either a high school diploma or a college degree and had an individual annual income of less than $35,000. Fifty-eight percent (58%) and 60% of the respondents were born in or raised in the city currently residing in, respectively. Descriptive statistics of the significant demographic variable in the statistical models are shown in Table 7.1.

Table 7.1. Survey sample pool demographics

CHARACTERISTIC	MIN/ MAX	AVE.	ST. DEV.
Individual Characteristic			
Male (1 if male, otherwise 0)	0/1	0.61	0.49
Marital Status			
Single (1 if single, otherwise 0)	0/1	0.36	0.48
Married (1 if married, otherwise 0)	0/1	0.45	0.50
Civil union (1 if in a civil union, otherwise 0)	0/1	0.04	0.20
Divorced (1 if divorced, otherwise 0)	0/1	0.12	0.33
Separated (1 if separated, otherwise 0)	0/1	0.02	0.15

Table 7.1. (*continued*)

CHARACTERISTIC	MIN/ MAX	AVE.	ST. DEV.
Age			
18-25 years old (1 if 18-25 years old, otherwise 0)	0/1	0.09	0.28
26-35 years old (1 if 26-35 years old, otherwise 0)	0/1	0.20	0.40
36-50 years old (1 if 36-50 years old, otherwise 0)	0/1	0.24	0.43
over 50 years old (1 if over 50 years old, otherwise 0)	0/1	0.47	0.50
Highest Level of Education			
Some high school (1 if some high school is highest level of education, otherwise 0)	0/1	0.03	0.17
High school diploma (1 if high school diploma is highest level of education, otherwise 0)	0/1	0.34	0.47
Technical college degree (1 if technical college degree is highest level of education, otherwise 0)	0/1	0.16	0.37
College degree (1 if college degree is highest level of education, otherwise 0)	0/1	0.35	0.48
Post Graduate Degree (1 if post graduate degree is highest level of education, otherwise 0)	0/1	0.12	0.33
Respondent Approximate Income			
No Income (1 if respondent has no income, otherwise 0)	0/1	0.08	0.27
Under $19,999 (1 if respondent income is less than $19,999, otherwise 0)	0/1	0.26	0.44
$20,000-$34,999 (1 if respondent income is between $20,000-$34,999, otherwise 0)	0/1	0.24	0.42
$35,000-$49,999 (1 if respondent income is between $35,000-$49,999, otherwise 0)	0/1	0.17	0.38
$50,000-$74,999 (1 if respondent income is between $50,000-$74,999, otherwise 0)	0/1	0.87	0.34
$75,000-$99,999 (1 if respondent income is between $75,000-$99,999, otherwise 0)	0/1	0.06	0.24
$100,000 and above (1 if respondent income is greater than $100,000, otherwise 0)	0/1	0.04	0.21
Employment Status			
Employed for wages or salary (1 if employed for wages or salary, otherwise 0)	0/1	0.41	0.49
Self-employed (1 if self-employed, otherwise 0)	0/1	0.09	0.29
Out of work and looking for work (1 if out of work and looking for work, otherwise 0)	0/1	0.05	0.22
Out of work and not currently looking for work (1 if out of work and not looking for work, otherwise 0)	0/1	0.01	0.11
Homemaker (1 if a homemaker, otherwise 0)	0/1	0.13	0.33
Student (1 if a student, otherwise 0)	0/1	0.06	0.24
Retired (1 if a retired, otherwise 0)	0/1	0.21	0.41
Unable to work (1 if a unable to work, otherwise 0)	0/1	0.10	0.30
Primary Source of News			
Newspaper (1 if primary source of news is the newspaper, otherwise 0)	0/1	0.36	0.48
Internet (1 if primary source of news is the Internet, otherwise 0)	0/1	0.66	0.47
Television (1 if primary source of news is the television, otherwise 0)	0/1	0.75	0.43
Radio (1 if primary source of news is the radio, otherwise 0)	0/1	0.26	0.44
Social media (1 if primary source of news social media, otherwise 0)	0/1	0.15	0.36

Table 7.1. (*continued)*

CHARACTERISTIC	**MIN/ MAX**	**AVE.**	**ST. DEV.**
Other			
Grew-up in city currently reside in (if grew-up in the city currently residing in, otherwise 0)	0/1	0.60	0.49
Born in city currently reside in (if born in the city currently residing in, otherwise 0)	0/1	0.58	0.49
Number of years lived in city currently reside in (years)	0.25/ 80	32.94	20.69
Responsible for water bill (1 if responsible for water bill, otherwise 0)	0/1	0.71	0.45
Household Characteristics			
Household Approximate Income			
Under $19,999 (1 if household income is less than $19,999, otherwise 0)	0/1	0.03	0.18
$20,000-$34,999 (1 if household income is between $20,000-$34,999, otherwise 0)	0/1	0.16	0.37
$35,000-$49,999 (1 if household income is between $35,000-$49,999, otherwise 0)	0/1	0.18	0.39
$50,000-$74,999 (1 if household income is between $50,000-$74,999, otherwise 0)	0/1	0.17	0.38
$75,000-$99,999 (1 if household income is between $75,000-$99,999, otherwise 0)	0/1	0.23	0.42
$100,000 and above (1 if household income is greater than $100,000, otherwise 0)	0/1	0.12	0.32
Under $19,999 (1 if household income is less than $19,999, otherwise 0)	0/1	0.10	0.30
Classification of Area Reside In			
Urban (1 if reside in an urban area, otherwise 0)	0/1	0.40	0.49
Suburban (1 if reside in a suburban area, otherwise 0)	0/1	0.50	0.00
Rural (if reside in a rural area, otherwise 0)	0/1	0.08	0.28
Ownership of Household			
Mortgage or loan (1 if household is owned via a mortgage or a loan, otherwise 0)	0/1	0.47	0.50
Owned free and clear (1 if household is owned free and clear, otherwise 0)	0/1	0.20	0.40
Rented (1 if household is rented, otherwise 0)	0/1	0.31	0.46
Other			
First household owned (1 if household is the first household owned, otherwise 0)	0/1	0.36	0.48
Length of time owning household (years)	0/1	16.23	13.64
Number of people living in household (people)	1/9	2.59	1.34
Number of children under the age of 18 living in household (children under the age of 18)	0/5	0.56	0.93
Number of children under the age of 5 living in household (children under the age of 5)	0/3	0.17	0.49
Number of cars in household (cars)	0/8	1.49	0.93

While it may seem obvious that residents of shrinking cities would be aware of a shrinking city when residing in one, people's perspectives are often drawn from observations made by highly localized conditions. Shrinking cities often have several sub-areas that experience stability or even robust growth, and people in these subareas may have a very different view of infrastructure issues. The survey distributed to residents of the shrinking cities did not specify that the targeted sample consisted of residents in cities experiencing urban decline, but merely stated that the survey was investigating public perceptions of water infrastructure. A question posed at the beginning of the survey was, "In the past four decades, my city has: decreased in population; had no change in population; increased in population; or I do not know." As shown in Figure 7.1, only 53.9% of the residents were aware that population decline had occurred in their city[8].

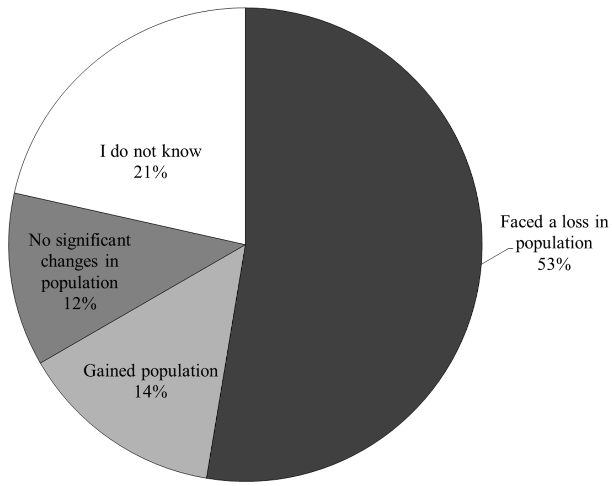


Figure 7.1. Survey respondents' awareness of population dynamics in his/her city

Another interesting finding arising from the final survey results is that over 70% of the survey respondents indicated that they would be willing to pay higher rates for improved water or wastewater services (Figure 7.2) that may be potentially achieved via implementing the infrastructure retooling alternatives. However, although there is a willingness to pay higher rates, a majority of respondents did not know their water and wastewater utilities are financially self-sustaining services or are fiscally strained (shown in Figure 7.3). This may point out a communication gap between the public and the utility providers in understanding how the service is provided from a financial standpoint and the impact of fewer consumers on the per capita water and wastewater infrastructure systems costs. Furthermore, only 20% of respondents stated that they trusted their utility providers to make decisions in their (the customers') best interest. Outreach targeting the decision-makers' reasoning behind decisions may mitigate potential opposition from residents who are resistant to implementing changes, such as changes to the existing physical infrastructure system or service prices.

[8] Paragraph adapted from Faust et al. (2015b)

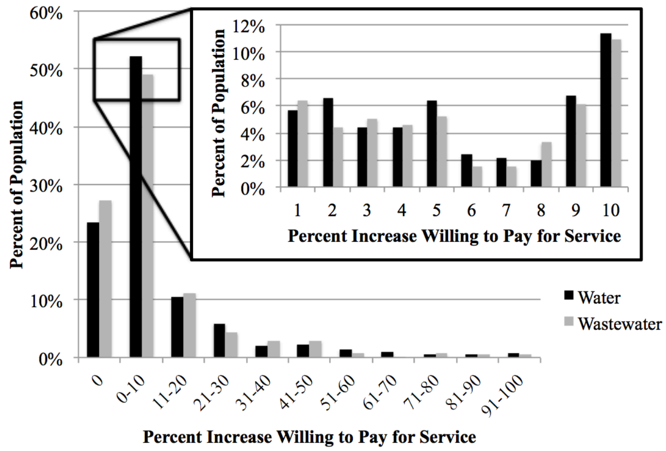
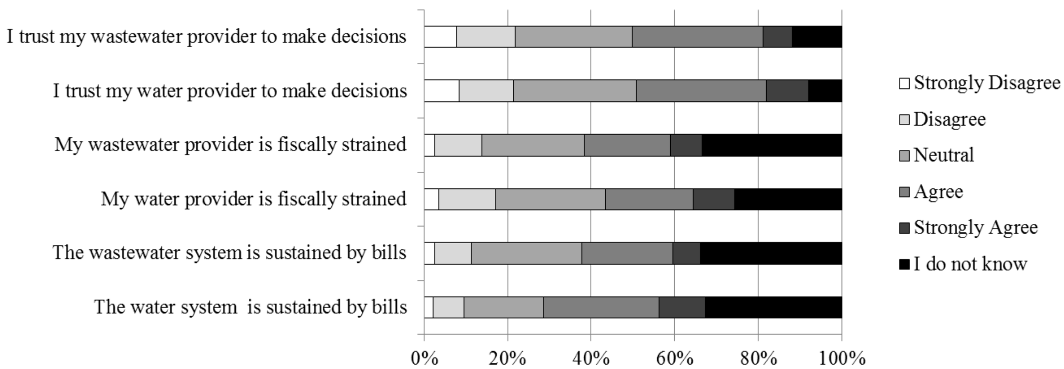
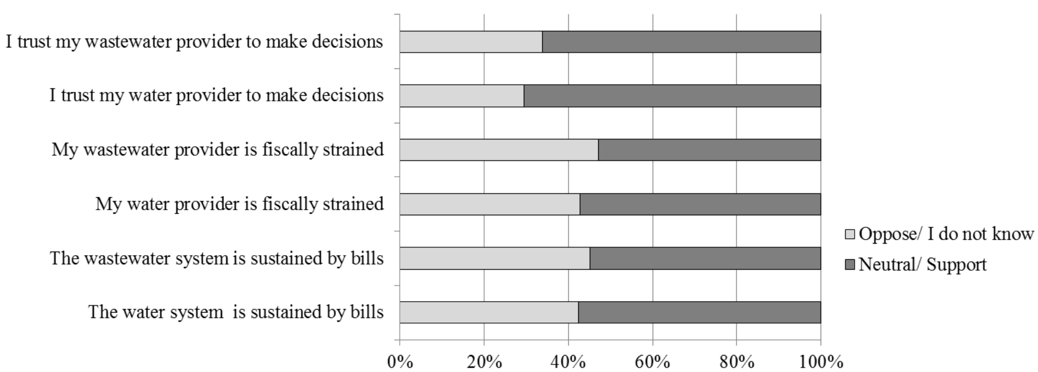


Figure 7.2. Willingness to pay for service



(a)



(b)

Figure 7.3. Water and wastewater questions regarding utility providers: (a) Expanded responses and (b) Collapsed, binary responses

The survey data indicated that there is support for implementing water and wastewater/stormwater infrastructure retooling alternatives (Figures 7.4 and 7.5). However, when asked directly what the respondent's *thinks* should be done in his or her city, the responses are drastically different, as shown in Figure 7.6, which captures the attitude towards select water infrastructure alternatives. The differences between attitudes and perceptions may be capturing factors such as, the NIMBY theory ("not in my backyard"), or simply that the respondent does not have a strong preference for a specific alternative. The attitude question was posed as a binary question, *agree* or *disagree*, to avoid decision paralysis and force a stance that is often missed when questions are posed on a multi-point scale with a *neutral* or *I do not know* option (Tversky and Shafir 1992). A simple example highlighting the difference between perception and attitude may be the installation of a wastewater treatment plant in a city. A resident in the city of the proposed plant may support the effort ("I support that effort of expanding the wastewater treatment capacity of my city") but would not necessarily seek its siting in his/her neighborhood ("I do not want a wastewater treatment plant adjacent to my neighborhood, viewable from my window").[9]

Understanding these perceptions and attitudes among the public towards a decision could aid in transitioning management practices or implementing infrastructure retooling alternatives by mitigating opposition and incorporating decisions that reflects the community vision. It should be noted that the views expressed in Figures 7.4-7.6 illustrate a snapshot in time of the public attitude and perception. Attitude and perceptions are dynamic, changing with external factors such as, additional information, experience, education, and outreach.

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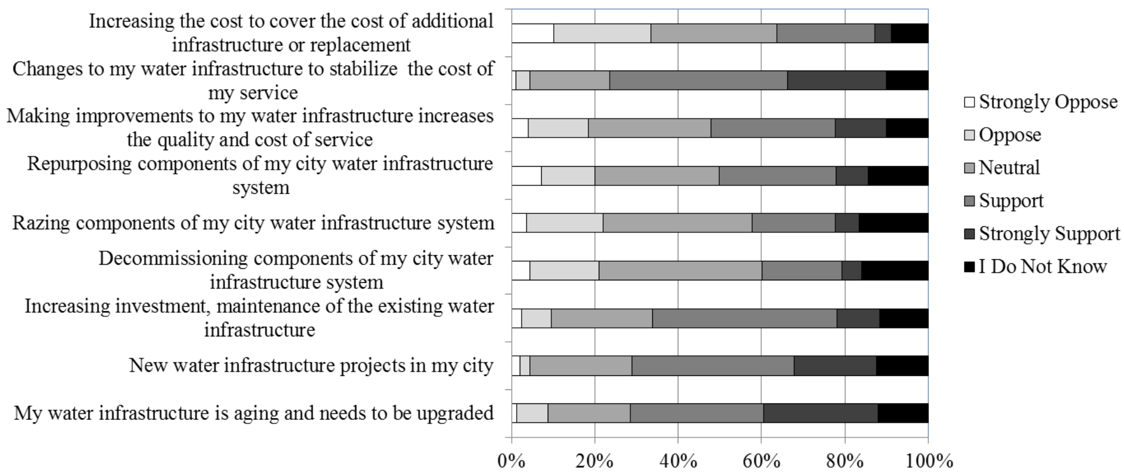
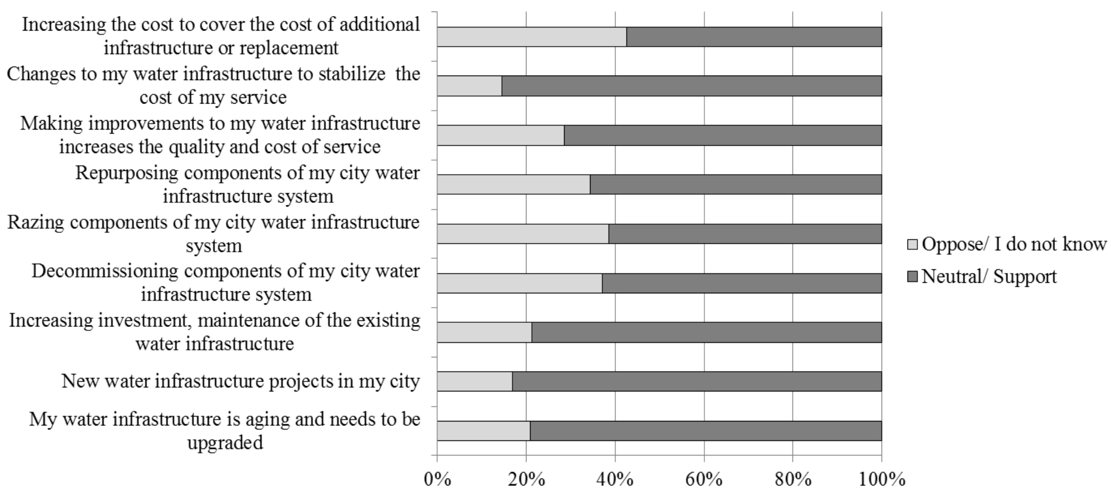
[9] Paragraph adapted from Faust et al. (2015a)

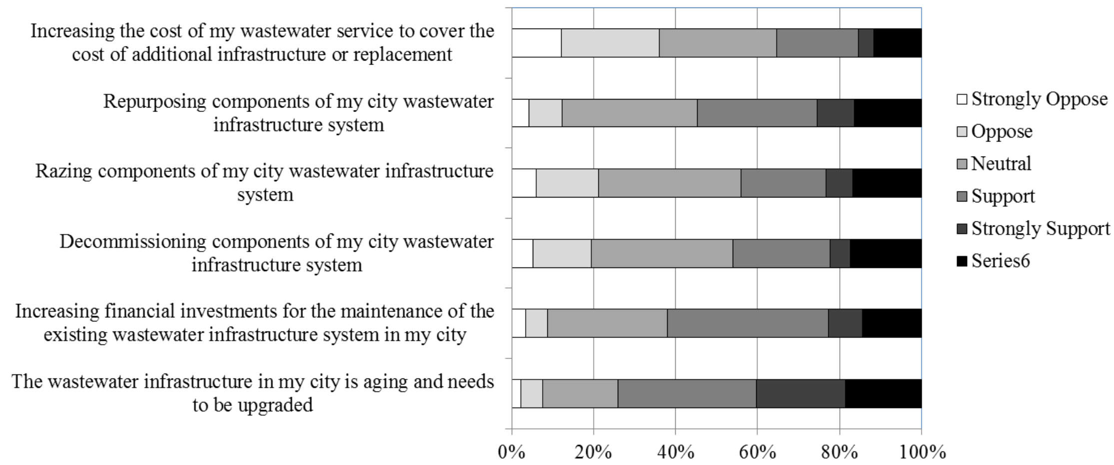


(a)

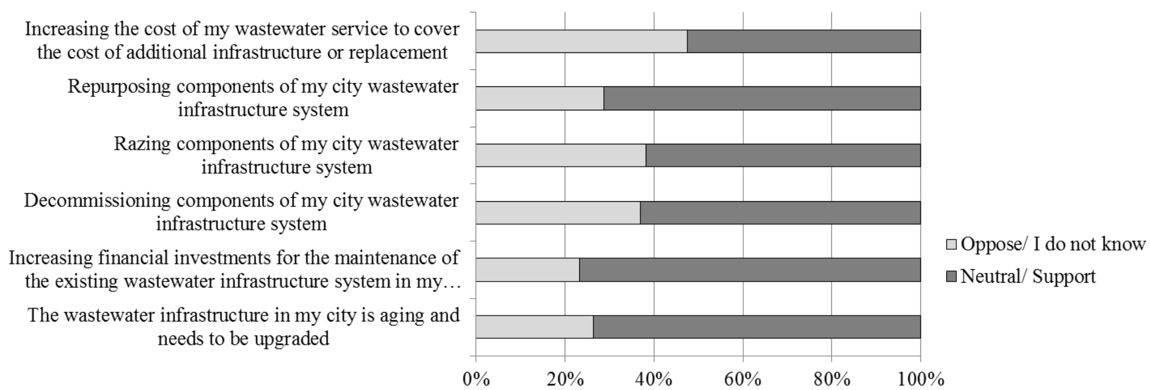


(b)

Figure 7.4. Responses regarding perceptions of water infrastructure retooling alternatives: (a) Expanded responses and (b) Collapsed, binary responses



(a)



(b)

Figure 7.5. Responses regarding perceptions of wastewater/stormwater infrastructure retooling alternatives: (a) Expanded responses and (b) Collapsed, binary responses

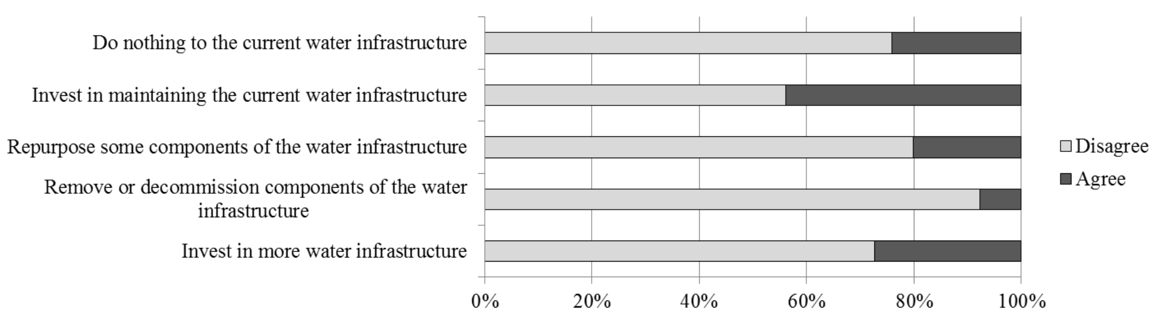


Figure 7.6. Responses regarding attitude towards select water infrastructure retooling alternatives

7.2. Attitude towards implementing specific water infrastructure alternatives[10]

Five water infrastructure management alternatives were explored to understand the attitudes of the shrinking city residents towards these alternatives. In the survey, each respondent was asked which alternatives of the following retooling alternatives should be implemented in his/her city:

1. Invest in expanding the current infrastructure footprint.
2. Raze or decommission infrastructure.
3. Repurpose infrastructure.
4. Invest in maintenance of current infrastructure.
5. Do nothing.

7.2.1. Statistical Modeling of Attitudes Results

Binary probit models were used to quantify the significant variables that increase the tendency towards agreeing (disagreeing) with the implementation of specific management. In Table 7.2, a positive (negative) parameter indicates an increased likelihood of agreeing (disagreeing) with the respective alternative. The marginal effects are shown in Table 7.3.

Table 7.2. Significant parameters for survey responses to the statement "I think my city should…" as determined by the binary probit models

	Invest in More Infrastructure	*Raze or Decommission Infrastructure*	*Repurpose Infrastructure*	*Invest in Maintenance of Current Infrastructure*	*Do Nothing*
Independent Variable	**Parameter (t-statistic)**	**Parameter (t-statistic)**	**Parameter (t-statistic)**	**Parameter (t-statistic)**	**Parameter (t-statistic)**
Constant	-0.855 (-8.644)	-1.652 (-8.701)	-1.766 (-6.186)	-0.908 (-3.090)	0.751 (2.231)
Gender (1 if male, otherwise 0)	-	-	0.284 (1.918)	-	-
Age (1 if over 50, otherwise 0)	-	-	-.0477 (-3.252)	-	-
Age (1 if less than 35, otherwise 0)	-	-	-	0.458 (2.029)	-0.456 (-1.893)
Income indicator (1 if less than $35,000, otherwise 0)	0.239 (1.704)	-	-	-	-0.284 (-1.825)
Employment status (1 if out of work and looking for work, otherwise 0)	-	-	-	0.564 (2.043)	-
Employment status (1 if retired, otherwise 0)	-	-	-	-	-0.328 (-1.819)
Identified race (1 if Black or African American, otherwise 0)	0.477 (2.877)	-	-	-0.386 (-2.394)	-

[10] Section adapted from Faust et al. (2015a)

Table 7.2. *(continued)*

	Invest in More Infrastructure	***Raze or Decommission Infrastructure***	***Repurpose Infrastructure***	***Invest in Maintenance of Current Infrastructure***	***Do Nothing***
Relationship Status (1 if single, divorced, or separated, otherwise 0)	-	-	0.282 (2.016)	-	-
Ownership of household (1 if someone in the household rents the household, otherwise 0)	-0.370 (-2.372)	-	-	-	-
Ownership of household (1 if someone in the household owns the house with a loan or mortgage, otherwise 0)	-	-	-	-	0.332 (2.285)
Number of cars in the household (cars)	-	-	-	-	-0.247 (-2.820)
Cars in the household indicator (1 if household has cars, otherwise 0)	-	-	-	0.375 (1.800)	-
Cars in the household indicator (1 if household has more than two cars, otherwise 0)	-	0.490 (1.917)	-	-	-
Indicator that city currently residing in is the same as grew up in (1 if grew up in the city currently residing in, otherwise 0)	-	-	-	-	-0.331 (-2.444)
Responsible for water bill indicator (1 if responsible, otherwise 0)	-	-	-	-	-0.422 (-2.708)
Primary news source (1 if social media, otherwise 0)	0.453 (2.599)	-	-	-	-
Primary news source (1 if internet, otherwise 0)	-	0.357 (1.713)	0.359 (2.261)	-	-0.355 (-2.462)
Primary news source (1 if newspaper, otherwise 0)	-	-	-	0.276 (2.176)	-
Primary news source (1 if television, otherwise 0)	-	-	0.311 (1.802)	-	-
Frequency of following the news (1 if daily, otherwise 0)	-	-	0.377 (1.913)	-	-
Cleveland, Ohio indicator (1 if currently residing in Cleveland, otherwise 0)	0.454 (2.419)	-	-	-	-
Flint, Michigan indicator (1 if currently residing in Flint, otherwise 0)	-	0.601 (1.713)	-	-	-
Gary, Indiana indicator (1 if currently residing in Gary, otherwise 0)	0.702 (1.693)	-	-	-	-
Ohio State indicator (1 if currently residing in Ohio, otherwise 0)	-	-0.510 (-2.265)	-	-	-

Table 7.2. *(continued)*

	Invest in More Infrastructure	***Raze or Decommission Infrastructure***	***Repurpose Infrastructure***	***Invest in Maintenance of Current Infrastructure***	***Do Nothing***
Pennsylvania State indicator (1 if currently residing in Pennsylvania, otherwise 0)	-	-	-	-0.402 (-1.984)	-
Scranton, Pennsylvania indicator (1 if currently residing in Scranton, otherwise 0)	-	-	-	-	0.679 (1.763)
Trenton, New Jersey indicator (1 if currently residing in Trenton, otherwise 0)	0.824 (2.047)	-	-	-1.318 (-2.355)	-
Log Likelihood	*-250.691*	*-114.9553*	*-213.1905*	*-296.415*	*-231.8582*
AIC	*517.704*	*240.044*	*440.631*	*609.154*	*484.211*
BIC	*550.345*	*260.510*	*469.223*	*641.792*	*524.920*

Table 7.3. Marginal effects for survey responses to the statement "I think my city should…" as determined by the binary probit models

	Invest in More Infrastructure	**Raze or Decommission Infrastructure**	**Repurpose Infrastructure**	**Invest in Maintenance of Current Infrastructure**	**Do Nothing**
Gender (1 if male, otherwise 0)	-	-	~~0.074~~	-	-
Age (1 if over 50, otherwise 0)	-	-	-0.126	-	-
Age (1 if less than 35, otherwise 0)	-	-	-	0.170	-0.153
Income indicator (1 if less than $35,000, otherwise 0)	0.080	-	-	-	-0.082
Employment status (1 if out of work and looking for work, otherwise 0)	-	-	-	0.221	-
Employment status (1 if retired, otherwise 0)	-	-	-	-	-0.090
Identified race (1 if Black or African American, otherwise 0)	0.168	-	-	-0.147	-
Relationship Status (1 if single, divorced, or separated, otherwise 0)	-	-	0.075	-	-
Ownership of household (1 if someone in the household rents the household, otherwise 0)	-0.115	-	-	-	-
Ownership of household (1 if someone in the household owns the house with a loan or mortgage, otherwise 0)	-	-	-	-	0.099

Table 7.3. *(continued)*

	Invest in More Infrastructure	**Raze or Decommission Infrastructure**	**Repurpose Infrastructure**	**Invest in Maintenance of Current Infrastructure**	**Do Nothing**
Number of cars in the household (cars)	-	-	-	-	-0.073
Cars in the household indicator (1 if household has cars, otherwise 0)	-	-	-	0.142	-
Cars in the household indicator (1 if household has more than two cars, otherwise 0)	-	0.083	-	-	-
Indicator that city currently residing in is the same as grew up in (1 if grew up in the city, otherwise 0)	-	-	-	-	-0.100
Responsible for water bill indicator (1 if responsible, otherwise 0)	-	-	-	-	-0.133
Primary source of news (1 social media, otherwise 0)	0.160	-	-	-	-
Primary source of news (1 if internet, otherwise 0)	-	0.041	0.091	-	-0.110
Primary source of news (1 if newspaper, otherwise 0)	-	-	-	0.109	-
Primary source of news (1 if television, otherwise 0)	-	-	0.077	-	-
Frequency of following the news (1 if daily, otherwise 0)	-	-	0.090	-	-
Cleveland, Ohio indicator (1 if currently residing in Cleveland, otherwise 0)	0.162	-	-	-	-
Flint, Michigan indicator (1 if currently residing in Flint, otherwise 0)	-	0.112	-	-	-
Gary, Indiana indicator (1 if currently residing in Gary, otherwise 0)	0.263	-	-	-	-
Ohio State indicator (1 if currently residing in Ohio, otherwise 0)	-	-0.058	-	-	-
Pennsylvania State indicator (1 if currently residing in Pennsylvania, otherwise 0)	-	-	-	-0.151	-
Scranton, Pennsylvania indicator (1 if currently residing in Scranton, otherwise 0)	-	-	-	-	0.241
Trenton, New Jersey indicator (1 if currently residing in Trenton, otherwise 0)	0.311	-	-	-0.372	-

7.2.2. Discussion of Significant Parameters Impacting Attitude

When exploring viable infrastructure retooling alternatives, decision-makers may use the estimated models to identify which individuals have an increased likelihood of opposition, allowing for proactive efforts, such as outreach or incorporating participatory processes (e.g., town hall meetings, focus groups), to mitigate any potential resistance. In the statistical analyses, locations were recurring, significant variables for indicating an initial propensity to support (oppose) the implementation of specific alternatives. Consistent with the previous finding about the willingness to pay increased rates for improved reliability of service discussed in Section 7.1, individuals were willing to support implementing new retooling alternatives in their cities. Specific locations in which residents indicated support of implementation of a management alternative included:

- **Cleveland, Ohio.** Residents of Cleveland have a 0.162 increase in the probability of supporting measures to invest in more physical water infrastructure.
- **Flint, Michigan**. Residents of Flint have a 0.112 increase in the probability of supporting decommissioning or razing water infrastructure.
- **Gary, Indiana.** Residents of Gary have a 0.263 increase in the probability of supporting investing in more physical water infrastructure.
- **Scranton, Pennsylvania.** Residents of Scranton have indicated a 0.241 increase in the probability that the utility providers should maintain the status quo.
- **Trenton, New Jersey.** Residents of Trenton have indicated a 0.311 increase in the probability of supporting measures to invest in more physical water infrastructure.

The locations in which residents opposed the selected alternatives were:

- **Shrinking cities in Ohio.** Residents of shrinking cities in Ohio have a 0.058 decrease in the probability of supporting decommissioning or razing water infrastructure.
- **Shrinking cities in Pennsylvania.** Residents of shrinking cities in Pennsylvania have a 0.151 decrease in the probability of supporting the investment of maintenance of current water infrastructure.
- **Trenton, New Jersey**. Residents of Trenton have a 0.372 decrease in the probability of supporting measures that invest in the maintenance of current water infrastructure.

Location variables are important to consider for decision makers when considering viable alternatives to explore further for potential implementation. The initial propensity to support or oppose different infrastructure retooling alternatives may be due to a communication gap or lack of awareness towards issues inherent to shrinking cities. For instance, Cleveland, Gary, and Trenton were significant positive location parameters that are more likely to support investing in more infrastructure, indicating a lack of knowledge surrounding the relationship between the fixed grid infrastructure system and the declining population. This location specific information may be a conversation starter between the residents and utilities on how to move forward within the community vision, to dispel incorrect information regarding utilities in a shrinking city, or to discuss the viability of infrastructure retooling alternatives with increased likelihood of support.

Many demographics were found significant to influence the attitude towards retooling alternatives that were evaluated in the five models. It is important to note that these models capture a moment in time, when the survey was deployed, and attitudes are dynamic.

Age was a signification demographic variable, with individuals less the 35 years old being more likely to oppose the status quo/doing nothing alternative and more likely to support maintaining existing infrastructure. Conversely, individuals over the age of 50 were more likely to oppose repurposing infrastructure. These findings may be capturing a resistance to change as openness for progressive change has been shown to decline as individuals age (Westerhoff 2008).

Men are more likely to support repurposing infrastructure, possibly reflecting the importance that males can play in household incomes and decision-making (Wang et al. 2013). Additionally, individuals who are single, divorced, or separated, are more likely to support repurposing infrastructure further supporting that retooling alternatives may be viewed as a viable method to stabilize costs when living expenses are not shared amongst partners.

Individuals with incomes less than $35,000 are more likely to support increasing investment in more infrastructure and less likely to support doing nothing. African Americans in shrinking cities are more likely to support investing in more infrastructure as opposed to investing in maintaining current infrastructure. However, those individuals who are out of work are more likely to support investing in maintain infrastructure, likely recognizing this retooling alternative to be seemingly less financially burdensome on the customers/rate-payers.

Ownership of cars increased the likelihood of opposition for the ‘do nothing’ alternative. Consistent with this finding is that individuals with more than two cars were more likely to support decommissioning or razing infrastructure and individuals with any cars (more than zero) in the household were more likely to support maintaining existing infrastructure. This finding may be capturing some measure of wealth and mobility that would make these people less likely to be impacted by increasing investments for maintenance or may simply reflect the economics involved in owning additional cars which results in less disposable income and thus, motivation to find a way (decommissioning or razing infrastructure or maintain infrastructure) to stabilize future utility rates.

Ownership of homes was a significant parameter. Renters were more likely to oppose investing in more infrastructure, possibly capturing a disinterest in investing in an area that the renter is not permanently tied to or the economics involved in renting a household and having less disposable income (as discussed with car ownership). If the home is owned via a loan, the individual is more likely to support doing nothing to the water infrastructure, seemingly capturing the decrease in disposable income due to loan payments and the view that doing nothing, in the near future, will not change rates and further strain the low incomes rampant in shrinking cities.

Those responsible for their water bill were found to be less likely to support doing nothing for water infrastructure. Additionally, individuals who grew-up in the city and are retired are also less likely to support doing nothing for water infrastructure. As the average income in shrinking cities is typically below the average income for the state, these individuals may see retooling alternatives as a viable method to stabilize or reduce water service costs, one of many living expenses.

The primary source of news of the respondents was a significant variable in many models. The significance of the primary source of news may be due to the age group primarily using the medium as a source of news (e.g., radio as a primary news source is often reaching older generations as discussed by Kohut et al. (2010)), the stories that are highlighted via the medium and the flexibility to search for own new stories of interest. For instance, the Internet provides for flexibility to choose from a wide range of new stories, whereas the radio provides the listener with limited flexibility.

7.3. Perception towards specific water infrastructure alternatives[11]

Decommissioning water infrastructure components or increasing the cost of service to cover additional infrastructure or replacement costs are two retooling alternatives that represent extreme ends of the spectrum from the perspective of reducing the physical infrastructure footprint or maintaining/increasing the physical infrastructure footprint at increased service costs. This section explores the perceptions of residents in shrinking cities of these two extreme ends of the management/ retooling alternative spectrum.

7.3.1. Effects of Population-Decline Awareness

A critical component as to how people might react to these two retooling alternatives (decommissioning or increasing costs) is whether or not they are aware that their city is shrinking. As previously mentioned, only slightly more than 50% (53.9%) of the residents were aware that population decline had occurred in their city (Figure 7.1). To test if the probability that people oppose decommissioning, or rate increases, is fundamentally different between respondents who are aware that their city's population is declining and those who are not, likelihood ratio tests are conducted. The test statistic for this is (Washington et al. 2011),

$$X^2 = -2[LL(\beta_T) - LL(\beta_a) - LL(\beta_{na})] \qquad \text{[Eqn. 7.1]}$$

where $LL(\beta_T)$ is the log-likelihood at convergence of the model estimated with the data from all respondents (those aware of the population decline and those who are not), $LL(\beta_a)$ is the log-likelihood at convergence of the model using only respondents aware of the population decline, and $LL(\beta_{na})$ is the log-likelihood at convergence of the model using only respondents who are not aware of the population decline. This X^2 statistic is χ^2 distributed with degrees of freedom equal to the summation of the number of estimated parameters in the aware and not-aware models model minus the number of estimated parameters in the all-respondent model. The resulting X^2 statistic provides the confidence level that the null hypothesis (that the parameters are the same between those who are aware and those who are not) can be rejected. For the decommissioning model the X^2 statistic is 26.55. With 8 degrees of freedom, the χ^2 test indicates that we can be over 99.9% that the aware and not-aware models are not the same. For the cost-raising model, the X^2 statistic is 27.72 and with 10 degrees of freedom, the χ^2 test indicates that we can be about

[11] Section adapted from Faust et al. (2015b)

99.8% that the aware and not-aware models are not the same. Given these findings, separate models are estimated for respondents who indicated that they were aware of population declines in their city and those who are not, for both decommissioning and increased-cost alternatives (a total of 4 separate statistical models).

7.3.2. Statistical Modeling of Perceptions Results

Tables 7.4-7.7 present the model estimation results respectively for:

1. Decommissioning water infrastructure for residents aware of population decline in their city.
2. Decommissioning water infrastructure for residents unaware of population decline in their city.
3. Increasing costs of water infrastructure service to cover additional infrastructure and replacement for residents aware of population decline in their city.
4. Increasing costs of water infrastructure service to cover additional infrastructure and replacement for residents unaware of population decline in their city.

The results show that many variables were found to be statistically significant in determining opposition to decommissioning and to cost increases as alternative methods to sustaining infrastructure. The effects of some variables were found to vary across the respondent population (as indicated by the statistical significance of the standard deviation for random parameters, all of which were found to be normally distributed), suggesting considerable heterogeneity across the respondent population.

Table 7.4. Model of the probability of opposing decommissioning water infrastructure for residents aware of population decline (all random parameters are normally distributed)

Independent Variable	Parameter (t-statistic)	Standard Deviation (t-statistic)	Marginal Effect
Fixed Parameters			
Constant	0.454 (0.825)	*fixed*	
Employment status (1 if unable to work, otherwise 0)	-4.365 (-1.941)	*fixed*	-0.012
Number of cars in household (1 if household has 3 or more cars, otherwise 0)	-13.887 (-2.964)	*fixed*	-0.039
Buffalo, New York indicator (1 if currently residing in Buffalo, otherwise 0)	2.327 (2.464)	*fixed*	0.008
Michigan Indicator (1 if currently live in MI, otherwise 0)	-3.640 (-2.046)	*fixed*	-0.014
Responsible for Water Service Payment (1 if responsible, otherwise 0)	-2.657 (-3.392)	*fixed*	-0.010
Random Parameters			
Age (1 if over 50, otherwise 0)	-2.009 (-2.076)	15.044 (3.554)	-0.006
Relationship status (1 if married, otherwise 0)	-6.773 (-2.977)	21.624 (3.481)	-0.012
Log likelihood at convergence		-98.74	
AIC		217.480	
BIC		250.661	
Number of observations		204	

Table 7.5. Model of the probability of opposing decommissioning water infrastructure for residents unaware of population decline (all random parameters are normally distributed)

Independent Variable	Parameter (t-statistic)	Standard Deviation (t-statistic)	Marginal Effect
Fixed Parameters			
Constant	0.466 (0.507)	*fixed*	
Age (1 if over 50, otherwise 0)	2.497 (3.021)	*fixed*	0.008
Employment status (1 if retired, otherwise 0)	-13.892 (-1.683)	*fixed*	-0.017
Frequency of following the news (1 if daily, otherwise 0)	-2.340 (-2.318)	*fixed*	-0.008
Education (1 if educated beyond high school, otherwise 0)	-3.233 (-3.181)	*fixed*	-0.011
Household Income (1 if more than $75,000, otherwise 0)	2.383 (2.696)	*fixed*	0.008
Primary source of news (1 if newspaper, otherwise 0)	1.846 (2.317)	*fixed*	0.006

Table 7.5. *(continued)*

Independent Variable	**Parameter (t-statistic)**	**Standard Deviation (t-statistic)**	**Marginal Effect**
Random Parameters			
Gender (1 if male, otherwise 0)	-4.244 (-2.783)	10.630 (3.513)	-0.013
Length of time owning home (1 if 10 years or more, otherwise 0)	-63.355 (-2.141)	171.887 (2.226)	-0.016
Log likelihood at convergence		-78.230	
AIC		178.460	
BIC		213.273	
Number of observations		175	

Table 7.6. Model of the probability of opposing increasing the cost of water infrastructure service to cover additional infrastructure and replacement for residents aware of population (all random parameters are normally distributed)

Independent Variable	**Parameter (t-statistic)**	**Standard Deviation (t-statistic)**	**Marginal Effects**
Fixed Parameters			
Constant	-1.718 (-2.742)	*fixed*	
Household Income (1 if more than $75,000, otherwise 0)	-1.593 (-2.039)	*fixed*	-0.006
Birmingham, Alabama indicator (1 if currently residing in Birmingham, otherwise 0)	8.220 (2.512)	*fixed*	0.032
St. Louis, Missouri indicator (1 if currently residing in St. Louis, otherwise 0)	20.434 (3.451)	*fixed*	0.08
Primary source of news (1 if newspaper, otherwise 0)	3.125 (3.710)	*fixed*	0.012
Random Parameters			
Employment status (1 if retired, otherwise 0)	-9.719 (-3.466)	16.191 (3.496)	-0.038
Children present in household (1 if kids under the age of 5 live in household, otherwise 0)	-1.491 (-1.040)	12.539 (2.758)	-0.006
Number of people residing in household (1 if live alone, otherwise 0)	6.002 (3.288)	12.351 (3.429)	0.024
Location grew up (1 if grew up in city currently residing in, otherwise 0)	-7.301 (-3.236)	23.216 (3.598)	-0.029
Log likelihood at convergence		-111.3696	
AIC		248.739	
BIC		291.875	
Number of observations		204	

Table 7.7. Model of the probability of opposing increasing the cost of water infrastructure service to cover additional infrastructure and replacement for residents unaware of population decline (all random parameters are normally distributed)

Independent Variable	Parameter (t-statistic)	Standard Deviation (t-statistic)	Marginal Effects
Fixed Parameters			
Constant	-5.816 (-2.848)	*fixed*	
Age (1 if over 50, otherwise 0)	3.848 (2.595)	*fixed*	0.056
Education (1 if educated beyond high school, otherwise 0)	-2.663 (-2.346)	*fixed*	-0.038
Employment status (1 if employed for salary or wages, otherwise 0)	-7.163 (-3.292)	*fixed*	-0.103
Number of people residing in household (1 if live alone, otherwise 0)	8.444 (3.103)	*fixed*	0.122
Number of cars in household (cars)	2.087 (3.072)	*fixed*	0.03
Relationship status (1 if single, otherwise 0)	-5.192 (-3.186)	*fixed*	-0.075
Location of birth (1 if born in city currently residing in, otherwise 0)	3.146 (2.522)	*fixed*	0.045
Random Parameters			
Employment status (1 if retired, otherwise 0)	-8.161 (-2.622)	37.169 (2.818)	-0.118
Children present in household (1 if kids under the age of 5 live in household, otherwise 0)	8.363 (3.184)	6.419 (2.953)	0.121
Length of time owning home (1 if 10 years or more, otherwise 0)	5.088 (2.749)	3.999 (2.374)	0.073
Pittsburgh, Pennsylvania indicator (1 if currently residing in Pittsburgh, otherwise 0)	-10.612 (-2.311)	39.752 (2.746)	-0.153
Primary source of news (1 if newspaper, otherwise 0)	-0.348 (-0.426)	11.941 (3.254)	-0.005
Log likelihood at convergence		-70.682	
AIC		177.364	
BIC		234.330	
Number of observations		175	

7.3.3. Discussion of Significant Parameters Impacting Perceptions

With regard to the location-parameter findings, all survey respondents from locations other than those included in the model are considered the baseline (since their parameter is implicitly zero) and the significant locational parameters included in the model are interpreted relative to these. Turning first to the locational findings with regard to decommissioning infrastructure, Table 7.4 shows that residents of Buffalo, New York, who are aware of the urban decline occurring, have an increased likelihood of opposing decommissioning water infrastructure and residents of shrinking cities in Michigan have a decreased likelihood of opposing decommissioning water infrastructure. The differences in these locations could be the result of a number of factors including the economic, political, and social climate. For residents unaware of the population decline in their city, no locational distinctions were found to have a statistically significant effect on their likelihood of opposing decommissioning of water infrastructure.

With regard to opposition to increasing costs, Table 7.6 shows that, for increasing the cost of service to cover additional infrastructure or replacement, residents of Birmingham, Alabama and Saint Louis, Missouri who are aware of the urban decline occurring in their cities, both have an increased likelihood of opposing increasing the cost of service relative to other locations. In addition, residents of Pittsburgh, Pennsylvania, who are unaware of the urban decline occurring in their city (Table 7.7) have, on average, a decreased likelihood of opposition towards increasing the cost of service, but in this case the Pittsburgh location indicator variable is a normally distributed random parameter implying that 60.5% of the residents having a decreased likelihood of opposing increasing the cost of service and 39.5% having an increased likelihood of opposing increasing the cost of service. Furthermore, Pittsburgh indicator variable has a high marginal effect with an average decrease in the probability of opposition of 0.153. Given that the marginal effects vary across respondents as do the parameters this finding shows a strong influence of this variable on opposition probabilities and considerable heterogeneity among Pittsburgh residents. Overall, the locational findings point out specific geographic regions where issues relating to infrastructure sustainability must be given careful consideration.

For individuals unaware of the population decline in their cities, individuals over the age of 50 were found to be more likely to oppose both decommissioning (Table 7.5) and cost increases (Table 7.7). These findings may be capturing a resistance to change as openness for progressive change has been shown to decline as individuals age (Westerhoff 2008). However, the effect of being over 50 years of age has a more ambiguous effect for those individuals who are aware of population declines in their city with regard to decommissioning infrastructure (Table 7.4). This random-parameter finding for this variable indicates that 55% of the individuals with this demographic have a decreased likelihood of opposing decommissioning but that 45% have an increased likelihood of opposing decommissioning. This suggests considerable variance with respect to age with regard to the likelihood of opposition that seems to interact with the awareness regarding the urban decline.

Table 7.4 shows that individuals who are aware of population decline in their city and unable to work, and those responsible for their water bill, were found to be less likely to oppose decommissioning water infrastructure. These individuals may see decommissioning as a viable alternative to stabilize or reduce water service costs, one of many living expenses, which may be a concern for individuals unable to work or responsible for the water bill, as the average income in shrinking cities is typically below the average income for the state. In addition, for those aware of population decline in their cities, the random-parameter estimate for relationship status in Table 7.4 shows that 62% of married individuals are less likely to oppose decommissioning water infrastructure with 38% more likely to oppose suggesting considerable heterogeneity across the population with regard to marital status.

Individuals who follow the news daily but were still unaware of population decline in their cities were found to be less likely to oppose decommissioning water infrastructure (Table 7.5). This may be due to the nationwide focus on aging infrastructure and an active management alternative to cease to use portions of the degrading physical footprint. With regard to gender for those unaware of population declines in their cities, the estimated parameter was found to be random (Table 7.5) with 65.5 % of males being less like to oppose decommissioning water infrastructure and 34.5% more likely to oppose. This suggest considerable heterogeneity in responses among males and the significance of this variable may reflect the importance that males can play in household incomes and decision-making (Wang et al. 2013).

If respondents grew up in the city in which they currently reside and are aware of population declines in their cities, they were more likely to oppose cost increases as a means of achieving sustainability (Table 7.6). This may reflect a resistance to change among individuals with long histories in the same residential location (with regard to water management) and this finding is consistent with the previous work of Kiparsky et al. (2013) with regard to the evolution of water management. Along these same lines, a respondent unaware of the population decline who was born in the city in which they currently reside also had an increased probability of opposing cost increases to achieve sustainability (Table 7.7).

Individuals employed for a salary or wages were found to be less likely to oppose cost increases if they were unaware of population declines in their city (Table 7.7). These individuals have a presumably reliable income and can afford some increased service costs. Additionally, those individuals who identify themselves as single in their relationship status and are unaware of population declines in their city are less likely to oppose increasing costs (Table 7.7), which is in contrast to the parameter estimate for those who reside alone who are more likely to oppose increasing costs. However, the single-in-relationship parameter estimate may be capturing those who live with roommates or unmarried partners, sharing the burden of living expenses.

Individuals owning three or more cars and aware of population declines in their city were less likely to oppose decommissioning (Table 7.4). This is likely capturing some measure of wealth and mobility that would make these people less likely to be impacted by decommissioning. In contrast, for those unaware of population decline in their city, each additional car they owned was found to increase the probability of opposing increasing costs to sustain infrastructure (Table 7.7). This may simply reflect the economics involved in owning additional cars which results in less disposable income.

Respondents indicating that newspapers were their primary source of news were more likely to oppose cost increases if they were aware of population declines in their city (Table 7.6). If they were unaware of population declines, the random parameter estimate shows that 51.2% were less likely to oppose cost increases while 48.8% were more likely to oppose cost increases (Table 7.7). These findings show considerable variability across the population in general and particularly between groups of individuals that are and are not aware of population declines in their cities.

For the length of time owning a home (10 years or more) for those aware of declining populations in their city, the random parameter estimate in Table 7.5 shows that 64.4% of people with this time of home ownership tenure are less likely to oppose decommissioning and 35.6% are more likely to oppose. For those unaware of population declines in their city, the random parameter results in Table 7.7 show that 89.5% are more likely to oppose cost increases and 10.5% are less likely to oppose cost increases. These findings again underscore fundamental differences in those aware and unaware of the city's declining population, but also show the heterogeneity across the population with respect to home ownership duration.

With regard to household income, those households making more than $75,000 annually were more likely to oppose decommissioning if they were unaware of population declines in their city

(Table 7.5) and less likely to oppose cost increases if they were aware of population declines in their city (Table 7.6). This shows a rather complex relationship among income, awareness, and opposition probabilities.

Individuals who were retired and unaware of declining populations in their city were less likely to oppose decommissioning (Table 7.5) and, with regard to cost increases, the random-parameter estimates in Table 6 show that 58.7% were less likely to oppose prices increases but 41.3% were more likely to oppose cost increases (it is noteworthy the marginal effect for this variable is rather large, with retired individuals having on average a 0.118 lower probability of opposition with all else held constant). For retired individuals aware of their declining populations, 72.6% were less likely to oppose prices increases, with 37.4% more likely to oppose cost increases. As with other findings, this shows considerable variability over the respondent sample.

The presence of children under 5 years of age in the household was found to produce random parameters in both models of the probability of opposing increasing costs. For the model using respondents aware of population declines in their city, the presence of children under 5 years of age in the household decreased the probability of opposition for 54.7% of respondents and increased the probability of opposition for 45.3% of respondents. For the model using respondents unaware of population declines in their city, the presence of children under 5 years of age in the household decreased the probability of opposition for only 9.6% of respondents and increased the probability of opposition for 90.4% of respondents. While the parameter estimates indicate considerable heterogeneity in these results, there is a general trend that respondents with small children are going to be opposed to cost increases which is a likely reflection of the economic realities of raising a child.

7.4. Summary

As cities explore implementing various retooling alternatives to transition to sustainable infrastructure management, understanding the sources of opposition and which alternatives the community may support allows for incorporating the community vision and public participation while possibly mitigating opposition to the alternatives. Less than 20% of the survey respondents expressed no desire to participate in the decision-making of the water or wastewater infrastructure management, indicating that communication avenues must be open between city managers and engineers who understand the societal needs and the community’s vision in developing alternatives and incorporating some level of participatory decision-making for sustainable outcomes.

The statistical analyses show that a wide variety of factors influence the attitudes and perceptions of residents in shrinking cities pertaining to water retooling alternatives. In regard to the perception of residents (Section 7.3), the statistical significance of the random parameters suggests that there is considerable heterogeneity across the respondent population. Perhaps the most important findings in the context of perception is that it is important to know whether residents of shrinking cities are actually aware that their city is experience population declines because this single factor has an enormous effect on policy opposition probabilities. In the context of attitude, which generates much narrower margins of support of a specific alternative, this awareness of whether shrinking is occurring is not necessary. However, arguably, perception is what is of interest to policy and decision makers. An individual may support an infrastructure effort regardless of his/her attitude. He/she may think decommissioning should be implemented (attitude) but would still support repurposing or razing, as these are also progressive management changes (perceptions) that accomplish similar goals as decommissioning.

The various model estimation results show that many of the same socioeconomic and demographic variables influenced opposition probabilities in attitude and perception models. These socio-economic and demographic findings may be used to evaluate resident populations in specific shrinking cities to determine the initial viability of different policy alternatives, and to target specific groups with information campaigns and political strategies and compromises to mitigate potential opposition. Understanding the public perceptions and incorporating the public opinions into the decision-making process may allow for sustainable water infrastructure retooling alternatives for fiscally strained, shrinking cities.

As mentioned in Chapter 3, previous literature pertaining to the public's stance in the context of declining urban populations have examined quality of life, and perceptions towards abandonment and vacancies, without addressing underground infrastructure in any capacity (e.g., Greenberg and Schneider 1996; Bright 2000; Hollander 2010; Hollander 2011). Underground infrastructures are unseen, and the public generally lacks the same level of awareness of operations and conditions of these systems compared to above-ground infrastructure systems, such as roads and bridges. However, price elasticity studies (USEPA ND; Espey et al. 1997; Lipsey and Chrystal

1999; NRDC 2012) have shown that consumers are sensitive to price changes for water service, illustrating that consumer behavior is directly tied to the utility service provided. The retooling alternatives explored in this chapter have the potential to reduce or stabilize the costs of service, but dependent on how the necessity of these alternatives is perceived, the public may not support a specific alternative. Understanding public perception and attitude is critical for an infrastructure project's success as decisions lacking adequate public support may pose risks such as inefficient or unsuccessful implementation due to public opposition (Susskind and Cruikshank 1987; Global Water Partnership Technical Advisory Committee 2000, Gerasidi et al. 2009, Nancarrow et al. 2010, Faust et al. 2013).

This chapter addressed the gap within literature and contributes to the body of knowledge by illustrating the viability of evaluating public views towards underground infrastructure and potential infrastructure retooling alternatives using binary probit models and binary logit models with random parameters. Models, which were best fit with random parameters, demonstrated the appropriateness for capturing the heterogeneity of the populations in regard to public views towards underground infrastructure in shrinking cities. Further contributing to the body of knowledge is quantifying that influential parameters may not be translational across level of awareness regarding contextualized surroundings, an aspect not considered in the previous studies in urban decline.

CHAPTER 8. INTERDEPENDENCY ANALYSIS OF WATER, WASTEWATER AND STORMWATER INFRASTRUCTURES

"Be it through direct connectivity, policies and procedures, or geospatial proximity, most critical infrastructure systems interact. These interactions often create complex relationships, dependencies, and interdependencies that cross infrastructure boundaries."

-Pederson et al. (2006)

Chapter 8 discusses the evaluation of physical interdependencies between the water, wastewater, and stormwater infrastructure systems, and non-physical human-infrastructure interdependencies using a hybrid agent based-system dynamics (AB-SD) model. The system dynamics model uses feedback loops between the infrastructure systems to assess how the impacts of varying parameters, such as water and wastewater billing rates, price elasticity, and urban decline rates, in an individual infrastructure system cascade throughout other infrastructure systems. This AB-SD model explores the behaviors and implications of these interdependencies and allows for evaluating real-world behavior in artificial settings (Winz et al. 2009). For instance, non-physical interdependencies between the infrastructure systems explored within the system dynamics component of the model include the impacts of urban decline on the total water demanded and wastewater produced. An example of a physical interdependency explored is the wastewater produced from residential water demand both within the analysis area and citywide.

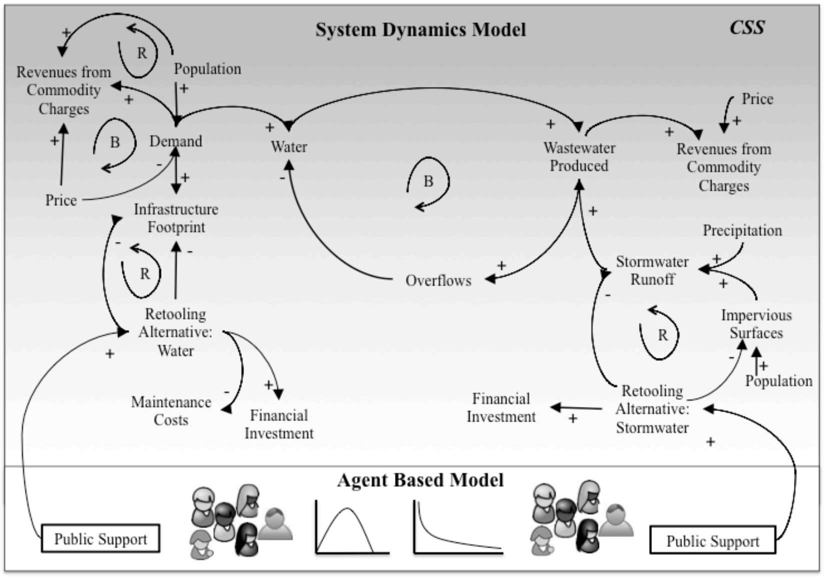
Further complicating the existing infrastructure performance and interdependencies are that these infrastructures are impacted by the consumer interactions. An example of a non-physical disrupter arising from consumers is the impact of behavior changes resulting from water price elasticity on the water and wastewater infrastructure demands. Survey analyses (such as demonstrated in Chapter 7) may reveal public opposition towards infrastructure retooling alternatives that could delay the implementation of the alternative. Agent-based modeling is used to evaluate the public as autonomous agents with individual levels of support/opposition (non-physical disruptor) towards a proposed retooling alternative (physical disruptor). When the threshold of support for a retooling alternative is met, the retooling alternative evaluated in the model "enters" the work plan for the city in the system dynamics component. This interaction between the public (agents) and the infrastructure retooling alternative captures the time taken to reach a level of community consensus for an infrastructure retooling alternative.

8.1. Abstraction of the Hybrid Agent Based-System Dynamics Model Components

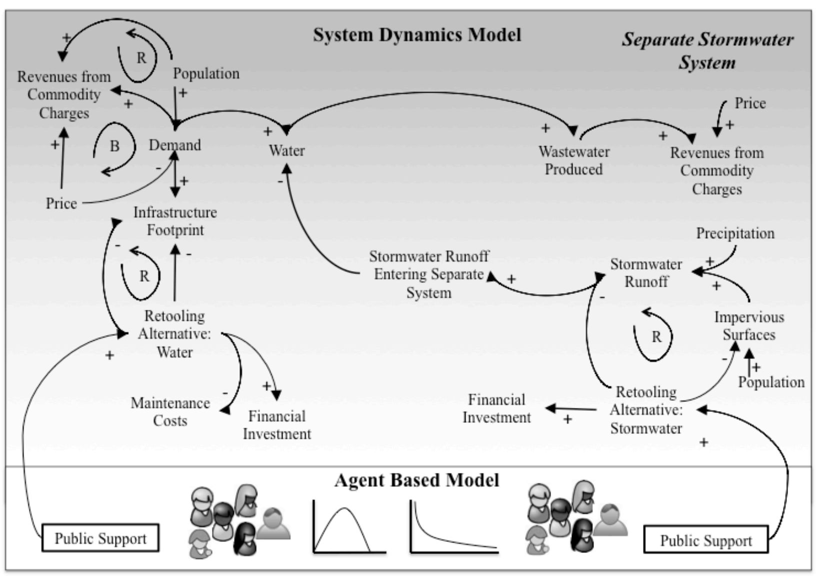
The abstraction of the components that are relevant and quantifiable for the analysis, and the relationships between the variables are shown in these causal loop diagrams that conceptualize the model in Figure 8.1. Figure 8.1 depicts two causal loop diagrams, one each for a city operating on a combined sewer system and a separate stormwater system. The signs (+/-) within the diagrams indicate whether the beginning node/variable will have a positive or negative impact on the end node/variable, with justification for each sign presented in Table 8.1. A complete loop within the influence diagram is termed a feedback loop, which is the algebraic product of the sum of the links (Kirkwoord 1998). Positive feedback loops reinforce change within a model, where as a negative loop, balances the system, converging the system towards a goal (Kirkwood 1998).

The scope and context of the analysis occurs on two levels: (1) citywide, and (2) the neighborhood/analysis area. The analysis area is a residential area that is a subset of the city, has a high vacancy rate or is abandoned, and is a candidate for implementing retooling alternatives. Evaluating the interdependencies at this granular level within the city facilitates viewing the outputs and the impact of the retooling alternatives within a neighborhood. Citywide analysis considers the total population in the coupled human and water sector infrastructure interdependencies (as opposed to the smaller population considered in the analysis area).

The infrastructure retooling alternatives demonstrated in this framework are decommissioning water pipelines and decommissioning impervious surfaces, for the water infrastructure retooling alternative and the stormwater retooling alternative, respectively. Decommissioning water pipelines consists of cleaning and capping underutilized pipelines in areas of high vacancy to reduce the built infrastructure footprint, decrease citywide water network maintenance costs, and possibly allow for improved water quality by lessening the presence of stagnant water and water age from underutilization (Faust and Abraham 2014). Decommissioning impervious surfaces reduces the generated stormwater runoff entering the CSS or separate stormwater system, which may improve water quality by reducing the potential for wastewater/non-point source pollutant entering the open source waters.



(a)



(b)

Figure 8.1. Causal loop diagram for the AB-SD model: (a) Combined sewer system and (b) Separate stormwater system

Table 8.1. Causal loop diagram parameters and justifications

Start Node	End Node	Sign	Justification
Demand	Infrastructure Footprint	+	As the demand increases, the physical infrastructure footprint expands to meet the growing needs.
Demand	Revenues From Commodity Charges	+	Decreased demand from behavior or population decline results in less total revenues for the utility.
Demand	Water	+	Consequentially, when total demand increases, the total quantity of water used within the city also increases.
Impervious Surfaces	Stormwater Runoff	+	Impervious surfaces generate runoff as precipitation is not able to infiltrate the ground onsite.
Overflows	Water	-	Overflows release pollutants into open water sources, reducing the quality of water.
Population	Demand	+	As the population decreases, the total water demand decreases. This may also represent a decrease in water demand due to changing behaviors.
Population	Impervious Surface	+	To meet the needs of increasing populations, the number of impervious surfaces in the city increases (e.g., homes, roads).
Population	Revenues From Commodity Charges	+	Increased number of customers yields an increased amount of revenue for the utility.
Precipitation	Stormwater Runoff	+	Increased precipitation generates additional runoff upon saturation of the soils.
Price	Revenues From Commodity Charges	+	Increased billing rates for water/wastewater usage results in increased revenues for the utility.
Price	Demand	-	As price increases, the price elasticity of water indicates that behavior changes and per capita usage decreases.
Public Support	Retooling Alternatives: Water	+	Increased public support for infrastructure retooling alternatives increases the sustainability of such infrastructure projects and the motivation for additional projects.
Public Support	Retooling Alternatives: Wastewater	+	Increased public support for infrastructure retooling alternatives increases the sustainability of such infrastructure projects and the motivation for additional projects.
Stormwater Runoff	Wastewater Produced	+	In combined sewer systems, wastewater and runoff combine in a single system to be transported to the wastewater treatment plant.
Stormwater Runoff	Stormwater Runoff Entering Separate System	+	In separate systems, stormwater enters the stormwater system and is transported directly to outlet points to surrounding water sources.
Stormwater Runoff Entering Separate System	Water	-	Increased nonpoint source pollutants in runoff may enter groundwater and open water sources, reducing water quality.
Retooling Alternatives: Stormwater	Financial Investment	+	Incorporating new infrastructure retooling alternatives requires financial investment.

Table 8.1. *(continued)*

Start Node	End Node	Sign	Justification
Retooling Alternatives: Stormwater	Impervious Surfaces	-	Decommissioning impervious surfaces or implementing low impact development practices can reduce the number of underutilized impervious surfaces.
Retooling Alternatives: Stormwater	Stormwater Runoff	-	Incorporating low impact development or decommissioning impervious surfaces allows for onsite infiltration of precipitation.
Retooling Alternative: Water	Financial Investment	+	Incorporating new infrastructure alternatives requires financial investment.
Retooling Alternative: Water	Infrastructure Footprint	-	Many retooling alternatives maintain or reduce the physical footprint of the existing infrastructure.
Retooling Alternative: Water	Maintenance Costs	-	Retooling alternatives, such as decommissioning, would reduce the required maintenance costs, in conjunction, with the reducing the physical infrastructure footprint.
Wastewater	Overflows	+	An increased quantity of wastewater has the potential for exceeding system capacity, resulting in an increased number of overflows.
Water	Wastewater Produced	+	As demand for water increases, the quantity of wastewater produced increases.

Table 8.2 summarizes the different classes of objects constructed to model the behavior of the interdependencies in the hybrid agent based-system dynamics model. Each object class has a specific function within the model that is influenced by the parameters, variables, and decision rules. The object classes include: public support (one each for the water and stormwater retooling alternative at the analysis area level), water demand (citywide level and analysis area level), wastewater produced (citywide level and analysis area level), stormwater runoff (analysis area level), utility generated revenues (one each for the water and wastewater utility), and the infrastructure retooling alternative payoff period (one each for the water and stormwater retooling alternative at the city level).

Table 8.2. Summary of the object classes in the AB-SD model

Object Class(es)	Type (number of objects)	Function	Parameters and variables	Examples of decision rules and formulas
Public support- Water infrastructure retooling alternative Public support- Stormwater infrastructure retooling alternative	Agent (0.1* Population) Agent (0.1* Population)	Simulation of the individual's behavior in the context of support for a retooling alternative	• Public support • Public opposition • Rate of adoption • Population trajectory	• Rate of adoptions • Percentage of agents returning to opposition state from support/adoption state • Historical decline rate (US Census Bureau 2011)

Table 8.2. *(continued)*

Object Class(es)	Type (number of objects)	Function	Parameters and variables	Examples of decision rules and formulas
Water demand-Citywide Water demand-Analysis area	System dynamics (SD) (1) SD (1)	Simulation of the residential consumer water demands	• Per capita daily water use • Population • Population trajectory • Price elasticity • Rate increases • Rate increase ceiling	• Increase rates annually if rate increase ceiling is not exceeded • Per capita demand due to increased rates based on price elasticity
Wastewater produced-Citywide Wastewater produced-Analysis area	SD (1) SD (1)	Simulation of the wastewater produced from residential consumption (and stormwater in city's operating on CSSs)	• Water demanded • Percentage of water consumed entering the wastewater system • Quantity of stormwater entering (CSS only; see Object Class *Stormwater* for further details)	• In more humid regions, a higher percentage of water enters the wastewater system (Grigg 2012) • The sum of the wastewater and stormwater (CSS only)
Stormwater Runoff–Analysis area Stormwater Runoff – Analysis area post implementing stormwater retooling alternative	SD (1) SD (1)	Simulation of the stormwater runoff generated in the analysis area *(Runoff generated has a separate stock variable if city has a separate stormwater system)*	• Historical rainfall for city • Land use • Soil type • Area of analysis area • Non-point source pollutants' event mean concentration	• Equations generated using hydraulic modeling for quantity of runoff produced based on the land use, soil type, rainfall and analysis area size • Increase in rainfall, increases quantity of non-point source pollutants
Water utility generated revenues-Citywide Wastewater utility generated revenues-Citywide	SD (1) SD (1)	Simulation of the revenues generated	• Service Price • Water consumed • Operation costs equivalent to the total revenues at time 0 (t_0) • Maintenance cost saving from water retooling alternative (*impacting generated water utility revenues only)*	• Billing based on volumetric pricing of water consumed • The difference between the total revenues at time x (t_x) and t_0 (i.e., operation costs) is the generated revenues at t_x. • Service price must be below the willingness-to-pay threshold determined via survey analysis
Water infrastructure retooling alternative payoff period Stormwater infrastructure retooling alternative payoff period	SD (1) SD (1)	Simulation of the time taken to pay of a retooling alternative once implemented into the work plan	• Cost • Public support • Percentage of generated revenues earmarked for project • Generated revenues	• Retooling alternative enters city work plan (and budget) when threshold of public support is met • Project is paid off using generated revenues

Figure 8.2 shows how the different object classes interact within the AB-SD model to yield the different outputs of interest. The public support classes are modeled as agents, with each agent representing an autonomous individual within the public. The remaining object classes are modeled using system dynamics that aggregate the resource (e.g., water consumer, generated revenues) over time.

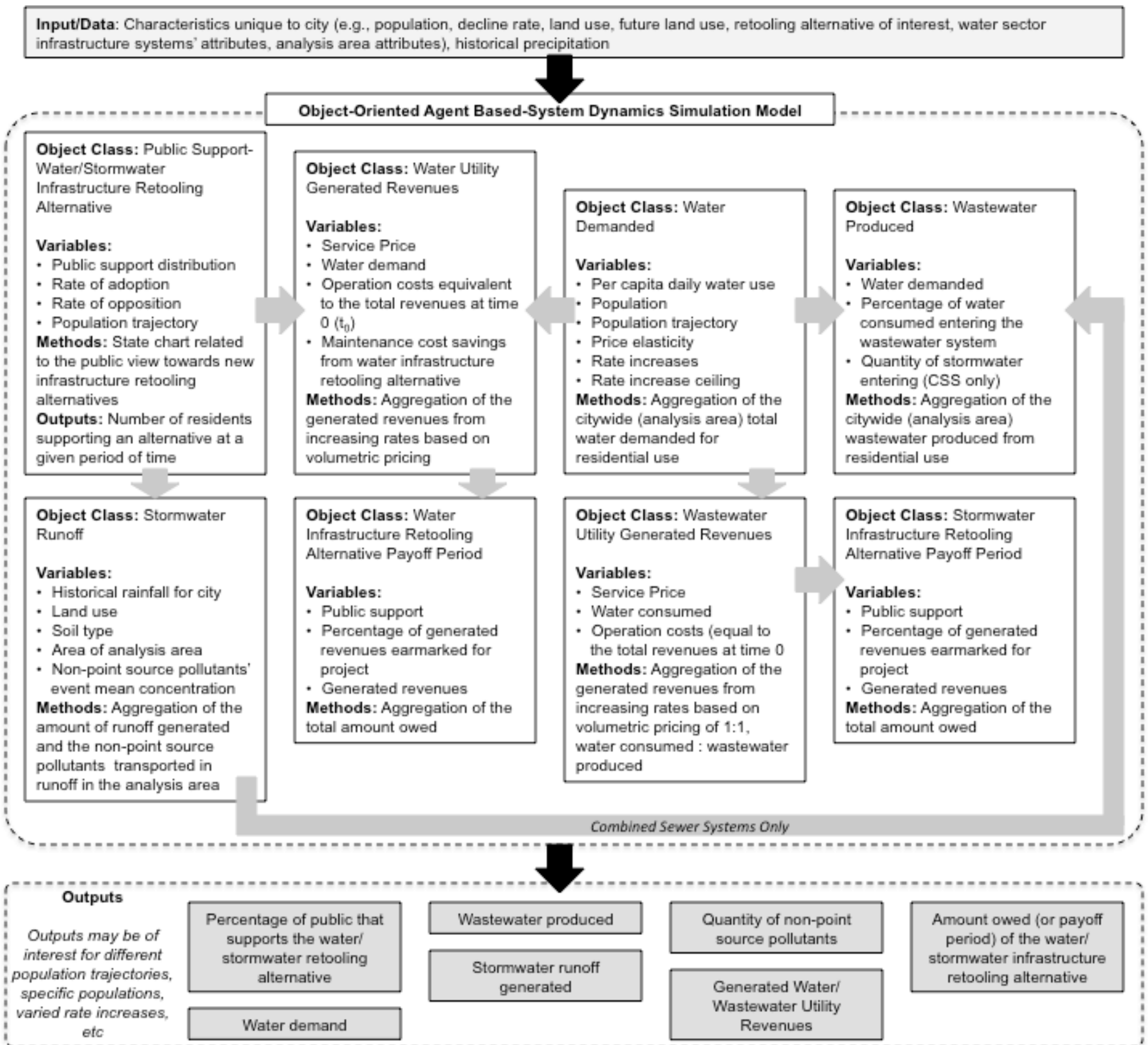


Figure 8.2. Components of the AB-SD model

8.2. Implementation of the Hybrid Agent Based-System Dynamics Model

An overview of the system dynamics (SD) component is shown in Figure 8.3. The two agent classes interact with the system dynamics classes via the stocks, "*Public Support for Water/Stormwater Retooling Alternative*," in real time. The stock variable links the agents to the implementation of the the retooling alternatives in the model. When the necessary percentage of public support for an infrastructure retooling alternative is reached, the retooling alternative enters the work plan for the city (the *implemented* variable in Figure 8.3), and the cost for the retooling alternative is initiated into the model. The continuous AB-SD model is discretized into weekly intervals and aggregated over the week throughout the simulation time of 520 week (10 years). A brief description of the key object classes incorporated into the AB-SD model follows. The parameters, variables, and states (where the autonomous agents exist) comprising the AB-SD model are discussed in detail in Appendix H.

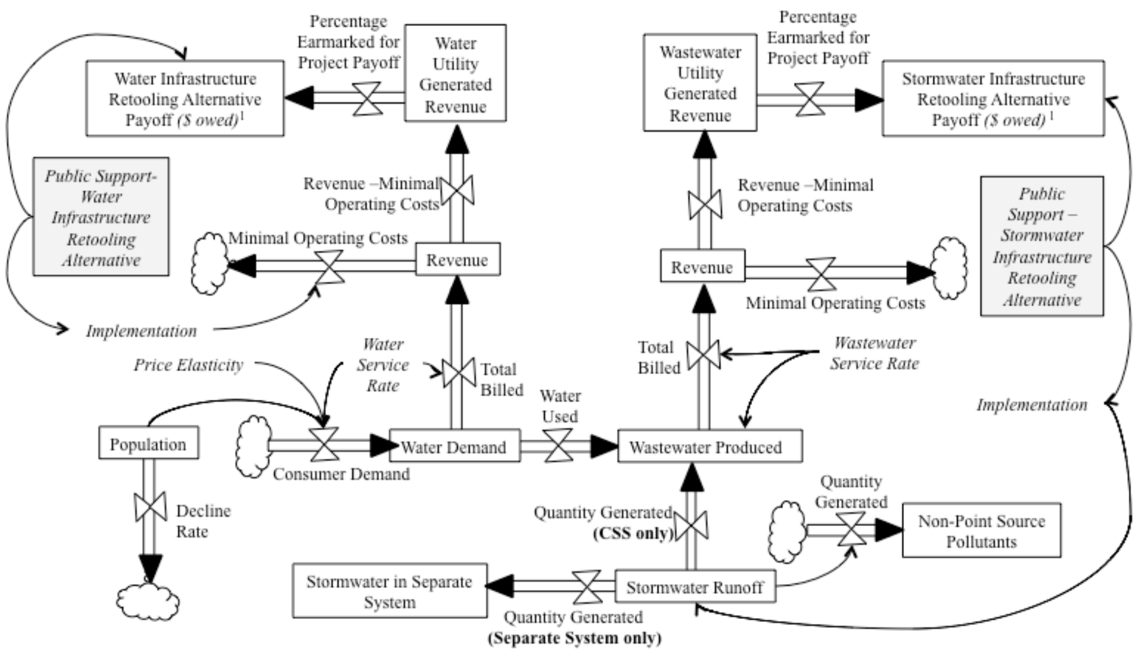


Figure 8.3. Stock and flow vairables, with select parameters comprising the system dynamics model

Water Demand: The total water demand is a function at each time step of the population, per capita demand, and price elasticity. *Price Elasticity*, in Figure 8.3, relates the changes in water price to the water demand change ranging from -0.2 to -0.5 (Lipsey and Chrystal 1999), and these values fall within the range of other established price elasticity studies in literature (e.g., Espey et al. 1997; Dalhuisen et al. 2003; Worthington and Hoffman 2008; Hung and Chie 2012). Price elasticity, which is unitless, is equal to the ratio of the percent change in per capita water demand to the percent change in price (percent of rate changes), shown in Eqn. 8.1:

$$Price\ Elasticity = \frac{\Delta Quantity\ Demanded}{Quantity\ Demanded} \bigg/ \frac{\Delta Rate}{Rate\ (t_0)} \qquad \text{[Eqn. 8.1]}$$

where, ΔRate is the difference between Rate(t) and Rate(t_0). Rate(t), the *Water/Wastewater Service Rate,* indicates the service rate at the current time step during the simulation (see Eqn 8.2).

$$Rate\ \left(\frac{\$}{1{,}000G}\right) at\ any\ time_t = Rate(t_{t-1})(1 + \int \frac{d(Rate)}{dt} dt) \qquad \text{[Eqn. 8.2]}$$

For instance, using Eqn. 8.2 to calaculate the increase service rate, assume the service rate for 1000 gallons for the first 52 weeks (1 year) of the simulation (t_0- t_{52}) is \$2.59. At t_{53}, the service rate increases by 3%, resulting in the following rate:

$$Rate\ \left(\frac{\$}{1{,}000G}\right)(t_{53}) = \$2.59(1 + 0.03) = \$2.67 \qquad \text{[Eqn. 8.3]}$$

The demand for water will reduce in response to these increased rates (from \$2.59 to \$2.67). Eqn. 8.4 estimates the reduction in water use, per 1,000 gallon, by rearranging Eqn.8.1 and using an example price elasticity of -0.35 (the median value within the -0.2 to -0.5 range incporated into the model, as:

$$\Delta Quantity\ Demanded\ = (Price\ Elasticity)\left(\frac{\Delta Rate}{Rate\ (to)}\right)(Quantity\ Demanded)$$
$$= (-0.35)\left(\frac{\$2.67-\$2.59}{\$2.59}\right)(1000\ gallons) = -10.81\ gallons$$

[Eqn. 8.4]

10.81 gallons, or a shift in consumption to approximately 989 gallons for the 1,000 previously consumed.

The rate increases at a user defined percentage each year (52 weeks), until the billable rate for service reaches the willingness-to-pay ceiling established by the residents. The rate increases within the model are representative of the human-infrastructure interaction and not intended to represent the rate structure of any particular city. The structure of rate setting varies from city to city, and is often set by consultants, for both water and wastewater utilities. Interviews with subject matter experts from Midwestern shrinking cities indicated this method of raising rates and billing services based on volumetric use was adequate to analyze the implications of increasing rates for the infrastructure services.

Wastewater Produced: The percentage of water that enters wastewater system (through use of drinking water and CSS) ranges from 60% to 85% in dry to humid regions, respectively (Grigg 2012). If the city is operated on a CSS, the *Stormwater Runoff Object Class* contributes to the wastewater produced.

Stormwater Runoff: Stormwater runoff is a function of the historical precipitation, the current land use, and soil type. In separate stormwater systems, the runoff is aggregated over the simulation time for the analysis area. The quantities of non-point source (NPS) pollutants are tracked throughout the simulation in the area before and after implementation of the stormwater retooling alternative to assess, the impact of the stormwater infrastructure retooling alternative on the total pollutants entering the wastewater system (for CSS) or the stormwater system (for separate stormwater systems).

Water Utility Generated Revenues: The minimum revenue necessary to operate the infrastructure system is the calaculated as the quanitity of revenue gathered service costs at the beginning of the simulation at t_0. As shown in Eqn 8.5, additional revenue from increased billing rates is considered as the generated revenues greater than the total revenue at t_0. The rationale for including this assumption in two fold. First, the revenue at t_0 is necessary to operate the infrastructure system due to the high fixed costs associated with these infrastructures. Second, SMEs in shrinking cities have indicated that they are operating on the minimal, necessary financial resources, and thus operational and maintenance costs cannot be reduced further from the operations costs at t_0.

$$Generated\ Revenues\ (\$)\ at\ time\ t = Revenues\ (t) - Revenues\ (t_0) \qquad \text{[Eqn. 8.5]}$$

Generated revenues is shown using a simple example in Eqn. 8.6. If the water demand is 110,000,000 gallons per week at t_0, multiplying by a service rate of $2.59 per 1,000 gallons yields $284,900 per week in revenues. This value, at the beginning of the simulation (t_0), is assumed to the revenue threshold necessary to operate the water infrastructure system. If, due to population decline and price elasticity, weekly demand were to fall to 103,000,000 gallons per week billed at $2.85 per 1,000 gallons, the weekly revenues would then be $293,550, an increase from the revenues at t_0 ($284,900) that are needed to operate the system. Thus, generated revenues may be calculated as:

$$Generated\ Revenues\ (\$)\ = \$293{,}550 - \$284{,}900 = \$8{,}650\ per\ week \qquad \text{[Eqn. 8.6]}$$

Wastewater Utility Generated Revenues: The billing of wastewater is modeled as a 1:1 ratio of water demand to wastewater produced. Price elasticity is not considered in the context of wastwater rate increases as price elasticity in the context of wastewater produced has not been quanitfied in literature. However, there is speculation that raising wastewater rates will also result in price elasticity on water (USEPA ND; NRDC 2012), although no data regarding the realtionship between wastewater, water, and price elasticities was available from published sources known to the author. Similar to the *Water Utility Generate Revenues Object Class*, the generated revenues are those above the operation revenue (revenues at t_0) shown in Eqn. 8.3.

Water/Stormwater Infrastructure Retooling Alternative Payoff Period: The payoff period is the time taken to pay off the financial investment (i.e., cost) of the retooling alternative. A retooling alternative may be paid off by earmarking a percentage of generated revenues (calculated in Eqn. 8.5) to reduce the amount owed on the project (see Eqn. 8.7). “Water/Stormwater Retooling Alternative Payoff” in Eqn. 8.7, refers to the stock depicted in Figure 8.3.

$$Total\ payoff\ amount\ remaining\ on\ retooling\ altenative\ (\ \$) =$$
$$Initial\ cost\ (\$)\ of\ retooling\ altenative\ -$$
$$\int \frac{d(Water/StormwaterRetoolingAlternativePayoff\ \ (\$))}{dt}\, dt$$

[Eqn. 8.7]

To provide an example for discussion purposes (see Eqn. 8.8), assume the retooling alternative has $80,000 owed on the original cost of $100,000. The difference ($20,000) on the project was paid down using generated revenues in previous time steps during the simulation. Ten-percent (10%) of the generated revenues from Eqn. 8.6 ($865) is earmarked for paying off the project at the current time step, yielding the new amount owed as $79,135.

$$Total\ payoff\ \ amount\ remaining\ on\ retooling\ altenative(\$) = \$100{,}000 - \$20{,}865 = \$79{,}135$$
[Eqn. 8.8]

The project payoff period, estimated in Eqn. 8.9, is the total simulation time taken for the cost of the retooling alternative to be paid off (that is, the total payoff amount remaining on retooling alternative in Eqn. 8.7 is $0).

$$Payoff\ Period = Time_y\ that\ total\ payoff\ amount\ remaining\ on\ retooling\ altnerative\ is\ equal\ to\ \$0 - Time_x\ that\ the\ retooling\ altnetive\ cost\ is\ iniated\ into\ the\ model$$
[Eqn. 8.9]

The retooling alternative cost is initiated into the model after the desired level of public support for the retooling alternative is reached (discussed further in the following object class). If the retooling alternative cost is initiated into the model at t_{100} and the amount owed on the project reaches $0 at t_{300}, the payoff period would be 200 weeks, as shown in Eqn. 8.10.

$$Payoff\ Period = 300\ week - 100\ weeks = 200\ weeks\ or\ 3.85\ years$$
[Eqn. 8.10]

Public Support-Water/Stormwater Infrastructure Retooling Alternative: Generating desired levels of support is necessary prior to the implementation of an infrastructure retooling alternative to avoid delays in implementation and ensure the infrastructure retooling alternative is accepted by the community. Each public support object class includes a state chart with two primary states of interest: support or oppose. The transition to the states of *support* and *oppose* is based on the survey data from the survey distributed to residents of shrinking cities indicating their level of support towards the infrastructure retooling alternative incorporated into the model. Each agent is assigned an initial value from the probability distribution plot fit to the survey data. For decommissioning water infrastructure, the agents are assigned a value from a Weibull (3.63226, 3.36921) distribution. For decommissioning stormwater infrastructure, the agents are assigned a value from a Weibull (3.62009, 3.44894) distribution. If the agent's value is greater than four (representing support/strongly support), the agent moves into the state of *support*, elsewise, the agent transitions into the state of *oppose*.

Agents in the state of *oppose* are capable of moving back to the state of *support* if the agent's opinion changes due to new information or due to delayed implementation of an infrastructure retooling alternative. Agents may also leave the state of *support* (or the state of *oppose*) if they are moving away from the city, which occurs at the rate of departure based on the historical population trajectory. Agents in the state of *oppose* move to the state of *support* at the rate of adoption. In this model, the rate of adoption for smartphones is used (see Figure 8.4) as no data exists for the adoption of infrastructure retooling alternatives. The rate of adoption is calculated by using two independent studies conducted by industry researchers, Neilson Company (Neilson Company 2012) and BI Intelligence (Haggestuen 2013). Both Neilson Company and BI Intelligence compiled data and synthesized findings from surveys and published reports from around the world on the mobile industry to provide accessible information about the evolving industry. The relationship between the adoption of smartphone technology from the previously existing feature phone technology is analogous to the adoption of water retooling alternatives. Water and wastewater/stormwater infrastructures are existing infrastructures with established management methods (mirroring feature phones) and the proposed infrastructure retooling alternatives are new approaches to managing these existing infrastructures (mirroring smartphones).

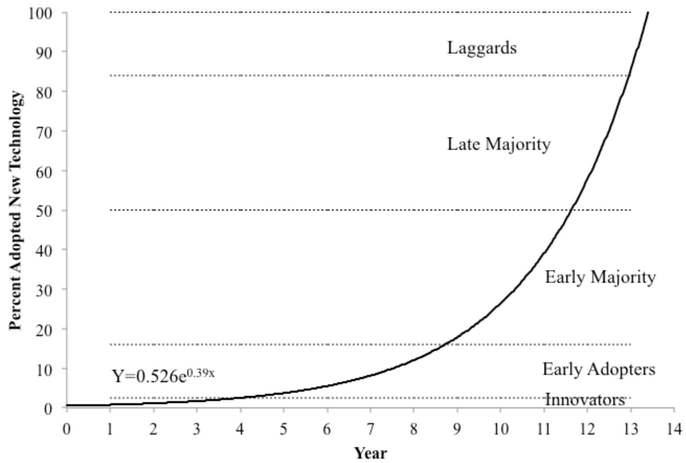


Figure 8.4. Rate of adoption used in the agent based component (adapted from Robinson 2009; Neilson Company 2012; Haggestuen 2013)

8.3. Validation and Verification

Validation and verification for the model occurred throughout the model development using four primary steps (Sargent 2004) outlined in Table 8.3, namely: conceptual model validation, computerized model verification, operational validation, and data validity. The first step in the validation and verification process occurred during the development of the causal loop diagrams in March 2013 with conference calls with SMEs in 5 Midwestern shrinking cities. The conceptual model validation included confirming that the theories, assumptions, data to be incorporated into the model, and representation of the system were reasonable. Following the abstraction of the model, operational validity was assessed by examining model stability over multiple simulation runs, logic correctness using traces throughout the simulation, and appropriateness of model response when the extreme ends of the parameters' plausible ranges were used. Face-to-face meetings with three SMEs in May 2013 and five SMEs in October 2014 were conducted to gain feedback on the developed computerized models. During these meetings, SMEs reviewed the computerized model components and logic to ensure that the AB-SD model accurately represented the conceptual model, and that the AB-SD model's behavior accurately represented the system. Furthermore, the SMEs confirmed that the model responded appropriately to varying parameters and the outputs were logical. SMEs stated that the model could be helpful for utility management and produces useful results. Five (5) SMEs were asked to provide quantitative feedback on difference aspects of the AB-SD Model in the October 2014, of which the average of the quantitative values for different model components are shown in Table 8.4. Each SME involved in the verification and validation of the model had a minimum of 15 years of experience working with the city water or wastewater utilities from the operations or management side.

Table 8.3. Steps in validation and verification

Validation and Verification Components	Justification
Data Validity (Sargent 2004) Data is correct, reliable, and able to represent system or population	Data used in analysis included outputs from Chapters 5 and 6, data provided by the cities, and published literature from reliable sources (e.g., NCDC 2014; USDA: NRCS 2013)
Conceptual Model Validation (Sargent 2004) The theories, assumptions, and representations of the problem are accurate	Conceptual model verification occurred throughout the development process, beginning in March 2013 with conference calls with utility managers from 5 Midwestern shrinking cities to discuss and verify the model assumptions and interdependencies. The causal loop diagrams were validated in May 2013 via face-to-face visits with Flint and Saginaw. The final model was validated for the theories, assumptions and representation by 5 SMEs in Flint and Saginaw. Validation scores may be found in Table 8.4.
Computerized Model (Sargent 2004) The computer model accurately represents the conceptual model	Dynamic testing was performed to ensure the individual components of the model were correct and the results were consistent across case studies. Dynamic testing consisted of tracing the behavior of the modeling under various conditions (e.g., increased/decreased decline rates, different cost of service increases, increased/decreased per capita water demands) to observe that the relationships in the causal loop diagram were accurately represented. The final model was validated that is accurately represents the conceptual models by 5 SMEs in Flint and Saginaw. See Table 8.4 for specific scores of the final model.
Operational Validity (Sargent 2004) The behavior of the model accurately represents the system	Dynamic testing was performed to ensure the individual components of the model were correct and the results were consistent across case studies. Dynamic testing consisted of tracing the behavior of the modeling under various conditions (e.g., increased/decreased decline rates, different cost of service increases, increased/decreased per capita water demands) to observe that the relationships in the causal loop diagram were accurately represented. The final model was validated that the behavior of the model is reasonable by 5 SMEs in Flint and Saginaw. Validation scored for the model may be found in Table 8.4
Operational Validity (Sargent 2004)**:** **Degenerate Tests** Behavior of model responds appropriately to changes in parameters	Sensitivity analyses were conducted and discussed in Section 8.4 and 8.5.
Operational Validity (Sargent 2004)**:** **Extreme Condition Tests** The model behaves appropriately when the extreme ends of ranges for parameters is used	Sensitivity analyses were conducted and discussed in Section 8.4 and 8.5.

Table 8.3. *(continued)*

Validation and Verification Components	**Justification**
Operational Validity (Sargent 2004)**:** **Internal Validation** Multiple run replications occur to ensure consistency	Multiple runs with varying parameter values occurred prior to the sensitivity analysis to ensure model stability.
Operational Validity (Sargent 2004)**:** **Traces** Ensure logic is correct as moving throughout the model during a simulation	Trace runs occurred to verify the model logic was correct and as represented in the causal loop diagrams.
Coherence Logic and understandability of results	The results and conclusions drawn were easily understood based on the face-to-face validation and verification meetings that occurred in October 2014.

Table 8.4. Quantitative feedback from 5 SMEs for validation and verification purposes

Aspect of the AB-SD Model	**Averages***
The components of the model represent the most critical aspects of the system needed for modeling the goal.	**4.6**
The abstraction of the components and interactions in the model are complete.	**4.8**
The behavior of the model is reasonable.	**4.4**
The theories and assumptions underlying the model are correct.	**4.6**
The model's representation of the system and the model's structure, logic, and causal relationships are reasonable.	**5**
The assumptions regarding the model's parameters, variables, and interactions are reasonable.	**5**
The level of detail and the relationships used for the model are appropriate for the intended purpose.	**4.6**
The output of the simulation model has the accuracy required for the model's intended purpose.	**4.4**
The simulation behavior is reasonable in the context of produced results.	**4.4**
The model could be helpful for utility management and produces useful results.	**5**

***(1: poor, 2: needs significant improvements, 3: needs modifications to be useful, 4: good enough, 5: excellent)*

8.4. Parameter Variation

The individual simulation and parameter variation (comparable to a sensitivity analysis) capabilities in AnyLogic are used to assess the impact of parameters on the AB-SD model's behavior. During a parameter variation, a deterministic parameter is varied within a user-defined range at user-defined increments. For example, for the parameter variations discussed below, the parameter for rate increase for water, is varied between 1%-10%, annually, over multiple simulations. The results of the analyses are shown in Figures 8.5-8.18, where the intensity of the color corresponds to the probability of *y* occurring at time x (t_x); darker portions of the chart indicate higher probabilities of being closer to the median of all simulations. The x-axis tracks the simulation time, and the y-axis indicates the output of the outcome of interest. In the graph, if a vertical 'slice' is made at an instance in time, the probability of any y occurring is determined, bounded by the inner two quartiles (similar to a boxplot without the whiskers). The lightest grey shade that is shown in the figures tracks the simulation time and is meaningless in the interpretation of the graphs.

Table 8.5 summarizes the parameters varied in the parameter variation analyses, the range in which the parameter is varied, and the rationale for varying the particular parameter. The outputs evaluated that are dependent on the uncertain parameters within this model are:

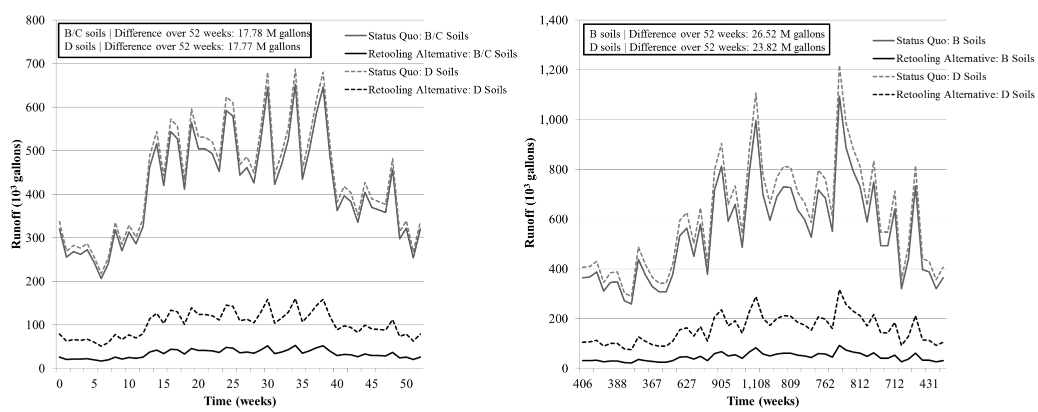
1. Generated runoff.
2. Non-point source pollutants.
3. Citywide residential water demand.
4. Water revenues gained from increasing water rates.
5. Wastewater revenues gained from increasing water rates.
6. Time period to pay off the water infrastructure retooling alternative (decommissioning pipelines).
7. Time period to pay off the stormwater retooling alternative (decommissioning impervious surfaces).
8. Time period to generate desired level of support

Table 8.5. Parameters evaluated parameter variation

Independent Parameter	Flint		Saginaw		Rationale
	Base case values	Minimum value, maximum value, increment	Base case values	Minimum value, maximum value, increment	
Soil Type	B(C) soils	(0,1,1)	B Soils	(0,1,1)	Soil type is a binary variable. Zero (0) is used for D soils, and 1 indicates B(C) soils in this model.
Water rate annual increase	3%	(0.01, 0.1, 0.01)	3%	(0.01, 0.1, 0.01)	Future rate increases have not been established or determined, thus a range of possible values, up to the willingness to pay threshold establish in Chapter 7 were evaluated.
Wastewater rate annual increase	3%	(0.01, 0.1, 0.01)	3%	(0.01, 0.1, 0.01)	
Revenues directed for water retooling alternative pay off	10%	(0.1, 0.7, 0.1)	10%	(0.1, 0.7, 0.1)	This variable evaluates the pay off periods for a project. As retooling alternatives have not been implementing in cities, there are no case studies discussing the financing of t retooling alternatives. Therefore, different ranges for earmarked revenues for paying off the project were evaluated to assess the pay off period.
Revenues directed for stormwater retooling alternative pay off	10%	(0.1, 0.7, 0.1)	10%	(0.1, 0.7, 0.1)	
Decline Rate (per week)	0.03104%	+/-30%	0.024671%	+/-30%	The decline rate is based on historical census data, but may differ in the future based on factors such as, right-sizing efforts, dynamics of industries, or improvement of crime rates. This parameter was varied to observe if the time period necessary to generate support was sensitive to the rate of decline.
Rate of Adoption	$(0.5257e^{0.3917})/52$	+/-30%	$(0.5257e^{0.3917})/52$	+/-30%	This parameter was varied to observe how time period necessary to generate support was sensitive to the rate of adoption. The rate of adoption is based on smart phone adoption, as the rate of adoption for infrastructure alternatives has not been captured or quantified in literature.

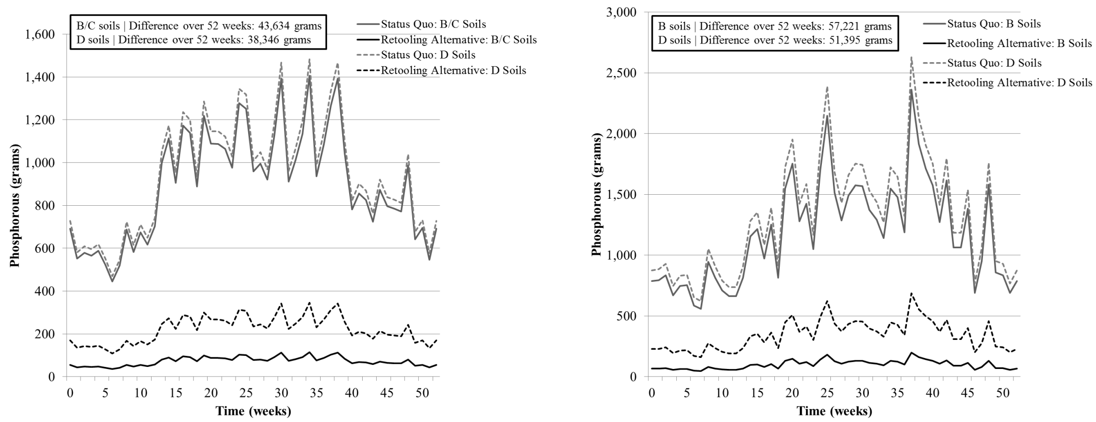
Water quality must be considered when evaluating the source treatment and wastewater treatment needs. The concentration of pollutants must be monitored as stormwater flows or overflows enter the water sources. The reduction in NPS pollutants entering the separate stormwater or CSS is evaluated in the model, using Baird and Jennings (1996) event mean concentrations of NPS pollutants based on land use. Increased NPS pollutants degrade the water quality, with specific concern towards phosphorous, as the Great Lakes are phosphorous limited (USEPA 2012). The phosphorous resulting from watershed runoff is a major contributor to the *"…eutrophication and the proliferation of nuisance algae"* in the Great Lakes (GLEAM 2014).

For the stormwater infrastructure system, the soil type parameter was varied (other parameters in Table 8.5 were held at their base case values). The remaining parameters values contributing to the stormwater runoff, namely, event mean concentration of NPS pollutants and historical rainfall data, are deterministic at t_x. Figures 8.5-8.7 depict the annual reduction of stormwater runoff and NPS pollutants due to implementation of the retooling alternative in the analysis areas. The runoff in Flint (and consequentially the NPS pollutants) is reduced by 91.9% and 76.7% for B/C soils and D soils, respectively, after the stormwater infrastructure retooling alternative is implemented. The runoff in Saginaw (and NPS pollutants) is reduced by 91.6% and 73.9% for B soils and D soils, respectively, after the stormwater infrastructure retooling alternative is implemented. The graphs for the phosphorous and dissolved phosphorous (Figures 8.6 and 8.7) are shown to illustrate the correlated reduction of NPS pollutants, as the quantity of NPS pollutants are a function of the generated runoff.



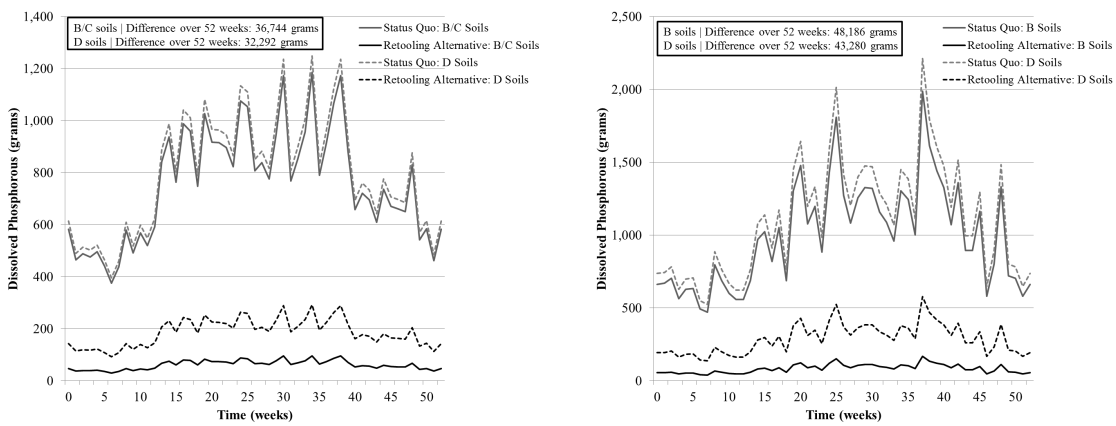
(a) (b)

Figure 8.5. Runoff generated annually in analysis areas: (a) Flint and (b) Saginaw



(a) (b)

Figure 8.6. Annual phosphorous (grams) in analysis areas: (a) Flint and (b) Saginaw



(a) (b)

Figure 8.7. Annual dissolved phosphorous (grams) in analysis areas: (a) Flint and (b) Saginaw

Within this AB-SD model there are two parameters, population and price elasticity, connected directly to citywide residential water demand. The increase in prices may only increase by approximately 10%, which is the average percentage that residents would be willing to pay for water (and wastewater) service in the shrinking, as determined by the survey deployed (discussed further in Chapter 7). By using the willingness-to-pay value, it is assumed that prices can increase to this point without extreme opposition towards the utility provider. To assess the impact of price elasticity at a granular scale, Figure 8.8 shows the impact of rate increases on the per capita weekly water demand. The parameter varied over multiple simulations is the annual percentage rate increase (until the rate increase ceiling, in this case approximately 10%, is met). Lipsey and Chrystal's (1999) price elasticity model for water demand was used in this model. In this model, the price elasticity ranges from -0.2 to -0.5, and falls within the range of other established price elasticity values in literature (e.g., Espey et al. 1997; Dalhuisen et al. 2003; Worthington and Hoffman 2008; Hung and Chie 2012). The wide variance of demand at any given time resulting from the price elasticity is visible, ranging by up to 55 gallons per capita per week. As indicated in Figure 8.8, the most probable range in demand is a decrease of 25 to 50 gallons per capita per week. For planning purposes, utility managers should be cognizant of the probably ranges of decrease in water usage arising from rate increases, counteracting the possible generated revenues from increased rates.

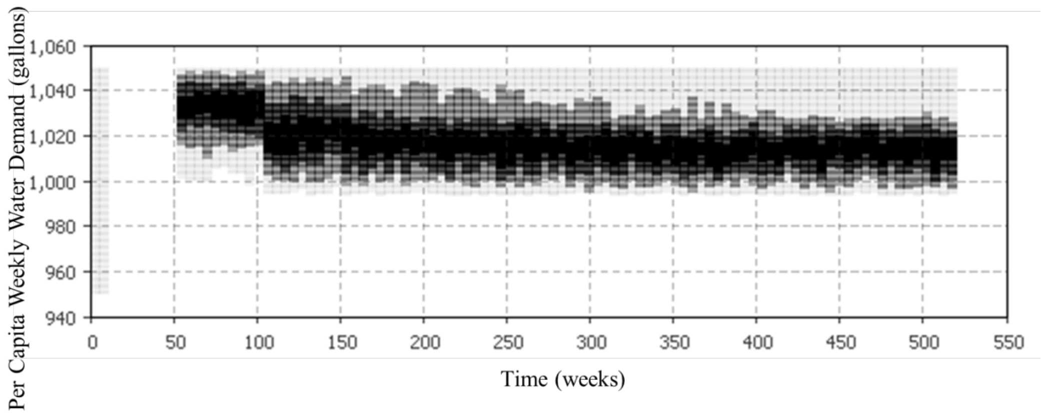
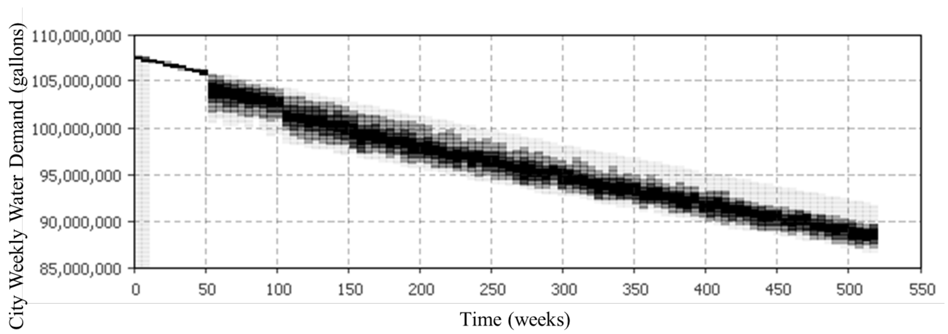


Figure 8.8. Impact of varying annual water rate increases on the per capita weekly water demand

Long term planning for utilities in cities that are experiencing chronic decline should account for an overall expected continuous decline in citywide residential water demand. Figure 8.9 shows estimated citywide residential water demand ranges over the simulation time (10 years). The parameter varied in this simulation is the annual water rate increase, while other parameters were maintained at the base case values, indicated in Table 8.5. Citywide water demand ranged up to 5 million gallons per week, with the most probable ranges spanning 1 to 2 million gallons per week for Saginaw and Flint, respectively. This wide range for residential water demand may necessitate a large available capacity of citywide water to account for differing behavior of residences and uncertain declines, indicating that the excess capacity typical to shrinking cities may be beneficial to meet potential needs for the wide water demand ranges. Utility managers can use this information to estimate a probable range of water demands (and hence, wastewater produced), as opposed to a single estimate value based solely on population. For instance, if Flint's population declines to approximately 95,000, the probable water demand ranges from 94,750,000 to

97,750,00 gallons per week, and may vary between 94,500,000 to 100,000,000 gallons per week. Similarly, if Saginaw's population falls below 48,000, water demands may range between 47,000,000 to 49,300,000 gallons citywide per week.



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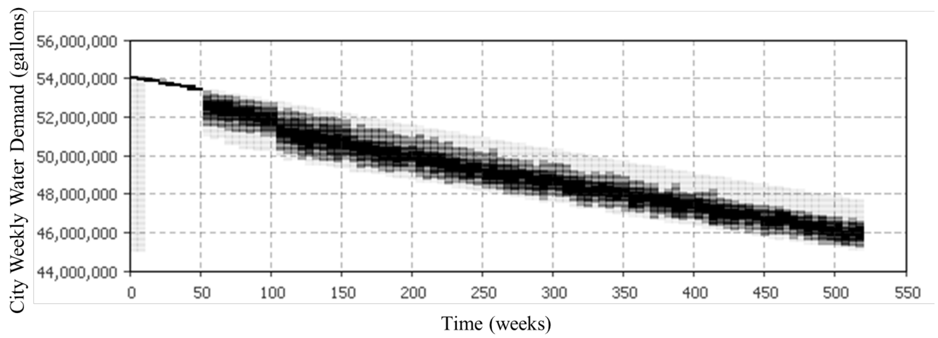
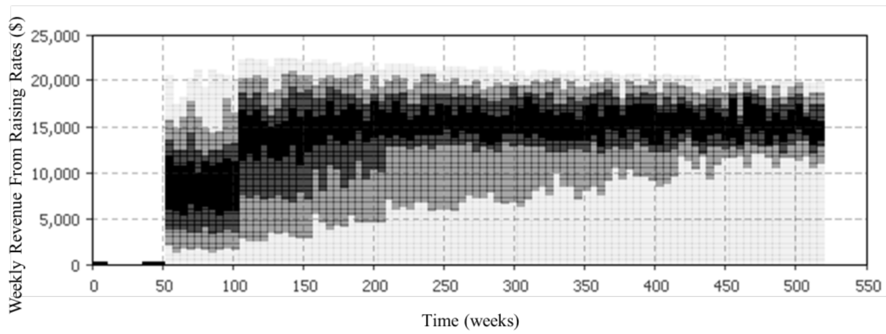


(b)

Figure 8.9. Impact of varying water rate increases and population on the citywide weekly residential water demand: (a) Flint and (b) Saginaw

The varying demand from price elasticity and population decline will directly impact the water revenues generated from increasing the water prices, shown in Figure 8.10. As discussed previously in Section 8.2, the generated revenues are those above the baseline, t_0 revenues. That is, the increased rate will be multiplied by a lower per capita demand from behavior changes due to the increased prices. Revenues gained from increasing water rates vary over the course of the simulation. Near the beginning of the simulation, Flint is most likely to generate between $6,000 and $12,000 dollars per week in revenues from increased rates, whereas Saginaw is most likely to generate between $2,500 and $6,000 per week in revenues. The magnitude difference results from the different in population sizes, where Flint has an initial population of 102,434 and Saginaw has an initial population of 51,508. As the simulation progresses, and the approximate 10% rate increase ceiling is met, Flint is most likely to bring in around $15,000 of revenues per week, while Saginaw is most like to generate $7,500 per week.



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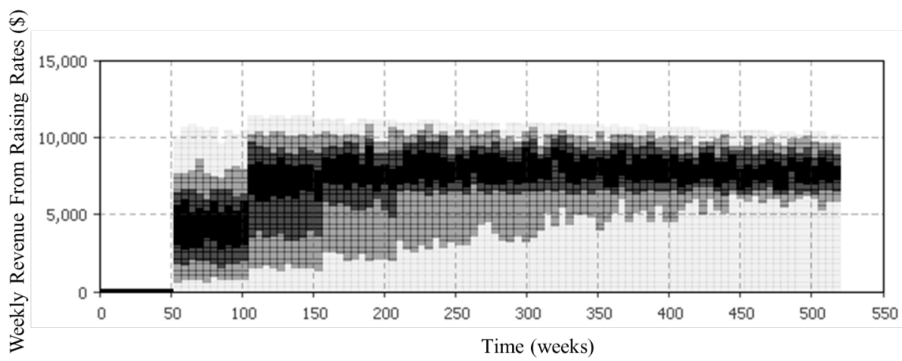
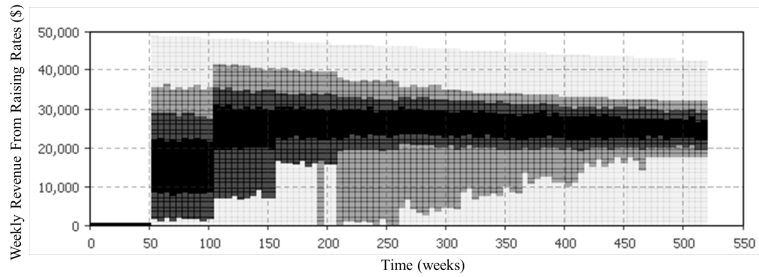


(b)

Figure 8.10. Generated water revenues from water rate increases: (a) Flint and (b) Saginaw

Figure 8.11 shows the impact of varying rates for both water and wastewater on the total wastewater revenues that may be generated from increasing wastewater rates. Within the most probable generated revenues across all annual rate increases assessed, the range in expected to vary by approximately $10,000 per week, or approximately $500,000 annually. This large difference in the uncertainty of additional revenue that may be gained from potential rate increases should be considered for financial planning purposes.



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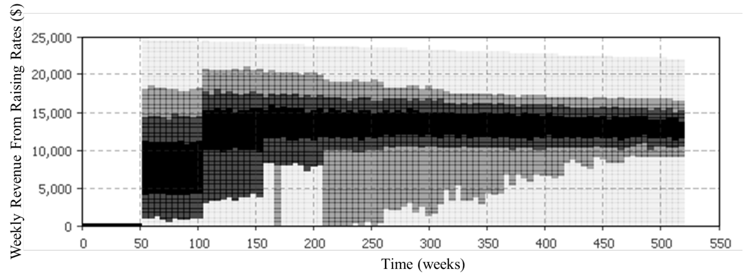

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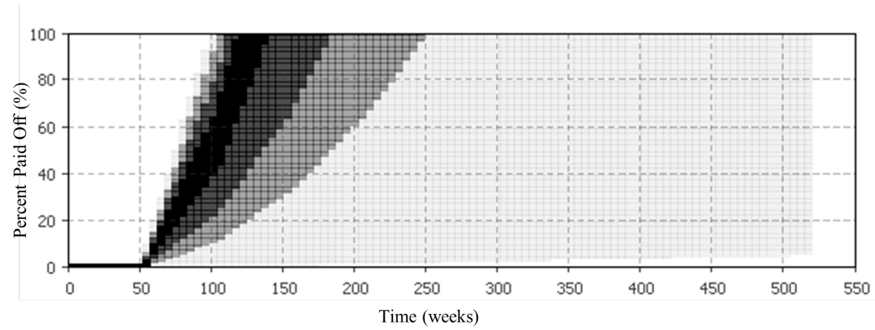
Figure 8.11. Generated wastewater revenues from water rate and wastewater rate increases: (a) Flint and (b) Saginaw

Figure 8.12(a) estimates the pay off period for the water infrastructure retooling alternative over 10 city blocks (0.07 square miles of residential neighborhood, i.e., the original analysis area described in Chapter 4) in Flint. Figure 8.18(b) estimates the pay off period for the water infrastructure retooling alternative over 16 city blocks (0.16 square miles of residential neighborhood, i.e., the original analysis area described in Chapter 4) in Saginaw. The pay off periods shown in Figure 8.12 depicts a scenario in which 10% of the revenues generated from increased rates are earmarked for paying off the water retooling alternative. The varying parameter is the annual percentage increase in water rates after the 1st year.

Based on varying annual water rate increases, Flint is most likely to pay off the water infrastructure retooling alternative in 1.5 years, but can take up to 2.6 years. On the other hand, the highest probability of Saginaw to pay off the water infrastructure retooling project is in 3.25 years, but may take up to 7.1 years. The difference in pay off periods between Flint and Saginaw is a result of a larger analysis area and lower population (i.e., fewer rate payers) in Saginaw.



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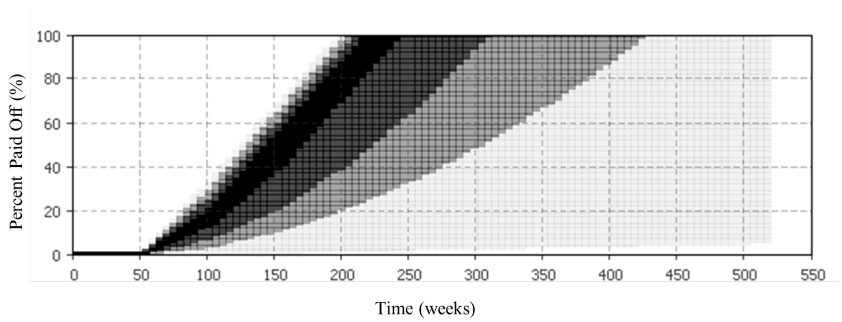

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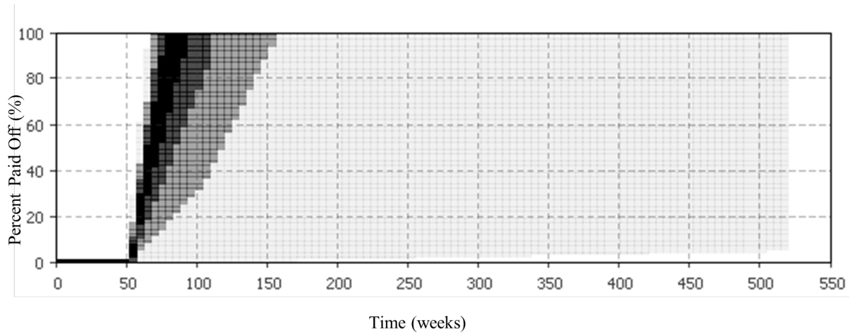
Figure 8.12. Water infrastructure retooling alternative pay off with 10% of rate revenues, and varying water rate increases: (a) Flint and (b) Saginaw

Understanding tradeoff between pay off period and diverting resources may be relevant if the utility's goal is to pay the alternative off quickly. If the pay off period is not of great concern to the utility, the utility may wish to earmark limited resources to paying off the retooling alternative (increasing the pay off period), while investing a greater percentage of resources towards immediate concerns, such as time-sensitive maintenance or rehabilitation needs. Figure 8.13 estimates the pay off periods by varying the percentages of the revenue gained from increasing water rates that are diverted to pay off the water infrastructure retooling project (while maintaining other parameters at their base case values as indicated in Table 8.5). Flint is most likely to pay off the water retooling alternative in less than 1.3 years, but may take up to 3.1 years. Saginaw is most likely to pay off the alternative in less than 2.7 years, but may take up to 7 years.



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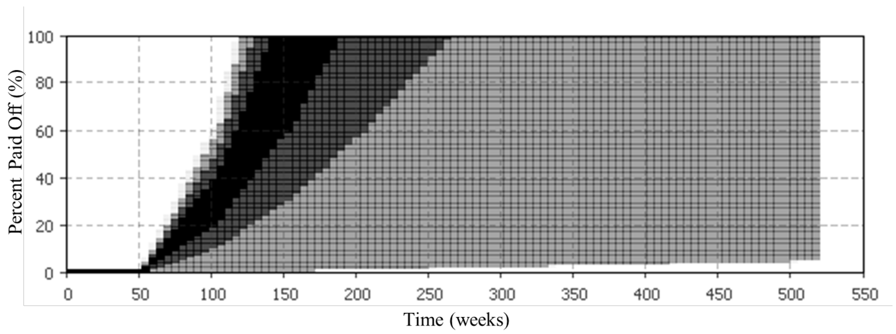

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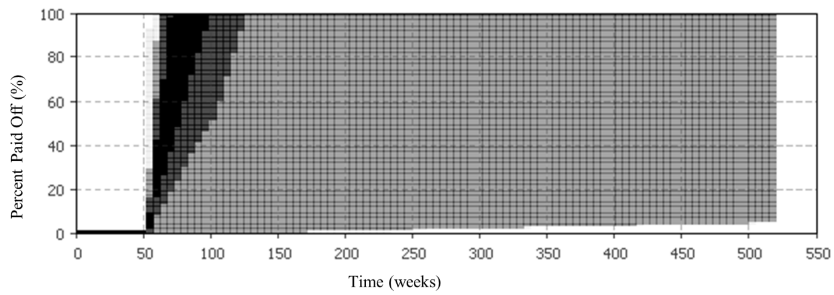
Figure 8.13. Water infrastructure retooling alternative pay off with a 3% water rate increase and varying percentages of revenue diverted to pay off project: (a) Flint and (b) Saginaw

As expected, the uncertainty associated with varying both parameters (increasing water rates and earmarking a percentage of generated revenues from the rate increases to pay off the project) is much greater than the uncertainty in only considering the percentage of generated revenues earmarked from the rate increases, as shown in Figure 8.14. In Saginaw, the water infrastructure decommissioning project has the highest probability to be paid off in less than 3.3 years but may take up to 7.8 years, based on the combination of parameters. In Flint, the water infrastructure decommissioning project is most likely to be paid off in less than 1.34 years, but may take up to 3.3 years.



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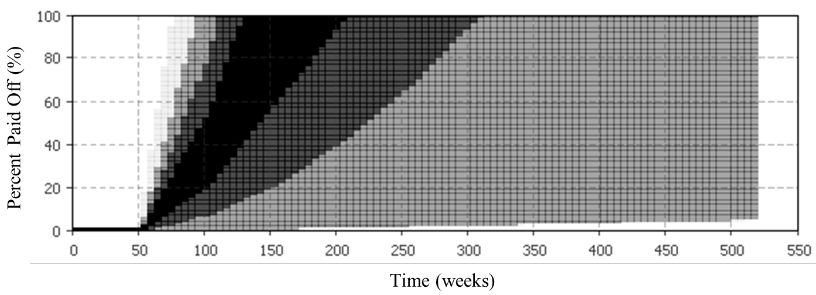

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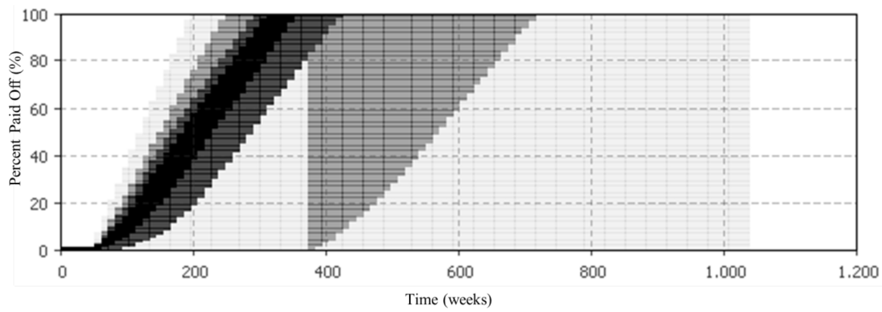
Figure 8.14. Water infrastructure retooling alternative pay off period with varying annual water rate increases, and varying percentages of revenue from rate increases diverted to pay off project: (a) Flint and (b) Saginaw

The uncertainty in project pay off periods for the water retooling alternative associated with varying the water rate increase seen in Figure 8.12 is analogous to the uncertainty in paying off the stormwater retooling infrastructure project. Figure 8.15 illustrates the stormwater retooling alternative pay off period based on varying water rate increases and wastewater rate increases (with the remaining parameters held at their base case value indicated in Table 8.5). Water rate increases are relevant due to the interdependencies between the two infrastructures. Increased water billing rates results in decreased per capita water demand that reduces the volume of wastewater produced and billed to the customer. Figure 8.16 depicts the difference when this uncertainty is not accounted for in varying water rate increases, by holding the water rate increase at 3% annually and only varying the wastewater rate increase.

In Flint, when the uncertainty with both water and wastewater rates are considered, the stormwater infrastructure retooling alternative is most likely to be paid off at 5.8 years and as late as 13.5 years. When only the uncertainty associated with rising wastewater rates are considered, the stormwater retooling alternative's pay off period may be as late as 8.1 years. The difference in possible pay off periods (5.4 years) is a result of the uncertainties associated with water rates and wastewater rates, as opposed to solely considering the uncertainty associated with wastewater rates. A similar relationship between stormwater payoff period, and water and wastewater rates may be seen in Saginaw with a difference in possible payoff periods of 6.1 years. However, the drastic difference in the latest pay off period of approximately 13.5 years for Flint and Saginaw is due to the, lower population in Saginaw (resulting in lower total billed demand as compared to Flint) and a surface analysis area requiring decommissioning that is approximately twice the size. The analysis area for decommissioning in Saginaw is 0.16 square miles versus Flint's 0.07 square miles. This model captures the non-physical disrupter, water rate increases, cascading into the wastewater infrastructure system, impacting not only the wastewater demands on the system, but also the impact on generated revenues; a relationship not previously captured in literature.



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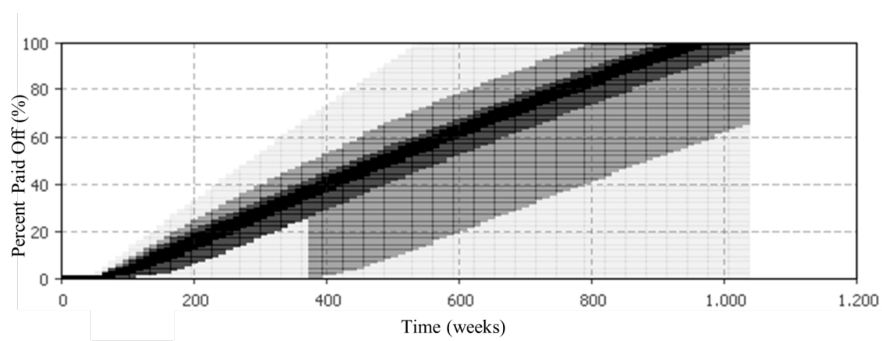

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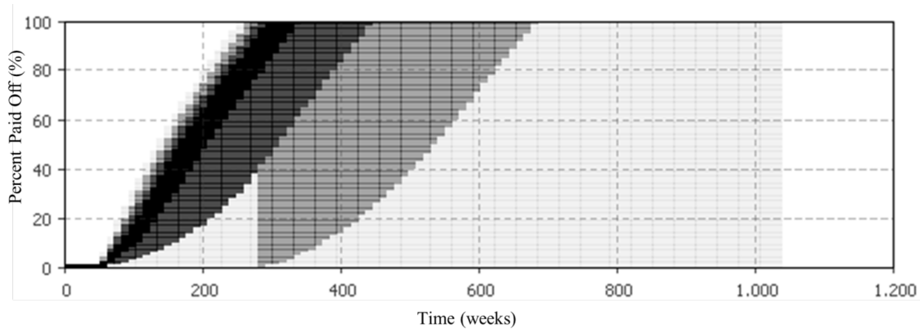
Figure 8.15. Decommissioning stormwater infrastructure alternative pay off with varying annual water and wastewater rate increases, and 10% of revenue from rates diverted to pay off project: (a) Flint and (b) Saginaw



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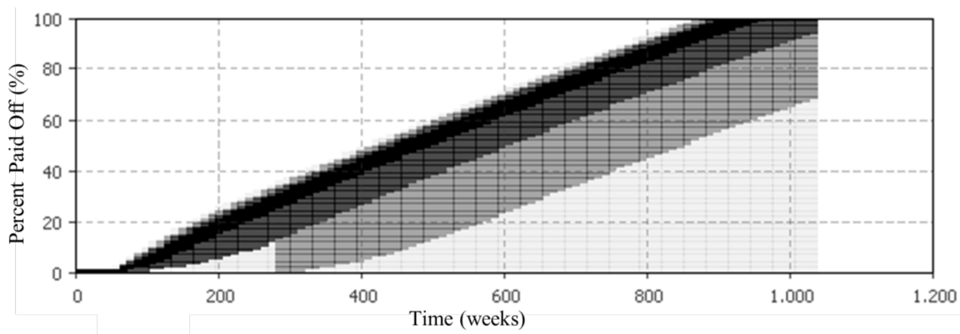


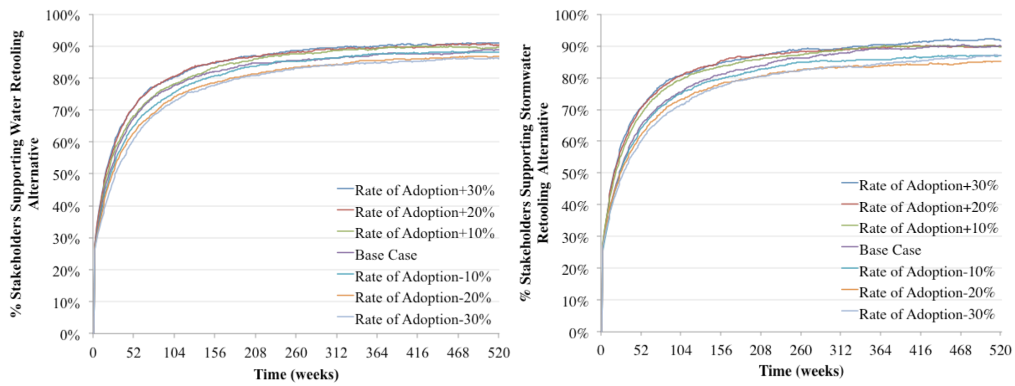
(b)

Figure 8.16. Decommissioning stormwater infrastructure project pay off with varying wastewater rate increases, 3% water rate increases, and 10% of revenue from rates diverted to pay off project: (a) Flint and (b) Saginaw

As discussed in Section 8.2, the AB component models the support generated for the infrastructure retooling alternatives before the infrastructure retooling alternatives enter the work plan for the city. The model assumes that if the desired level of support is met prior to implementing the retooling alternative, the resistance from the public can be mitigated. The initial number of residents in the state of *support* for decommissioning water and stormwater infrastructure differ slightly based on their individual weibull distributions, as discussed in Section 8.2. The transition of the residents initially in the state of *oppose* (at t_0) to the state of *support* follows the defined rate of adoption, thus appearing to be similar to Figure 8.4. When the percentage of residents within the state of *support* is equal to or greater than the minimum threshold of support needed to implement a retooling alternative, the retooling alternative is initiated into the work plan for the city. As the minimal level of support increases, the time it takes to gain additional support also increases. For instance, to move from 60% to 70% support for the water infrastructure retooling alternative takes 26 additional weeks, whereas to move from 70% to 80% support takes 67 additional weeks, 2.5 times the time to gain the previous 10% in support. The latter portion of the late majority and laggards in the rate of adoption curve do not support the new idea (management alternative) as quickly as the previous adopters (Hoffman 2011), creating a time obstacle in order to gain the amount of desired support. When considering the participatory processes, decision makers will have to make the trade-off between the level of support, the resources to encourage the adoption of the alternatives that influences the rate of adoption, and the targeted time period for implementation.

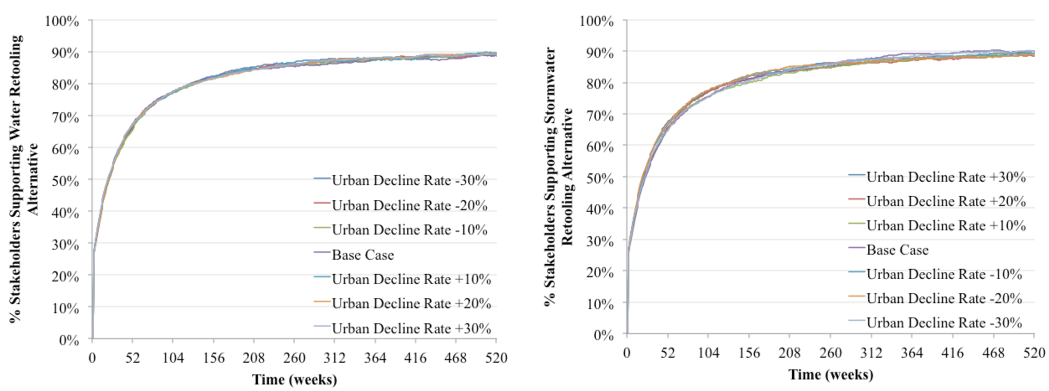
The pattern of support of both agent classes (Figures 8.17 and 8.18) is an emergent property arising from the systematic interaction of the agents transitioning between states. This behavior is sensitive to the rate of adoption, but is not sensitive to the population decline rate of the city. When varying the adoption rate, the time in which agents reach different levels of support differs significantly between the rate of adoption +/-30%, indicated by the high standard deviation between the results in Table 8.6. However, varying population decline rates has negligible impact upon the time period taken to gather the desired level of support, indicated by a low standard deviation in Table 8.6. In the AB-SD model, it is assumed that the population decline rate applies to the agent class, irrespective of agent's state. However, the attitude at t_x may be influential in determining whether the agent leaves the city. For instance, Herz (2006) discusses that increasing prices and deteriorating utility services can perpetuate the existing urban decline. Thus, those who view a need for implementing retooling alternatives *may* be those who are more likely to leave the city. Further analysis regarding *why* people are leaving and their views towards infrastructure services at the time when they leave would be necessary to determine if the different states (of support/ opposition) should decline at different rates, as opposed to applying a uniform decline rate across all states, and all agents.

Within the AB component, during the 10-year simulation, the city is not able to ever reach full consensus of support (that is 100% support), due to the transition into the state of *oppose* and the emigration from the city resulting from continued urban decline. 91% and 90% are the greatest levels of support achieved via multiple simulations of the stochastic model for water and stormwater infrastructure retooling alternatives, respectively.



(a) (b)

Figure 8.17. Percent of supporters for the retooling alternative over time during the simulation with parameter variations of rates of adoption: (a) water retooling alternative and (b) stormwater retooling alternative



(a) (b)

Figure 8.18. Percent of supporters for the retooling alternative over time during the simulation with parameter of population decline: (a) water retooling alternative and (b) stormwater retooling alternative

Table 8.6. Sensitivity towards the support for water and stormwater retooling alternatives

	Week That The Level of Support was Reached			
	50%	**60%**	**70%**	**80%**
Water Infrastructure Retooling Alternative: % Support (base case)	21	35	61	128
Water Infrastructure Retooling Alternative: Sensitivity of Rate of Adoption				
Rate of Adoption +30%	16	27	49	101
Rate of Adoption +20%	17	29	49	105
Rate of Adoption +10%	19	33	59	125
Rate of Adoption -10%	22	40	72	146
Rate of Adoption -20%	25	44	83	175
Rate of Adoption -30%	29	50	87	187
Average	21.3	37.2	66.5	139.8
Standard Deviation	5.0	9.0	16.7	35.9
Water Infrastructure Retooling Alternative: Sensitivity of Population Decline Rate				
Population Decline Rate +30%	20	36	63	129
Population Decline Rate +20%	22	35	62	129
Population Decline Rate +10%	22	36	63	130
Population Decline Rate -10%	22	38	65	130
Population Decline Rate -20%	22	36	64	128
Population Decline Rate -30%	20	36	63	127
Average	21.3	36.2	63.3	128.8
Standard Deviation	1.0	1.0	1.0	1.2
Stormwater Infrastructure Retooling Alternative: % Support (base case)	24	41	70	143
Stormwater Infrastructure Retooling Alternative: Sensitivity of Rate of Adoption				
Rate of Adoption +30%	17	28	50	94
Rate of Adoption +20%	17	31	51	97
Rate of Adoption +10%	19	33	56	109
Rate of Adoption -10%	25	42	74	161
Rate of Adoption -20%	26	47	82	197
Rate of Adoption -30%	29	52	93	196
Average	22.2	38.8	67.7	142.3
Standard Deviation	5.2	9.6	18.0	48.4
Stormwater Infrastructure Retooling Alternative: Sensitivity of Population Decline Rate				
Population Decline Rate +30%	22	35	63	130
Population Decline Rate +20%	22	39	66	135
Population Decline Rate +10%	23	40	68	138
Population Decline Rate -10%	21	36	63	131
Population Decline Rate -20%	20	35	63	130
Population Decline Rate -30%	23	39	69	133
Average	21.8	37.3	65.3	132.8
Standard Deviation	1.2	2.3	2.7	3.2

8.5. Sensitivity Analysis

Sensitivity analysis explores how the parameters impact the model's outcomes, by using traces of the runs to create tolerance intervals (Ford and Flynn 2005). The tolerance intervals are estimated similar to the parameter variation in Section 8.4, in that each simulation uses different values for the variables. However, unlike the parameter variation that takes user-defined, finite increments between the minimum and maximum user-defined values, the tolerance intervals are estimated using random parameters that fall between the minimum and maximum values (Ford and Flynn 2005). In this sensitivity analysis, all parameters from Table 8.7 are varied randomly during each run, whereas in the parameter variation only one or two variables are varied while the others remain constant. The parameters in Table 8.7 are those that are uncertain within the cities, such as future decline rate, or may have assigned ranges, such as price elasticity. The outputs evaluated that are dependent on the uncertain parameters within this model are:

1. Citywide residential water demand.
2. Citywide residential wastewater demand.
3. Water revenues gained from increasing water rates.
4. Wastewater revenues gained from increasing water rates.
5. Time period to pay off the water infrastructure retooling alternative (decommissioning pipelines).
6. Time period to pay off the stormwater infrastructure retooling alternative (decommissioning impervious surfaces).

Table 8.7. Parameters evaluated for correlation coefficients with outputs

Independent Parameter	**Flint**		**Saginaw**		**Rationale**
	Base case values	**Ranges used in analysis**	**Base case values**	**Ranges used in analysis**	
Decline rate (per week)	0.03104%	+/-10%	0.024671%	+/-10%	The decline rate is based on historical census data, but may differ in the future based factors such as, right-sizing efforts, dynamics of industries, or improvement of crime rates.
Price elasticity	-0.35	Uniform (-0.2, -0.5)	-0.35	Uniform (-0.2, -0.5)	Price elasticity is reported in literature as a range of values. Price elasticity values may be anywhere along the spectrum of ranges.
Water to wastewater ratio	0.85	Uniform (0.6, 0.85)	0.85	Uniform (0.6, 0.85)	Grigg (2012) provides a range of plausible values for the water demand entering the wastewater system.

Table 8.7. *(continued)*

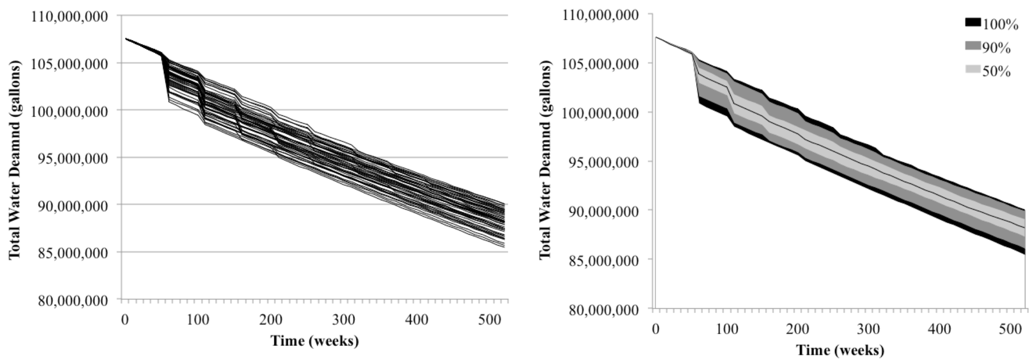
Independent Parameter	Flint		Saginaw		Rationale
	Base case values	Ranges used in analysis	Base case values	Ranges used in analysis	
Water rate annual increase	3%	Uniform (0.01,0.1)	3%	Uniform (0.01, 0.1)	Future rate increases have not been established or determine, thus a range of possible values, up to the willingness to pay threshold establish in Chapter 7 were evaluated.
Wastewater rate annual increase	3%	Uniform (0.01, 0.1)	3%	Uniform (0.01, 0.1)	
Revenues directed for water retooling alternative pay off	10%	Uniform (0.1, 0.3)	10%	Uniform (0.1, 0.3)	This variable evaluates the time pay off periods for a project. As retooling alternatives have not been implementing in cities, there are no case studies discussing the financing of the retooling alternative. There for, different ranges for earmarked revenues for pay off the project were evaluated to assess the pay off period and demonstrate the applicability of the framework.
Revenues directed for stormwater retooling alternative pay off	10%	Uniform (0.1, 0.3)	10%	Uniform (0.1, 0.3)	

The confidence of the tolerance intervals are estimated using Eqn. 8.11 (Ford and Flynn 2005):

$$Confidence = 1s - p^n - n * (1 - p) * p^{n-1} \qquad \text{[Eqn. 8.11]}$$

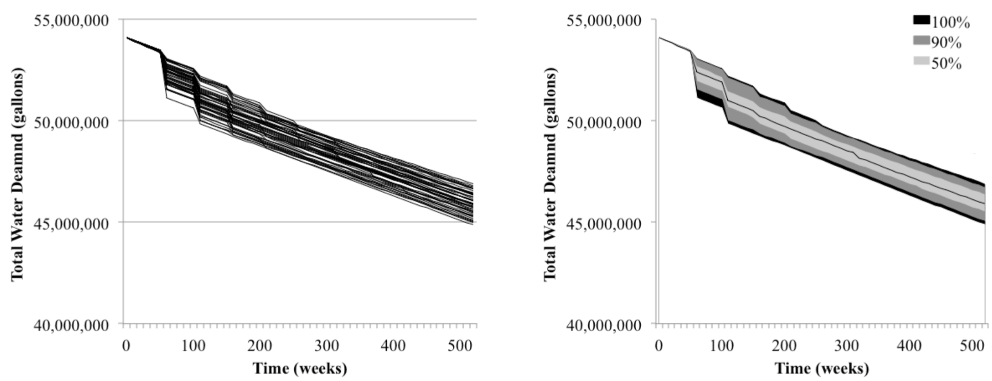
where n is the number of runs and p is the proportion of the results covered by the runs. The outputs from individual runs comprise the tolerance intervals based on the assumption that inputs can be varied independent from one another, which is a pragmatic assumption due to the many interdependencies between inputs inherent to a system dynamics model (Ford and Flynn 2005). The tolerance intervals in this study are developed using 50 simulations for each city, providing a 96.6% confidence that the extreme values of the simulation encompass 90% of the results.

The results of the ranges of citywide water demand for both cities are consistent with the findings from the parameter variation (Figures 8.19 and 8.20). Flint's most probable demand range for a given week is approximately 2 million gallons, whereas Saginaw's most probable weekly demand range for a given week is approximately 1 million gallons. These numbers are logical relative to one another, as the population of Saginaw is approximately half that of Flint. Similarly for citywide wastewater demand, the results were consistent with the parameter variation.



(a) (b)

Figure 8.19. Flint’s citywide residential water demand: (a) Sensitivity graph based on 50 traces and (b) Tolerance interval

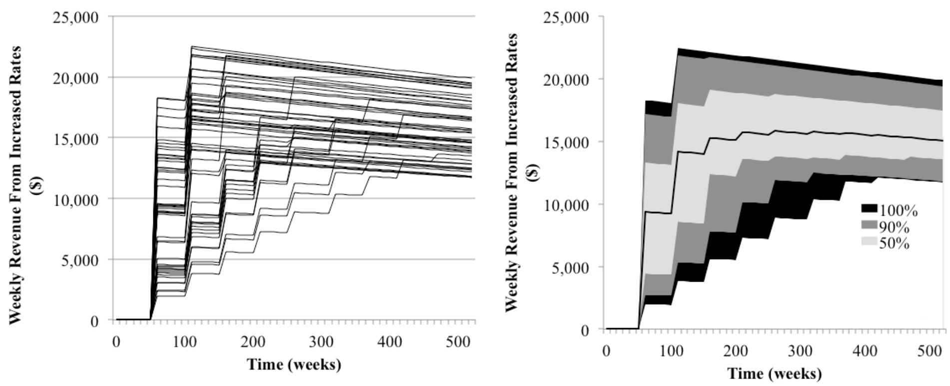


(a) (b)

Figure 8.20. Saginaw’s citywide residential water demand: (a) Sensitivity graph based on 50 traces and (b) Tolerance interval

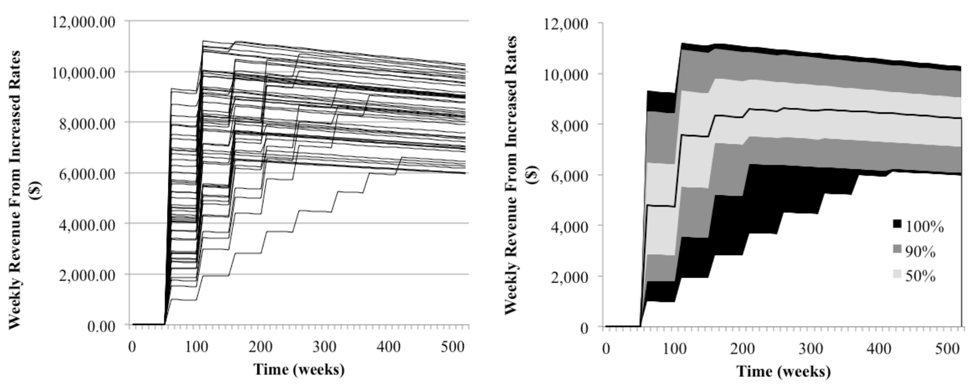
The results of the probable ranges for water revenues gained from increasing water rates is consistent the results from the parameter variation for both cities (Figures 8.21 and 8.22). However, what differed drastically from the parameter variation in Section 8.4, were the results from the revenue gained from wastewater rates. These sensitivity analyses captures the possibility that if the wastewater rates do not increase in approximately the same magnitude as water rates, the wastewater utility may face a loss in revenues (although this possibility is in the lower 5% of probable outcomes).

As discussed in Section 8.2, the AB-SD model does not reflect the structure of rates within the city, but the relationship between the consumptions and rate changes. Based on discussions with five SMEs in Flint and Saginaw in October 2014, the rates are often determined by outside consultants. In one city, the SMEs stated that the water and wastewater consultants who set the rates do not communicate with each other. In the absence of communication across utilities and when price elasticity is not accounted for in long-term planning, the wastewater utility can potentially lose total revenue (Figures 8.23 and 8.24). This loss of total revenue was not captured in the parameter variation, due to the fact that when water and wastewater rates are increased, both variables are increased from the minimum defined value to the maximum defined values, at pre-defined steps. In the sensitivity analysis, random values are assigned within the defined ranges, resulting in simulation runs with high water rate increases and low wastewater increases.



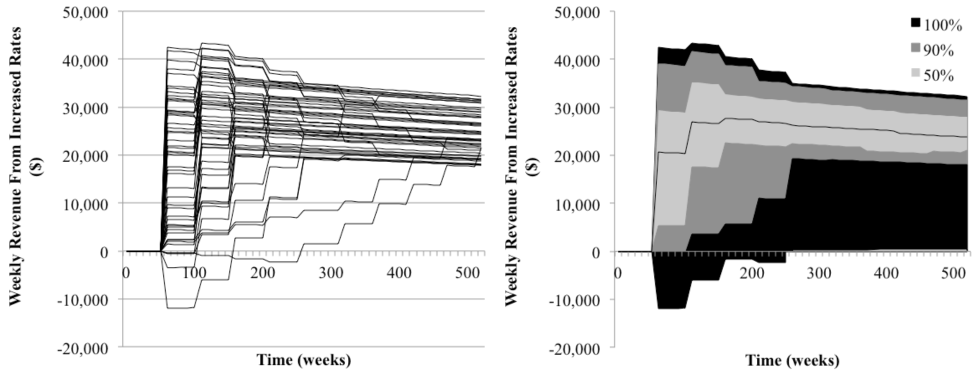
(a) (b)

Figure 8.21. Flint's citywide generated water revenues from increasing water rates: (a) Sensitivity graph based on 50 traces and (b) Tolerance interval



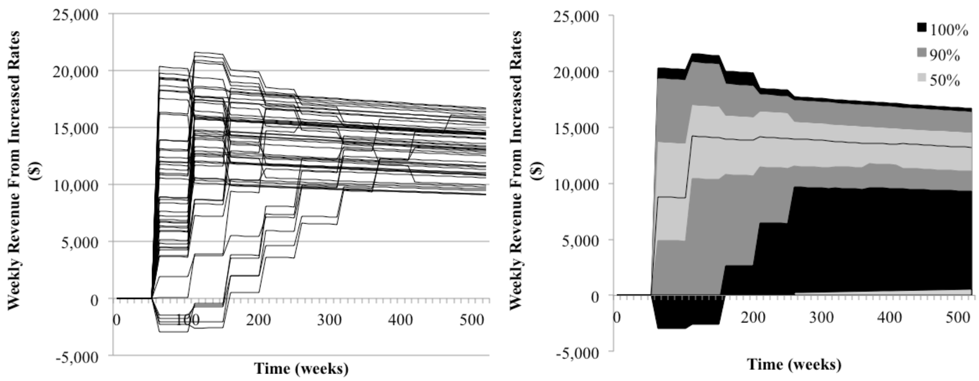
(a) (b)

Figure 8.22. Saginaw's citywide generated water revenues from increasing water rates: (a) Sensitivity graph based on 50 traces and (b) Tolerance interval



(a) (b)

Figure 8.23. Flint's citywide wastewater revenues generated from increasing water rates: (a) Sensitivity graph based on 50 traces and (b) Tolerance Interval



(a) (b)

Figure 8.24. Saginaw's citywide wastewater revenues generated from increasing water rates: (a) Sensitivity analysis based on 50 traces and (b) Tolerance interval

The pay off period for water and wastewater retooling projects are consistent with the parametric analysis discussed in Section 8.4. When only wastewater rates are varied, while water rates are held constant, Flint has a median payoff period of 5 years, but may take as long as 8.1 years, indicated by the upper 100% tolerance interval boundary. Saginaw's median payoff period is 15 years, but may take up to 20 years (see Table 8.8). However, there is a decrease in demand when water rates are increased, which in turn reduces the volume of wastewater produced and hence billed to the customer. The reduced wastewater revenues impacts the payoff period for the stormwater retooling alternatives, as indicated in the increase in payoff period when different water rates are considered as shown in Table 8.8. When both water and wastewater rates are varied, Flint's median payoff period of the retooling alternative in 6 years and as late as 13.5 years. In case the of Saginaw, when both water and wastewater rates are varied, the median payoff period is 17 years. The difference in the payoff periods between the two cities is due to the lower population in Saginaw (and thus, lower total revenues from services rendered as compared to Flint) and an analysis area requiring decommissioning that is approximately twice the size.

Table 8.8. Payoff period for retooling alternatives

10% of generated revenues earmarked	**Water retooling alternative payoff period** (median payoff period)	**Stormwater retooling alternative payoff period** (median payoff period)
Vary water rates →Flint	1.4 to 2.6. yrs (1.5 yrs)	-
Vary wastewater rates → Flint	-	4.2 to 8.1 yrs **(5.2 yrs)**
Vary water and wastewater rates → Flint	1.4 to 2.6. yrs (1.5 yrs)	4.5 to 13.5 yrs **(6.2 yrs)**
Vary water rates → Saginaw	3 to 7.1 yrs (3.25 yrs)	-
Vary wastewater rates → Saginaw	-	13.2 to 20 yrs **(15 yrs)**
Vary water and wastewater rates → Saginaw	3 to 7.1 yrs (3.25 yrs)	14.4 to 23 yrs **(17 yrs)**

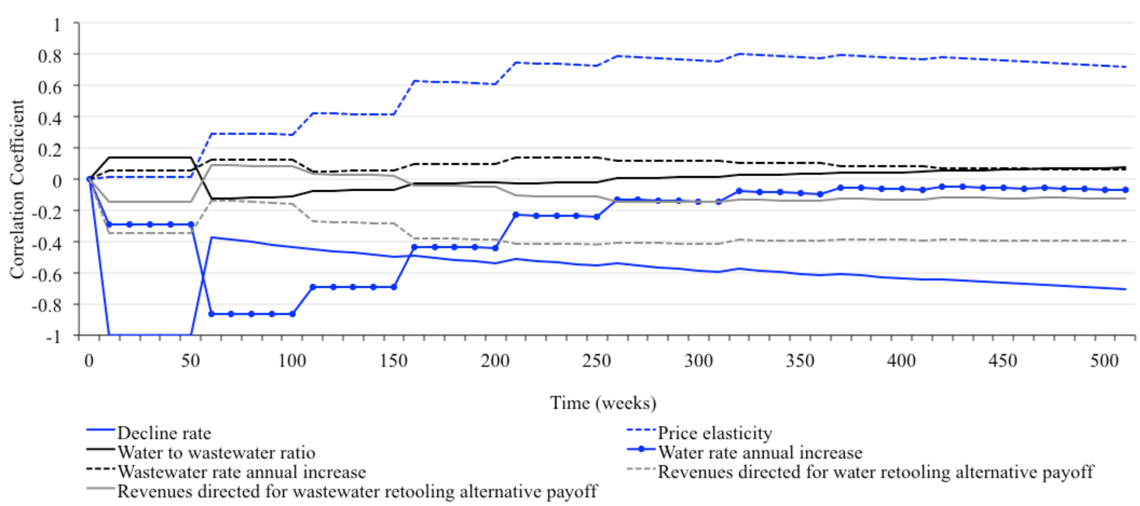
8.6. Statistical Screening

Statistical screening is used to calculate the correlation coefficients to identify the most influential inputs in the model impacting the outcome over the course of the simulation time (Ford and Flynn 2005; Taylor et al. 2009). The parameter influence on the outcome as the simulation progresses may be quantified, while simultaneously viewing the exogenous impacts on the model's behavior (Taylor et al. 2009). The correlation coefficient estimates the linear relation between an independent variable (input) and dependent variable (output) between a range of -1 to +1 using Eqn. 8.12 (Ford and Flynn 2005):

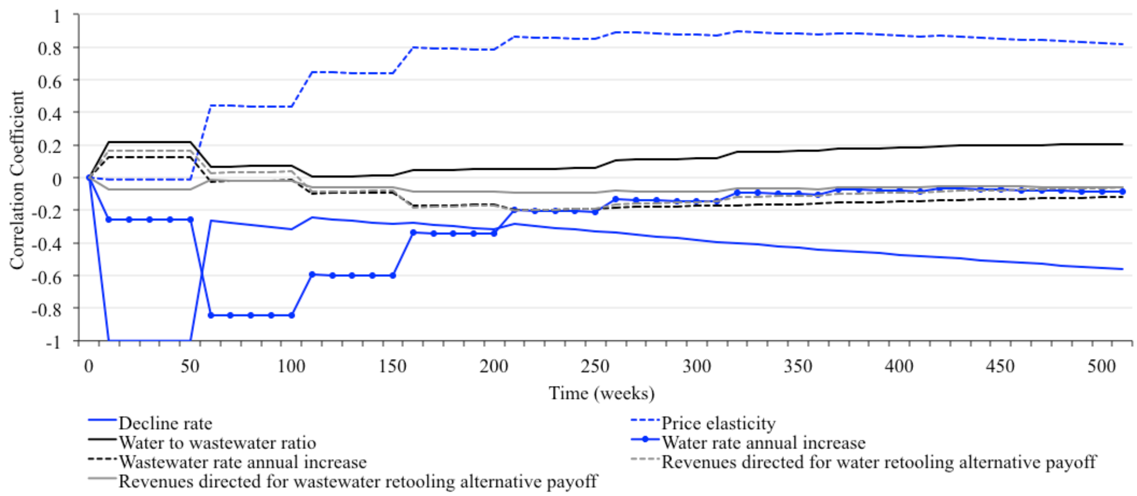
$$Correlation\ Coefficient = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2 \sum(Y_i - \bar{y})^2}} \qquad \text{[Eqn. 8.12]}$$

where X represents the independent parameters and Y represents the dependent parameter. The correlation coefficients are calculated for each case study and discussed jointly in this section to compare similarities and differences of the correlated parameters for the two cases. The independent and dependent variables evaluated for correlation coefficients are the same discussed in the sensitivity analysis in Section 8.5. Fifty (50) simulations are used to estimate the correlation coefficients, with each simulation assigning a random number to the parameters evaluated that lies within the defined range (Ford and Flynn 2005). The influential variables with correlation coefficients are depicted in blue in the graphs.

The most influential parameters determining the total citywide residential water demands are price elasticity, population decline rate, and the annual water rate increase (Figure 8.25). However, in Saginaw, although decline rate is influential, the decline rate has a weaker relationship with the citywide water demands than in Flint. This may be due to the total population size (102,434 people in Flint as opposed to 51,508 people in Saginaw as of 2010 (US Census Bureau 2011)) and the higher historic decline rate in Flint (0.0003104 per week in Flint as opposed to 0.00024671 per week in Saginaw (US Census Bureau 2011)). The larger population in conjunction with this higher rate results in a large number of people leaving the city over time. Within both cities, decline rates and price elasticity became more influential as the time progressed, while annual rate increases became less influential. These trends are likely capturing the fact that if there is a large rate increase in year 1, there is unlikely to be a large increase in the following year, as the rates may only increase to approximately 10%. Price elasticity, over time is more influential on the planned water demand than the decline rate of residents within the city. Thus, the correlation coefficient analysis supports the parameter variation and sensitive analyses findings that accounting for this consumer behavior is critical in long-term planning for the community water needs. This variance in water demand may be accounted for in planning by maintaining water capacity to meet the lower and upper bound needs spanning the probable price elasticity behavioral changes.



(a)

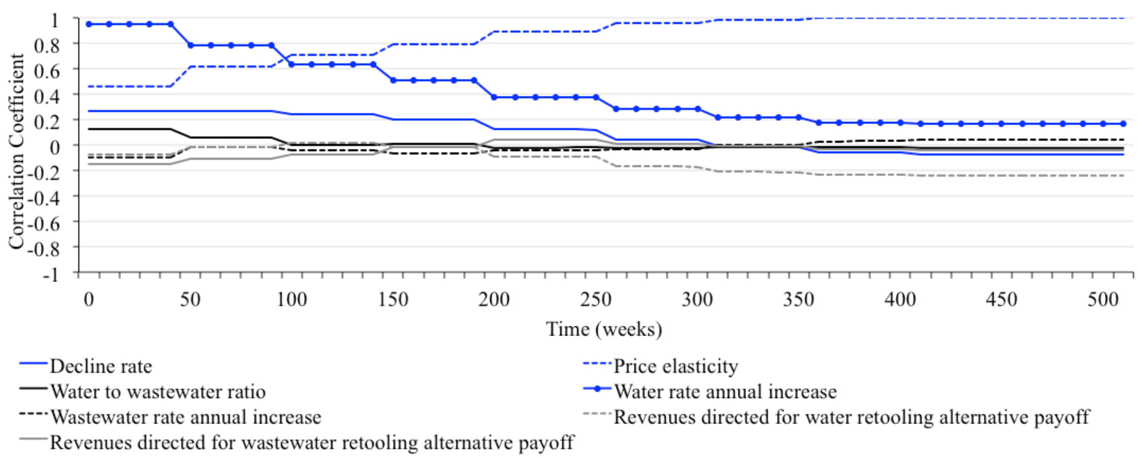


(b)

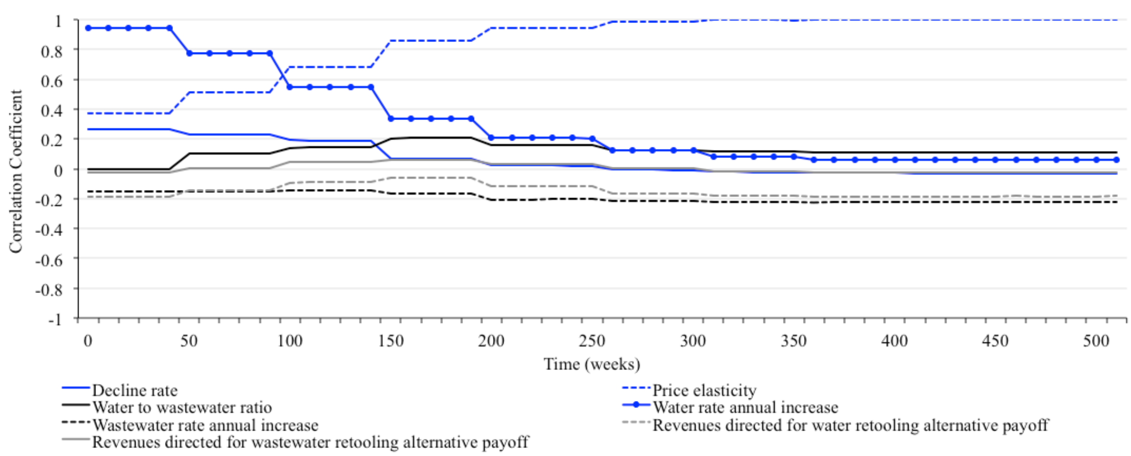
Figure 8.25. Correlation coefficients between primary input parameters and citywide residential water demand: (a) Flint and (b) Saginaw

Over the simulation time, the only parameter with a significant correlation coefficient (over approximately +/- 0.2) for residential wastewater demand was the parameter estimating the water that entered the wastewater system, with a correlation coefficient of approximately +1.0 for Flint and Saginaw. Within this model, this variable, as expected, has the strongest relationship with the output, as the output is dependent on the assumed percentage of water entering the wastewater system. When planning wastewater treatment plant needs, the correlation between the parameters estimated the water entering the wastewater system and the total wastewater produced citywide highlights that necessity of having an accurate understanding of the behavior of the residents (e.g., do the residents use water for landscaping which causes increased ground infiltration).

When considering water revenues generated from increasing water rates, the same parameters, decline rate, price elasticity, and water rate annual increase, were influential in Flint and Saginaw, with approximately the same magnitudes (Figure 8.26). It may be conjectured that the influential parameters impacting generated water revenues may not be dependent on the size of the city, as was the case for citywide water demand. As the simulation progresses, and more people leave the city, the decline rate becomes less influential in determining total revenues. At a constant decline rate, with a declining population overtime, fewer people are leaving per time step, reducing the total impact on the total revenues. However, as the decline rate becomes less influential at approximately year 3 in Flint, and year 2 for Saginaw, the price elasticity evolves into the parameter with the strongest relationship with the outcome. Although the population decline may be important at present time, the price elasticity resulting from rate increases may have a large impact over time on the total revenues generated from residential water use. This finding of the high correlations between price elasticity and generated revenues from residential water use further indicates that the water utility must consider price elasticity, even to a greater degree than the population trajectory when planning financially long term.



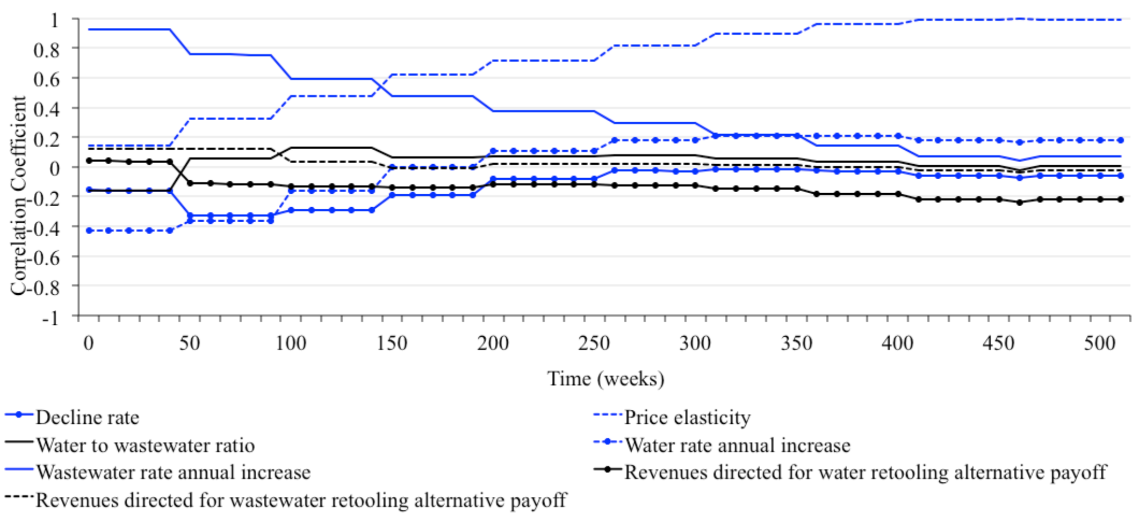
(a)



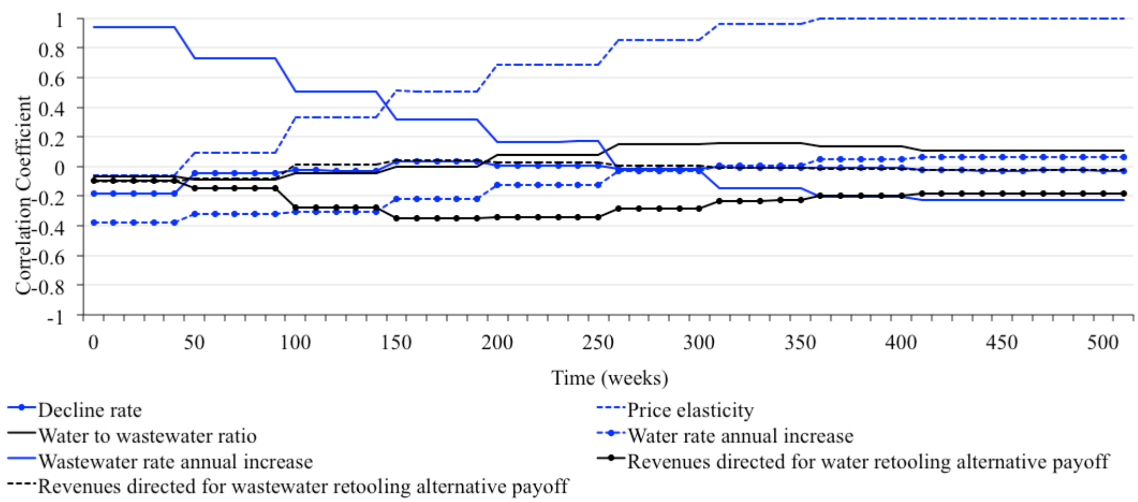
(b)

Figure 8.26. Correlation coefficients between primary input parameters and water revenues generated from increasing water rates: (a) Flint and (b) Saginaw

The influential variables identified for the wastewater revenues generated from increasing rates were similar to those identified in Figure 8.26. Throughout the simulation time for both cities, the decline rates and the price elasticity were the parameters with the strongest relationship with the output, shown in Figure 8.27. However, in years in which no increase in wastewater rate occurred, the price elasticity for water had the largest correlation coefficient. This relationship between price elasticity and wastewater revenues may be seen as the simulation progresses, and the price elasticity rises in importance, while the annual increase of utility rates decreases in importance. The shifting of correlations over the time is presumably due to the 10% increase in wastewater rate threshold being met. Another significant parameter is the water rate annual increase for both cities. When viewing the correlation coefficients, 2 out of 4 of the influential parameters relate to the water infrastructure system, price elasticity and water rate increase, illustrating the existing interdependencies between the water and wastewater infrastructures



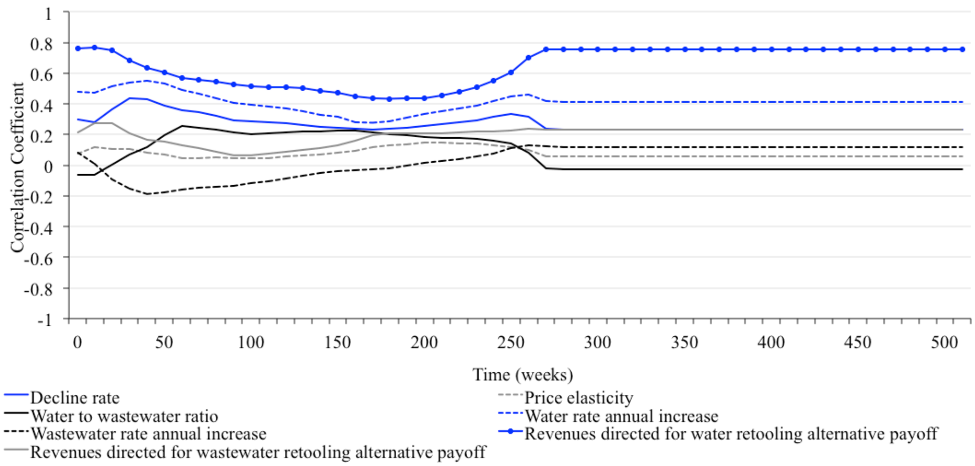
(a)



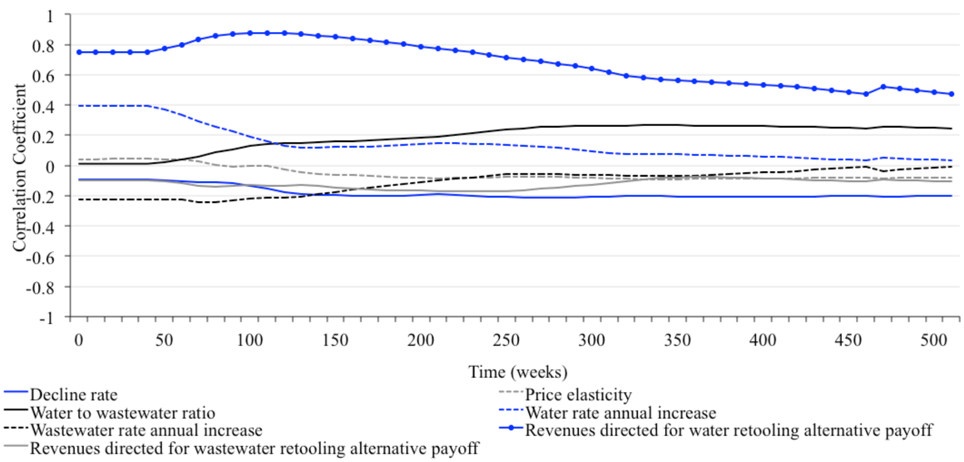
(b)

Figure 8.27. Correlation coefficients between primary input parameters and wastewater revenues generated from increasing wastewater rates: (a) Flint and (b) Saginaw

As expected, when considering the time period it takes to pay off a water retooling alternative from revenues generated due to water rate increases, the annual water rate increase and the percentage of revenues directed towards paying off the alternative are the most influential parameters in both cities (Figure 8.28). However, the decline rate is a third variable with a strong relationship with the pay off period for Flint, but not Saginaw. In Saginaw, the relationship between the revenues directed towards paying off an alternative has a stronger relationship than in Flint. As discussed in Section 8.4, this relationship between pay off periods and revenues earmarked for paying off the retooling alternative is likely due to the higher population and higher decline rate within Flint. In Saginaw, with the lower population and decline rate, fewer people are leaving the city over the simulation time, impacting the generated revenues from customers to a lesser degree.



(a)



(b)

Figure 8.28. Correlation coefficients between primary input parameters and time period to pay off the water retooling alternative: (a) Flint and (b) Saginaw

Similar to the time period it takes to pay off a stormwater retooling alternative from revenues gained due to rate increases, the wastewater rate increase and the percentage of revenues directed towards paying off the alternative are the most influential variables in both cities. A third influential variable in both cities is the annual water rate increase, near the beginning of the simulation. However, over the simulation time, this correlation coefficient becomes insignificant, leaving the aforementioned two variables (the wastewater rate increase and the percentage of revenues directed towards paying off the alternative) as the driving variables for the pay off period of the stormwater retooling alternative. The water rate increases were likely significant in the beginning of the simulation as the 10% threshold in rate increases had not been met, thus impacting the volume of wastewater produced and the volume billed. However, when water rate increases were not occurring, this variable did not have a high correlation coefficient. The presence of the water rate increase, even near the beginning of the simulation, highlights the interdependencies between the infrastructure systems that must be considered when evaluating aspects of the wastewater infrastructure system.

8.7. Single-Factor Sensitivity Analysis

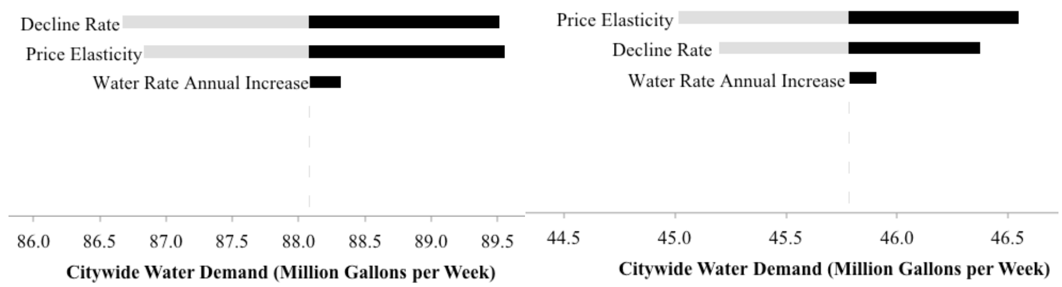
Tornado diagrams visually present a single-factor sensitivity analysis to allow quick assessment of the impact of each uncertain parameter on different outcomes. In this sensitivity analysis, all parameters considered are held at their base value while one parameter is adjusted to the defined minimal value and the defined maximum value. The parameter with the largest associated uncertainty associated, or the highest risk, spans the largest range in the diagrams. The output portrayed on the tornado diagram (Figure 8.29-8.32) is the final output value at 520 weeks/10 years. Table 8.7 shows the parameters considered (the same parameters as in Sections 8.5 and 8.6). Only parameters that impacted the outcome are labeled on each graph. The outputs evaluated that are dependent on the parameters are:

1. Citywide residential water demand.
2. Citywide residential wastewater demand.
3. Water revenues gained from increasing water rates.
4. Wastewater revenues gained from increasing water rates.

Table 8.9. Parameters evaluated for the single-factor sensitivity analyses

	Flint			**Saginaw**		
	Min	**Max**	**Base Value**	**Min**	**Max**	**Base Value**
Decline Rate	0.0279%	0.0341%	0.0310%	0.0222%	0.0271%	0.0247%
Price Elasticity	-0.2	-0.5	-0.35	-0.2	-0.5	-0.35
Water to Wastewater Ratio (based on humidity rates and assumptions on outdoor water uses)	0.6	0.85	0.725	0.6	0.85	0.725
Water Rate Annual Increase	0.01%	0.1%	0.03%	0.01%	0.1%	0.03%
Wastewater Rate Annual Increase	0.01%	0.1%	0.03%	0.01%	0.1%	0.03%

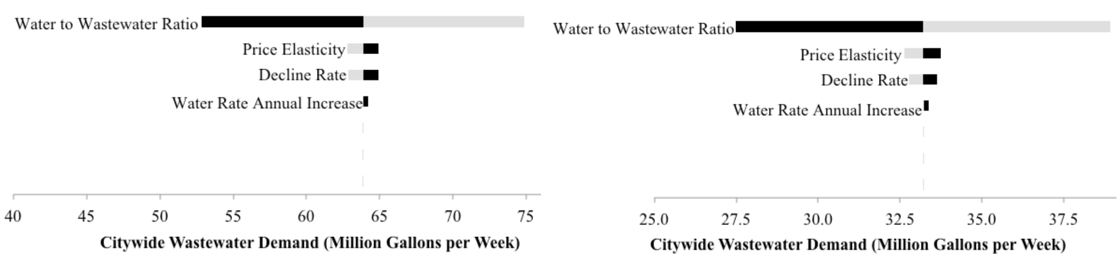
Consistent with the results from the statistical screening in Section 8.6, the same parameters impact citywide water demand in the single factor sensitivity analysis. Decline rate causes a higher variance on the citywide water demand in Flint than in Saginaw, as shown in Figure 8.29. Also similar to the findings in the Section 8.6, price elasticity yields a high variance in citywide water demand in Sagiaw than Flint. As mentioned in Section 8.6, the impact of price elasticity may be due to the total population and the higher historic decline rate in Flint.



(a) (b)

Figure 8.29. Tornado diagram for citywide residential water demand: (a) Flint and (b) Saginaw

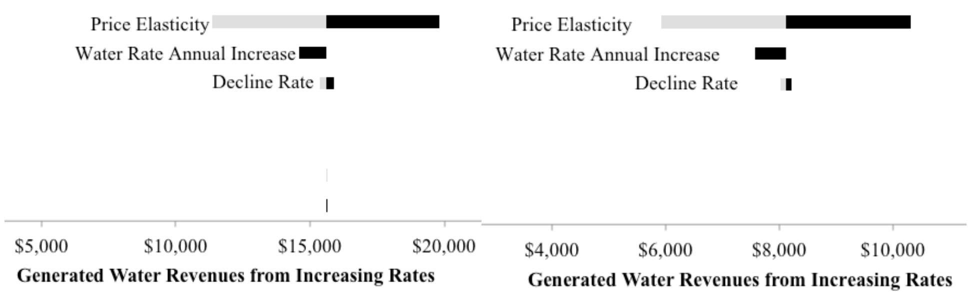
Figure 8.30 depicts the tornado diagram for citywide residential wastewater demand. Consistent with the statistical screening, the parameter influencing the outcome to the greatest degree is the water to wastewater ratio. However, the tornado diagram was able to capture three other parameters that impacted the outcome, albeit to a lesser degree: price elasticity, decline rate, and water rate annual increase.



(a) (b)

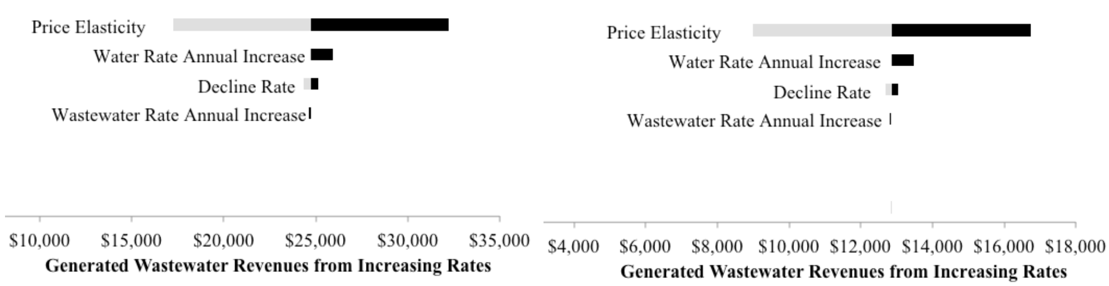
Figure 8.30. Tornado diagram for citywide residential wastewater demand: (a) Flint and (b) Saginaw

The same parameters were found to be influential on the generated water and wastewater revenues in the statistical screening and the single factor sensitivity analysis (Figures 8.31 and 8.32). Unlike the statistical screening, which provided how correlated the parameter was with the outcome, the tornado diagram quantifies the ranges of outcome values due to the paramter. For instance, price elasticity had an increasingly stronger correlation coefficient in the statistical screening at the simulation progressed. However, in Figures 8.31 and 8.32 price elasticity had the highest impact on the generated revenues, regardless of whether the correlation coefficient throughout varied in magnitude throughout the simlulation.



(a) (b)

Figure 8.31. Tornado diagram for generated water revenues: (a) Flint and (b) Saginaw



(a) (b)

Figure 8.32. Tornado diagram for generated wastewater revenues: (a) Flint and (b) Saginaw

8.8. External Validation of Findings

Similar relationships between parameters (e.g., population and demand) have been evaluated and discussed in the context of water sector infrastructure. Table 8.10 highlights studies with similar discussions and findings as those presented in this study.

Table 8.10. External validation of findings

Aspect of model	Findings within this study	Other studies with similar findings/discussions
Relationship of water demands and population	Positive correlation between population and total water demand	Giacomoni et al. (2013)
Influence of service price on total water demand by the city's residents	The price will have a direct impact on the total residential water demand	Athanasiadis et al. (2005)
Impact of land use/LID on runoff	Changing land uses or incorporating LID alternatives will impact the volume of runoff	USEPA (2014); Jia et al. (2015)
Use of stochastic variables versus deterministic variables	Stochastic modeling allows for viewing trade-offs on decisions made	Kang and Lansey (2013)

8.8. Summary

This chapter evaluates the physical interdependencies between the water infrastructure and wastewater infrastructure system and the impact of human interaction with these infrastructure systems. The AB-SD model enables the assessment of interdependencies between coupled human and water sector infrastructure systems, with the ability to tailor the model's parameters for the unique circumstances of the city (e.g., historical population dynamics, household size, soil type, precipitation patterns, decline rate). The model allows for the evaluation of the interactions of price elasticity and water demand, incorporating the uncertainty associated with the interdependencies such as wastewater produced and ranges of demand to anticipate utility planning needs. This model enables the visualization of the water sector interdependencies, such as the downward trajectory of water demand (and wastewater produced) within the uncertainty range resulting from price elasticity or the decrease in NPS pollutants due to the implementation of the stormwater infrastructure retooling alternatives. Table 8.11 summarizes the outcomes evaluated and the influential parameters identified via the analyses.

Table 8.11. Influential parameters impacting evaluated outcome, rationale, and summary of results

Outcome	**Influential parameters** (Parameters causing the most variance on the outcome from Section 8.7 are bold)	**Rationale**	**Results** (based on Sections 8.4-8.7)
Generated runoff	• Soil type	• Soil conditions (i.e., whether the soil exhibits characteristics of its natural state or displays characteristics of compaction) impact the generated runoff	• Runoff in Flint is reduced by 91.9% and 76.7% for B/C soils and D soils, respectively, post stormwater retooling alternative implementation • Runoff in Saginaw is reduced by 91.6% and 73.9% for B soils and D soils, respectively, post stormwater retooling alternative implementation
Non-point source pollutants	• Generated runoff • Soil type	• Soil conditions (i.e., whether the soil exhibits characteristics of its natural state or compaction) impact the generated runoff • The quantity of non-point source pollutants are correlated with the quantity of runoff	• NPS pollutants in Flint is reduced by 91.9% and 76.7% for B(C) soils and D soils, respectively, post stormwater retooling alternative implementation • NPS pollutants in Saginaw is reduced by 91.6% and 73.9% for B soils and D soils, respectively, post stormwater retooling alternative implementation
Citywide residential water demand	• **Price elasticity** • Water rate increases • **Decline rate (Flint)**	• Per capita water demand decreases when water rates increase • Decline rate is considerably more influential in the case of Flint possibly due to the total population size and the higher historic decline rate	• Demand ranges up to 5 million gallons per week • Flint's most probable ranges span 2 million gallons per week • Most probable ranges span 1 million gallons per week for Saginaw

Table 8.11. *(continued)*

Outcome	**Influential parameters** (Parameters causing the most variance on the outcome from Section 8.7 are bold)	**Rationale**	**Results** (based on Sections 8.4-8.7)
Citywide residential wastewater demand	• **Percent of water entering wastewater system** • Price elasticity • Water rate increases • Decline rate	• Per capita water demand decreases when water rates increase • Percent of water entering the wastewater system is influenced by the behavior of the residents (e.g., outdoor water use) and the humidity of the area • The number of consumers are declining over time	• Citywide wastewater demand ranged up to 4.25 million gallons per week • Most probable ranges span 1.7 million gallons per week for Flint • Most probable ranges span 0.85 million gallons per week for Saginaw
Water revenues gained from increasing water rates	• **Price elasticity** • Water rate increases • Decline rate	• Increased rates are multiplied by a lower per capita demand due to the increased prices • The number of consumers are declining over time	• Flint's most probably weekly generated revenue is approximately $15,000, with a possible range between $10,000 and $22,500 • Saginaw's most probably weekly generated revenue is approximately $7,500 with a possible range of between $6,000 and $12,000
Wastewater revenues gained from increasing water rates	• Wastewater rate increases • **Price elasticity** • Water rate increases • Decline rate	• Per capita water demand decreases when water rates increase, resulting in less billable wastewater • The number of consumers are declining over time	• Flint's most probable weekly generated revenue is approximately $25,000, with a possible range between $10,000 and $42,000 • Saginaw's most probably weekly generated revenue is approximately $14,000 with a possible range between $2,500 and $20,000

Table 8.11. *(continued)*

Outcome	**Influential parameters** (Parameters causing the most variance on the outcome from Section 8.7 are bold)	**Rationale**	**Results** (based on Sections 8.4-8.7)
Time period to pay off the water infrastructure retooling alternative	• Price elasticity • Water rate increase • Revenues earmarked for paying off project • Decline rate (Flint)	• Increased rates are multiplied by a lower per capita demand from behavior changes due to the increased prices, impacting the generated revenues • There is a tradeoff between pay off period and diverting resources (if the goal is to pay off the retooling project quickly, earmark more revenues to the retooling project) • Decline rate was influential in Flint possibly due to the total population size and the higher historic decline rate in Flint	• In Saginaw, the project is most likely to be paid off in less than 3.3 years but may take up to 7.8 years • In Flint, the project is most likely to be paid off in less than 1.34 years, but may take up to 3.3 years.
Time period to pay off the stormwater retooling alternative	• Wastewater rate increase • Revenues earmarked for paying off project • Water rate	• Per capita water demand decreases when water rates increase, resulting in less billable wastewater • There is a tradeoff between pay off period and diverting resources (if the goal is to pay off the retooling project quickly, earmark more revenues to the retooling project)	• In Flint, the probably pay off period is between 5.8 years and 13.5 years • In Saginaw, the probable pay off period is between 15.4 years and 26 years
Time period to generate desired level of support	• Rate of adoption	• The rate at which the public accepts the alternatives determines the time period in which different levels of support are gathered	• As the minimal level of support increases, the time it takes to gain additional support also increases • E.g., to move from 60% to 70% support for the water retooling alternative takes 26 additional weeks, and o move from 70% to 80% support takes 67 additional weeks, 2.5 times the time to gain the previous 10% in support • 91% and 90% are the greatest levels of support achieved

The impact of non-physical disrupters, such as price elasticity, rising water and wastewater rates, decline rates, and agent support/opposition, are captured in AB-SD model cascading to the water and wastewater/stormwater infrastructure system. The model quantifies the impact of population dynamics, price elasticity, and other influential parameters (identified via statistical screening), on potential project pay off periods, and total revenues from water/wastewater service bills, for both water and wastewater utilities. These factors were not quantified in previous interdependency models in literature known to the author. For instance, when considering citywide demand, expected population declines, water rate increases, and price elasticity must be factored into long-term planning, as indicated in the statistical screening. Irrespective of the urban decline, citywide water demands for both cities may vary up to 2.5 to 5 million gallons per week, with the most probable ranges spanning 1 to 2 million gallons per week. This finding suggests that the excess capacity typical to shrinking cities may be used to ensure the possible water demands throughout the city can be met. However, maintaining the excess capacity comes with a trade-off of increased water age due to longer retention times, as discussed in Chapter 3.

In the context of water revenues generated from increasing water rates, the demand rate, price elasticity, and percent rate increase are the strongest correlated parameters impacting the projected revenues gained from increasing the water prices. The increased rates will be multiplied by a lower per capita demand from behavior changes due to the increased prices, as well as emigration of residents leaving the city. For efficient planning purposes to continue to provide service to the community, water utility managers should be cognizant of the future water demand needs and the behavioral patterns that may counteract the possible revenues.

Additionally in the context of revenues, the statistical screening revealed that for long term planning, the wastewater provider should consider water price elasticity and water rate increases, in conjunction with the population decline rate and wastewater rate increase. As shown in the sensitivity analysis, in the absence of coordinated planning across interdependent systems, the wastewater utility may potentially lose total revenues. This study is the first known to the author to identify how consumer behavior regarding water use due to utility rates, impacts the wastewater system. Consumer behavior is modeled as non-physical disruptors in the water infrastructure system, cascading into the wastewater system, directly impacting the long-term community demand on wastewater infrastructure and revenues generated from consumers. Table

8.12 shows system dynamics models in literature that have considered human interaction with the water/wastewater network, and the gaps in these previous studied filled by this AB-SD model.

Table 8.12. Previous studies incorporating human interaction with the water or wastewater infrastructure

Previous Study	Model summary	Gap in previous study
Griggs and Bryson (1975)	Simulation model considering: financial accounting, water balance, water use, and population growth	Study only considers the water system, and does not consider the wastewater system. The study does not consider the interdependencies between the water and wastewater systems.
Ahmad and Prashar (2010)	System dynamics model evaluating the relationship between population growth, land use changes, water demands, and water availability	Study only considers the water system, and does not consider the wastewater system. The study does not consider the interdependencies between the water and wastewater systems.
Adeniran and Bamiro (2010)	Simulation model considering finance, production, distribution, and operations and maintenance of a water system	Study only considers the water system, and does not consider the wastewater system. The study does not consider the interdependencies between the water and wastewater systems.
Rehan et al. (2011)	System dynamics model considering the financial water and wastewater interdependencies managed by the same utility	In Rehan et al. (2011), the consumer base and pipeline are considered constant, whereas the AB-SD model allows for populations dynamics and changing physical infrastructure footprint. The AB-SD model also does not require for the same utility to manage both infrastructure systems, thus allowing for utility rates to be set independently in each system.

The population of city appears to determine whether decline rate is an influential parameter within the model as exposed by the statistics screening. For the case study based in Flint, the citywide residential water demand, time period to pay off the water retooling alternative, and time period to pay off the stormwater retooling alternative were significantly correlated with decline rate. The influence of population and decline rate on the evaluated outcomes may be due to Flint's population size and higher historic decline rate. The medium-sized population, in conjunction with this higher decline rate results in a large number of people leaving the city at each time step throughout the simulation impacting the demands and revenues. The influence of decline rate on the citywide residential water demand, time period to pay off the water retooling alternative, and time period to pay off the stormwater retooling alternative is not highly correlated in the case study based in Saginaw, which has a small population size and lower decline rate. It is speculated from these results that the decline rate is more influential in medium cities, than in small cities, in terms of planning for demands and new infrastructure project pay offs. However, with two cities as case studies, this conclusion can only be conjectured and not confirmed. Prior studies evaluating urban decline's impact on the infrastructure systems (e.g., Schlor et al. 2009; Hoornbeek and Schwarz 2009; Butts and Gasteyer 2011; USEPA 2014) have not identified the plausibility that non-physical disrupters, specifically decline rates, may be relevant in different classifications of cities (such as, medium cities demonstrated in this study), as opposed to spanning all shrinking cities. Identifying when population dynamics are relevant for impacting an outcome pertaining to infrastructure planning (such as, citywide demand, project pay off periods) may allow for cities to incorporate this parameter when appropriate. By categorizing cities in which certain non-physical disruptors are not relevant can aid in cities avoiding spending time and money, investigating the impact of such disrupters.

In the context of the public support for retooling alternatives, the AB-SD model provides a framework and model for approximating the time period that it will take to gather the desired level of public support using shrinking city residential survey data and market adoption strategies. Incorporating market adoption strategies, a commonly used business practice for technologies and products, is a method that has not be applied to participatory processes for infrastructure to determine time periods for adopting new infrastructure management strategies within cities. Existing, proposed tools to foster participatory processes include stakeholder interactions via methods such as, game theory models (Supalla 2000; Wang et al. 2003), computer tools that interact with the users (Cai et al. 2004), decision trees used for comparison (Lund et al. 2008; Lund et al. 2009). Applying market adoption strategies and agent based modeling is not a method to increase support or evaluate the level of support at a moment of time, but is a strategy to understanding the emergent behavior occurring over time to reach the desired level of support.

The agents' pattern of support is an emergent property arising from the systematic interaction of the agents transitioning between states that can be both visualized during simulation, as well as quantified at any time point throughout the simulation. The sensitivity of the agent class to the population decline and rates of adoptions in participatory processes as well as the estimation of the maximum achievable level of support that may be gained in a time period were assessed. When considering participatory processes and gathering public support, in general, as the minimal level of support sought after increases, the time it takes to gain additional support also increases. When considering the participatory processes, decision makers will have to make the trade-off between level of support, resources to encourage the adoption of the alternatives (that influences the rate of adoption), and targeted time period for implementation. The AB component of the model indicates that the behavior of the city's residents is influenced by rates of adoption, independent of the present urban decline. The rate at which people adopt new ideas and shift towards levels of support may influenced through ways such as educational brochures and community meetings to encourage dialog regarding the decisions made.

The hybrid AB-SD model provides a framework for assessing coupled human and water sector problems. Previous water sector studies on interdependencies have focused on water sector infrastructure interdependencies with *other* critical infrastructures (e.g., energy, roads), but have not considered interdependencies *within* the water sector. Furthermore, this study brings in another dimension beyond evaluating the endogenous water sector interdependencies by addressing the exogenous, complex human interactions with water sector infrastructure. Complexity is defined as the interaction of multiple (often independent) components that yield non-linear patterns of behavior. Complexity is addressed in this study by integrating human interaction as objects (agent classes) and within objects (specifically the system dynamics classes) to evaluate the influence of human behavior on management aspects of the infrastructure systems, such as future demands, financial aspects or participatory processes. Assessing epistemic uncertainty in the proposed framework is done through the modeling of price elasticity (portraying user behavior and rate changes (a surrogate for management decisions)) as stochastic parameters, as opposed to the traditional modeling approach using deterministic parameters (e.g., see Zhou and Hu 2009) to understand a range of possible outcomes, as opposed to a singular outcome. Epistemic uncertainty is also assessed in this study through the implementation time, in which the AB-SD framework builds a plausible decision-making process using market-based strategies and agents to evaluate the consequences of participatory processes on the timeframe to implement different retooling alternatives.

CHAPTER 9. CONCLUSIONS AND RECOMMENDATIONS

"The more I live, the more I learn. The more I learn, the more I realize, the less I know."

— *Michel Legrand*

Declining populations in cities nationwide (and worldwide) have resulted in a fixed infrastructure footprint larger than necessary to support the current population and a decreased number of rate-payers, which creates challenges for managing water sector infrastructure. The impact of underutilization resulting from urban decline on the water sector infrastructures' performance and the technical viability of retooling alternatives for right-sizing water sector infrastructure are not well understood. This research aimed to address these gaps in the body of knowledge and the body of practice regarding the underutilization of water and wastewater/stormwater infrastructures and evaluating viable retooling alternatives. The first two sections of this chapter summarize the research conducted and the analyses results. Section 9.3 presents the limitations of this study. The fourth section of this chapter presents the contributions of this research to the body of knowledge and the body of practice. Finally, recommendations for future research are presented, as a jumping block for this study, to continue to understand issues pertaining to the underutilization of infrastructure and how to manage infrastructure systems that have reached the end of their useful life-cycle, yet are still operational.

9.1. Summary of the Research

This dissertation examined the underutilization of water and wastewater/stormwater infrastructure in the context of urban decline. The methodological framework used to evaluate the underutilization of water and wastewater/stormwater infrastructures was demonstrated using two case studies, Flint, MI and Saginaw, MI. These case studies demonstrate the applicability of the framework spanning two size classifications for cities, small and medium cities.

The impact of physical and non-physical disrupters on the water infrastructure's ability are evaluated to provide adequate levels of service, as well as the impact of physical disrupters on the stormwater generated. Network analyses and hydraulic simulations were the primary methods used to assess the performance of the water and wastewater infrastructure, respectively. The study demonstrated the technical viability of decommissioning water infrastructure and consolidating demand to aid in right-sizing cities. Implementing these infrastructure retooling alternatives allows for reducing the physical footprint of the network or consolidating the service area of not only water demand, but other services such as, mail service and street sweeping.

Public views towards water and wastewater/stormwater infrastructure issues and retooling alternatives were examined using survey analyses and statistical analyses. Gaps in knowledge and awareness were identified and the demographic and location parameters influencing attitudes and perceptions were estimated. These public views towards water and wastewater infrastructures and participatory processes are an important aspect to consider when evaluating alternatives for the infrastructure systems to ensure the city moves forward within the community vision, while mitigating opposition.

Finally, the interdependency analysis analyzed the water sector infrastructures and the human-infrastructure interactions, and evaluated the impact of non-physical disrupters arising from human behavior on the performance of and generated revenues for the infrastructure systems evaluated. Additionally, emergent behavior arising from the interdependencies was observed and the influential parameters on the different outcomes, such as generated revenues, demands, and retooling alternative pay off periods were identified. The necessity to marry the concepts of participatory processes, human-interaction with infrastructure, and infrastructure retooling alternatives when managing the water and wastewater/stormwater infrastructures is demonstrated throughout the dissertation.

9.2. Summary of the Results

The methodological framework applied in this dissertation answers the research questions and accomplishes the research objectives that were outlined in Chapter 1. Table 9.1 summarizes the models used and findings from the analyses.

Table 9.1. Analyses components, analysis performed, and types of findings

Analyses Component	**Analyses Performed**	**Types of Findings**
Establishment of metrics	Synthesis of literature and SME interviews	• Network pressures and fire flow capabilities are used to measure performance of the water infrastructure systems in the presence of non-physical and physical disruptors • The reduction in stormwater runoff is used to measure the effectiveness of four retooling alternatives, namely, decommissioning impervious surfaces, transitioning land uses, and incorporating bioretention cells
Abstraction of the water and wastewater/ stormwater infrastructure issues	Synthesis of literature, SME interviews, and survey data	• Although urban decline manifests uniquely within each shrinking city, water and wastewater/stormwater infrastructure issues such as, rising per capita costs, increased water age, personnel challenges are typical to shrinking cities • Retooling alternatives may mitigate these identified issues by right-sizing the infrastructure footprint for the current and project populations and potentially reduce or stabilize costs
Impact of non-physical and physical disrupters on the water infrastructure system	Network analyses	• The water infrastructure network is able to provide adequate services in the presence of the non-physical disrupters examined in this study, namely, further urban decline and consolidation of decline • Decommissioning pipelines less than 12 inches in diameter is a viable retooling alternatives in the case study analysis areas • The viability of decommissioning pipelines equal to or greater than 12 inches in diameter is case dependent • The socioeconomic status of the area impacts the viability of decommissioning larger diameter pipelines that are greater or equal to 12-inches in diameter. • Factors such as, connectivity of and the potential for dead end pipelines, should be considered when considering decommissioning pipelines
Impact of physical disrupters, in the form of retooling alternatives (decommissioning impervious surfaces, transitioning land uses, and incorporating bioretention cell), on the generated runoff	Hydraulic simulations	• The reduction in runoff based on the following retooling alternatives is quantified: decommissioning impervious surfaces, transitioning land uses, and incorporating bioretention cell • The performance of the retooling alternatives under synthetic storm conditions is evaluated • The return on the financial investment in terms of runoff reductions from the status quo is presented • The differences in runoff based on soil conditions (B(C) soils versus D soils) is evaluated • The cost and impact of bioretention cells that may leave existing infrastructure in place are compared • The number of lots needed to transform to bioretention cells to accomplish the reductions in runoff evaluated is estimated

Table 9.1. *(continued)*

Analyses Component	**Analyses Performed**	**Types of Findings**
Evaluation of the stakeholder views	Qualitative analyses and statistical modeling	• Parameters which influence perceptions towards retooling alternatives are not translational across levels of awareness regarding the population dynamics of the city • Demographic factors which influencing the attitudes and perceptions of retooling alternatives such as, age, number of cars, employment, and gender. • Locations that are significant parameters influencing initial support/opposition towards different retooling alternatives are identified • Binary probit models with random parameters captured the heterogeneity of the resident population • Approximately half of residents are aware they reside in a shrinking city • A majority of respondents are willing to pay up to approximately 10% more for water and wastewater services
Analyses of the interdependencies	Hybrid agent based-system dynamics model	• Payoff periods for decommissioning water infrastructure and decommissioning impervious surfaces, and total revenues generated from residential use are estimated under uncertain conditions, such as population decline rates or price elasticity • Water rates and water price elasticity can impact the wastewater revenues, with a potential to cause a decrease in total revenues, if water and wastewater rates are not coordinated • The size of the population and magnitude of decline rate is conjectured to be correlated parameters with the citywide demand and the payoff periods for retooling alternatives • The public's support of a retooling alternative in a city, an emergent property from the systematic interaction of the residents in the city, is sensitive to rate of adoption of a retooling alternatives, but is not sensitive to decline rate of population

The tools demonstrated in the framework for the individual water and wastewater/stormwater infrastructure systems are open source, and available to fiscally strained cities. The framework was used to evaluate the following retooling options: consolidation of demand, decommissioning water pipelines, decommissioning impervious services, transitioning land uses, and implementing bioretention cells. All retooling alternatives evaluated were technically viable methods to aid in right-sizing, in terms of either providing adequate pressure for the water infrastructure system or reducing stormwater runoff. A significant finding is that the socioeconomic status of the neighborhood may impact the ability to provide adequate service, thereby demonstrating the tight coupling of water infrastructure and human-infrastructure interactions.

The analyses of public views about water and wastewater infrastructure issues and implementing water retooling alternatives in shrinking cities demonstrated the applicability of survey analyses and statistical analyses, and more specifically, binary probit models with and without random parameters, as a means to gain insight into the residents' knowledge, awareness, attitudes, and perceptions. Statistical analysis provided a way to understand the drivers of attitude and perceptions, as well as the considerable heterogeneity across the respondent population. This framework is also capable of identifying location specific parameters that indicate an increased level or support or opposition towards different retooling alternative. The analyses conducted yielded important results that have direct implications for the city management and retooling alternatives. One such result that had direct implications on the support/opposition towards different retooling alternatives is that approximately half of the residents were aware they lived within shrinking cities. A second result is that there exists a willingness to pay more for improved water and wastewater service. A third finding is that a majority of residents indicated that they did not trust their utility providers to make decisions in the customers' best interest and wanted to be involved in the decision making process. This finding indicates that participatory processes should be incorporated into infrastructure management to encourage the implementation of sustainable retooling alternatives.

The agent based-system dynamics model developed in this study provides a framework that can be used in practice and literature for understanding the interdependencies between the infrastructure systems, as well as the human-infrastructure interaction. The emergent behaviors in the system observed included the implications of not coordinating rates across infrastructures, the impact of price elasticity urban decline on the long term demand planning for the infrastructure assessed, as well as the systemic interactions between the autonomous agents to gain desired levels of support. This model not only allows for understanding the human-infrastructure interactions, but can also aid utility companies in planning from a demand or revenues perspective. Long-term planning may be improved by observing the impact of different decisions or human behaviors in a simulated environment to understand the impact on the system.

9.4. Limitations of the Study

The framework presented in this study was illustrated using two case studies - a small city and a medium sized city. Therefore, the results cannot be confirmed for cities with population over 500,000 or populations smaller than 50,000. Another limitation is that the vacant and abandoned parcels are those that are known to the city or land bank. However, in reality, there may be more vacant or abandoned homes, or homes thought to be vacant or abandoned and illegally tied to the system. The uncertainty regarding the total residential demands placed on the system will change the demands and hence, the viability of different decommissioning scenarios.

The viability of using different stormwater retooling options was demonstrated using two case studies, one each for separate stormwater systems and combined sewer systems. By increasing the number of case studies, the impact of runoff across cities with vacant or abandoned residential land and brownfields can be analyzed. The cost estimates used in the demonstration are intended to provide a general comparison. More extensive cost analysis of labor, materials, and expected maintenance expenses, would be needed to assess the financial viability of these alternatives.

A limitation of this study in the context of public views is that survey analyses reflect the views in a moment in time, when the survey was completed. Views are dynamic, evolving with outreach, information, and changing conditions.

The relationships between decline rate, population size, and outcomes such as citywide demand, could only be conjectured due to the sample size of two cities. Relationships between the specific aspects of water infrastructure management and correlated parameters, such as city characteristics specific to size or decline rates, may be confirmed with a larger sample of cities. These limitations were addressed in the interdependency model development through the structure of the object classes that allows for easily adjusting the total population and the population dynamics of the city for different growth or decline patterns. The individual parameters within the model that are unique to the city (e.g., household side, decline rate, per capita water use) can be varied within the model to reflect the circumstance of different cities. In regard to capturing the attitudes at a snapshot in time, this is an acknowledged limitation that could be addressed by deploying survey to the local communities at the time of analysis.

9.5. Contributions of the Research

The study conducted in this dissertation makes various contributions to the body of knowledge and the body of practice in the area of water and wastewater infrastructure management and the underutilization of water and wastewater infrastructures. The methodological framework incorporates a mixed-method qualitative and quantitative approach to understand the implications of the urban decline and viability of retooling alternatives. The methodology can be applied to assess interdependencies, non-physical and physical disrupters in the context of infrastructure in cities and the public views towards infrastructure issues and retooling alternatives.

9.5.1. Contributions to the Body of Knowledge

Previous research in the context of urban decline has not focused on the underground, unseen infrastructure systems, to understand the repercussions of urban decline and underutilization. Additionally, literature has not evaluated the impact of human-infrastructure interactions on the water sector infrastructure interdependencies. The research presented in this dissertation aims to fill this gap in the body of knowledge.

In Chapter 3, published literature and interviews with SMEs from four Midwestern shrinking cities were synthesized to identify issues spanning cities experiencing urban decline, such as rising per capita costs, and increased water age. Previous work regarding infrastructure in shrinking cities focused on the aspects of the financial burden of water and wastewater utilities falling on the consumer (Schlor et al. 2009; Butts and Gasteyer 2011) or water age (Barr 2013), without holistically discussing multiple problems together spanning the infrastructure system such as, the rising per capita costs, personnel challenges, water age, and underutilization. Aside from issues spanning shrinking cities, issues characteristic to the type of utility provider operating in the shrinking city were identified. For example, public water utilities had to operate their facilities using minimal personnel, whereas private utilities did not face this challenge. Private utilities dedicated more personnel to connecting/disconnecting water service in shrinking cities than other cities following the typical population growth trajectory.

Chapter 5 describes a framework proposed to evaluate the impact of both non-physical disrupters (consolidation and decline of demands) and physical disrupters (decommissioning pipelines) on an underutilized water infrastructure network. This component of the study, demonstrated the relationship between socioeconomic status of the residents in shrinking cities and the operational capability of the infrastructure system. Different daily use patterns of infrastructure services by individuals of varying socioeconomic statuses changes the viability of retooling alternatives. The coupling of human interaction with water infrastructure performance is demonstrated by the inability of the system to provide adequate water pressures and fire flows when select retooling alternatives are applied. Furthermore, this human-infrastructure coupling impacts which management alternatives may be implemented to flexibly retool the infrastructure system for a smaller population. Having this knowledge of the intended future needs of the area can assist decision makers in ensuring that retooling alternatives do not impede the performance of the system for the current *or* projected population. To the author's knowledge, this relationship pertaining to the viability of management alternatives has not been identified in literature or practice.

The framework demonstrated Chapter 6 may be used to evaluate the effectiveness of re-zoning and transforming land, as well as incorporating low-impact development (LID) alternatives into underutilized infrastructure in a cost-effective manner. By exploring the viability of LID alternatives using open-source software, this study demonstrates the feasibility of exploring alternatives within underutilized areas for fiscally strained cities hesitant to spend resources. Furthermore, Chapter 6 discusses the low-impact development alternatives in terms of vacant lots within the case study cities, providing a reference to the relative area necessary per city block to accomplish the reductions in runoff has not been addressed previously in literature.

Chapter 3 identifies a gap in literature pertaining to the public's stance in the context of declining urban populations. Previous studies have focused on the quality of life and perceptions towards abandonment and vacancies without considering underground infrastructure in any capacity. Chapter 7 demonstrated the application of binary probit models with and without random parameters to assess attitudes and perceptions, and captures the heterogeneity of the populations towards different retooling alternatives. Further contributing to the body of knowledge is quantifying that influential parameters may not be translational across level of awareness regarding contextualized surroundings, an aspect not considered in prior literature known to the author.

The hybrid AB-SD model in Chapter 8 contributes to literature by evaluating not only the endogenous water sector interdependencies, but also the exogenous, complex human interactions with water sector infrastructure. Complexity, defined as the interaction of components yielding non-linear patterns of behavior, is addressed in this study by integrating human interaction as objects (agent classes) and within objects (specifically, the system dynamics classes) to evaluate the influence of human behavior on management aspects of the infrastructure systems, such as future demands, financial aspects or participatory processes. Assessing epistemic uncertainty in the proposed framework occurs by modeling the human behavior (i.e., price elasticity) and management decisions (i.e., rate changes) as stochastic parameters, as opposed to the traditional modeling approach using deterministic parameters to understand a range of possible outcomes, as opposed to a singular outcome. Epistemic uncertainty is also assessed in this study with the implementation time, in which the AB-SD framework builds a plausible decision-making process using market-based strategies and agents to evaluate the consequences of participatory processes on the timeframe to implement different retooling alternatives. This is first model, to the author's knowledge, that captures not only the physical interdependencies between the water sector infrastructure, but the human interdependencies with the water sector infrastructure, as well

9.5.2. Contributions to the Body of Practice

The research presented in Chapter 5-8 develops a quantitative method to assess the impact of urban decline and underutilization on the water and wastewater/stormwater infrastructure systems, and retooling alternatives for these infrastructures to aid in right sizing the infrastructure footprint. The analyses conducted in Chapters 5-8 builds upon the qualitative analysis in Chapter 3. The specific contribution to the body of practice will be presented in this section by the contributions of each chapter.

A gap in the body of practice identified by SMEs and literature in shrinking cities is the lack of knowledge pertaining to issues spanning shrinking cities that may not be unique to one city. A second gap identified via SMEs is the technical viability of retooling alternatives that have been qualitatively discussed, as well as which retooling alternatives have been considered across shrinking cities. Chapter 3 identifies issues that span shrinking cities and the retooling alternatives that may mitigate these issues. Although the issues identified in Chapter 3 may manifest differently in each shrinking city, the list is typical to cities that have experienced considerable urban decline. Furthermore, retooling alternatives for water and wastewater/stormwater infrastructure have been compiled in order to allow each city to assess which alternatives may be most appropriate for the decline pattern and community vision.

Chapter 5 provides a framework for assessing the residential impact of urban decline and different retooling alternatives on the performance of the water infrastructure system. The primary tool used within the framework, EPANET, is open source making it readily accessible to fiscally strained cities. The analyses identified the viability of two retooling alternatives:

consolidation of demand and decommissioning pipelines, for right-sizing the city. Decommissioning pipelines was determined viable for diameters less than 12 inches and case dependent for diameter equal or greater than 12 inches. The results demonstrated that the socioeconomic status of the area determined which alternatives were viable, a finding not evident in prior research, that quantifies the tight coupling of the demographic make-up of the area and the performance of the infrastructure under various physical disrupters.

Chapter 6 demonstrates a methodological approach for quantifying the impact of retooling alternatives on the generated runoff. This approach is especially important for cities on combined sewer systems, as the retooling alternatives were capable of significantly reducing the runoff entering the underground infrastructure, which may reduce the volume of and quantity of overflows, a necessity outlined by the Clean Water Act. In the instance that cities cannot afford the financial investment to separate combined sewers, implementing retooling alternatives may be a cost effective method for reducing the strain on the wastewater treatment plant. The findings from this chapter are also relevant to cities operating on separate sewer systems, as providing a methodology to reduce not only the runoff, but the non-point source pollutants entering the open water sources. By reducing the runoff (and non-point source pollutants) entering the stormwater system, water source quality can potentially be improved. Furthermore, in this chapter, the impact on generated runoff of not only decommissioning impervious surfaces, but transitioning land uses, or implementing bioretention cells instead of decommissioning impervious surfaces was quantified for comparison. Similar to Chapter 5, Chapter 6 uses an open source tool, SWMM, which is accessible at no cost to cities to perform analysis specific to the areas topography, current land uses, and local precipitation patterns.

Chapter 7 provides a qualitative and quantitative methodology for assessing public views towards infrastructures in shrinking cities. This methodology can aid in incorporating public views into decision-making and right-sizing efforts. The study shows that awareness of the population dynamics in the city influences the perceptions regarding different retooling alternatives. Furthermore, demographics and location parameters were identified that influence the support/opposition towards retooling alternatives. Prior studies on the public's stance has surrounded issues such as quality of life or perceptions towards abandonment, without evaluating the public stance towards underground infrastructure, a gap filled in this study.

The framework developed in Chapter 8 provides a quantitative method for cities to evaluate the physical infrastructure and human-infrastructure interdependencies. No known prior studies have quantified the water-wastewater-stormwater-human interaction interdependencies. The model is capable of being tailored to any cities specific infrastructure by varying parameters, such as local water demand, population, decline (growth) rate, billing rate, or rate increase. The model can predict future water and wastewater needs based on projected rate increases and population trends, as well as the complex interaction between billing rates, financial return, and water demand.

9.6. Recommendations for Future Research

Although the impact of urban decline has been well studied by political and social scientists, the implications of urban decline and underutilization on infrastructure systems are just beginning to be appreciated. There are many avenues that can extend from this study.

One avenue would be to extend the physical infrastructure and human-infrastructure interdependencies analyses to encompass a large sample of cities spanning various size classifications. By doing so, relationships between the magnitude of the decline rate, the population size of time, and the outcome of different management strategies could be confirmed, as opposed to conjectured. Furthermore, by extending the analysis to numerous shrinking cities, factors such as regional characteristics (e.g., weather, number of shrinking cities in area), local policies, and driver(s) of decline may shed light into the infrastructure issues arising from the circumstances of shrinkage. For instance, New Orleans, Louisiana is a shrinking city as a result from Hurricane Katrina. The drastic urban decline occurring in a very short duration, with the damage from the natural disaster, may have other prominent issues that are not seen in the gradual chronic decline occurring over many decades. This may add new knowledge and practical methods to efficiently and flexibly manage and maintain infrastructure of various growth (decline) patterns occurring from different drivers. This future research in infrastructure retooling alternatives may extend the current growth paradigm to consider the entire lifecycle of infrastructure.

This study evaluated two critical infrastructure systems, water and wastewater/stormwater infrastructure under various physical and non-physical disrupters. The work done in infrastructure management can be extended to other infrastructure systems, such as transportation, electricity, natural gas, or emergency services, to understand the implication of urban decline or underutilization spanning multiple systems. These infrastructure systems are in need of identifying retooling alternatives and methods to provide adequate services, and understand how urban decline is impacting the services provided, which have not been explored in literature or practice. ASCE (2013b)'s report provided a grade of C+ for bridges and D+ for energy, indicated that the infrastructure systems nationwide need investment that will be increasingly difficult to accomplish in fiscally strained cities.

Research in the public views at the point in time when people leave the city (or move to the city) is an extension for future work to understand the impact of urban decline on the public. Herz (2006) discusses that increasing per capita costs in conjunction with deteriorating utility services can perpetuate existing population decline. Understanding this relationship between immigrant and emigration, to and from a city, as well as the perceptions towards infrastructure services may provide insight into factors perpetuating the urban decline that are not as prominent as the major drivers, such as de-industrialization, natural disaster, or aging populations.

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APPENDICES

Appendix A. Taylor & Francis Reprint Permission

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Taylor & Francis
Taylor & Francis Group

Title: Statistical analysis of public perceptions of water infrastructure sustainability in shrinking cities

Author: Kasey M. Faust, Fred L. Mannering, Dulcy M. Abraham

Publication: Urban Water Journal

Publisher: Taylor & Francis

Date: Feb 23, 2015

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Appendix B. American Society of Civil Engineers Reprint Permission

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ASCE
AMERICAN SOCIETY OF CIVIL ENGINEERS

Conference Proceeding:	Construction Research Congress 2014: Construction in a Global Network
Conference Proceeding Paper:	Front Matter
Author:	Daniel Castro-Lacouture, Javier Irizarry, Baabak Ashuri
Publisher:	American Society of Civil Engineers
Date:	05/13/2014

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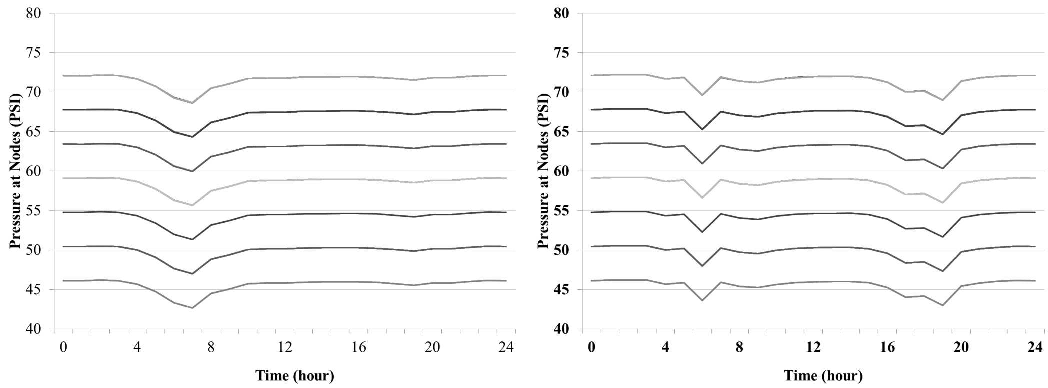
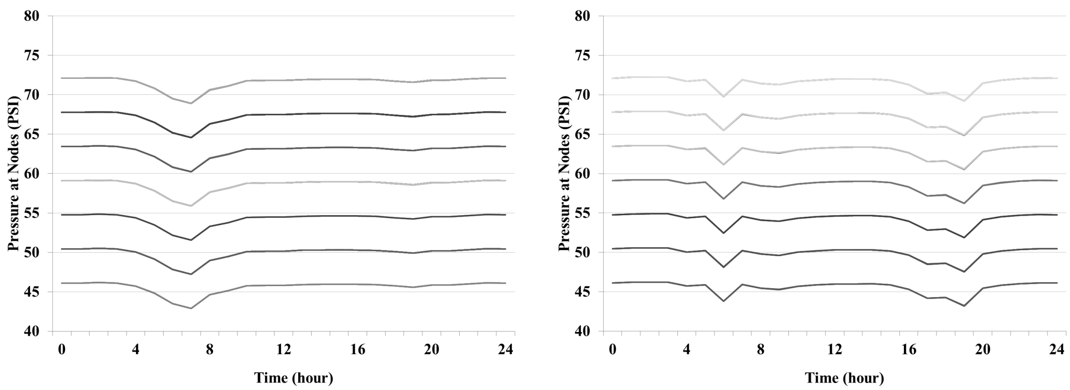
Appendix C. Results of Flint's Small Diameter Pipeline Analysis



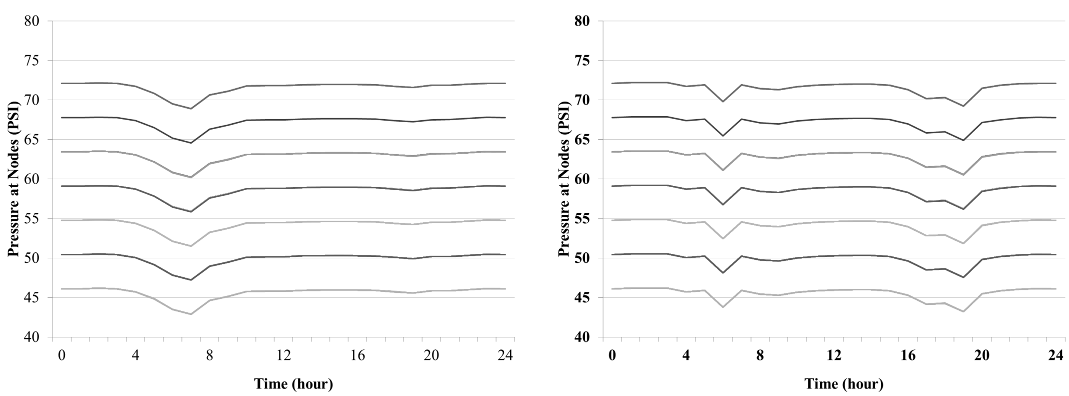
(a) (b)

Figure C.1. Flint's Status quo network using the baseline demand: (a) Single Family Demand Pattern and (b) Low-Income Single Family Demand Pattern



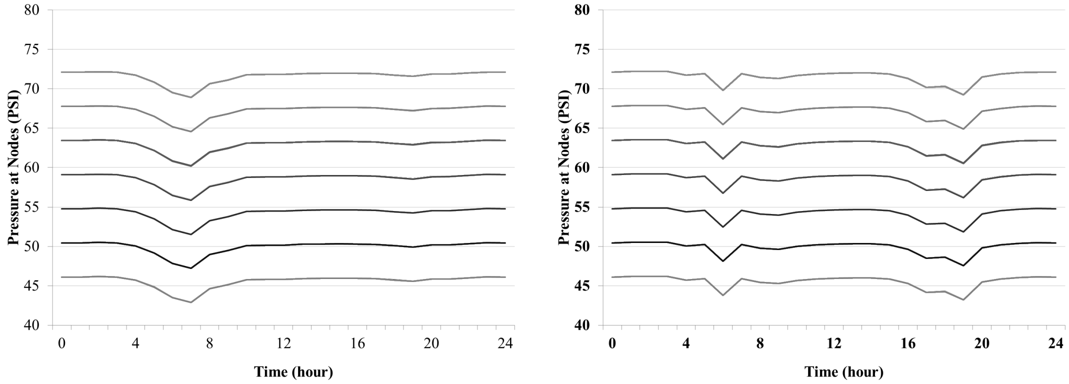
(a) (b)

Figure C.2. Flint's Scenario 1 using the baseline demand: (a) Single Family Demand Pattern and (b) Low-Income Single Family Demand Pattern



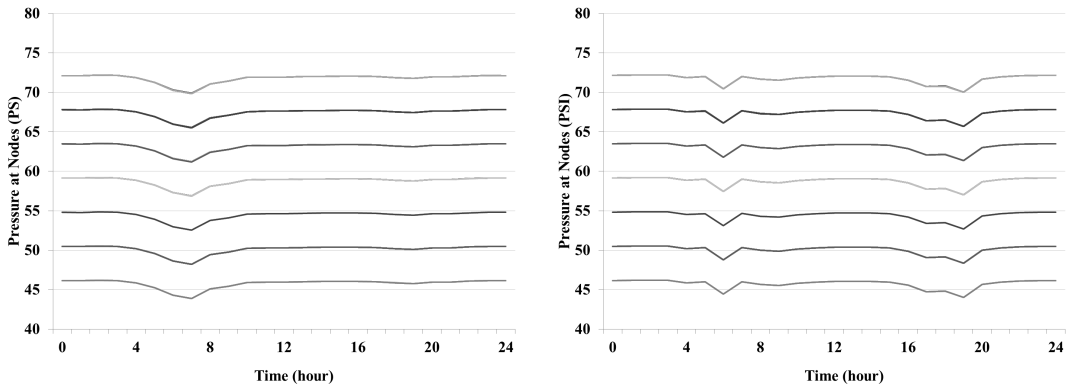
(a) (b)

Figure C.3. Flint's Scenario 2(a) using the baseline demand: (a) Single Family Demand Pattern and (b) Low-Income Single Family Demand Pattern



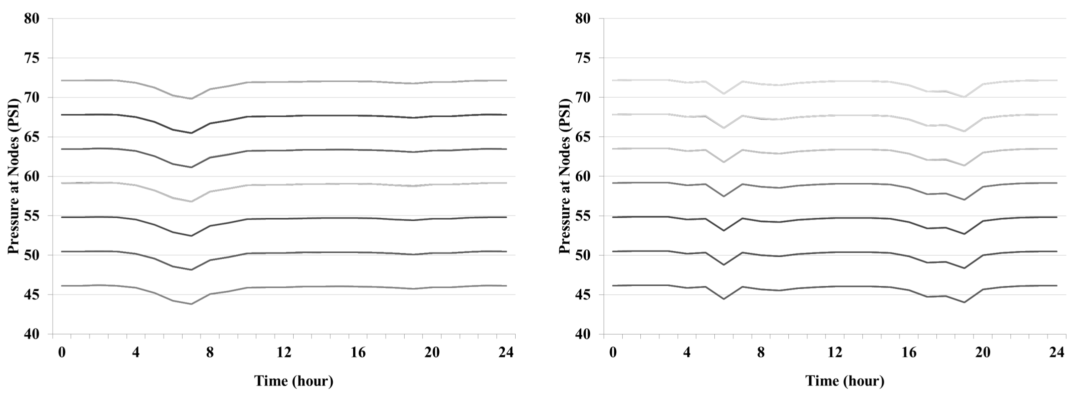
(a) (b)

Figure C.4. Flint's Scenario 2(b) using the baseline demand: (a) Single Family Demand Pattern and (b) Low-Income Single Family Demand Pattern



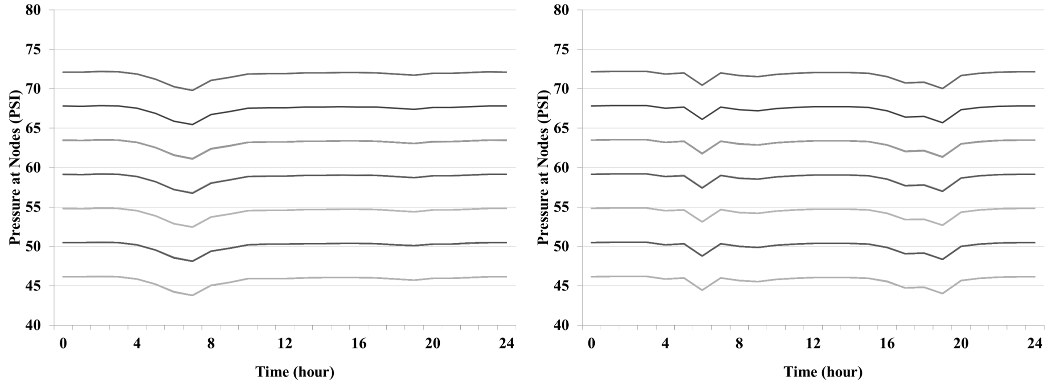
(a) (b)

Figure C.5. Flint's status quo network using a 10-year population decline in demand: (a) Single Family Demand Pattern and (b) Low-Income Single Family Demand Pattern



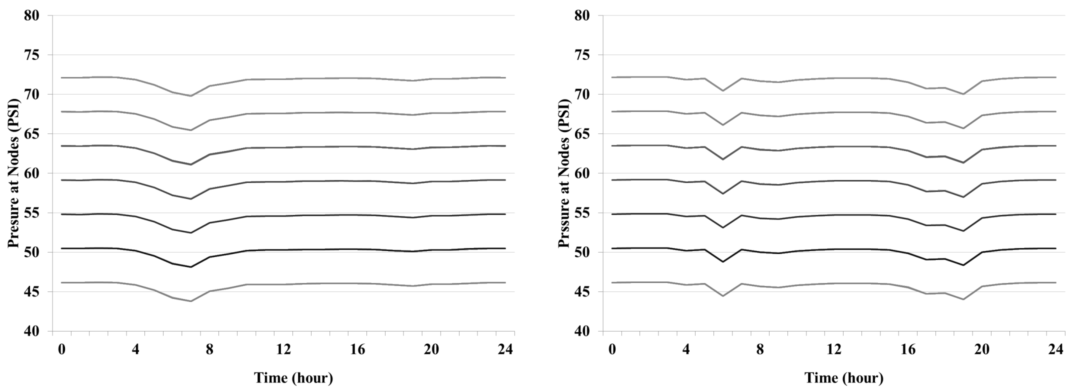
(a) (b)

Figure C.6. Flint's Scenario 1 using a 10-year population decline in demand: (a) Single Family Demand Pattern and (b) Low-Income Single Family Demand Pattern



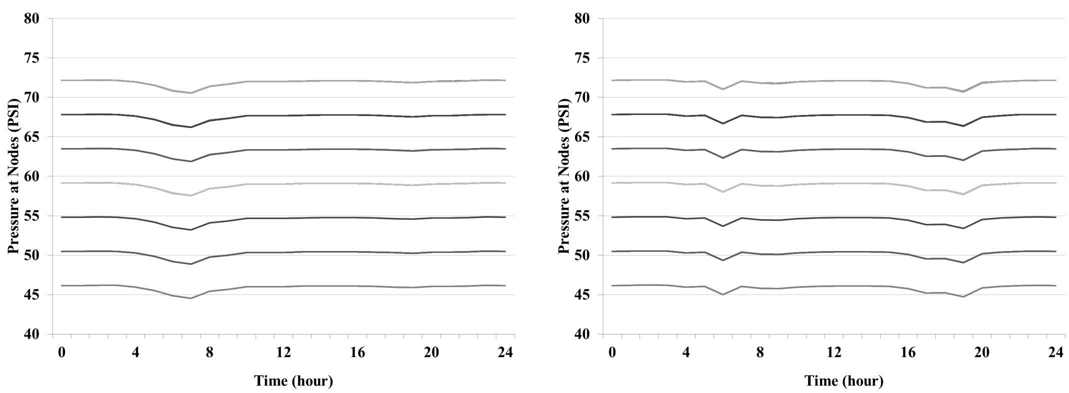
(a) (b)

Figure C.7. Flint’s Scenario 2(a) using a 10-year population decline in demand: (a) Single Family Demand Pattern and (b) Low-Income Single Family Demand Pattern



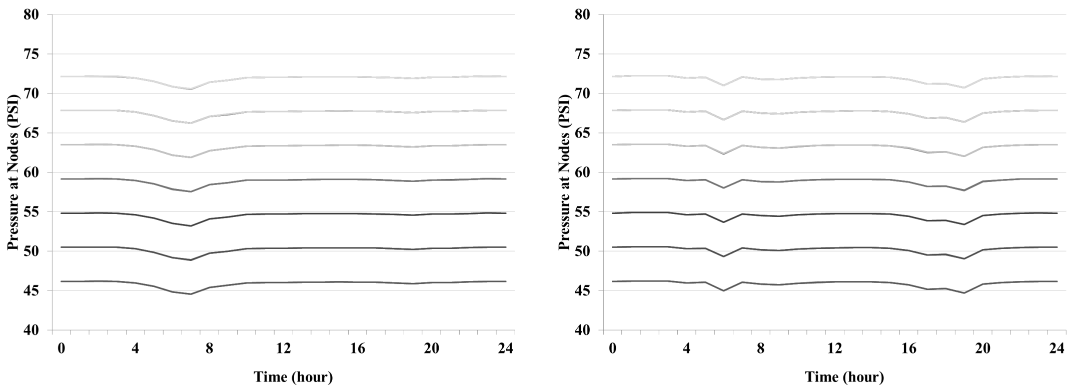
(a) (b)

Figure C.8. Flint’s Scenario 2(b) using a 10-year population decline in demand: (a) Single Family Demand Pattern and (b) Low-Income Single Family Demand Pattern



(a) (b)

Figure C.9. Flint’s status quo network using a 20-year population decline in demand: (a) Single Family Demand Pattern and (b) Low-Income Single Family Demand Pattern



(a) (b)

Figure C.10. Flint's Scenario 1 using a 20-year population decline in demand: (a) Single Family Demand Pattern and (b) Low-Income Single Family Demand Pattern

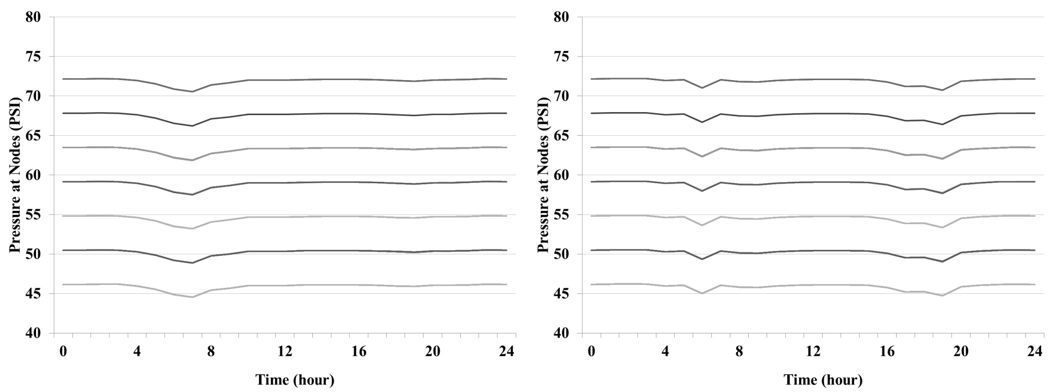


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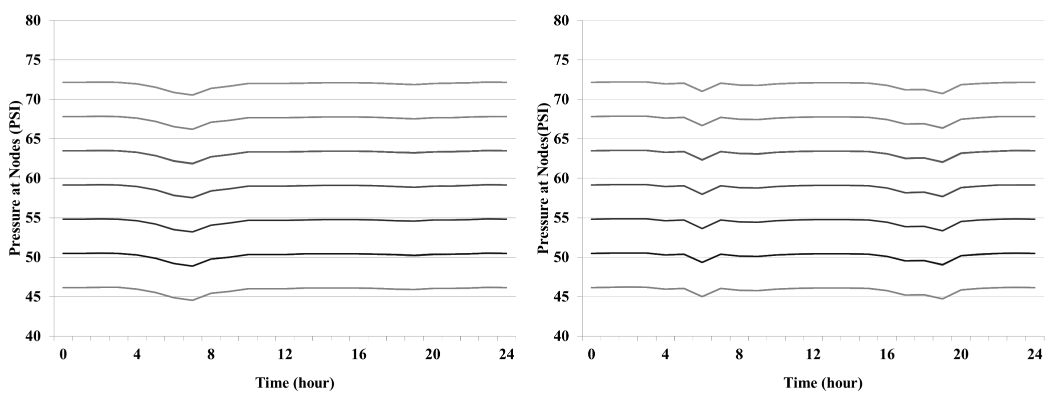
Figure C.11. Flint's Scenario 2(a) using a 20-year population decline in demand: (a) Single Family Demand Pattern and (b) Low-Income Single Family Demand Pattern



(a) (b)

Figure C.12. Flint's Scenario 2(b) using a 20-year population decline in demand: (a) Single Family Demand Pattern and (b) Low-Income Single Family Demand Pattern

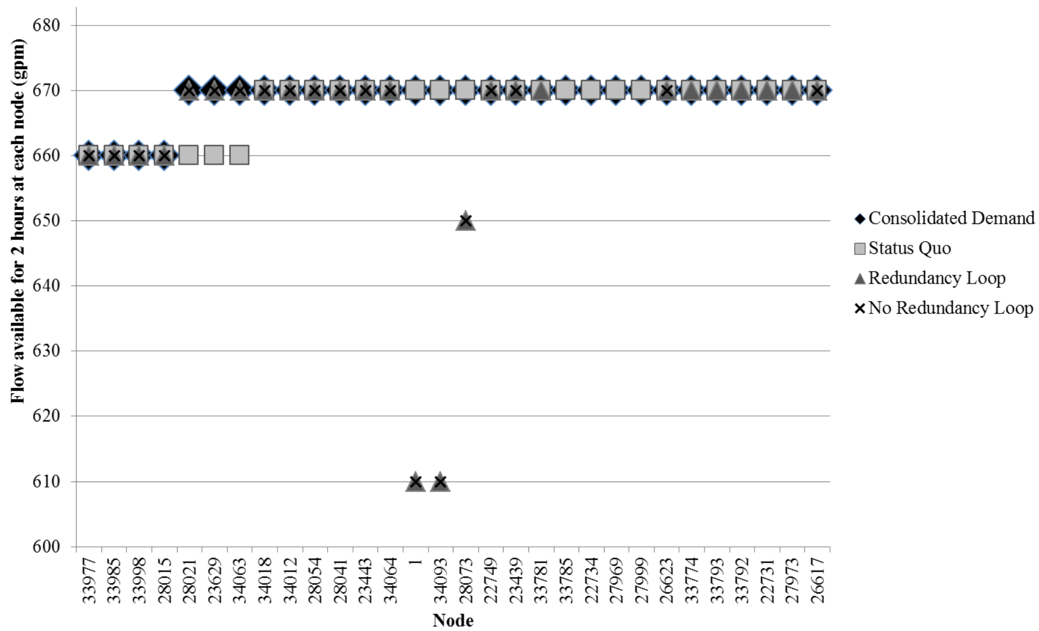


Figure C.13. Flint's maximum flow available at each intersecting node for 2-hour duration while maintaining all nodes at a 20-psi minimum using the Single Family Demand Pattern and the baseline demand

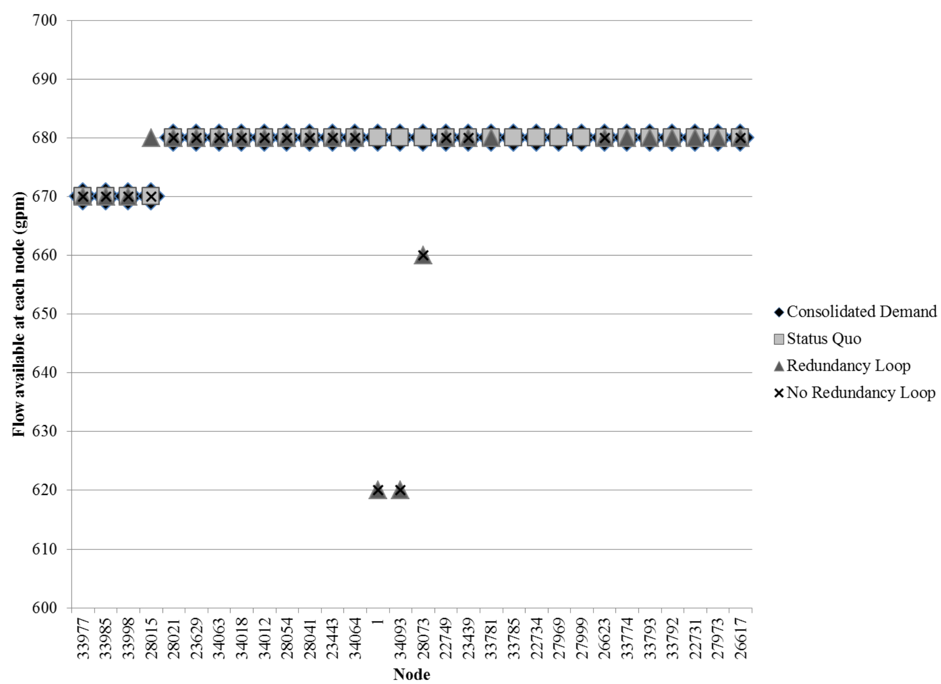


Figure C.14. Flint's maximum flow available at each intersecting node while maintaining all nodes at a 20-psi minimum using the Single Family Demand Pattern and the baseline demand

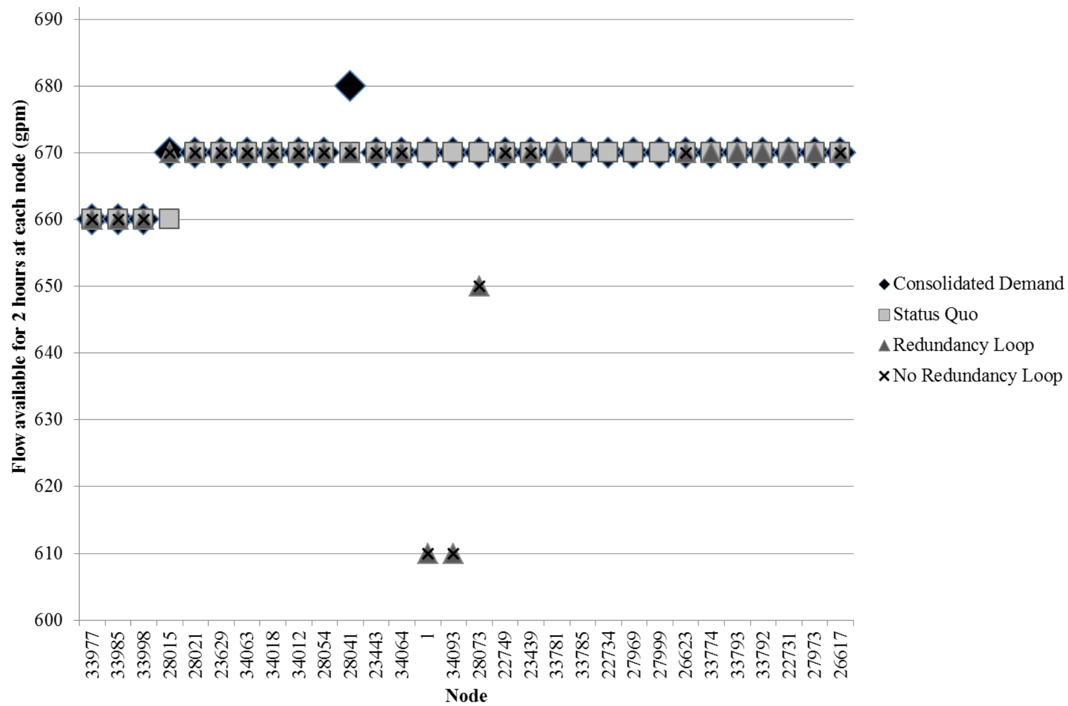


Figure C.15. Flint's maximum flow available at each intersecting node for 2-hour duration while maintaining all nodes at a 20-psi minimum using the Low-Income Single Family Demand Pattern and the baseline demand

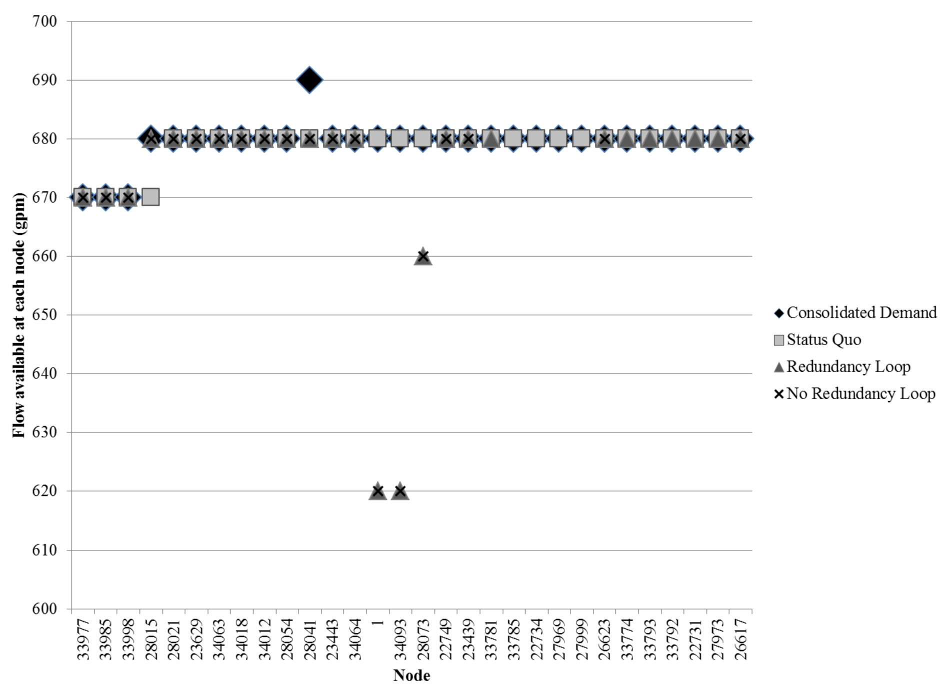


Figure C.16. Flint's maximum flow available at each intersecting node while maintaining all nodes at a 20-psi minimum using the Low-Income Single Family Demand Pattern and the baseline demand

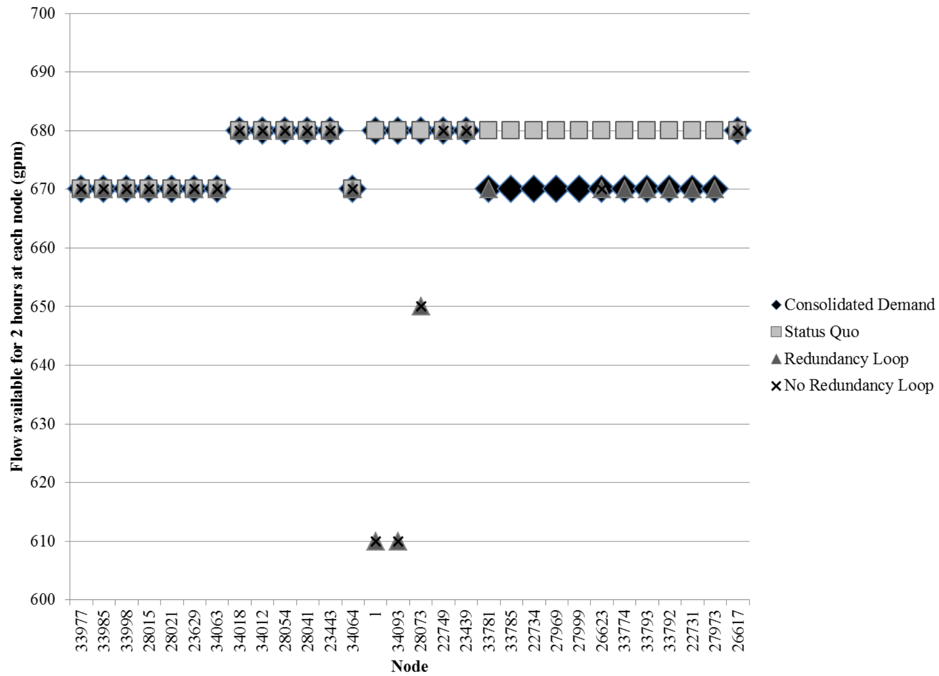


Figure C.17. Flint's maximum flow available at each intersecting node for 2-hour duration while maintaining all nodes at a 20-psi minimum using the Single Family Demand Pattern and 10-year population decline in demand

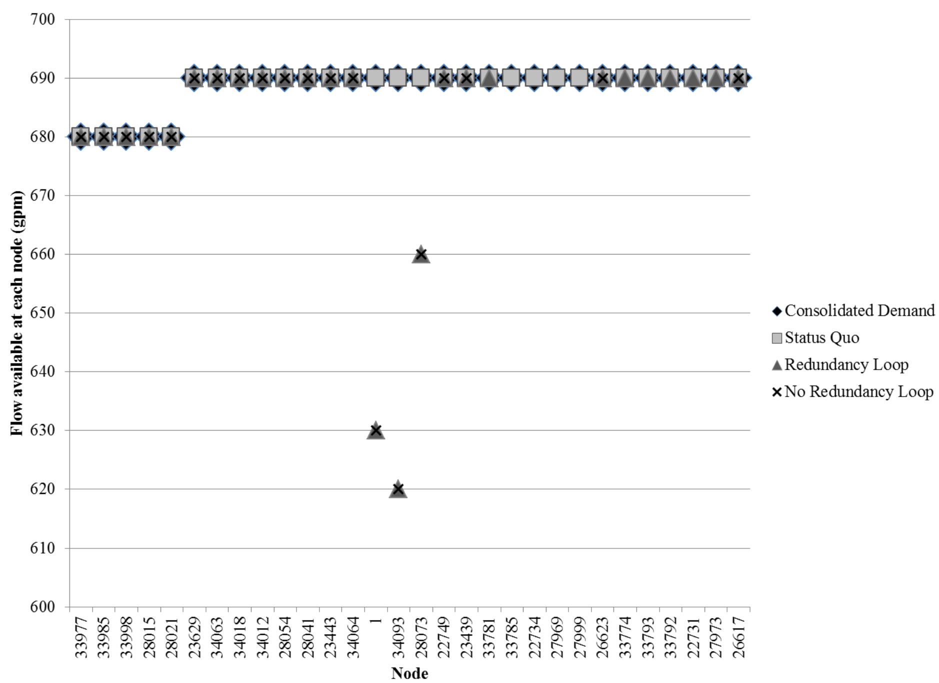


Figure C.18. Flint's maximum flow available at each intersecting node while maintaining all nodes at a 20-psi minimum using the Single Family Demand Pattern and 10-year population decline in demand

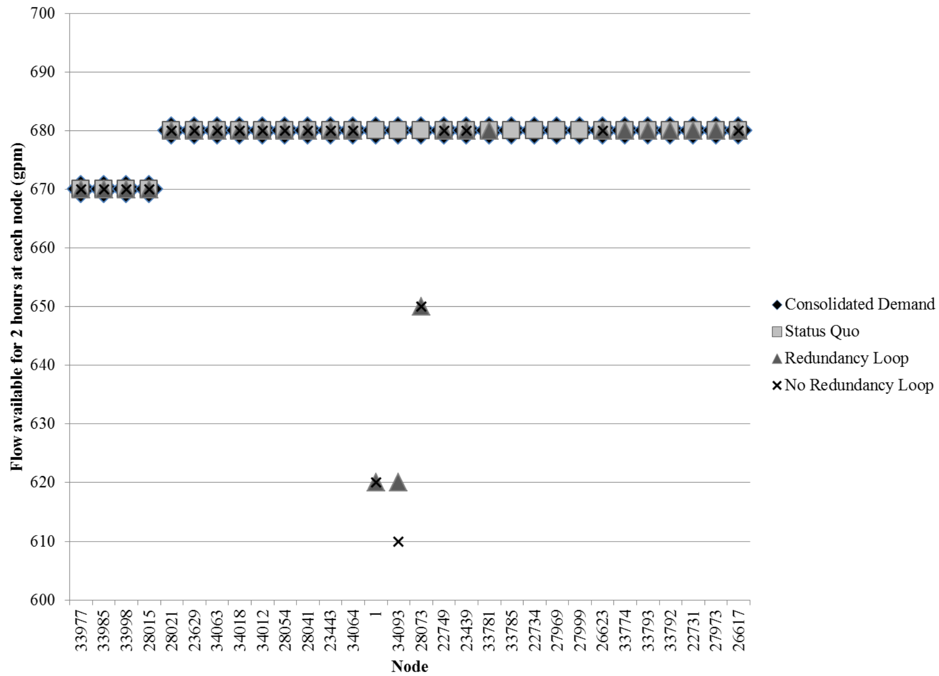


Figure C.19. Flint's maximum flow available at each intersecting node for 2-hour duration while maintaining all nodes at a 20-psi minimum using the Low-Income Single Family Demand Pattern and the 10-year population decline in demand

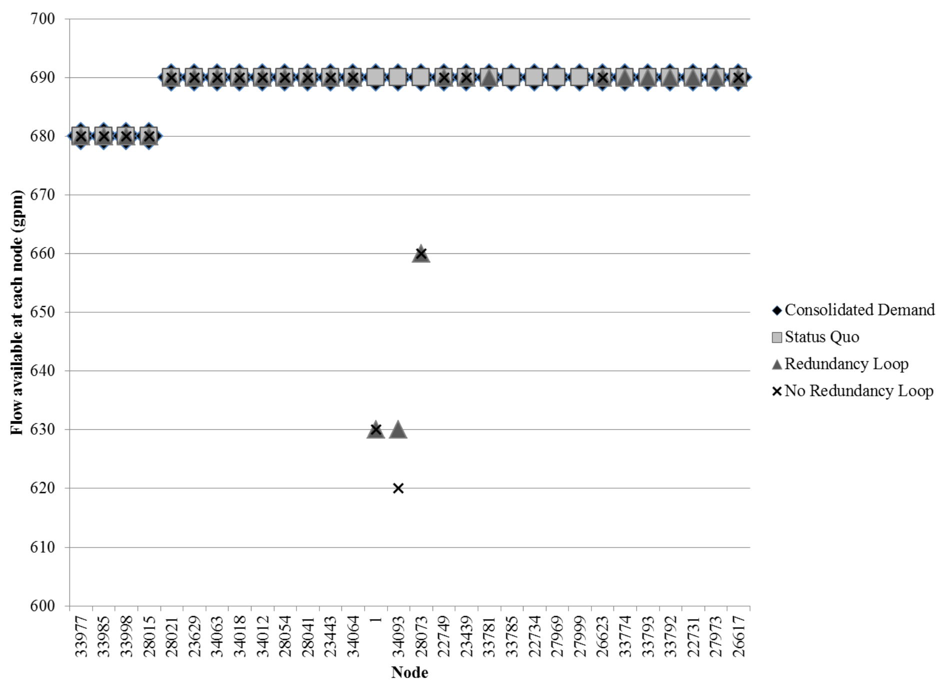


Figure C.20. Flint's maximum flow available at each intersecting node while maintaining all nodes at a 20-psi minimum using the Low-Income Single Family Demand Pattern and 10-year population decline in demand

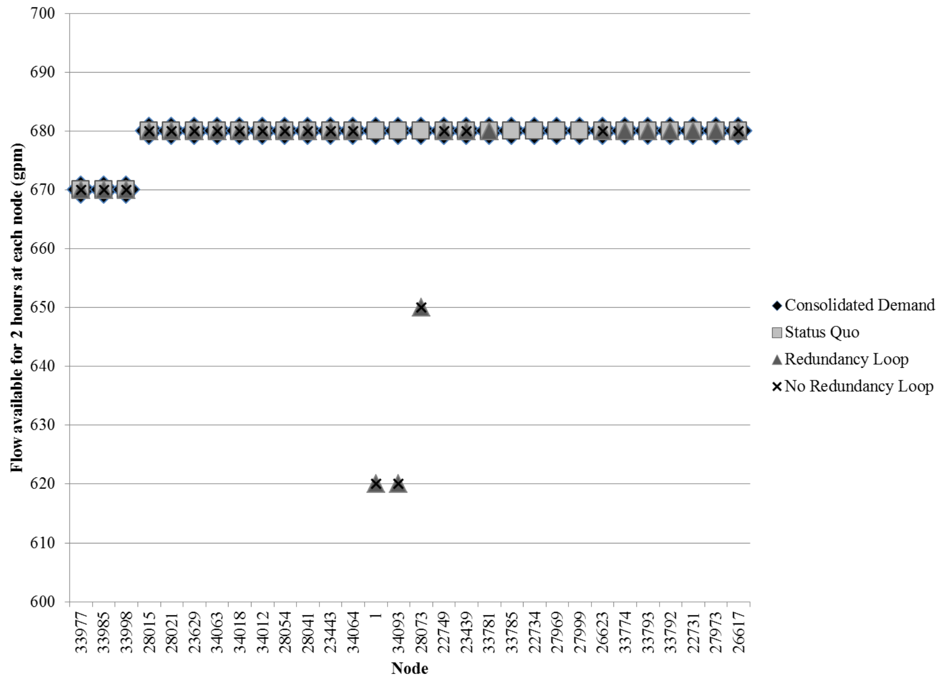


Figure C.21. Flint’s maximum flow available at each intersecting node for 2-hour duration while maintaining all nodes at a 20-psi minimum using the Single Family Demand Pattern and the 20-year population decline in demand

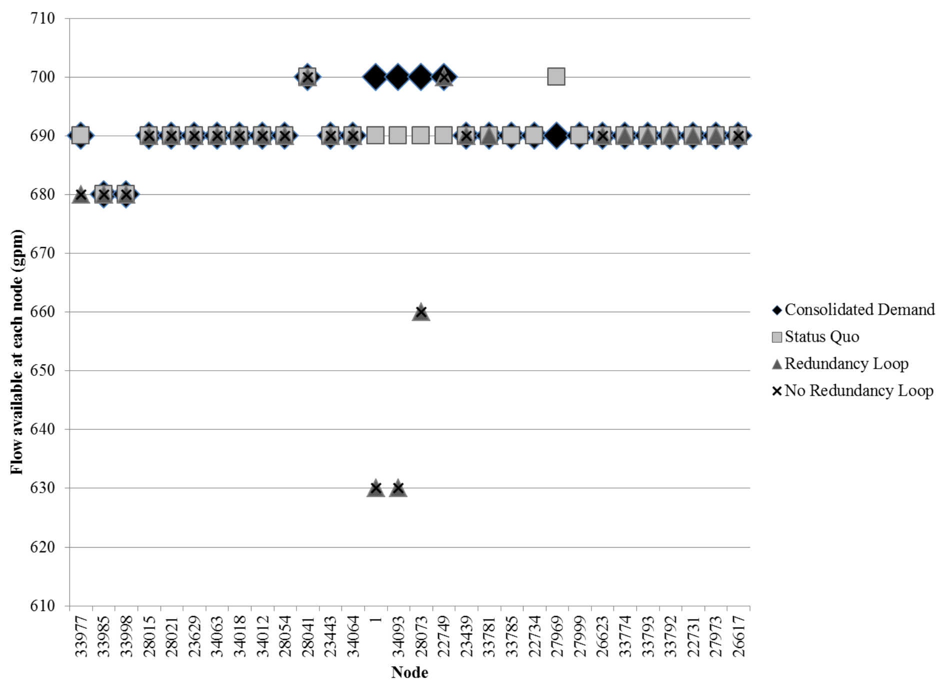


Figure C.22. Flint’s maximum flow available at each intersecting node while maintaining all nodes at a 20-psi minimum using the Single Family Demand Pattern and 20-year population decline in demand

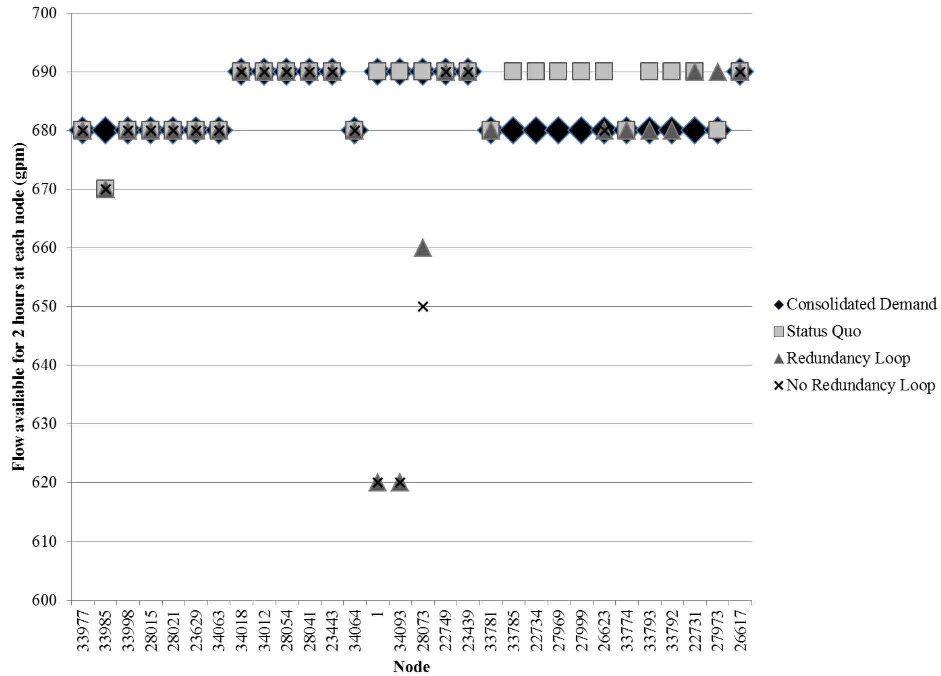


Figure C.23. Flint’s maximum flow available at each intersecting node for 2-hour duration while maintaining all nodes at a 20-psi minimum using the Low-Income Single Family Demand Pattern and the 20-year population decline in demand

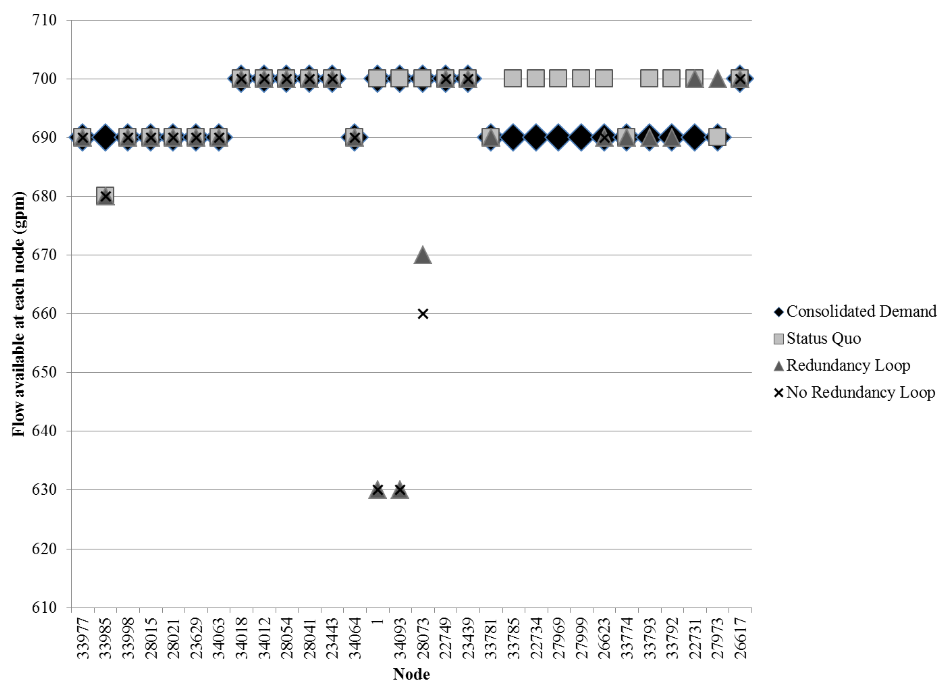
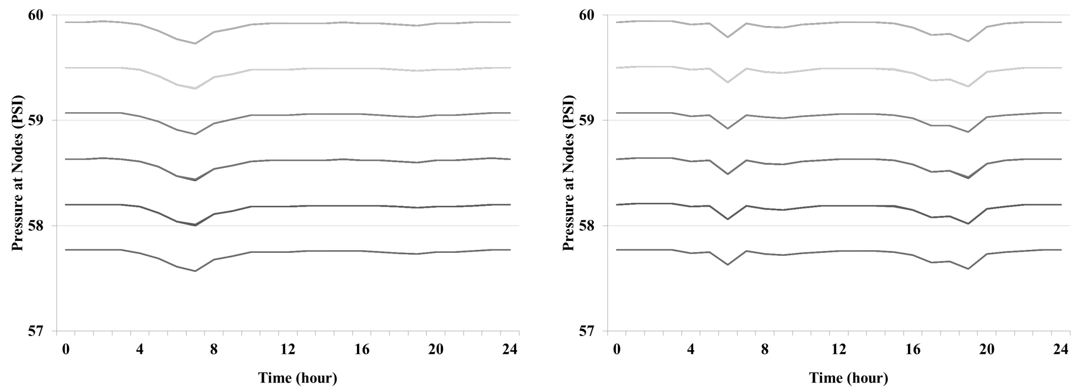


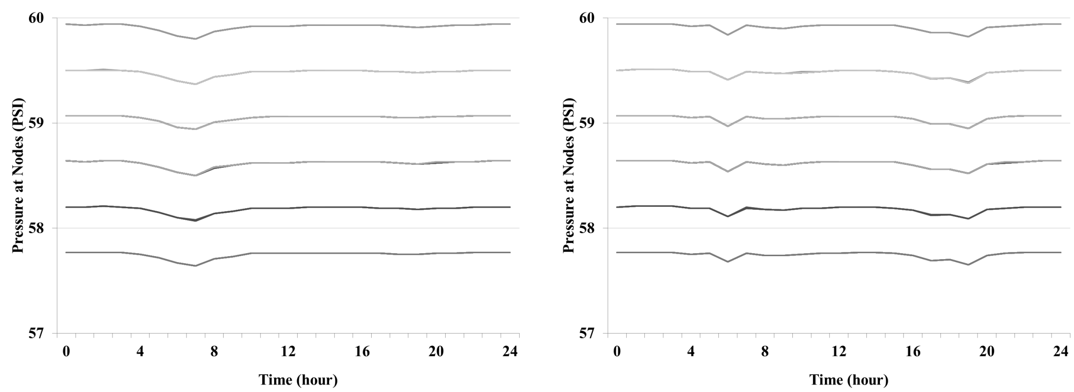
Figure C.24. Flint’s maximum flow available at each intersecting node while maintaining all nodes at a 20-psi minimum using the Low-Income Single Family Demand Pattern and 20-year population decline in demand

Appendix D. Results of Saginaw's Small Diameter Pipeline Analysis



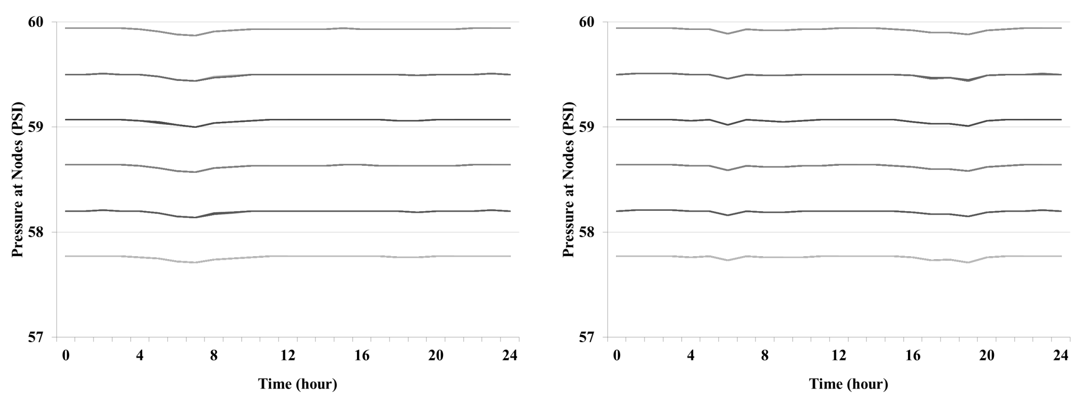
(a) (b)

Figure D.1. Saginaw's status quo network: (a) Single Family Demand Pattern and (b) Low-Income Single Family Demand Pattern



(a) (b)

Figure D.2. Saginaw's Scenario 1(a): (a) Single Family Demand Pattern and (b) Low-Income Single Family Demand Pattern



(a) (b)

Figure D.3. Saginaw's Scenario 1(b): (a) Single Family Demand Pattern and (b) Low-Income Single Family Demand Pattern

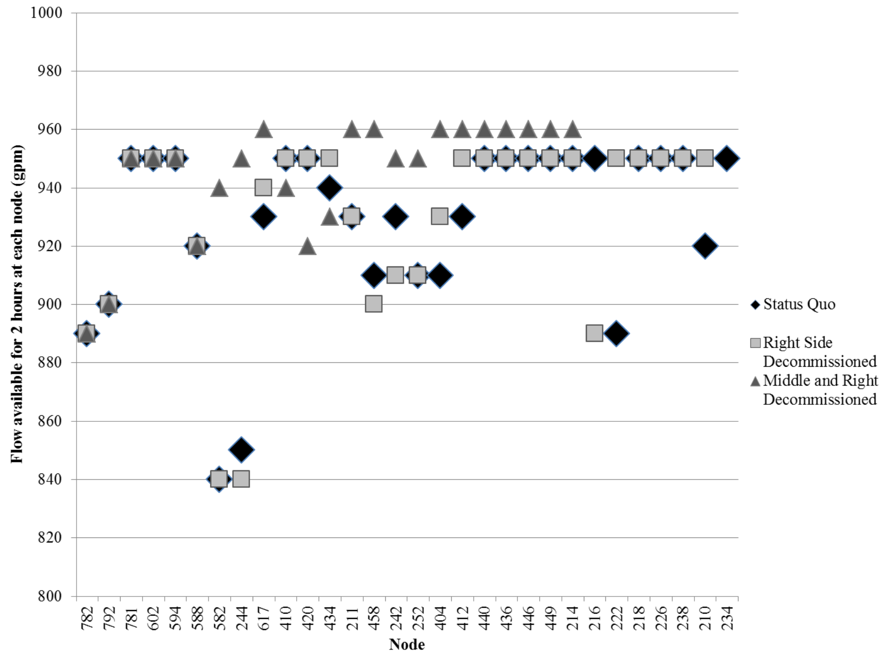


Figure D.4. Saginaw's maximum flow available at each intersecting node for 2-hour duration while maintaining all nodes at a 20-psi minimum using the Single Family Demand Pattern

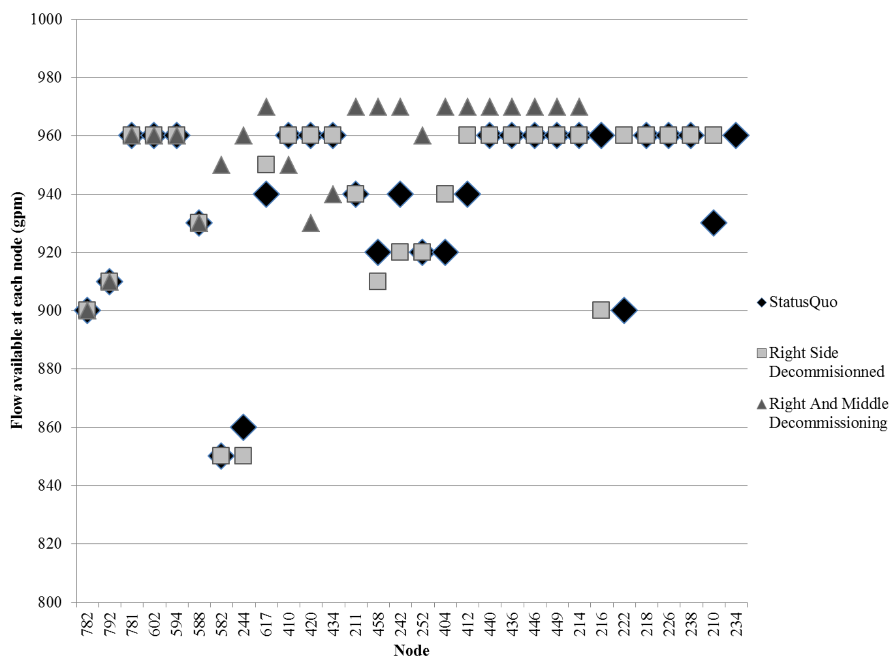


Figure D.5. Saginaw's maximum flow available at each intersecting node while maintaining all nodes at a 20-psi minimum using the Single Family Demand Pattern

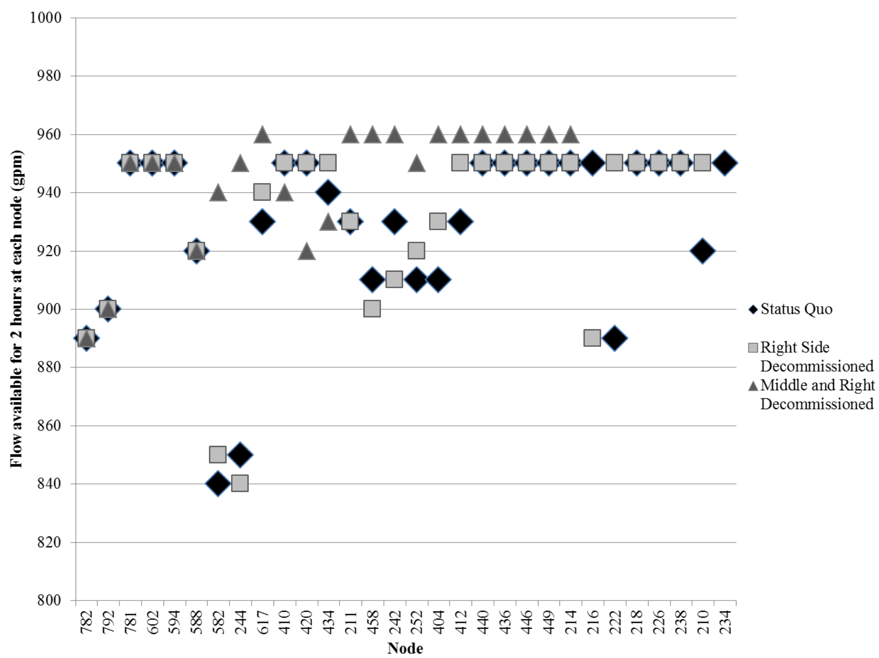


Figure D.6. Saginaw's maximum flow available at each intersecting node for 2-hour duration while maintaining all nodes at a 20-psi minimum using the Low-Income Single Family Demand Pattern

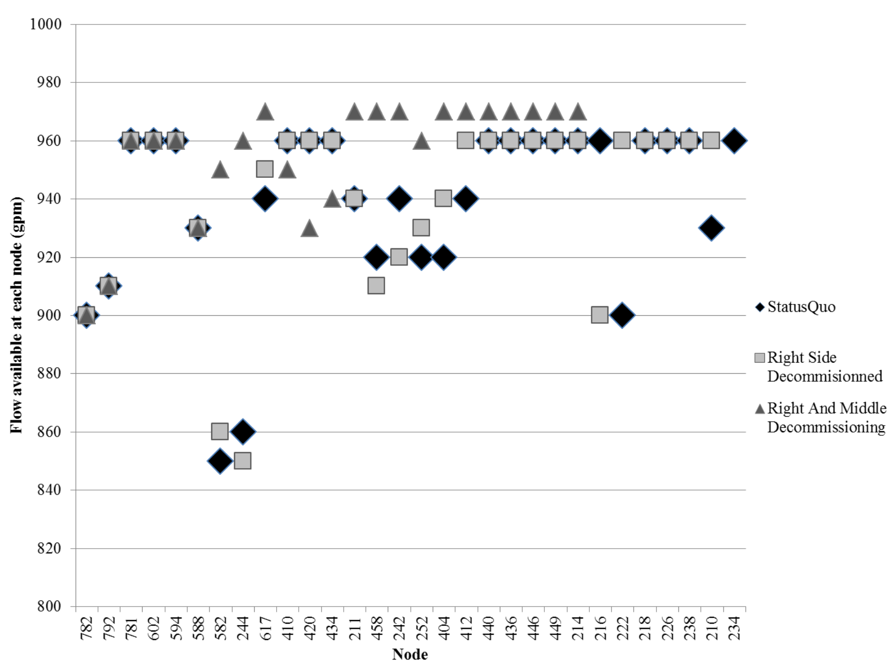


Figure D.7. Saginaw's maximum flow available at each intersecting node while maintaining all nodes at a 20-psi minimum using the Low-Income Single Family Demand Pattern

Appendix E. Institutional Review Board Exemption

PURDUE
UNIVERSITY

HUMAN RESEARCH PROTECTION PROGRAM
INSTITUTIONAL REVIEW BOARDS

To:	DULCY ABRAHAM CIVL 1241
From:	JEANNIE DICLEMENTI, Chair Social Science IRB
Date:	09/11/2013
Committee Action:	**Exemption Granted**
IRB Action Date:	09/11/2013
IRB Protocol #:	1309013972
Study Title:	Impact Assessment of Infrastructure and Infrastructure Interdependencies in Shrinking Cities

The Institutional Review Board (IRB) has reviewed the above-referenced study application and has determined that it meets the criteria for exemption under 45 CFR 46.101(b)(2) .

If you wish to make changes to this study, please refer to our guidance **"Minor Changes Not Requiring Review"** located on our website at http://www.irb.purdue.edu/policies.php. For changes requiring IRB review, please submit an **Amendment to Approved Study** form or **Personnel Amendment to Study** form, whichever is applicable, located on the forms page of our website www.irb.purdue.edu/forms.php. Please contact our office if you have any questions.

Below is a list of best practices that we request you use when conducting your research. The list contains both general items as well as those specific to the different exemption categories.

General

- To recruit from Purdue University classrooms, the instructor and all others associated with conduct of the course (e.g., teaching assistants) must not be present during announcement of the research opportunity or any recruitment activity. This may be accomplished by announcing, in advance, that class will either start later than usual or end earlier than usual so this activity may occur. It should be emphasized that attendance at the announcement and recruitment are voluntary and the student's attendance and enrollment decision will not be shared with those administering the course.
- If students earn extra credit towards their course grade through participation in a research project conducted by someone other than the course instructor(s), such as in the example above, the students participation should only be shared with the course instructor(s) at the end of the semester. Additionally, instructors who allow extra credit to be earned through participation in research must also provide an opportunity for students to earn comparable extra credit through a non-research activity requiring an amount of time and effort comparable to the research option.
- When conducting human subjects research at a non-Purdue college/university, investigators are urged to contact that institution's IRB to determine requirements for conducting research at that institution.
- When human subjects research will be conducted in schools or places of business, investigators must obtain written permission from an appropriate authority within the organization. If the written permission was not submitted with the study application at the time of IRB review (e.g., the school would not issue the letter without

proof of IRB approval, etc.), the investigator must submit the written permission to the IRB prior to engaging in the research activities (e.g., recruitment, study procedures, etc.). This is an institutional requirement.

Category 1

- When human subjects research will be conducted in schools or places of business, investigators must obtain written permission from an appropriate authority within the organization. If the written permission was not submitted with the study application at the time of IRB review (e.g., the school would not issue the letter without proof of IRB approval, etc.), the investigator must submit the written permission to the IRB prior to engaging in the research activities (e.g., recruitment, study procedures, etc.). This is an institutional requirement.

Categories 2 and 3

- Surveys and questionnaires should indicate
  - only participants 18 years of age and over are eligible to participate in the research; and
  - that participation is voluntary; and
  - that any questions may be skipped; and
  - include the investigator's name and contact information.
- Investigators should explain to participants the amount of time required to participate. Additionally, they should explain to participants how confidentiality will be maintained or if it will not be maintained.
- When conducting focus group research, investigators cannot guarantee that all participants in the focus group will maintain the confidentiality of other group participants. The investigator should make participants aware of this potential for breach of confidentiality.
- When human subjects research will be conducted in schools or places of business, investigators must obtain written permission from an appropriate authority within the organization. If the written permission was not submitted with the study application at the time of IRB review (e.g., the school would not issue the letter without proof of IRB approval, etc.), the investigator must submit the written permission to the IRB prior to engaging in the research activities (e.g., recruitment, study procedures, etc.). This is an institutional requirement.

Category 6

- Surveys and data collection instruments should note that participation is voluntary.
- Surveys and data collection instruments should note that participants may skip any questions.
- When taste testing foods which are highly allergenic (e.g., peanuts, milk, etc.) investigators should disclose the possibility of a reaction to potential subjects.

Appendix F. Survey

City you reside in:________________

Over the past 4 decades, my city has:
A. Faced a loss in population.
B. Gained population.
C. Has had no significant changes in population.
D. I do not know.

How has population change impacted the price of my water bill:
A. Decreasing my monthly water bill.
B. Increasing my monthly water bill.
C. It has not changed my monthly water bill at all.
D. I do not know.

The present level of physical WATER infrastructure necessary to provide service to my city at its current population is:
A. More than enough water infrastructure.
B. Not enough water infrastructure.
C. The right amount of water infrastructure.
D. I do not know.

My household uses an average of ____gallons of WATER per month

My WATER service bill is for:
A. Water service only.
B. Water and wastewater service combined.
C. I do not know.

Answer If My water service bill is for: Water and wastewater service combined Is Selected
My average combined monthly WASTEWATER and WATER bill is (please enter "do not know" if applicable)______

Answer If My water service bill is for: Water service only Is Selected Or My water service bill is for: I do not know Is Selected
My average monthly WATER bill is (please enter "do not know" if applicable)______

Answer If My water service bill is for: Water service only Is Selected And My water service bill is for: I do not know Is Selected
My average monthly WASTEWATER bill is (please enter "do not know" if applicable)______

Are you responsible for paying for your WATER bill or a portion of your WATER bill?
A. Yes
B. No

The amount of physical WATER infrastructure (e.g., pipes, reservoirs) in my city impacts the cost of my WATER bill.
A. Agree

B. Disagree
C. Do not know

The quality (defined as uninterrupted, clean WATER, at an adequate pressure) of service from my WATER provider has changed in the past 10 years?

A. Not applicable, I have not lived in the city more than 10 years.
B. The quality of service has decreased dramatically.
C. The quality of service has decreased slightly.
D. There is no noticeable change in service.
E. The quality of service has improved slightly.
F. The quality has improved dramatically.

My city needs to (choose all that apply):

A. Invest in more water infrastructure.
B. Remove or decommission (i.e., cease to use) components of the water infrastructure system.
C. Repurpose some components of the water infrastructure system.
D. Invest in maintaining the current water infrastructure system.
E. Do nothing to the current water infrastructure system.

Would you support decommissioning, razing, or repurposing WATER infrastructure (choose all that apply)?

A. I would support decommissioning (i.e., ceasing to use, but leaving the components in place) components of my city's water infrastructure system.
B. I would support razing (i.e., removing) components of my city's water infrastructure system.
C. I would support repurposing (for instance, contracting out excess capacity, using wells as opposed to the citywide water grid) components of my city's water infrastructure system.
D. No, all components of my city's water infrastructure system should be in place for their current purposes.

How much MORE would you be willing to pay for improved reliability of your WATER service? Leave the slider at "0" if you would not be willing to pay more for your water service for a more reliable system

______ Percent (%) increase in current water bill (1)

How much MORE would you be willing to pay for improved reliability of your WASTEWATER service? Leave the slider at "0" if you would not be willing to pay more for your water service for a more reliable system

______ Percent (%) increase in current wastewater bill (1)

The present level of physical WATER infrastructure necessary to provide service to my city at its current population is:

A. More than enough water infrastructure.
B. Not enough water infrastructure.
C. The right amount of water infrastructure.
D. I do not know

Based on your understanding of the WATER infrastructure system, please indicate your opinion on the following statements:

	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)	I do not know (6)
The water infrastructure system in my city is aging and needs to be upgraded	❍	❍	❍	❍	❍	❍
The water infrastructure system in my city is sustained by revenues solely generated by water bills	❍	❍	❍	❍	❍	❍
My water provider is fiscally strained	❍	❍	❍	❍	❍	❍
I trust my water provider to make appropriate decisions that are in my best interest	❍	❍	❍	❍	❍	❍
I would like to be actively involved in the decision-making process for the water infrastructure in my city	❍	❍	❍	❍	❍	❍

Based on your understanding of your WASTEWATER infrastructure system, please indicate your opinion on the following statements:

	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)	I do not know (6)
The wastewater infrastructure in my city is aging and needs to be upgraded	❍	❍	❍	❍	❍	❍
Revenues solely generated by wastewater bills sustain the wastewater infrastructure n my city	❍	❍	❍	❍	❍	❍
My wastewater provider is fiscally strained	❍	❍	❍	❍	❍	❍
I trust my wastewater provider to make appropriate decisions that are in my best interest	❍	❍	❍	❍	❍	❍

Based on your understanding of the WATER infrastructure system, please indicate your opinion on the following statements:

	Strongly Oppose (1)	Oppose (2)	Neutral (3)	Support (4)	Strongly Support (5)	I do not know (6)
New (e.g., new pipes, new reservoirs) water infrastructure projects in my city	❍	❍	❍	❍	❍	❍
Increasing financial investments for the maintenance of the existing water infrastructure system in my city	❍	❍	❍	❍	❍	❍
Decommissioning (i.e., ceasing to use, but leaving the components in place) components of my city's water infrastructure system	❍	❍	❍	❍	❍	❍
Razing (i.e., removing) components of my city's water infrastructure system	❍	❍	❍	❍	❍	❍
Repurposing components (for instance, contracting out excess capacity, using wells as opposed to the citywide water grid) of my city's water infrastructure system	❍	❍	❍	❍	❍	❍
For validation purposes, please choose "oppose"	❍	❍	❍	❍	❍	❍
Making improvements to my water infrastructure system that would increase the quality of the service AND increase the cost of service	❍	❍	❍	❍	❍	❍
Changes to my water infrastructure system that would stabilize (i.e., stop rate increases) the cost of my service (e.g., upgrading or replacing infrastructure components)	❍	❍	❍	❍	❍	❍
Increasing the cost of my water service to cover the cost of additional infrastructure or replacement	❍	❍	❍	❍	❍	❍

Based on your understanding of your WASTEWATER infrastructure system, please indicate your opinion on the following statements:

	Strongly Oppose (1)	Oppose (2)	Neutral (3)	Support (4)	Strongly Support (5)	I do not know (6)
Increasing financial investments for the maintenance of the existing wastewater infrastructure system in my city	❍	❍	❍	❍	❍	❍
For validation purposes, please choose "support"	❍	❍	❍	❍	❍	❍
Decommissioning (i.e., ceasing to use, but leaving the components in place) components of my city's wastewater infrastructure system	❍	❍	❍	❍	❍	❍
Razing (i.e., removing) components of my city's wastewater infrastructure system	❍	❍	❍	❍	❍	❍
Repurposing components (for instance, contracting out excess capacity of sewer system for non-public purposes) of my city's wastewater infrastructure system	❍	❍	❍	❍	❍	❍
Increasing the cost of my wastewater service to cover the cost of additional infrastructure or replacement	❍	❍	❍	❍	❍	❍

Are you? *Female, Male*

Marital Status: *Single, Married, Civil Union, Divorced, Separated*

What is your identified ethnicity? *Hispanic or Latino, Not Hispanic or Latino*

What is your identified race (choose all that apply)? *American Indian or Alaska Native, Asian, Black or African American, Native Hawaiian or Other Pacific Islander, White, Other* _______

How would you classify the area you grew up in? *Urban, Suburban, Rural*

Did you grow up in the city you are currently living in? *Yes, No*

Were you born in the city you currently live in? *Yes, No*

How long have you lived in your city?

What is the highest completed level of education? *Some high school, High school diploma, Technical college degree, College degree, Post Graduate Degree*

How many people live in your household?

How many children under the age of 18 live your the household?

How many children under the age of 5 live in your household?

How many cars does your household have?

Is your household...? *Owned by you or someone in this household with a mortgage or loan, Owned by you or someone in this household free and clear (without a mortgage or loan), Rented, Other* ____________________

Is this the first household you have owned? *Yes, No, Not Applicable*

Answer If Is this the first household you have owned? Yes Is Selected
Length of time you have owned this home?

What is your approximate annual income? *No income, Under $19,999, $20,000-$34,999, $35,000-$49,999, $50,000-$74,999, $75,000-99,999, $100,000 and above*

What is the approximate annual household income of the household you consider home? *No income, Under $19,999, $20,000-$34,999, $35,000-$49,999, $50,000-$74,999, $75,000-99,999, $100,000 and above*

Are you responsible for your water utility bill: *Yes, No*

What is your employment status (choose all that apply)? *Employed for wages or salary, Self-Employed, Out of work and looking for work, Out of work but not currently looking for work, A homemaker, A student, Retired, Unable to work*

What is your primary source of news (choose all that apply)? Newspaper, Internet, Television, Radio, Social Media

Frequency of following the news: *At least once per day, At least once per week, At least once per month, Never*

Political Views: *Republican, Democrat, Independent, Other* ___________

Do you have any comments/concerns about the WATER infrastructure system in your city?

Do you have any comments/ concerns about the WASTEWATER infrastructures system in your city?

Appendix G. Descriptive Statistics from Survey

Table G.1. Water and wastewater questions regarding utility providers

	The water system is sustained by bills	The wastewater system is sustained by bills	My water provider is fiscally strained	My wastewater provider is fiscally strained	I trust my water provider to make decisions	I trust my wastewater provider to make decisions
Strongly Disagree	2%	3%	4%	3%	8%	8%
Disagree	7%	9%	14%	11%	13%	14%
Neutral	19%	26%	26%	25%	29%	28%
Agree	28%	22%	21%	21%	31%	31%
Strongly Agree	11%	7%	10%	8%	10%	7%
I do not know	33%	34%	26%	33%	8%	12%
Oppose/ I do not know	42%	45%	43%	47%	29%	34%
Neutral/ Support	58%	55%	57%	53%	71%	66%

Table G2. Responses regarding perceptions of water retooling alternatives

	My water infrastructure is aging and needs to be upgraded	New water infrastructure projects in my city	Increasing investment for maintenance of the existing water infrastructure	Decommissioning components of my city water infrastructure	Razing components of my city water infrastructure
Strongly Oppose	1%	2%	2%	4%	4%
Oppose	7%	2%	7%	17%	18%
Neutral	20%	25%	24%	39%	36%
Support	32%	39%	44%	19%	20%
Strongly Support	27%	20%	10%	5%	6%
I do not know	12%	13%	12%	16%	17%
Oppose/ I do not know	21%	17%	21%	37%	39%
Neutral/ Support	79%	83%	79%	63%	61%

Table G3. Responses regarding perceptions of additional water retooling alternatives

	Repurposing components of my city water infrastructure system	Making improvements to my water infrastructure increases the quality and cost of service	Changes to my water infrastructure to stabilize the cost of my service	Increasing the cost to cover the cost of additional infrastructure or replacement
Strongly Oppose	7%	4%	1%	10%
Oppose	13%	14%	3%	23%
Neutral	30%	29%	19%	30%
Support	28%	30%	43%	23%
Strongly Support	8%	12%	24%	4%
I do not know	14%	10%	10%	9%
Oppose/ I do not know	34%	29%	14%	43%
Neutral/ Support	66%	71%	86%	57%

Table G.4. Responses regarding perceptions of wastewater retooling alternatives

	The wastewater infrastructure in my city is aging and needs to be upgraded	Increasing financial investments for the maintenance of the existing wastewater infrastructure	Decommissioning components of my city wastewater infrastructure	Razing components of my city wastewater infrastructure	Repurposing components of my city wastewater infrastructure	Increasing the cost of my wastewater service to cover the cost of additional infrastructure replacement
Strongly Oppose	2%	4%	5%	6%	4%	12%
Oppose	5%	5%	14%	15%	8%	24%
Neutral	18%	29%	34%	35%	33%	29%
Support	34%	39%	24%	21%	29%	20%
Strongly Support	22%	8%	5%	6%	9%	4%
I do not know	19%	14%	17%	17%	16%	12%
Oppose/ I do not know	26%	23%	37%	38%	29%	48%
Neutral/ Support	74%	77%	63%	62%	71%	52%

Table G.5. Responses regarding attitude towards select water infrastructure retooling alternatives

	Invest in more water infrastructure	Remove or decommission components of the water infrastructure	Repurpose some components of the water infrastructure	Invest in maintaining the current water infrastructure	Do nothing to the current water infrastructure
Agree	27%	8%	20%	44%	24%
Disagree	73%	92%	80%	56%	76%

Appendix H. Agent Based and System Dynamics Modeling Parameters, Variables, and Justifications

Table H.1. System dynamics parameters, variables, and justifications

VARIABLE	VALUE	JUSTIFICATION
Revenues and Rates: Water		
PerDecInWDemand	Welasticity*PerIncFromYr1	Based on the elasticity, this value yields the decrease in water demand.
PerIncFromYr1	(WRate-WRateYr1)/WRateYr1	This variable tracks the percentage increase of the rates throughout the simulation.
PerOfRateRevForProj	Varies	This is the percent of the revenues gained from the increased water rates that is intended for the water infrastructure decommissioning project.
ProjRev *(Flow Variable)*	WDecReturn>=0?0:(Rev-RevYr1)*PerOfRateRevForProj*WInfraBudget	The revenue from the increased rates that is intended for the project transitioned to RevForProj via this flow variable until WDecReturn is $0, indicating the project has been paid off.
QuantIncrease	PerIncFromYr1>WillingToPayW?0:RateIncPerYear*WRateYr1	QuantIncrease increases the rate by the set percentage as long as the rate has not exceeded what the residents indicated they were willing to pay in the survey.
RateIncPerYear	Varies	The commodity rates for water usage increase by a set percentage each year.
RateRev *(Flow Variable)*	Rev-RevYr1-ProjRev	The revenue that is gained by the increased rates, not intended for the decommissioning project is moved via this flow variable to the RateRevNotOnProj.
RateRevNotOnProj *(Stock Variable)*	Initial value = 0	RateRevNotOnProj diverts the revenue from rates that is not for the decommissioning project to this stock variable.
Rev *(Flow Variable)*	TotalDemandPerWeek/1000*WRate	The total revenue for the time step (week) from water usage, transitions to TotRev via this flow variable.
RevForProj *(Stock Variable)*	Initial value = 0	The revenue from the increased rates that is intended for the project is diverted to this variable until WDecReturn is $0, indicating the project has been paid off.
RevYr1 *(Flow Variable)*	WDemandYr1*TotalPop/1000*WRateYr1	This flow variable tracks the amount of revenue that would be made if no rate changes (resulting in water demand changes) occurred to the system, with the only changing variable being population.
TotRev *(Stock Variable)*	Initial value = 0	This stock variable captures the total revenue gained by raising rates and distributes it to RevForProj and RateRevNotOnProj. The revenue difference is accounts for the elasticity in demand and is based on the revenue from year 1 when demand is 150 gpcpd.
Welasticity	uniform(-0.2,-0.5)	The price elasticity of demand is equal to the ratio of the percent change in demand in quantity to the percent change in price. Lipsey and Chrystal (1999) defines the price elasticity of water as ranging from -0.2 to -0.5.

VARIABLE	VALUE	JUSTIFICATION
WillingToPayW	0.10748	The survey questioned what percentage more residents would be willing to pay for water service. The value used is the average of the responses, approximately 10%.
WRate *(Stock Variable)*	Initial value: WRateYr1	The water usage commodity rate for year 1 is set at $2.59/1000 gallons, which is the commodity rate for Saginaw, Michigan.
WRateInc *(Flow Variable)*	QuantIncrease*YrlyRate Trigger	This variable increases the stock variable which tracks the current commodity rate for water usage
WRateYr1	$2.59	The water usage commodity rate for year 1 is set at $2.59/1000 gallons, which is the commodity rate for Saginaw, Michigan.
YrlyRateTrigger	RateIncTable(time()-(Int-1)*52)	YrlyRateTrigger creates the timeframe that the city rates are reevaluated at, which in this instance is annually.
Revenues and Rates: Wastewater		
RateIncPerYearWW	Varies	The commodity rates for wastewater usage increase by a set percentage each year.
WillingToPayWW	0.1002851	The survey questioned what percentage more residents would be willing to pay for wastewater service. The value used is the average of the responses, approximately 10%.
WWPerOfRateRevForProj	Varies	This is the percent from the revenues gained from the increased rates that is intended for the wastewater infrastructure decommissioning project.
WWProjRev *(Flow Variable)*	WWDecReturn>=0?0:(WWRev-WWRevYr1)*WWPerOfRateRevForProj*WWInfraBudget	The revenue from the increased rates that is intended for the project transitioned to WWRevForProj via this flow variable until WWDecReturn is $0, indicating project is paid off.
WWRate *(Stock Variable)*	Initial value: WWRateYr1	The wastewater usage commodity rate for year 1 is set at $4.59/1000 gallons, which is the commodity rate for Saginaw, Michigan.
WWRateInc *(Flow Variable)*	WWQuantIncrease*YrlyRateTrigger	This variable increases the stock variable that tracks the current commodity rate for wastewater usage
WWRateRev *(Flow Variable)*	WWRev-WWRevYr1-WWProjRev	The revenue that is gained by the increased rates, not intended for the decommissioning project is moved via this flow variable to the WWRateRevNotOnProj.
WWRateRevNotOnProj *(Stock Variable)*	Initial value = 0	WWRateRevNotOnProj diverts the revenue from rates that is not for the decommissioning project to this stock variable.
WWRateYr1	$4.59	The wastewater usage commodity rate for year 1 is set at $4.59/1000 gallons, which is the commodity rate for Saginaw, Michigan.
WWRev *(Flow Variable)*	TotalDemandPerWeek/1000*WWRate	The total revenue for the time step (week) from wastewater produced, transitions to WWTotRev via this flow variable. Wastewater quantities are billed based on a 1:1 relationship with water demand.
WWRevForProj *(Stock Variable)*	Initial value = 0	The revenue from the increased rates that is intended for the project is diverted to this variable until WWDecReturn is $0, indicating the project has been paid off.

VARIABLE	VALUE	JUSTIFICATION
WWRevYr1 *(Flow Variable)*	WDemandYr1*TotalPop /1000*WWRateYr1	This flow variable tracks the amount of revenue that would be made if no rate changes (resulting in water demand changes and quantity of wastewater produced) occurred to the system, with the only changing variable being population.
WWTotRev *(Stock Variable)*	Initial value = 0	This stock variable captures the total revenue gained by raising rates and distributes it to WWRevForProj and WWRateRevNotOnProj.
WWPerIncFromYr1	(WWRate-WWRateYr1)/WWRateYr1	This variable tracks the percentage increase of the rates throughout the simulation.
WWQuantIncrease	WWPerIncFromYr1>WillingToPayWW?0:RateIncPerYearWW*WWRateYr1	WWQuantIncrease increases the rate by the set percentage as long as the rate has not exceeded what the residents indicated they were willing to pay in the survey.
Retooling Alternative: Water		
ABMAdoptW *(Stock Variable)*	Generated in ABM model	Generated based on the adoption of the idea. Currently the adoption rate of smart phones is incorporated into the model, as the data for this adoption rate is available. Additionally, the adoption rate may be transferable, as cell phones were an existing infrastructure and smart phones were a new alternatives for that existing infrastructure. Similarly, water infrastructure management practices are an in-place, existing, infrastructure, and retooling alternatives are new alternatives for this existing infrastructure.
CostPerBlockW	$8,245	This variable is the total cost for water infrastructure, per block, based on Saginaw, MI's conceptual study.
ImpWAlt	WPercentAdopt>WSupThresh?1:0	The ImpWAlt variable triggers the model to move the project forward into the infrastructure budget upon receiving enough support from the public.
NumOfBlocksW	Flint: 10 blocks Saginaw: 20 blocks	The total number of blocks decommissioned.
PercentPopWSHs	0.1	The percentage of the city's population that has interest in the neighborhood retooling alternative implementation. This value considers the people in and surrounding the neighborhood(s).
WConst	WInfraBudget>0?delay(WInfraBudget,WTimeToImp):0	The WConst variable changes from 0 to 1 when construction of the project is complete based on the delay (WTimeToImp) from entering the budget (WInfraBidget).
WDecCosts	-1*CostPerBlockW*NumOfBlocksW	This variable calculates the total cost for decommissioning water infrastructure in analysis area.
WDecReturn *(Stock Variable)*	WDecCosts	The stock variable, in this instance, tracks the total cost for decommissioning solely water infrastructure for the area, and subtracts the savings from maintenance throughout the simulation.
WDecSav *(Stock Variable)*	-1*WConst*WklyDecWSavings*NumOfBlocksW	Once water infrastructure decommissioning has occurred (described with the WDecReturn), this variable subtracts the savings in water infrastructure maintenance from the total costs.

VARIABLE	VALUE	JUSTIFICATION
WInfraBudget	ImpWAlt>0?1:0	This changes from 0 to 1 when the project has moved into the water infrastructure budget.
WklyDecWSavings	$94/52 per block per week	Based on Saginaw, MI's conceptual study, this is the estimated savings in maintenance for solely water infrastructure, per block, per week.
WPercentAdopt	ABMAdoptW/(PercentPopWSHs*TotalPop)	This is the percentage of the population that has adopted the new alternative and now is in the neutral/support category.
WSupThresh	0.6	The ratio of population that supports or is neutral towards the infrastructure alternative to the population with interest in this particular project that is needed to move the project forward.
WTimeToImp	52 weeks	This is the time is takes for design and construction to be complete from the time the project enters the budget.
Retooling Alternative: Wastewater		
ABMAdoptWW *(Stock Variable)*	Generated in ABM model	Generated based on the adoption of the idea. Currently the adoption of smart phones is used as the data for this adoption rate is available. Additionally, the adoption rate may be transferable, as cell phones were an existing infrastructure and smart phones were a new alternatives for that existing infrastructure. Similarly, water infrastructure management practices are an in-place, existing, infrastructure, and retooling alternatives are new alternatives for this existing infrastructure.
CostPerSF	$16/9	This variable is the total cost for decommissioning impervious surfaces based on discussions with SMEs in and work with the City of Saginaw.
ImpWWAlt	WWPercentAdopt>WWSupThresh?1:0	The ImpWWAlt variable triggers the model to move the project forward into the infrastructure budget upon receiving enough support from the public.
NumOfBlocksWW	Flint: 20 blocks Saginaw: 35 blocks	The total number of blocks with impervious surfaces decommissioned.
PercentPopWWSHs	0.1	The percentage of the city's population that has interest in the neighborhood retooling alternative implementation. This value considers the people in and surrounding the neighborhood(s).
TotalArea	AnalysisArea*5280*5280*(PercentImpervSQ-PercentImperv)	Estimates the total area that will be decommissioned for the retooling alternative.
WklyDecWWSavings	$375/52 per block per week	This variable subtracts the monetary savings from the total financial investment. Currently savings are in the form of roadway maintenance.
WWConst	WWInfraBudget>0?delay(WWInfraBudget,WWTimeToImp):0	The WConst variable changes from 0 to 1 when construction of the project is complete based on the delay (WWTimeToImp) from entering the budget (WWInfraBidget).
WWDecReturn *(Stock Variable)*	WWDecCosts	This is the total cost for decommissioning impervious surfaces, implementing low impact development options, or incorporating green infrastructure.

VARIABLE	VALUE	JUSTIFICATION
WWDecCosts	-1*TotalArea* CostPerSF	WWDecCosts estimates the total costs for the retooling alternative.
WWDecSav	-1*WWConst* WklyDecWWSavings	Once decommissioning impervious surfaces, implementing low impact development options, or incorporating green infrastructure has occurred (described with the WDecReturn), this variable subtracts the savings from the total costs.
WWInfraBudget	ImpWWAlt>0?1:0	The project moves into the wastewater/stormwater infrastructure budget without delay (i.e., immediately).
WWPercentAdopt	ABMAdoptWW/(PercentPopWWSHs*TotalPop)	This is the percentage of the population that has adopted the new alternative and now is in the neutral/support category.
WWSupThresh	0.6	The ratio of population that supports or is neutral towards the infrastructure alternative to the population with interest in this particular project that is needed to move the project forward.
WWTimeToImp	52 weeks	WWTimeToImp is the time is takes for design and construction to be complete from the time the project enters the budget.
Water Usage		
Decline	DeclineRate*TotalPop	The number of people leaving each time step (week).
DeclineNeigh	DeclineRate*NeighborPop	The change in population within the analysis area based on the historic population trends.
DeclineRate	Flint: 14.6% over ten year | 0.0003104 per week	The percentage of the population leaving each time step (week).
	Saginaw: 12.04% over 10 years | 0.00024671 per week	
NeighborPop	PplePerHome*NumberOfHomes	The population within the analysis area.
NeighDemandPerWeek	NeighborPop*WaterDemand	Water demand in analysis area per week.
NeighPopLeave	DeclineNeigh	The change in population in the analysis area based on the historic population trends.
NeighWater *(Flow Variable)*	NeighDemandPerWeek*(1-RelocationTrigger)	NeighWater adds the total water demand for the analysis area into the NeighWaterDemand stock variable.
NeighWaterDemand *(Stock Variable)*	Initial value: 0	This stock variable tracks the total water demand for the analysis area throughout the simulation time.
NumberOfHome	Flint initial value: 337 homes	Number of occupied home in analysis area based on GIS data from the respective cities.
	Saginaw initial value: 88 homes	
PopLeave *(Flow Variable)*	Decline	The change in population based on the historic population trends.
PplePerHome	Flint: 2.48	The number of people per home based on US Census Data (2011).
	Saginaw: 2.59	

VARIABLE	VALUE	JUSTIFICATION
Relocation	Flint: 0 Saginaw: 1	Zero (0), if the population is consolidated within the analysis region, i.e., does not leave the neighborhood; 1, if the population is relocated out of the analysis area, i.e., leaves the neighborhood.
RelocationTrigger	WConst+Relocation>1? 1:0	If residents are relocated from the neighborhood, this variable reduces the analysis area's water demand to zero.
TotalDemandPer Week	TotalPop*WaterDemand	The total city water demand per week.
TotalPop *(Stock Variable)*	Flint initial value: 102, 434 people Saginaw initial value: 51, 508 people	This stock variable tracks the total population throughout the simulation.
TotalWaterDeman d *(Stock Variable)*	Initial value: 0	This stock variable tracks the total water demand for the city throughout the simulation time.
TotWater *(Flow Variable)*	TotalDemandPerWeek	Adds the total city water demand into the TotalWaterDemand stock variable.
WaterDemand	150*7*(1+PerDecInWD emand)	The total demand is estimated by multiplying the per capita daily water demand (Grigg 2012) by seven days. The demand is further decreased based on the price elasticity and the current commodity rate.
WConst	WInfraBudget>0?delay(WInfraBudget,WTimeT oImp):0	This variable triggers when construction of the project is complete based on the delay (WTimeToImp) from entering the budget (WInfraBudget).
Wastewater/Stormwater Produced		
AltGalToL	GalToL*CubicFtToGal	Converts the gallons of runoff generated under the retooling alternative simulated to liters.
Analysis Area	Flint: 0.14 square miles Saginaw: 0.16 square miles	The analysis area in square miles.
CitySWProduced	Flint: N/A Saginaw: 7.5 MGD* 7 days	The total stormwater generated in the city. This variable is only applicable for Saginaw model, as discussions with SMEs in Flint indicate that the separate stormwater system is not metered.
CSOTrigger	Flint: 1 Saginaw: 0	This triggers whether the system operates as a CSS or a separate sewer system. Zero (0) indicates that the system is a CSS, and 1indicates that the system has separate wastewater and stormwater systems.
CubicFtToGal	((SoilTrigger*RunoffBC Soil+(1-SoilTrigger) *RunoffDSoil)/12)*(Ana lysisArea*27878400)*(7 .48052)	This variable converts cubic feet of runoff for the retooling alternative to gallons.
CubicFtToGalSQ	((SoilTrigger* RunoffBCSoilSQ+ (1- SoilTrigger) *RunoffDSQ)/12)* (AnalysisArea *27878400)* (7.48052)	This variable converts cubic feet of runoff for the status quo scenario to gallons.

VARIABLE	VALUE	JUSTIFICATION
DissolvedPhos *(Stock Variable)*	0	The stock variable that determines the total dissolved phosphorous entering the wastewater/stormwater system under the retooling alternative.
DP *(Flow Variable)*	0.00048*AltGalToL	The total dissolved phosphorous (in grams) entering the wastewater/stormwater system under the retooling alternative, to be tracked in the respective stock variable (DissolvedPhos). Baird and Jennings' (1996) event mean concentrations are used for residential land.
HeavyMetals *(Stock Variable)*	0	The stock variable that determines the total heavy metals entering the wastewater/stormwater system under the retooling alternative.
HM *(Flow Variable)*	0.00011685*AltGalToL	The total heavy metals (in grams) entering the wastewater/stormwater system under the status quo scenario, to be tracked in the respective stock variable (HeavyMetals). Baird and Jennings' (1996) event mean concentrations are used for residential land.
N *(Flow Variable)*	0.00182*AltGalToL	The total nitrogen (in grams) entering the wastewater/stormwater system under the retooling alternative, to be tracked in the respective stock variable (Nitro). Baird and Jennings' (1996) event mean concentrations are used for residential land.
NeighSW *(Flow Variable)*	(1-CSOTrigger)* (WWConst*CubicFtToGal+(1-WWConst)* CubicFtToGalSQ)	The total stormwater generated in the analysis area, that is transported via the combined sewer overflow system (if CSO present) enters the stock variable tracking total wastewater produced (NeighWWProduced) via this variable.
NeighSWProduced *(Stock Variable)*	0	The total stormwater generated in the analysis area that is transported via separate stormwater is tracked via this stock variable.
NeighWW *(Flow Variable)*	NeighWaterDemand*WWLoss	The wastewater produced from water demand throughout the analysis area enters the stock variable tracking wastewater produced in the analysis area via this flow.
NeighWWLoss *(Stock Variable)*	0	This stock variable tracks the total water that is 'loss' and does not enter the wastewater system in the analysis area throughout the simulation time.
NeighWWProduced *(Stock Variable)*	0	This stock variable tracks the total wastewater produced in the analysis area.
Nitro *(Stock Variable)*	0	The stock variable that determines the total nitrogen entering the wastewater/stormwater system under the retooling alternative.
NLossWWFlow *(Flow Variable)*	NeighWaterDemand*WWLoss	Water from the analysis area that does not enter the wastewater system for reasons, such as infiltration and inflow (Grigg 2012), enters the stock variable via this flow variable.
P *(Flow Variable)*	0.00057*AltGalToL	The total phosphorous (in grams) entering the wastewater/stormwater system under the retooling alternative, to be tracked in the respective stock variable (Phos). Baird and Jennings' (1996) event mean concentrations are used for residential land.

VARIABLE	VALUE	JUSTIFICATION
PercentImperv	Varies	This is the percentage of impervious surfaces post decommissioning.
PercentImpervSQ	Flint: 65%	The status quo percentage of impervious surfaces
	Saginaw: 38%	
Phos *(Stock Variable)*	0	The stock variable that determines the total phosphorous entering the wastewater/stormwater system under the retooling alternative.
Rainfall	Area specific NCDC data	Rainfall is determined using National Climate Center Data data. Weekly averages based on historic data are used in the simulations.
RainfallWk	Rainfall(time()-(Int-1)*52)	Determines the rainfall, based on historic rainfall patterns from the city, using local weather station data, each week.
RunoffBCSoil	Flint: (0.949*PercentImperv+0.0544)*RainfallWk	The runoff generated for B/C soils, based on the retooling alternative. Equation generated using SWMM simulation results (Chapter 6) and Minitab.
	Saginaw: (0.9714*PercentImperv+0.0338)*RainfallWk	
RunoffBCSoilSQ	Flint: (0.949*PercentImpervSQ+0.0544)*RainfallWk	The runoff generated for B/C soils, based on the status quo. Equation generated using SWMM simulation results (Chapter 6) and Minitab.
	Saginaw: (0.9714*PercentImpervSQ+0.0338)*RainfallWk	
RunoffD	Flint: (0.834*PercentImperv+0.165)*RainfallWk	The runoff generated for D soils, based on the retooling alternative. Equation generated using SWMM simulation results (Chapter 6) and Minitab.
	Saginaw: (0.8725*PercentImperv+0.1168)*RainfallWk	
RunoffDSQ	Flint: (0.834*PercentImpervSQ+0.165)*RainfallWk	The runoff generated for D soils, based on the status quo. Equation generated using SWMM simulation results (Chapter 6) and Minitab.
	Saginaw: (0.8725*PercentImpervSQ+0.1168)*RainfallWk	
Soil Trigger	Varies	Indicates whether B(C) soils or D soils are being simulated. Zero (0) is used for D soils, and 1 indicates B(C) soils.
SQDissolvedPhos *(Stock Variable)*	0	The stock variable that determines the total dissolved phosphorous entering the wastewater/stormwater system under the status quo scenario.
SQDP *(Flow Variable)*	0.00048*SQGalToL	The total dissolved phosphorous (in grams) entering the wastewater/stormwater system under the status quo scenario, to be tracked in the respective stock variable (SQDissolvedPhos). Baird and Jennings' (1996) event mean concentrations are used for residential land.
SQGalToL	GalToL*CubicFtToGalSQ	Converts the gallons of runoff generated under status quo conditions to liters.

VARIABLE	**VALUE**	**JUSTIFICATION**
SQHeavyMetals *(Stock Variable)*	0	The stock variable that determines the total heavy metals entering the wastewater/stormwater system under the status quo scenario.
SQHM *(Flow Variable)*	0.00011685*SQGalToL	The total heavy metals (in grams) entering the wastewater/stormwater system under the status quo scenario, to be tracked in the respective stock variable (SQHeavyMetals). Baird and Jennings' (1996) event mean concentrations are used for residential land.
SQN *(Flow Variable)*	0.00182*SQGalToL	The total nitrogen (in grams) entering the wastewater/stormwater system under the status quo scenario, to be tracked in the respective stock variable (SQNitrogen). Baird and Jennings' (1996) event mean concentrations are used for residential land.
SQNitrogen *(Stock Variable)*	0	The stock variable that determines the total nitrogen entering the wastewater/stormwater system under the status quo scenario.
SQP *(Flow Variable)*	0.00057*SQGalToL	The total phosphorous (in grams) entering the wastewater/stormwater system under the status quo scenario, to be tracked in the respective stock variable (SQPhos). Baird and Jennings' (1996) event mean concentrations are used for residential land.
SQPhos *(Stock Variable)*	0	The stock variable that determines the total phosphorous entering the wastewater/stormwater system under the status quo scenario.
SQSS *(Flow Variable)*	0.041*SQGalToL	The total suspended solids (in grams) entering the wastewater/stormwater system the status quo scenario, to be tracked in the respective stock variable (SQTSS). Baird and Jennings' (1996) event mean concentrations are used for residential land.
SQTSS *(Stock Variable)*	0	The stock variable that determines the total suspended solids entering the wastewater/stormwater system under the status quo scenario.
SS *(Flow Variable)*	0.041*AltGalToL	The total suspended solids (in grams) entering the wastewater/stormwater system under the retooling alternative, to be tracked in the respective stock variable (TSS). Baird and Jennings' (1996) event mean concentrations are used for residential land.
SWSeparate *(Flow Variable)*	(CSOTrigger)*(WWConst*CubicFtToGal+(1-WWConst)*CubicFtToGalSQ)	The total stormwater generated in the analysis area, that is transported via separate stormwater system enters the stock variable tracking total stormwater produced (NeighSWProduced) via this variable.
SWSQFlow	CubicFtToGalSQ	The total stormwater generated in the analysis area, given status quo conditions, to compare against the impact of retooling alternatives enter the stock variable (SWStatusQuo) via this flow variable.
SWStatusQuo *(StockVariable)*	0	The total stormwater generated in the analysis area, given status quo conditions, to compare against the impact of retooling alternatives is tracked via this stock variable.

VARIABLE	VALUE	JUSTIFICATION
TLossWWFlow *(Flow Variable)*	TotalWaterDemand*WWLoss	Water from the city that does not enter the wastewater system for reasons, such as infiltration and inflow (Grigg 2012), enters the stock variable via this flow variable.
TotalWW *(Flow Variable)*	0	The wastewater produced from water demand throughout the cities enters the stock variable via this flow.
TotalWWProduced *(Stock Variable)*	0	This stock variable tracks the total wastewater produced throughout the city during the simulation time.
TSS *(Stock Variable)*	0	The stock variable that determines the total suspended solids entering the wastewater/ stormwater system under the retooling alternative.
TSWFlow	CitySWProduced	The total stormwater generated in the city enters the stock variable tracking total wastewater produced. This variable is only applicable for Saginaw model as discussion with SMEs in Flint indicate that the separate stormwater system is not metered.
TWWLoss *(Stock Variable)*	0	This stock variable tracks the total water that is 'loss' and does not enter the wastewater system throughout the city during the simulation time.
WaterToWW	0.85	The percentage of water that enters wastewater system. Grigg (2012) states that the percentages range from 60% to 85% in dry to humid regions, respectively. Due to the Midwest being a humid region, and to estimate wastewater quantities liberally, 0.85 is used in the model.
WWConst	WWInfraBudget>0?delay(WWInfraBudget,WWTimeToImp):0	This variable triggers when construction of the project is complete based on the delay (WWTimeToImp) from entering the budget (WWInfraBidget).
WWLoss	1-WaterToWW	The percentage of water that does not enter wastewater system.

Table F2. Agent states in the agent based model

States	Water Transition	Wastewater Transition
State → InitialPop	Full population of agents transition to the InitialPop	
InitialPop → Branch	Initial population transitions to the support and oppose state based on the survey data. Each agent is assigned a value based on the probability distribution plot of the respective opposition/support for the alternative. For decommissioning water infrastructure, the agents are assigned a value from a weibull(3.63226, 3.36921) distribution. For decommissioning wastewater infrastructure, the agents are assigned a value from a weibull(3.62009, 3.44894) distribution. If the agent's value is greater than 4 (representing support/ strongly support from the survey data), the agent moves into the support state, elsewise, the agent transitions into the opposition state.	
Oppose → LikeToAdopt	0.5257*exponential(0.3917)/52 Transitioning based on an adoption rate. The adoption rate indicates that the agent has "adopted" the idea.	
LikeToAdopt → Adopt	Transitions immediately to Adopt based on the above described adoption rate.	
Adopt → Branch		
Branch → Oppose	uniform(0.0005,0.001) A percentage of individuals shift back to the Oppose state from Adopt.	
Branch → LeftTown	Population leave the Adopt state based on the decline trends of the city.	
Branch → BackToAdopt	A majority of the individuals remain in the Adopt state once transitioned to the state.	
Oppose → LeftTown	Population leave the Adopt state based on the decline trends of the city.	

VITA

VITA

Kasey M. Faust was born in Anchorage, Alaska in 1986. After receiving her Bachelor's in Civil and Environmental Engineering from the University of Washington in 2009, she attended Purdue University for her graduate studies. While at Purdue University she received her Master's in Civil Engineering in 2010, focusing her Master's research on decision making for capital-intensive water infrastructure decision. She then received a Master's in Industrial Engineering in 2013. During her doctoral studies, she evaluated the impact of urban decline on water sector infrastructure and analyzed water sector infrastructure interdependencies. Additionally, she evaluated infrastructure retooling alternatives for addressing challenges due to underutilization and fiscal constraints in cities facing urban decline, and explored public perceptions towards infrastructure issues and alternatives in shrinking cities.