Three Essays on Water Economics

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Introduction

This dissertation focuses on the issue of water infrastructure renewal in potable water distribution networks. This subject is related to the literature of water supply economics. Sound management of water supply is essential for our society because water is unlike any other good; it is vital to human survival. The particularity of water is that water demand always exists in various forms such as drinking water, gardening water, in recreational forms, industrial use, and of course in agricultural use. We focus particularly on urban water supply; which is supplied by local water utilities. Tap water is treated first at treatment plants for potabilization and then transported through a complex network of water mains that are hidden under our feet, as illustrated in Figure 1[1]. Water utilities are faced with an obligation to always satisfy the volume demanded by households. There are no substitutes for water; thus, price elasticity of demand is very low. In the event of droughts or rare climate problems, water utilities must find ways to guarantee supply. This is why it is essential to focus on supply side economics of water. Despite the essentialness of water supply in our daily lives, the infrastructure that guarantees this supply has been neglected until recently. The consequence we face today is the pressing need for water mains renewal. In most of the developed countries, the installation of water mains had begun around the beginning of the 20th century. The particularity of water mains is that they are long-lived. The average expected lifetime of water mains could range from 50 years to 100 years or even more. The oldest mains are commonly found in large cities; whereas fairly young mains can be found in

[1] This figure is found on the EPA website: https://www.epa.gov/dwsixyearreview/drinking-water-distribution-systems

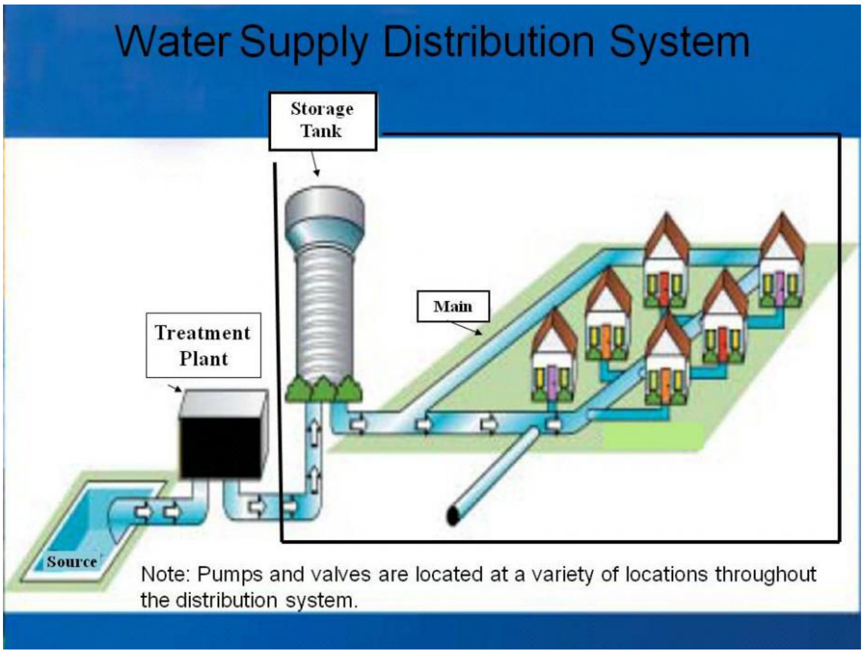

Figure 1: Illustration of a typical water distribution network provided on the website of EPA

rural areas. According to a recent report by AWWA (2012), water utilities in the U.S. are confronted with a daunting era of water mains replacement. Many networks face severe cases in which mains are already obsolete and on the verge of breaking. The main reason stems from the fact that replacement of mains have been lagging behind significantly in the United States and France alike[2]. Before we talk about the reasons behind the failing water infrastructure, we present a few facts and figures concerning the current condition of the water mains in France and the United States.

Figures 2, 3 and 4 reflect the current state of the water main networks in France and the north Americas. Figures 2 and 4 show that about half of the mains are composed of cast iron and PVC (Ductile iron is also prevalent in the U.S.) materials. According to Folkman (2012), cast iron mains have the highest failure rates, while PVC have the lowest. Although the lifetime of some pipes can be expected to last to up to 100 years at installation, due to the corrosivity, these expected lifetimes can vary. Even PVC pipes

[2]We focus on these two examples in particular, since we use data from these two countries for calibration purposes in this dissertation.

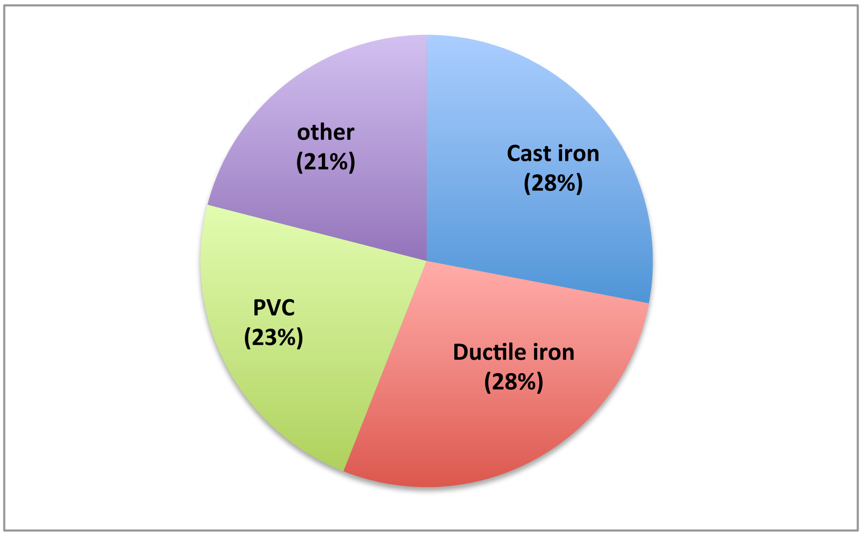

Figure 2: The composition of main materials in the U.S. and Canada.

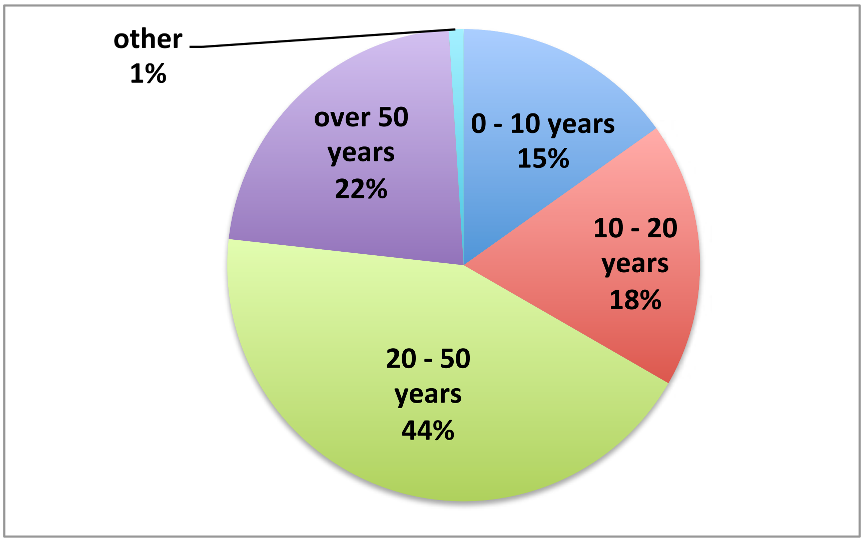

Figure 3: Age of mains as the percentage of the total network in the U.S. and Canada.

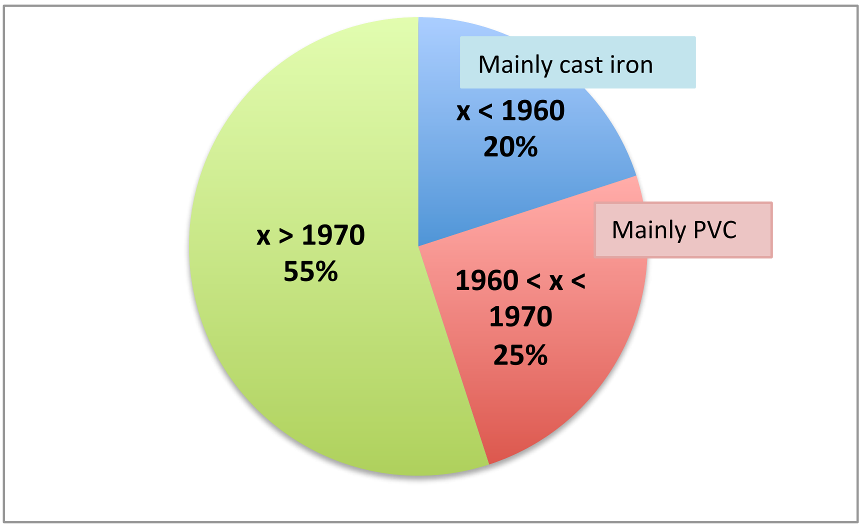

Figure 4: Average age of pipes in France.

that are known for its durability could range from 50 to 100 years (AWWA, 2012). Therefore, as we can see in Figure 3, almost a quarter of the total length of mains in the north Americas must be taken under consideration for imminent renewal. Moreover, about 45% are aged between 20 to 50 years, which means that there are candidates for renewal in the very near future. Similarly in France, about 20% are aged beyond 50 years and another 25% that are nearing 50 years. Overall, in both parts of the world, utilities face water main renewal needs. In both countries, annual replacement rates should be double of what it is currently observed today. For instance, in the U.S. the annual replacement rate is about 0.5%, which means that mains are expected to last for about 200 years (Morrison et al., 2013). Similarly in France, the rates are about 0.6% on average; which is half of the necessary amount. Given these information, we naturally ask ourselves why network renewal is behind schedule and what are the consequences of postponing renewal?

Before answering why network renewal is behind schedule, we first investigate the consequences of postponing water mains replacement. One of the main consequences of obsolete water mains is water leakage. Water lost through the form of leakage wastes the resources put into the production of potable water, such as energy and chemicals used for treatment purposes (Martins et al., 2012; AWWA, 2012; Xu et al., 2014). Leakage also allows pollutants to compromise the quality of the water (Colombo and Karney, 2002). Moreover, water loss is foregone potential revenue for the water utilities. Severe cases of obsolescence could lead to main breaks, which involves serious repercussions on the community. It results in traffic interruptions, flooding and temporary supply interruptions (Garcia and Thomas, 2003). Despite these risks, why is network renewal behind schedule?

There are several reasons that could explain this phenomenon. They are both economic and socio-political factors. For instance most leakages in water mains are "invisible" to the naked eye. Of course, once it is visible it is often due to main breaks, which is the worst case scenario where these mains must immediately be replaced. Leaky pipes could be replaced before it is too late. Thanks to metering devices, utilities can measure the volume of water that is lost between the treatment plants and the service connections. In developed countries the majority of water loss is composed of leakage. However, water loss can easily be neglected by utilities due to the very small value attached to water. Since the unit cost of water production is very small, water loss could be compensated by pumping more water into the system or by raising water pumping pressure. In comparison, imagine an oil pipeline that is leaking, the authorities in charge of oil supply may not easily neglect such leakage. Hence, the fact that losses are invisible and that the costs are cheap partly explain the motivation behind network renewal. We now present further economic factors that influence the decision for water mains replacement.

According to a technical report based on French utilities by Canneva et al. (2012), one determining factor of mains replacement can be explained by the degrees of *economies of scale*. If utilities operate with economies of scale, heavy investment costs can be better dealt with. This is because costs can be divided over a large volume of output. They observe that in a rural utility, the burden of the water infrastructure cost per inhabitant is greater compared to an urban utility; which can explain why costly investments tend to be put aside. They also mention seasonal factors that differentiate the challenges faced by urban water supply to rural water supply. For instance, water consumption could vary significantly for one season to another due to touristic reasons and families with second houses. This means that networks need to be adapted to the potential capacity, which adds to the cost burden. Indeed financial feasibility is one of the main reasons behind water mains replacement decisions. As Mizutani and Urakami (2001) writes, in a network industry where it is heavily capital intensive, the relative size of output to the network length is important to consider. A smaller length of network and higher output leads to cost advantages. Due to this difference in the relative size, they have seen ten-fold differences in the price of water charged to users.

There is a vast literature on the study of economies of scale in water industries. The main contributions are summarized in the paper by Saal et al. (2013). According to their results, most studies found that long-run economies of scale prevail for average sized utilities. However, the discrepancies arise in rural and large urban utilities. For example, Sauer (2005) shows that a large proportion of rural utilities operate with economies of scale and that these utilities could reduce their average costs by increasing output. On the other hand, studies showed that the degrees of economies of scale tend to decrease as the size of operation increases; especially for excessive volumes of output which could be observed in the largest utilities (large urban cities). These results are contradictory to what has been mentioned in the report by Canneva et al. (2012). The analysis on the degrees of economies of scale in water industries is not that straightforward. Indeed, the greater the output (volume of water supplied), the smaller the average cost per output; however, exceeding a certain threshold of output could backfire on the utility in terms of rising total water production costs. One of the main characteristics of water distribution industries is that water demand has to be satisfied; hence, an excessive amount of demand may lead to increasing costs due to higher costs of water production which include importing water from other utilities, expanding storage and treatment plant capacity and replacing mains with larger ones.

Therefore on the one hand, small rural utilities could benefit from expansion of output to cover their infrastructure costs; however, on the other hand, very large cities face output limits that can create diseconomies of scale. Merging of small utilities have been suggested as a remedy to benefit from economies of scale in the paper by Mizutani and Urakami (2001); however, Martins et al. (2006) writes that merging utilities should be decided with care in order to make sure not to become too large which would trigger diseconomies of scale.

Another difficulty faced by utilities in terms of water mains replacement decision concerns *cost recovery*. In order for water utilities to assure sustainable management of water services, "correct" pricing is essential. In Europe, there are guidelines that have been defined concerning water pricing. It is known as the principle of cost recovery which is specified in Article 9 of the European Water Framework Directive of the year 2000. It emphasizes the concept of reflecting the total cost of water services on the price paid by users, including the environmental and resource costs associated with water extraction (Dige, 2013; Kanakoudis et al., 2011). However implementing full cost recovery can be challenging. This is because water pricing is a sensitive topic.

Water in society is perceived as a public good, a free-access good and a human right. Therefore, debates on raising water prices are highly unpopular. As Hanemann et al. (2006) states, "it is notoriously difficult for publicly owned urban water utilities to obtain political approval for even trivial rate increases while other household utilities such as cable television raise their rates with impunity". Moreover, in the U.S., most water agencies set prices to cover the past investment costs associated with water networks, whereas future replacement costs are not included. Again, this is due partly to the fact that the majority of water services in the U.S. are publicly owned; hence, "there is a strong ethos to avoid making profit on the sale of water". There is indeed a large difference between the prices observed in France compared to the U.S., which is presented in the first chapter of this dissertation. However, like oil, metal and wood, water is a natural resource that is defined as an economic good. It has officially been recognized as an economic good at the 1992 International Conference on Water and the Environement in Dublin (Hanemann et al., 2006). Bottled water that are sold in supermarkets can be easily associated to a private economic good; however, the water we use to shower at home, extinguish fires and provide fountains in schools can be easily forgotten that there is any economic value attached to it. Looking at the time of the Roman Empire, water was seen as essential to the existence of their civilization. We can see today in parts of Europe the remains of their highly skilful water conveyance systems, known as Aqueducts. Investment in water infrastructure was the key to their sustainability.

There have been solutions suggested to overcome this sensitive subject. Qureshi and Shah (2014) explains that "effectively communicating an infrastructure's improvement needs is vital to obtain approval for investment funding via rate increases". If the public were exposed to better awareness of the consequences of obsolete water infrastructure, price increases induced by cost recovery may not appear as a taboo.

In addition to the difficulty of society's acceptance towards price hikes, utilities themselves are reluctant to raise prices due to the potential negative impact on revenues. There is a large literature that is based on estimations of price elasticities. According to Olmstead et al. (2006), there exists a perception that consumers do not respond to water price signals. However, based on US residential demand data, they find an elasticity of -0.33. Due to the presence of somewhat elastic behavior, regions that have a dry climate install certain pricing structures such as the Increasing Block pricing method where marginal prices increases with quantity consumed. This type of pricing helps control demand at times of scarcity. However, due to price caps and profit restrictions, efficient pricing is challenging for utilities. Meta analysis results reveal a large range of elasticity values (Espey et al., 1997; Arbués et al., 2003; Yoo et al., 2014). According to the literature, the value of elasticity varies significantly from one study to another primarily due to difference in the choice of explanatory variables, estimation techniques. As we can see, even though price elasticity of demand for water is small and sometimes close to zero, in some cases high prices could result in significant reduction of water demand. Utilities are already facing a fall in domestic demand today, mainly due to the rise in water-efficient home appliances (Barraqué et al., 2011); hence, rate increases are unpopular. Because water pricing is not a straightforward issue; there exists a vast literature based solely on the structure of water pricing. It is said that the usual marginal cost pricing method for assuring efficient allocation is not compatible with natural monopoly firms operating with economies of scale; which is the main characteristic of water utilities. This is why the literature on pricing structures is quite dense. The main pricing structures common today are based on second-best solutions such as increasing and decreasing block tariffs, two part tariffs and Ramsey pricing. These methods are welfare improving and also allow utilities to recover costs (Saal et al., 2013). Throughout this dissertation we study the importance of cost recovery of water mains replacement.

As we mentioned in the beginning, political factors could play a key role in influencing prices because opinion of voters on prices has influence on electoral votes (Chong et al., 2015; Pérard, 2009). This means that the organizational structure of water utilities have a role in the decision making process of water utilities concerning network renewal. There exists a large literature that debates over the preference of public over private ownership and vice versa of water utilities. Overall, the results are conflicting. While privatization has proven beneficial on the grounds of better technical knowledge and efficiency, the actual results on "efficiency" are quite conflicting (Pérard, 2009; Dore et al., 2004; Cavaliere et al., 2015). First of all the notion of privatization in the water sector is not homogeneous. For instance the operation of French utilities differs in general from the European norm where ownership of water infrastructure belongs to the state. In comparison, in the U.K., when privatization occured, even the infrastructure fell under private ownership. As Dore et al. (2004) writes, based on the textbook theory of economics, the traditional concept of privatization which is based on increased efficiency and benefits for consumers via a reduction in prices is not exactly what we observe in the water industry and many industries alike (electricity, telephone line and railway companies) that experience zero to very small competition, which is a typical characteristic of natural monopolies. According to their study, the U.K. privatization of water industry showed that the improvement in water quality is probably one of the strongest benefits of privatization; however, they also argue that this is also probably because of the simultaneous installation of regulatory authorities that oversaw water quality. Similar results concerning better water quality under outsourced provision is revealed in the paper by Chong et al. (2015). However, along with their previous article on private participation, they reveal that better performance is associated with higher water prices (Chong et al., 2006). Furthermore Dore et al. (2004) also states that in the French case, while one reason of rapid price increases due to privatization during 1994-1999 could be explained by large capital spending program for updating infrastructure; another reason could be explained by corruption through the presence of cross-subsidies, political arrangements and special privileges. Moreover, until recently, subsidies were extremely common in French water utilities even after a wave of privatization of water provision. At the time their paper had been written, two thirds of the capital expenditures were still funded by subsidies. However as Renaud et al. (2012) writes, now that subsidies are not allowed, cost recovery is enforced through higher prices. This is also why in general, the rise in water prices have been quite significant in the past years. According to Dore et al. (2004), the main failure of public sectors was the failure to enforce cost recovery principles that would have allowed sound budget planning for gradual network renewal investments.

According to the literature we presented, we can draw a few hypotheses concerning network renewal. (1) Water mains replacement should be less burdensome in terms of cost for water utilities that operate with economies of scale. (2) In Europe where cost recovery principles are enforced, water utilities may raise prices in association with network renewal. However, we have seen that price rises are extremely unpopular; hence, this may act negatively towards decisions on network renewal. (3) Furthermore, the literature shows that prices and decisions on network renewal could vary depending on the organizational structure. Private utilities may be more active in network renewal accompanied by setting higher prices; whereas public utilities may maintain lower prices which would slow down costly investments such as network renewal. Given these conflicting forces that could potentially influence positively or negatively water mains renewal, we evaluate in this dissertation the level of network quality that could either be cost-minimizing or profit-maximizing for the water utilities. Network quality is defined as the proportion of renewed mains to the total length of mains. We develop theoretical models based on cost minimization and profit maximization in the first and second chapter. In the third chapter we conduct an empirical study on the water mains replacement rates observed in France in 2013. Most of our analysis is based on French water utilities as access to up-to-date open-source data on all the utilities were available for France.

Introduction to the chapters of the dissertation

In the first chapter, I develop a cost minimization model and a profit maximization model to study the optimal water main network quality. In the second chapter I develop a profit maximizing switching time model to study the optimal "timing" of replacement of water mains that are already obsolete. And finally, in the third chapter I conduct an empirical analysis on the water mains replacement rates in France to study the impact of water service operator type.

First Chapter: *Optimal water main quality index*

The first chapter is divided into two parts. In the first part, we develop a cost minimization problem and in the second part we develop a profit maximization problem. Both models solve for the optimal water main network quality index. This quality index is defined as the ratio of good quality mains to bad quality mains in a given water main network. We consider mains that are older than 50 years as bad quality mains. A 100% quality index would imply that the water main network should consist only of good quality mains; in other words, only of mains younger than 50 years. This level of quality index is associated with the minimum level of water loss. We use utility-level data from France and the U.S. in our simulations in order to take into account different characteristics of water utilities and how they impact the resulting water network quality. The results could shed light on the reason why in some utilities we may observe high water loss accompanied with low water mains replacement rates (which was the initial motivation of this dissertation). The main results of our model show that several factors play a key role in determining the quality index. The index is extremely sensitive to the cost of water production, which means that utilities that depend on costly sources of water, such as imported water or surface water that requires a high degree of treatment must maintain a high water man quality index in order not to waste it away through leakage. The difference between a rural utility and an urban utility also has significant impact on the quality index. In a large urban utility, we often observe economies of network density, which is the characteristic of large demand size relative to the total length of the network. This implies that the trade off between the cost of water loss and the cost of good quality mains is significantly higher in large urban utilities than in rural utilities. Hence, in most cases the results show that the cost efficient quality index is very small (often 0%) in rural utilities compared to urban utilities (often 100%).

In this chapter, we further investigate the issue of cost recovery. In Europe, the cost recovery principle is enforced in the water industry. In other words, costs associated to the water distribution service should be reflected in the price paid by users. This means that network renewal costs should be included in the price as well. However, this also implies that prices would inevitable increase. If demand is assumed to be perfectly inelastic, cost recovery would not have any influence on demand; however, if demand is somewhat responsive to prices, the resulting optimal network quality index is affected. Results show that under pure cost efficiency measures, cost recovery has almost no impact; whereas under profit maximization objectives, cost recovery does have a large impact. This difference is due to the fact that cost recovery under cost minimization only impacts demand, which in turn has an impact on the total water production. Overall, the effect of cost recovery is absorbed by the minor difference it creates in the total volume of water loss. However, under profit maximization, cost recovery has a direct effect on revenue; which consequently raises the optimal quality index significantly in comparison to the cost efficient quality index. However, results differ again between rural and urban utilities. Where price caps are low (particularly in public utilities), quality indices cannot reach 100% since prices exceed the price caps. Hence, overall, results show that rural utilities face the largest challenge in meeting high network quality while recovering costs. In other words water loss regulations and cost recovery principle may not be compatible in certain rural utilities due to the lack of economies of network density and price caps.

In the last part of this chapter, we investigate the impact of leakage detection activities on the optimal network quality index. We show that utilities that engage in leakage detection activities can raise the "efficiency" of their network quality. This means that if the worst' mains are correctly identified, water loss reduction could be achieved with a smaller quality index. This is particularly beneficial for large urban water utilities where roadworks and service interruptions due to network renewal could be highly disruptive to the community compared to a small rural utility.

Second Chapter: *Optimal switching time for water main replacement*

The model developed in the second chapter is very different to the ones in Chapter 1. The purpose of this chapter is to evaluate the optimal timing for utilities to replace their "obsolete" mains. We suppose that there is a certain section of mains that have reached obsolescence (characterized by the rate of water loss) and that the utility must decide when to replace them. They have an option to rehabilitate mains before replacing them. The benefit of rehabilitation is that it costs much less than replacement and it extends the longevity of the current mains. The results we obtain show that rehabilitation is generally not "economical" in urban utilities where mains have already reached obsolescence. This is primarily due to similar reasoning as in Chapter 1 concerning the trade off between the cost of water loss and the cost of replacement. Since water loss reduction is a high priority in very large urban utilities (in terms of cost efficiency), rehabilitation which only temporarily reduces leakage is not worth the cost of rehabilitation. On the other hand, in rural utilities, rehabilitation could be beneficial in terms of extending the longevity of the current mains; however, it is not the case for mains that are highly corrosive (those that degrade fast). On the other hand, once cost recovery is implemented; it is beneficial for both types of utilities to replace immediately. And finally, our results show that rehabilitation could be beneficial (in terms of extending the longevity) if water losses are smaller; in other words, if they are done before the mains have reached obsolescence.

Third Chapter: ***Water mains replacement and the role of outsourced water provision: A case study of French water utilities***

In the third chapter I study the factors that influence the rate of replacement of water mains in French utilities. The main focus of this chapter is to study the impact of in-house provision or outsource provision on the rate of replacement. We have seen in Chapters 1 and 2 that utility-specific characteristics could have a large impact on the quality of the water main network. However, in practice many qualitative factors such as the type of service provider (public, private, PPP) could have an impact on the performance of the utilities, as mentioned in the literature in the Introduction. The regression models used in this chapter are the Tobit-type 2 (Heckit) and the Two-Part model in order to deal with endogeneity in the water loss variable. We also test selection bias that might be caused by self-selection of water utilities into either in-house or outsource depending on the expectation of the need for network renewal. However, results show that there is no selection bias. The estimation results show that contrary to the theoretical results in chapter 1 that showed small network quality for rural utilities, the regression results show that replacement rates are negatively related to total network length. We also observe a predominance of high replacement rates in small rural utilities. This discrepancy could be explained by the fact that for very small network lengths (smaller then 10 km), even for a short length of network that is replaced, the resulting proportion of replaced to total network length is naturally large. Moreover, in practice, water mains are often replaced alongside other roadworks in rural utilities. And thirdly, our regression results also reveal that replacement rates are indeed larger on average in very large urban utilities (greater than 10,000 inhabitants per commune); hence, it is consistent with the results obtained in Chapter 1.

The main conclusion that we draw from the results is that the replacement of mains are on average higher under in-house provision. However, results also show that outsourced utilities with a contract that have been signed recently exhibit higher replacement rates; perhaps in response to the current need for replacement. Nevertheless, on average, in-house provision is associated with higher replacement rates. This could be due to the fact that outsourced utilities may have objectives assigned by the local authority that differ from network renewal such as water quality improvement. Moreover, in rural utilities, water losses are smaller in outsourced utilities, which justifies smaller replacement rates. Results also show that water loss, tariff, knowledge and intercommunality have a positive and significant effect on replacement rates. The fact that intercommuanlity has a positive effect implies that merging small communes could be beneficial in achieving better network quality. However, as we have seen in Chapter 1, merging utilities does not guarantee scale economies. It is important to compare the relative size of the network to the volume of demand.

Chapter 1

Optimal water main quality index

1.1 Introduction

Water loss is a major issue that concerns all nations around the world. In developed countries, water leakage from water mains is the main source of water loss. In the U.S. "for decades, these systems - some built around the time of the Civil War - have been ignored by politicians and residents accustomed to paying almost nothing for water delivery"[1]. Such a scenario is not exclusive to the U.S.; the presence of leakage from water mains is a concern in Europe as well. The underlining reason why leakage is oftentimes neglected is because they are mostly "invisible" and is associated with very small monetary value. Moreover leakage reduction activities are very costly; hence, water utilities compensate leakage by pumping more water or by adjusting water pressure in the mains. The Water Framework Directive put forward by the European Union in 2000, is one example of a supranational level enforcement strategy which requires water utilities in Europe to be able to cover their total cost. In other words, it enforces utilities to set water tariffs that cover not only the cost of water supply but also the cost of leakage reduction (Elnaboulsi, 2009). However, water utilities are concerned that an increase in water tariffs may reduce the demand for water, which may lead to lower revenues. Lower revenues would inhibit utilities from engaging in leakage reduction.

[1] *The New York Times* March 14, 2010.

In France, about 800 million euros are spent annually on replacing leaky mains. However, the current estimate of the need for mains renewal amounts to 1.5 billion euros, which is twice the current expense (Salvetti, 2013). Water utilities resort to pumping additional water and manipulating water main pressure since this is much cheaper and more practical than repairing or replacing mains. However, such temporary solutions cannot ensure water supply sustainability in the long run. Moreover, if only temporary solutions are implemented, water mains will keep aging, which will expose the utilities to a sudden surge in costs when the need for mains renewal becomes urgent (Elnaboulsi and Alexandre, 1998). For example, main breaks may occur frequently once the mains have exceeded their useful life, causing major disruptions in cities such as flooding, which would amount to high damage compensation costs (Morrison et al., 2013). Recently some projects have emerged to develop efficient methods for leakage reduction. For instance, the PALM project in Italy (2013) has developed a method that can help detect the origin of the leakage, facilitating maintenance and repair. Moreover, with their "efficiency calculator"[2], water utilities can estimate an optimal leakage ratio which is cost-efficient. In other words, utilities will decide whether to replace mains according to this threshold level of leakage. In the first part of this chapter, we propose a model based on cost-efficiency but we depart from their approach by proposing a model that takes into account the *cost-minimizing water main quality index*: an index that shows the proportion of "good" (young) mains in the network. The optimal quality is based on the trade-off between the cost of "good" mains and the cost of water loss. Furthermore, in the second part of this chapter we solve for a *profit maximizing water main quality index* that captures the effect of revenue which allows us to observe the impact of the principle of full cost recovery. The difference in the results from Part I and Part II reveal the significance of the objective function of the water utilities and the difference between rural utilities and urban utilities.

The existence of water loss has various repercussions: economic and financial impacts

[2]The efficiency calculator is a DSS (Decision Support System) which calculates the optimal level of leakage (the point where the marginal cost of leakage reduction equals the marginal cost of water production).

along with health and hygiene. Economically speaking, volumes of water that are lost through poorly maintained mains are extractions of water resources that are directly wasted, thereby aggravating water scarcity. Although water is never physically lost, the resources put into the production of water lost in leaks are lost forever (such as chemicals for treatment and energy for pumping) (Martins et al., 2012). In financial terms, water loss is the amount of water that is not sold to the consumer, hence a loss of potential revenue. Moreover, "leaky pipes are known for increasing pumping energy [...] and can increase the risk of compromised water quality by allowing intrusion of polluted groundwater" (Colombo and Karney, 2002). The rise in the total cost due to increasing water input is the "marginal cost associated with drilling, consisting mostly of energy and treatment cost" (Garcia and Thomas, 2001). This wasted energy has further consequences on the environment via emissions of CO2 and other greenhouse gases released by energy production and consumption.

We do not consider a dynamic model with "capital accumulation" since in our model the length of water mains is fixed (the kilometers of mains already exist and are given) and does not grow over time. This already existing stock of water mains consists of old and young mains. The distinction between old and young is determined by the expected lifetime of the mains which is supported by a huge literature on underground water mains deterioration. The question we ask is: how much of the existing water main network should consist of young mains? Since our models are based on a static framework, we refrain from using terms that evoke a dynamic nature. Therefore, we refer to young mains as "good quality mains" and old mains as "bad quality mains". Moreover we avoid the terms such as investments and replacement. When we talk about "cost of good quality mains", it implies the cost of replacing mains.

In Part I of this chapter, we develop a cost minimization problem where we define a cost function that comprises the cost of water production (pumping and treatment costs), the cost of good quality water mains and the cost of bad quality mains. The decision to increase the proportion of good quality mains or water extraction not only depends on their relative costs but on other parameters such as the demand. We calibrate the parameters of our model with French and American data in order to illustrate the theoretical results and observe the impact of the different parameters of the model. The results show that the quantity of good quality water mains depends highly on water production costs, the material of the mains and the demand for water. This part provides the threshold quality index that characterizes the technical aspects of the water mains network regardless the "profitability" of the utility. The solution we obtain is a theoretical guideline for the *minimum* threshold of water main network quality that should be achieved by a water utility.

In Part II of this chapter we develop a profit maximization model. The water utility, private or publicly operated, decides on the optimal water main quality which maximizes their profits. They are both faced with price caps; where private utilities have higher price caps than public water utilities. In both cases, the water network is owned by the state - a situation representative of the French case. We also show the effect of delegated services, where decisions on investments are taken by the local authority and not by the delegated firm. The quality index obtained in Part II allows comparison with the benchmark cost efficient quality index that is presented in Part I. Results show that cost recovery has a significant effect on the quality index under profit maximization. We can see that too much cost recovery may lead to excessive water main quality indices that are beyond the cost efficient water main quality indices. Moreover, we show that in certain cases, utilities cannot meet both objectives of full cost recovery and water loss reduction simultaneously. This is particularly the case with rural utilities that are characterized with small demand size relative to the size of their network, which has been highlighted in the paper by Mizutani and Urakami (2001).

In an interview with Christophe Audouin, a water professional in France who works for the water company Suez, he explained that in the case of France, where water infrastructure is entirely owned by the state, regardless the service provider, the driving force behind investment decisions is the *objective* defined by the local authority. If the contract does not specify network renewal, outsourcing may appear to have a negative effect on network renewal. Although our theoretical model is not specifically constructed to reflect the impact of organizational choice, we are able to recreate a scenario that reflects the importance of objectives defined in contracts signed with outsourced firms. The issue of the governance of water service provision is dealt with in Chapter 3 in depth. Overall, our results show that along with the impact of operator type, the specific characteristics of the utility plays a major role in determining the optimal network quality. These characteristics include the total length of mains, total demand, price elasticity of demand, cost of water production, cost recovery and the difference between urbanity and rurality. In line with Saal et al. (2013), the specification of our objective functions exhibit characteristics of natural monopolies that are highly capital intensive; in the sense that economies of scale is present but diminishes as output becomes very large.

This chapter is divided into two parts. We first present the literature review in the next section then we present Part I and and Part II of our chapter.

1.2 Literature Review

There are many papers that deal with the issue of water main replacement in the world of hydraulic engineering (among them, Mailhot et al. (2003), Berardi et al. (2008), Shamir and Howard (1979) and Elnaboulsi and Alexandre (1998)); yet this issue seldom appears in the economic literature as the prime focus of a study. We can find many papers today that estimate water utility cost functions and determine the efficiency frontier for evaluating performance levels, most commonly via the method of Data Envelopment Analysis (DEA), such as the paper by García-Sánchez (2006). Our aim is quite different from this traditional method of performance evaluation or the so-called benchmarking technique.

Within the economic literature, we find only a few papers that deal with water loss from water mains. Moreover, very few are based on a theoretical approach. For example, Pearson and Trow (2005) estimate “economic levels of leakage” (ELL). They conclude that if producing water is less costly than investing in leakage reduction, water utilities should extract additional water to compensate for the amount of water lost through leaks. The marginal cost of water is estimated by the difference in the cost of producing one more unit of water in terms of power (energy), chemicals (for treatment) and labor. Indeed, in practice for many utilities the cost of water extraction is low, which leads to pumping more water. The difference between our model and the ELL approach is the nature of the model. We develop a static firm cost minimization model subject to an output constraint, whereas the ELL model is a technical unconstrained cost minimization model, where short run costs are separated from long run costs. Moreover, the objective of our model is to obtain a “quality index” of the water main network and to provide a sensitivity analysis when parameter values change, whereas the goal of ELL is to estimate the optimal frequency of intervention (active leak detection) of the network. It is very useful for water utilities as a practical tool in planning the optimal interval for leakage detection activities. Lastly, the ELL model is based on substantial data from utilities and requires that utilities are already engaged in “active leakage control”, which is unlikely to be the case in most utilities outside the U.K. (Fanner et al., 2007). Our model requires very little data input but captures the overall impact of the leakage issue in a simple framework.

Another example is the theoretical paper applying contract theory to public water utility regulation by Garcia and Thomas (2003). They examine the impact of asymmetric information on the production decisions of regulated public water utilities. The asymmetry of information depicts the uncertainty of the delegated utility’s decision whether or not to exert effort in reducing water loss in favor of water network quality improvement. The solution of their model shows that due to asymmetric information between the local community and the water utility, information rents increase with reductions in water loss. Hence in the optimal contract, “the principal requires the operator not to reduce losses”. This result adds to the intuitive hypothesis of the likelihood that water loss reduction may be suboptimal if the cost of reduction exceeds the benefit, where the costs include the cost of transaction in their case. Although we do not have parameters that reflect asymmetric information as do models based on contract theory; in Part II of this chapter, we do recreate a scenario with outsourced utilities that reveal the situation where water loss reduction could be lower (less than the cost efficient network quality) due to asymmetric information between the local authority and the outsourced firm. This is primarily due to the specification of the objectives in the contracts.

Moreover, a recent theoretical approach to the analysis of water infrastructure has been developed by Hansen (2009). He tested the effects of population, capital and policy on the decision to invest in water utility infrastructure. He sets up a dynamic optimization problem constrained by capital depreciation. The empirical evidence proved the theoretical model relevant; however, applying a production function with inputs of capital, labor and infrastructure investment appears unsuitable to the characteristics of a water utility. In our model the production of output is simply defined as the sum of water demand and water loss.

Water loss often appears in empirical papers that assess the performance of the water utilities according to various factors such as ownership type and regional characteristics. For example the study by Chong et al. (2006), did not find evidence that the level of leakage, among the quality variables, has a significant effect on the "performance" variable estimated by prices. However, another study by Salvetti (2013) infers that "groups of water services complying with the French leakage regulation show a higher water price than the group of services failing to meet the regulation". She reasons that utilities abiding by the regulation set by the authorities tend to charge higher prices to customers. This evidence strongly supports our hypothesis of the water utilities' lack of concern about infrastructure quality because the burden is borne by the customers via higher prices. However, the price of water paid by customers may not be an overall indicator of how effectively the water utilities are managed since these water rates are heavily regulated. Price is a problematic measure of the true cost to the servicing utility.

The empirical findings of González-Gómez et al. (2012) explain the impact of key variables on the level of water loss in Andalusia, Spain. Their empirical evidence suggests that the financial burden of the water utility has a significant negative impact on water loss. This means that local governments that are under financial stress go further into debt in order to overcome leakage problems. This situation is supported by the positive relationship between private governance and water loss. Since the private entity is reluctant to act against leakage reduction, the local government takes on the burden. Moreover, densely populated regions positively impact water loss. The authors show that "water losses will be greater in those networks through which a greater volume of water is pumped". In addition, the lower the extraction cost of water the higher the water loss, and the older the mains, the greater the water loss. The results we obtain in our model are consistent with their findings.

Garcia and Thomas (2001) compare the marginal cost of labor applied to the infrastructure replacement (as most replacements are highly labor-intensive) and the marginal cost of pumping water (which consists mainly of energy costs) to decide whether or not to invest in leakage reduction. They conclude that a "joint production" of water loss and service output has a cost advantage since "short-run" marginal cost of main replacement is greater than the "short-run" marginal cost of pumping water to satisfy customer demand; thus reasoning by the concept of economies of scope. On the other hand, the results we obtain with our model show that depending on utility-specific characteristics, sometimes it is cost efficient to have the least leakage possible.

In line with the study by Garcia and Thomas (2001), Martins et al. (2012) estimate an empirical cost function in a similar manner with two outputs; water loss (y^l) and service output (y^s) to observe the effect of reducing water losses on the water utility performance in terms of cost effectiveness. They compare the cost of producing water loss and the cost of producing serviced water. The conclusion is that "the marginal cost of y^l is greater than the marginal cost of y^s". This can be viewed as an incentive for reducing water loss; it would be cost effective for the utility to produce without water losses.

Zschille and Walter (2010) infer from their empirical work on assessing the cost efficiency of the German water utilities, that "water losses and elevation differences in a service area turn out to be significant cost driver"; however, "incentives to reduce costs and corresponding prices are still missing in Germany so that there is no need for water utilities to supply water in an efficient way." Such a result evokes potential political implications on the regulation of water utilities.

As we can see, there have been several empirical studies applied to different countries that highlight the issue of water loss; however, a theoretical model illustrating the effect of water loss on the cost to the water utility is rarely found in the economic literature. However, very recently we have come across a working paper by Cavaliere et al. (2015) that models investments in water networks with water loss which we can draw some reference to. They analyze the impact of different ownership and governance structures on the investments for leakage reduction. Depending on the different organizational structures (privatization, partial privatization, municipalization), cost of funds, opportunity cost and efficiency of investment, there could be under or over investment of leakage reduction. The main contribution of their article is the effect of mixed organisational structures (partial privatization such as mixed ownership of the network) on the level of investment. They observe that this kind of structure could either result in over or under investment depending on the strategic decisions aimed at maximizing ownership shares. In other words, private shareholders take into account the risk of expropriation of the water network by the local authority before deciding the level of investment in leakage reduction. Moreover their calibration exercise shows that the efficiency of investment and the variable costs have a large impact on the final level of investment. Although we share several similarities in the functional form and variable definitions, we depart from the focus on cost of funds and focus instead on the utility-specific characteristics such as demand size, length of network and cost of water production that could influence the resulting optimal network quality. In our model utilities implement the cost recovery principle to cover the costs of network renewal. Furthermore our model does not assume perfect inelastic demand. There is a vast literature that shows the existence of weak but elastic behavior of demand towards water prices in studies conducted by Espey et al. (1997); Arbués et al. (2003); Garcia and Thomas (2003); Olmstead et al. (2006); Yoo et al. (2014). Hence the effect of cost recovery can be observed in the behavior of demand. "Full cost pricing" or "full cost recovery" is important because it implies self financing of water utilities. As Egenhofer et al. (2012) explains, water management should be financially viable and sustainable through cost recovery since public budgets are highly under stress in many of the member states of the EU. In particular, if costs are not recovered; it limits the availability of funds for other activities such as maintaining the quality of water supply. However, they also mention the limitations of this mechanism. For instance in poorer areas, cost recovery implies higher prices, which may not be feasible for the population; moreover these areas may require substantial investment which cannot be fully self financed, which means that the EU should provide financing tools for these cases. Indeed, we show that depending on the characteristics of the utility, meeting certain network quality requirements is not possible given a price cap that limits price increases. These utilities tend to be small, rural ones. On the other hand, in very large utilities that serve large cities, despite large costs, due to the large (output) demand size, cost per m^3 of water consumed is much smaller than in rural utilities. Moreover, since cost recovery has very little impact on the increase in price per m^3, where price caps are sufficiently high, cost recovery may even induce over investment in network renewal (greater than the cost efficient quality index).

We now present the first part of this chapter which is characterized by the first theoretical model based on the cost minimization approach. This part is co-written with Emmaunelle Taugourdeau. Part I is divided into five sections. The first and second sections introduce the theoretical model and the function specifications. The third section presents the simulation and results and the fourth section concludes. The

Appendix is presented in the fifth section.

Part I

A static cost minimization approach

1.3 Theoretical Model

1.3.1 The water utility's decision

We begin with a benchmark scenario where a water utility weighs the cost of water loss against the cost of good quality mains.

Consider a water utility that provides potable water to households through a water main network which is of fixed length M. The network is composed of good quality mains $\overline{M}$ and bad quality mains $\underline{M}$ with $M = \overline{M} + \underline{M}$. The cost supported by the utility is:

$$C(\overline{M}, \underline{M}, W^{in}) = \rho W^{in} + r\overline{M} + m\underline{M} \tag{1.1}$$

where ρ, r and m are fixed parameters that characterize the cost per unit of water produced (W^{in}), the cost per unit of good quality mains ($\overline{M}$) and the cost per unit of bad quality mains ($\underline{M}$). This cost, m, could reflect the cost of leakage detection activities and rehabilitation costs of obsolete mains. The network quality is characterized by the ratio of good quality mains over the total network $\left(\frac{\overline{M}}{M}\right)$. The greater the proportion of good quality mains, the higher the network quality. In other words, there is less water loss in the water mains. Since we are in a static framework we refrain from using the term "investment" or "replacement". The cost defined in 1.1 is the total variable cost of the water utility. We present further details on the distinction between good and bad quality mains in the next section.

The delivery of potable water is a process in which the produced volume of water is transported (after treatment) through the water mains and arrives to the households in the form of tap water. Therefore, we define the total production of potable water as the sum of water loss (W^l) and the volume consumed by households (q). The amount of water loss $\left(W^l\right)$ writes:

$$W^l = \alpha \left(\frac{\overline{M}}{M}\right) W^{in}, \tag{1.2}$$

where $\alpha\left(\frac{\overline{M}}{M}\right)$ is the fraction of water lost between the treatment plants and the service connections[3]. It takes on values from 0 to 1 without ever reaching 1 in order to maintain a positive quantity of water supplied to the consumers. As specified by Chakravorty et al. (1995) we can also interpret $\alpha(\cdot)$ as the conveyance loss rate function or as an iceberg cost function[4]. We consider that this rate of water loss depends negatively on the network quality, $\alpha'(\cdot) \leq 0$ and $\alpha''(\cdot) \geq 0$. In other words, the better the quality of the main network, the closer $\alpha(\cdot)$ is to zero; hence the smaller the water loss[5].

The total amount of water delivered to the tap by the utility must meet the required demand denoted as $q\left(p\left(\overline{M}\right)\right)$ with $q'(\cdot) < 0$ and $q''(\cdot) > 0$ where $p(\overline{M})$ is the price of water with $p'(\overline{M}) \geqslant 0$ and $p''(\overline{M}) \leqslant 0$. Based on a large empirical literature, the demand function depends on the price. There is a huge empirical literature that calculates the elasticity of demand justifying the impact of water price on demand. Even if the response is sometimes low for some countries (between -0.1 and -0.4), it is not negligible and has to be taken into account. In Espey et al. (1997), the price elasticity estimates range from -0.02 to -3.33. About 90% of the estimates are between 0 and -0.75 (see Yoo et al. (2014) for a more recent survey). Furthermore, we characterize the price of water as being a function of the good quality mains in order to take into account the fact that in network industries, the network quality drives prices. As stipulated by Lannier and Porcher (2014) and Porcher (2014), operators usually justify their higher prices by higher quality standards. Moreover, utilities are obliged by regional authorities to recover the cost of a good quality network in the price of water. Indeed, the European Directive 2000/60/EC stipulates that the prices users pay for water should cover the

[3]Water leaks between the service connection and the tap water is not the responsibility of the water utility.

[4]The concept of the iceberg cost is usually used to characterize transport costs: "*Specifically, of each unit of manufactures shipped from one region to the other, only a fraction $\tau < 1$ arrives*" Krugman (1991). This concept is also perfectly relevant to characterize water loss that occurs between the production location and the taps.

[5]Similarly we could consider that the rate of water loss is increasing with the quantity of bad quality mains. As the size of the network is fixed at M, reasoning with good or bad quality mains will lead to the same results.

costs invested in new infrastructure[6]. Therefore, our price function takes into account the fact that the water utility can reflect the rise in cost due to good quality mains in the price of water.
Since water production is exogenously determined by the constraint to satisfy demand and prices are regulated, utilities' objectives focus mainly on cost efficiency (Feigenbaum and Teeples, 1983). Hence, in this part of the chapter we begin with a cost minimization approach which solves for the optimal quality of the mains based essentially on the arbitrage between the cost of water loss and the cost of good quality mains.

The program of cost minimization writes as follows:

$$\min_{\overline{M}} \quad C(\overline{M}, \underline{M}, W^{in})$$

$$\text{subject to:} \qquad W^{in} - W^{l} \geqslant q\left(p\left(\overline{M}\right)\right) \tag{1.3}$$

$$W^{l} = \alpha\left(\frac{\overline{M}}{M}\right) W^{in} \tag{1.4}$$

$$\overline{M} + \underline{M} = M \tag{1.5}$$

$$W^{in} > 0 \tag{1.6}$$

$$\overline{M}, \underline{M}, W^{l} \geqslant 0 \tag{1.7}$$

$$0 \leq \alpha\left(\frac{\overline{M}}{M}\right) < 1 \tag{1.8}$$

where equation (1.3) reflects the supply constraint, i.e. the water delivered to the tap $\left(W^{in} - W^{l} = W^{in}\left(1 - \alpha\left(\frac{\overline{M}}{M}\right)\right)\right)$ must cover the demand $q(p(\overline{M}))$. After substituting constraints (1.3) to (1.8) into Expression (1.1), we are able to rewrite the cost function as a function of the good quality mains:

$$C(\overline{M}) = \frac{\rho q\left(\overline{M}\right)}{1 - \alpha\left(\frac{\overline{M}}{M}\right)} + mM + (r - m)\overline{M}$$

[6] Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy, Article 9 and Appendix 3.

For simplicity we replace $q\left(p\left(\overline{M}\right)\right)$ by $q\left(\overline{M}\right)$ from here on with $q'\left(\overline{M}\right) < 0$ and $q''\left(\overline{M}\right) > 0$: the better the quality, the higher the price of water, hence, the lower the demand[7].

The first order condition is given by:

$$\frac{\partial C}{\partial \overline{M}} = \rho \left(\frac{q'(\overline{M})}{\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)} + \frac{q\left(\overline{M}\right)\alpha'\left(\frac{\overline{M}}{M}\right)}{\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)^2} \right) + (r-m) \tag{1.9}$$

where the first two terms in brackets are negative and characterize the impact of the good quality mains on the water production quantity, (W^{in}). An increase of the network quality reduces the demand through a rise in water price and reduces the water loss. Both effects tend to diminish the volume of produced water. When r tends to zero or ρ is very large, Expression (1.9) can be negative for any values of $\overline{M} \in [0, M]$. This implies that when the cost of good quality mains is very low or when the cost of water production is very high, the optimal level of $\overline{M}$ is M. In other words, the entire main network should consist of only good quality mains[8]. Conversely, when the cost of water production is very low, Expression (1.9) may be positive for any $\overline{M} \in [0, M]$ implying that it is not optimal to have good quality mains. When an interior solution exists, the optimal proportion of good quality mains is the solution to $\frac{\partial C}{\partial \overline{M}} = 0$. The following second order condition confirms that the optimal quantity of $\overline{M}$ indeed minimizes costs.

$$\frac{\partial^2 C}{\partial \overline{M}^2} = \frac{\rho q''(\overline{M})}{\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)} + \frac{2\rho q'(\overline{M})\alpha'\left(\frac{\overline{M}}{M}\right)}{\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)^2} + \frac{\rho q \alpha''\left(\frac{\overline{M}}{M}\right)}{\left(1-\alpha\left(\frac{\overline{M}}{M}\right)^2\right)} + \frac{2\rho q\left(\overline{M}\right)\left(\alpha'\left(\frac{\overline{M}}{M}\right)\right)^2}{\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)^3} \geqslant 0$$

The implicit form of the optimal solution is given as follows:

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[7] $q'(\overline{M}) = q'(p)p'(M) > 0$ and $q''(\overline{M}) = q''(p)(p'(M))^2 + q'(M)p''(\overline{M}) > 0$.

[8] This is the case for any $r - m \leqslant 0$

$$\frac{q\left(\overline{M}\right)\alpha'\left(\frac{\overline{M}}{M}\right)}{\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)^2}+\frac{q'(\overline{M})}{\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)}=-\frac{(r-m)}{\rho}$$

The comparative static analysis with respect to the parameters ρ, r and m gives the following results: [9]

- When the cost of water production increases: $\frac{d\overline{M}}{d\rho} \geqslant 0$ and $\frac{dW^l}{d\rho} \leqslant 0$
- When the cost of bad quality mains increases: $\frac{d\overline{M}}{dm} \geqslant 0$ and $\frac{dW^l}{dm} \leqslant 0$
- When the cost of good quality mains increases: $\frac{d\overline{M}}{dr} \leqslant 0$ and $\frac{dW^l}{dr} \geqslant 0$

If the unit cost of water production (ρ) increases (for instance, due to an increase in energy cost or reduction in groundwater resources), the total cost of water loss (ρW^l) increases as well; hence, the proportion of good quality mains $\left(\frac{\overline{M}}{M}\right)$ increases which leads to lower water loss. If the cost of bad quality mains (cost of rehabilitation) increases, it becomes more attractive to have good quality mains than to maintain old mains. And finally, the greater the cost of good quality mains, the smaller the quantity of good quality mains, which consequently raises water loss. Moreover, higher water loss must be met with an increase in water production (W^{in}) since the utility must satisfy the demand constraint.

1.3.2 Function specification

Before conducting numerical simulations, we define the different functions of the model. In line with Chakravorty et al. (1995), we specify the water loss function as follows[10]:

$$\alpha\left(\frac{\overline{M}}{M}\right)=\alpha_0\cdot\left(1-\frac{\overline{M}}{M}\right) \tag{1.10}$$

When the entire water main network is composed of good quality mains ($M=\overline{M}$), then $\alpha\left(\frac{\overline{M}}{M}\right)=0$; i.e. there is no water loss since $W^l=\alpha\left(\frac{\overline{M}}{M}\right)W^{in}$. In reality, there

[9] The expression of the derivatives is given in Appendix 1.

[10] The linearity of the iceberg function is in line with the study done by Xu et al. (2013). In their study, the relationship between pipe age and pipe breaks is linear.

are unavoidable losses, which could easily be represented in our loss function: with $\alpha\left(\frac{\overline{M}}{M}\right) = \alpha_u + \alpha_0\left(1 - \frac{\overline{M}}{M}\right)$ where α_u represents the unavoidable rate of water loss. In order to maintain the simplest possible setting, we skip α_u. When the entire network consists of bad quality mains ($\overline{M} = 0$), then $\alpha(0) = \alpha_0$, which we refer to as the *base loss rate* (Chakravorty et al., 1995). In other words, α_0 represents the amount of water loss when all mains are bad quality mains. This value depends on the material used to construct the mains[11]. If the mains are composed of cast-iron, α_0 will be greater than the mains composed of PVC or HDPE (High Density Polyethylene) type plastic, which are more resistant to corrosion than cast-iron (Folkman, 2012).

We define the demand for water $q(p)$ as a function that depends on the water price:

$$q(p) = \frac{q_0}{p\left(\overline{M}\right)^{\theta}} \tag{1.11}$$

where q_0 is the annual average quantity desired by households which we refer to as "unconstrained demand" and θ is the price elasticity. $p\left(\overline{M}\right)$ is the price function that depends on the quantity of good quality mains as follows:

$$p\left(\overline{M}\right) = \left(\frac{r\overline{M}}{q_0}\right)\beta + \overline{p} \tag{1.12}$$

where $1 \geq \beta > 0$ represents the proportion of the cost of good quality mains that is reflected in the price of water. We consider this as the "political parameter" which characterizes the cost recovery of network renewal with $\beta = 1$ implying the maximum degree of cost recovery possible[12]. In our model cost recovery only deals with recovering the costs of good quality mains because network quality is the focus of our study. On the other hand, when $\beta = 0$, $p\left(\overline{M}\right) = \overline{p}$, which means that the water price does not

[11] In our reasoning we focus on the material; however, α_0 could depend on other external factors such as the pressure used to pump water through the network and the geographic characteristics (such as soil conditions).

[12] Although the price-setting decision is in the hands of the utilities, we refer to this parameter as "political" since cost recovery is usually enforced at a national or supra national level, for instance by the European Water Framework Directive (Kanakoudis et al., 2011).

cover the cost of good quality mains. The cost of water production (ρ) and the regular maintenance costs (m) are covered in $\overline{p}$. When $\beta = 0$ the quantity demanded does not depend on the good quality mains; hence the demand is fixed and defined as:

$$\overline{q} = \frac{q_0}{\overline{p}^{\theta}}$$

Such a scenario is quite relevant today. Even though the European Water Framework Directive insists utilities to reflect the full costs associated with water distribution (which could include a variety of costs; such as the environmental and resource costs associated with water extraction), the price of water barely covers the full supply cost nowadays.

Given these functions, we conduct numerical simulations to obtain the cost minimizing water mains quality ratio $\left(\frac{\overline{M}}{M}\right)$, which we refer to as the **quality index** in percentage form. We conduct several simulations over different values of key parameters (β, ρ, α_0) in order to observe the sensitivity of these parameters on the quality index. For these simulations, we used French and American data.

1.4 Simulation and Results

1.4.1 Calibration

We have compiled data from large databases such as the United States Environmental Protection Agency (EPA), the American Water Works Association (AWWA), l'Observatoire National des Services d'Eau et d'Assainissement (SISPEA), and l'Office National de l'Eau et des Milieux Aquatiques (ONEMA)[13].

We use the cost of pumping and treating of a m^3 of water for the calibration of ρ. The price elasticity θ is obtained by the results from empirical studies (Arbués et al., 2003; Olmstead et al., 2006) and β is the political parameter reflecting the degree of cost recovery which we manipulate to observe its impact on the quality index. The parameter α_0 is the rate of water loss when the entire water main network consists of

[13] All our data are available in excel format upon request.

bad quality mains, which we refer to as the *base loss rate* in reference to Chakravorty et al. (1995). On a country level basis, in France, around 60% of water mains are good quality mains and the associated average rate of water loss is 24% (Dequesne et al., 2014). Therefore, after computation, we set $\alpha_0 = 0.6$ [14]. On the other hand, in the U.S., there are around 80% good quality water mains and the associated average rate of water loss is 16% (Folkman, 2012). Hence, α_0 is 0.8. We note that α_0 in the U.S. is greater than in France which can be due to differences in the material of the mains. Although the proportion of young mains is greater in the U.S. than in France, the critical rate of water loss is higher. This is because in the U.S. the majority of the mains (60% of the total network) are made of iron-based material, the most corrosion-prone material that causes leakage, while only 23% is PVC (Reiff, 2012). On the other hand, a larger proportion (about 40%) of the mains in France are PVC type mains, meaning they are less prone to leakage (Majdouba et al., 2011). We let this parameter α_0 vary in our simulations to study different scenarios since the initial values are estimates purely based on our water loss function.

Moreover, we approximate the cost of good quality mains, r, as the cost of purchase and installation of one kilometer of new mains divided over the years of amortization[15] (Colbach, 2014). The years of amortization depend on the age of the expected lifetime of the good quality mains, which we define as mains younger than 50 years. Similarly bad quality mains are defined as mains older than 50 years. This choice is in line with several studies, among which are the studies developed by Majdouba et al. (2011) for France and Baird (2011) for the U.S. This cost r is also weighed according to the rurality or urbanity of the region. The cost of good quality mains in an urban region is four times higher than in a rural region[16]. Several reasons explain this difference: 1)

[14] α_0 was computed by solving the equation $\alpha\left(\frac{\overline{M}}{M}\right) = \alpha_0\left(1 - \frac{\overline{M}}{M}\right)$. For France, we substituted 0.24 into $\alpha(\frac{\overline{M}}{M})$ and 0.6 into $\frac{\overline{M}}{M}$. This means that, given the current proportion of good quality mains and the current rate of water loss, the α_0 reflects the intrinsic quality of the mains. For the same level of current quality index, if one utility has a larger rate of water loss than the other, this could mean that there are differences in the material of the mains.

[15] We apply the straight-line depreciation method introduced in (Janzen et al., 2016).

[16] For example, 1 kilometer of mains in an urban area costs around 600,000 €, while in a rural area it costs around 150,000 € in France.

in an urban area, the installation of pipes requires digging and excavating pavements which are much costlier than digging up dirt roads in rural areas, 2) The diameter of pipes must be much larger (and so more expensive) to distribute a higher volume of water through a smaller length of mains, and 3) mains can be of cheaper materials in rural areas because fewer inhabitants are concerned. As a result, r is much larger for a region that is urban than for a rural region[17]. The cost of bad quality mains, m, reflects the cost of rehabilitating or repairing old mains (for example, placing a lining in a leaky main in order to stop the leakage). The value of m per mile of mains is quite small compared to r; \$1,580 vs \$6,058 respectively in the U.S.; hence, we chose to set m equal to zero (Uni-Bell, 2011). A positive m would reduce the net cost of good quality mains and push the quality index slightly upwards; however, the consistency of the results will not be altered even if m is removed. In Part II of this chapter we revisit m by introducing leakage detection costs and in chapter 2 we study the effect of rehabilitating mains on network renewal. In this part we leave it out since we begin with the simplest framework.

Furthermore, the part of the price of water that does not reflect the cost of good quality mains ($\overline{p}$) is calibrated using the current price charged to consumers. We refer to $\overline{p}$ as the "water tariff" to distinguish between the price defined by the price function in section 1.3.2. $\overline{p}$ reflects the cost of the entire water distribution system, which includes wastewater services as well. In France about 40% of the price of water reflects the cost of wastewater services, 15.6% taxes, and 44.5% reflects the cost of potable water services. Moreover, we assume that $\overline{p}$ covers the cost of water production and the maintenance of existing mains. Finally the unconstrained demand, q_0, is obtained by multiplying current consumption volume by $\overline{p}^{\theta}$. Since $\overline{q}$ from $\overline{q} = \frac{q_0}{\overline{p}^{\theta}}$ is the current level of demand observed, q_0 is obtained by multiplying current observation by $\overline{p}^{\theta}$. When $\overline{p}$ is less than 1, its impact on demand is extremely small, hence, we set $q_0 = \overline{q}$.

[17] Sciences et Avenir, "Eau: il y a de la fuite dans le réseau", 20 mars 2014.

1.4.2 Results: Country-level analysis of the quality index

First we simulate the model using average values of France and the U.S.[18]. Although the core of the results is based on the simulations of municipality-level data, we also simulate average values of France and U.S. in order to obtain an approximate national quality index that could be compared to the approximated quality index we observe today. For instance, we expect to observe a higher quality index for the U.S. than for France. One reason is because α_0, the base loss rate, is greater in the U.S. than in France. The quality index would tend to be higher for high values of α_0 since old mains have higher levels of leakage than old mains with a smaller value of α_0. In other words, if the base loss rate is small, old mains (those that have exceeded their expected lifetime) have less leakage; which means that a large proportion of young mains is unnecessary (not cost-efficient for the utility).

The calibrated values of the parameters and the quality index for the U.S. and France are shown in Table 1.1. As we have anticipated, the quality index is lower in France (77%) than in the U.S. (100%) when cost recovery is zero ($\beta = 0$). The quality index for France increases only by one percentage point when β increases from zero cost recovery (0) to full cost recovery (1). The reason why cost recovery has almost no impact on the quality index is because of the design of our model. Regardless the level of cost recovery, our model solves for the optimal quality index that is most cost efficient based on the trade off between the cost of water loss and the cost of good quality mains. High cost recovery raises prices, which lowers quantity demand ($q'_\beta < 0$) (assuming that price elasticity of demand is greater than 0). Lower demand lowers water production (W^{in}) which then lowers water loss; hence total cost of water loss drops. In terms of cost efficient trade off; a lower total cost of water loss is reflected by a reduction in good quality mains. However, simultaneously, low good quality mains imply larger water loss; hence good quality mains rise. Depending on which opposing effect dominates, the overall impact of cost recovery could be negative or positive. Our simulation results

[18] The simulation was conducted using mathematica.

show that it is almost null. The following computation of the marginal effect of β on $\overline{M}$ shows that $\frac{d\overline{M}}{d\beta}$ could be positive or negative.

$$\frac{d\overline{M}}{d\beta} = -\frac{\rho q'_{\beta}\alpha'_{\overline{M}} + \rho q''_{\overline{M}\beta}\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)}{\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)\left(\rho q''_{\overline{M}} + 2\alpha'_{\overline{M}}(r-m)\right)} \tag{1.13}$$

where

$$q''_{\overline{M}\beta} = -\theta r \frac{\overline{p} - \theta\beta\left(\frac{r\overline{M}}{q_0}\right)}{\left(\left(\frac{r\overline{M}}{q_0}\right)\beta + \overline{p}\right)^{\theta+2}} < 0 \Longleftrightarrow \frac{\theta\beta\overline{M}r}{q_0} < \overline{p}$$

If the denominator of (1.13) is negative and the numerator is positive, $\frac{d\overline{M}}{d\beta} > 0$. If $q''_{\overline{M}\beta} < 0$, and the first term $\rho q'_{\beta}\alpha'_{\overline{M}}$, which is positive dominates the second term $\rho q''_{\overline{M}\beta}\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)$, which is negative, we indeed obtain a positive derivative. However if the second term dominates, the derivative is negative. If $\alpha\left(\frac{\overline{M}}{M}\right)$ is large, the second term becomes smaller; which means that the derivative is likely to be positive. This means that the effect of high water loss on the need for good quality mains dominates; hence the derivative ($\frac{d\overline{M}}{d\beta}$) is positive.

We see in the second part of this chapter that if the utility's objective is profit maximization, higher cost recovery has a large positive effect on the quality index. This is essentially because cost recovery has a positive impact on revenue. Under perfect inelastic demand, this positive effect is accentuated since higher cost recovery only results in a positive effect on profits.

We strongly emphasize that the value we obtain for the cost-minimizing water main quality index represents a minimalist scenario. For example, the index leaves out the cost of bad quality mains (m) and the negative environmental and health externalities due to water leakage. If included, they could potentially drive up the quality index. Although it is the minimalist scenario, we can see that the simulated quality indexes for both France and the U.S. are much higher than their current quality indices (60% for

France and 80% for the U.S.), which supports the fact that infrastructure investment today is lagging behind.

Parameters	Description	Values for France	Values for U.S.
α_0	Critical rate of water loss	0.6	0.8
M	Total main network distance	906,000 km	1,899,021 km
q_0	Unconstrained quantity demanded	4,656,115,200 m^3	78,994,211,989 m^3
ρ	Water extraction cost	1.5 € per m^3	1.24 $ per m^3
$\overline{p}$	Current price of water	3.39 € per m^3	1.32 $ per m^3
r	Cost of good quality mains	4,890 € per km	6,058 $ per km
θ	Price elasticity of demand	0.2	0.33
	Current rate of water loss (%)	24	16
	Percentage of Urbanity (%)	21	19
Result $\frac{\overline{M}}{M}$ (%)	Cost-minimising quality index (with $\beta = 0$)	**77**	**100**
Result $\frac{\overline{M}}{M}$ (%)	Cost-minimising quality index (with $\beta = 1$)	**78**	**100**

Table 1.1: Calibration and results for the United States and France

Figure 1.1 shows the sensitivity of the quality index to α_0 for values of the U.S and France. In the case of France, if the bad quality mains are associated with a base loss rate of less than 35%, it is cost efficient for the utility to maintain a 0% quality index (keeping all other parameter values fixed). However, the quality index rises rapidly once α_0 becomes greater than 35%. Compared to France, the quality index for the U.S. shoots up almost instantaneously for a very small increase in α_0. This sensitivity is explained by the difference in quantity demanded (q_0) and the water tariff ($\overline{p}$).

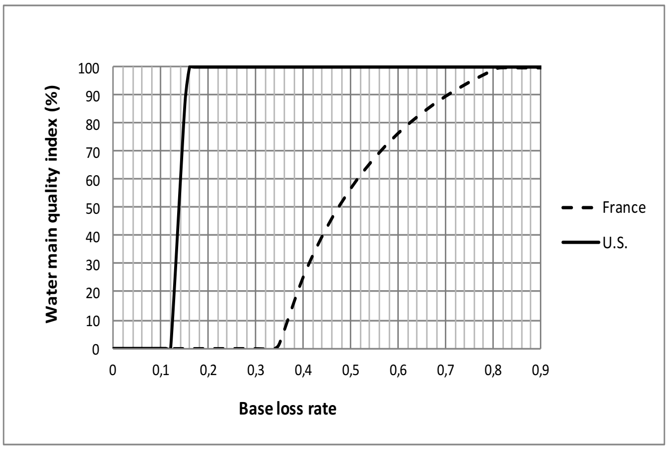

Figure 1.1: The impact of the **base loss rate** (α_0) on the quality index for average values of France and U.S.

It is clear from Table 1.1 that the total consumption is much greater in the U.S. than in France, which could be explained by the difference in population. Nevertheless, the average consumption per capita of potable water is almost four times greater in the U.S. than in France (0.617 m^3 per day per inhabitant for the U.S. and 0.151 m^3 per day per inhabitant for France). This means that the total production is much higher in the U.S. than in France. According to Rogers and Bettin (2011) as production volumes increase, it raises the need for utilities to obtain new and more expensive resources (for example, to search for a surface supply if groundwater is depleted). Hence, when leakage is lowered, production of water is also lowered, leading to lower total costs[19]. Moreover, the price of water paid by consumers in the U.S. is less than half the price in France. A low price leads to higher demand which requires a greater supply of water, hence, in line with the above reasoning, water loss reduction becomes beneficial. Finally, as mentioned previously, utilities that operate with network mains made of materials that are corrosion-prone face heavier burdens when mains become old in comparison to those operating with mains that are corrosion-free[20].

1.4.3 Results: Impact of regional differences on the quality index

We have taken examples of water utilities from the U.S. and water utilities from France with differing regional characteristics to further analyze the impact of parameters on the quality index.

French utilities

We selected four different water utilities in France. Paris, from the Seine-Normandie water agency, Sainte-Lizaigne from the Loire-Bretagne agency and Lyon and Tencin from the Rhone-Mediterranee-Corse water agency[21]. Paris is the capital and represents the

[19] The total cost of water loss is obtained by multiplying ρ (unit cost of water production) by the total volume of water loss.

[20] We should keep in mind that corrosion-free materials such as PVC may have negative health impacts due to chemical substances that may diffuse into the water. This effect is not captured in our model since we leave out health externalities.

[21] There are six different water agencies in France that represent six different water basins. Utilities that belong to these water agencies pay fees that include abstraction and pollution charges (Garcia and

largest city located in the North, while Lyon represents another large city in the South. On the other hand, Tencin and Sainte-Lizaigne represent small rural collectivities.

Table 1.2 shows the calibration of the four water utilities in France and their quality indices. These four utilities have different geographical and urban characteristics that are reflected in the simulated quality index. For instance, Paris has the largest total water demand (q_0) relative to the length of their network (M) out of the four utilities, hence we expect a high quality index. On the other hand, utilities like Tencin and Sainte Lizaigne that serve a rural population have a smaller demand size relative to the length of network. In line with Mizutani and Urakami (2001) it is important to consider the size of the network relative to output size in network industries that are heavily capital intensive. According to their results, a smaller length of network and higher output leads to cost advantages. This concept should not be confused with the scale economies; it is known as economies of network density where the spatial properties are included. However, it is not the density per se that is the key. Economies of network densities could be present in both urban and rural utilities. It depends on the relative size of the network and the output. In most cases, water utilities operate with economies of scale as output increases (due to the characteristic of a natural monopoly); however, "too much" output could cause diseconomies of scale; which is often present in very large utilities (Saal et al., 2013). This is because the greater the demand size, the greater the water production, which could lead to capacity constraints such as importing water from neighboring utilities which reflects in higher water production costs. Hence, although a larger output allows a bigger division of network renewal costs per m^3 consumed (economies of network density), it does not necessarily imply scale economies.

In addition to the advantage of cost sharing, there is a smaller impact of cost recovery on price increases in urban utilities due to a large demand base. However it is the opposite case for rural utilities where price per m^3 could rise rapidly. While water prices are usually controlled, a large price rise could backfire on the utility's revenue

Reynaud, 2004). Moreover, the utilities abide by regulations such as pollution levels and water quality set by each agency.

	Paris	Sainte Lizaigne	Lyon	Tencin
α_0	0.6	0.6	0.6	0.6
M	2097	27.9	3074	13.94
q_0	221,632,479	64,452	78,524,345	86,075
ρ	1.5	1	1	1
$\overline{p}$	3.28	4.2	3.10	3.82
r	12,000	3,000	12,000	3,000
θ	0.2	0.2	0.2	0.2
Density (inhabitant per km of main)	1084	47	371	105
Percentage of Urbanity (%)	100	0	100	0
Extraction method	48% groundwater	100% groundwater	95% groundwater	100% groundwater
Current rate of water loss (%)	8.3	30	20	6
quality index $\frac{\overline{M}}{M}$ (%) (with $\beta = 0$)	**100**	**35**	**100**	**95**
quality index $\frac{\overline{M}}{M}$ (%) (with $\beta = 1$)	**100**	**37**	**100**	**96**

Table 1.2: Calibration of parameters for the different water utilities in France.

due to a reduction in demand which can cause further financial distress (Brandes et al., 2010). Hence, rural utilities are inclined to postpone network quality improvements. As Janzen et al. (2016) writes, rural utilities face a larger financial obstacle than urban utilities. In the U.S. 96% of utilities serve populations of less than 3300 inhabitants. Similarly, according to SISPEA, in France 60% of utilities serve populations of less than 3000 and only 10% serve populations of more than 20,000. This shows that the financial difficulty faced by rural utilities is not a minor problem. The difference in the type of water resource is also a crucial factor since it will determine the cost of water production, which in turn will influence the quality index. The cost of water production is greater in the case of surface water since the water undergoes more treatment than groundwater.

According to the report by Majdouba et al. (2011), in France mains tend to be younger in rural areas and the majority of them are made of PVC material; hence, α_0 is most probably lower in rural areas than in urban areas. However, since we do not have the precise value for α_0 for each utility, we show the possible quality index values that each utility can obtain over the range of α_0 values in Figures 1.2 and 1.3. For instance, if $\alpha_0 = 0.4$ in rural areas, and if the cost of water production is 0.5, the quality index would be about 25% for Tencin and 0% for Sainte Lizaigne. In Table 1.2, we set α_0 to the average value of France ($\alpha_0 = 0.6$) so that the quality index we obtain reflects the case in which all utilities are faced with the same level of base loss rate. Moreover, we calibrate the cost of water production (ρ) with the values obtained from the reports by Corisco-Perez (2006) and Cadière (2012). The quality indices simulated by our model suggest 100% for Paris and Lyon, 35% for Sainte Lizaigne and 95% for Tencin with $\beta = 0$.

Although Tencin is a rural utility, their quality index is 95% when $\beta = 0$, while Sainte Lizaigne is only 35%. This is mainly due to the difference in the network size (27.9 km vs 13.94km). As a result, Sainte Lizaigne faces a larger cost burden for good quality mains than Tencin. Moreover, the demand is also smaller in Sainte Lizaigne, which means the total cost of water production is lower than Tencin. These factors work in favor of a lower quality index in Sainte Lizaigne compared to Tencin. In France, the average network size for a rural utility is around 14 to 20 kilometers[22], which shows that Sainte Lizaigne represents a rural utility at the far end of the scale. It turns out that rural utilities that belong to the Loire-Bretagne water agency have larger average network sizes; hence, these utilities face greater difficulties in quality improvement than other rural utilities with smaller network sizes.

Although the quality index observed today in Tencin is quite high (75%), it is lower to what we obtain in our simulation[23]. Moreover their rate of water loss is only 6%, which supports the evidence of a high quality index. On the other hand, we are not

[22] We estimated these values using 2013 municipal-level data from SISPEA.

[23] The current quality index for Tencin is extracted from the following report: www.documentation.eaufrance.fr/entrepotsOAI/AERMC/R221/4.pdf

aware of the current quality index in Sainte Lizaigne. However, their rate of water loss is 30% (it was higher in the previous year), and their average rate of main replacement over the past five years is 0%; hence, we suspect a much lower quality index in reality than the simulated result. Although, technically rural utilities are associated with low quality indices, we see in this example that the quality could vary largely even among rural utilities. Here we see that the network density is an important factor. The empirical results in Chapter 3 confirms this effect.

Moreover, we have set $\rho = 1$ for the utilities that extract water from groundwater resource; which is an average value provided in the report by Cadière (2012). In reality, it could range from 0.5 to 2 €$/m^3$. Hence, the following sensitivity analyses, shown in Figures 1.2 and 1.3, better reveals the impact of the differences in the characteristics of the utilities on the quality indices. We provide three scenarios for each utility with different levels of ρ over a range of different values of α_0 from 0 to 0.9. For instance, if $\rho = 0.5$, the quality index for Tencin at $\alpha_0 = 0.6$ is about 50% and a little under 10% for Sainte Lizaigne. This shows that a small difference in ρ can have a big impact on the quality index; this effect is depicted in Figure 1.4. A less than one euro increase in the cost of water production could raise the quality index from 0% to 100% for Tencin.

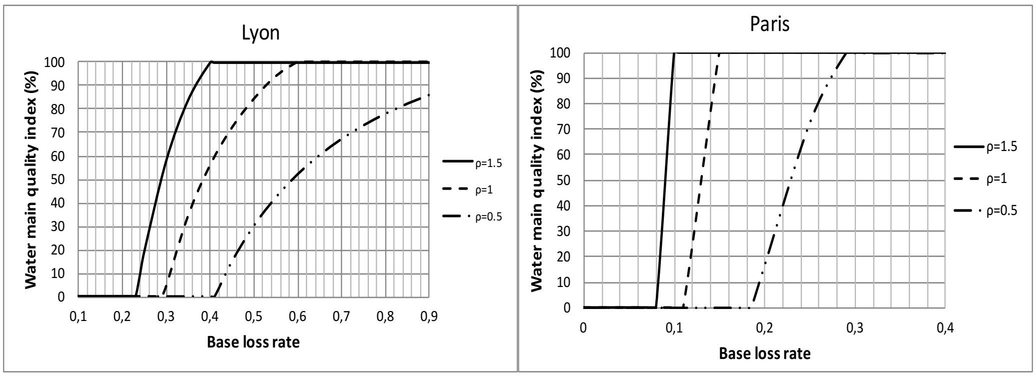

Figure 1.2: The impact of the **base loss rate** (α_0) on the quality index for Lyon and Paris at different levels of **water production cost** (ρ).

Paris and Lyon are both large urban agglomerations; hence a quality index of 100% is reasonable. However, Figures 1.2 and 1.4 reveal a significant difference between the two

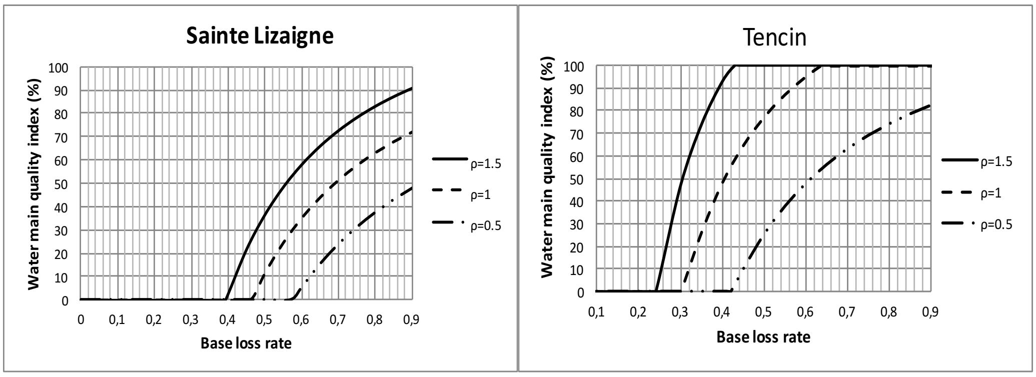

Figure 1.3: The impact of the **base loss rate** (α_0) on the quality index for Sainte Lizaigne and Tencin at different levels of **water production cost** (ρ).

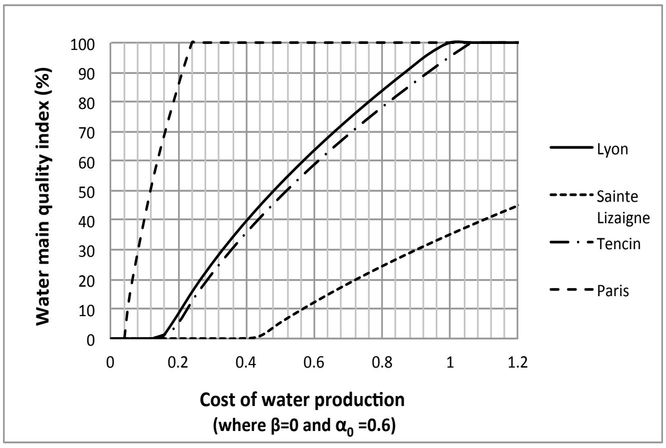

Figure 1.4: The impact of the **cost of water production** (ρ) on the quality index for the French utilities with $\alpha_0 = 0.6$.

utilities. In Paris, when $\rho = 0.5$, the quality index reaches 100% for all values of α_0 greater than 0.3. On the other hand, in Lyon, when $\rho = 0.5$, the quality index never reaches 100%. Although Lyon has urban characteristics, demand and density is smaller than Paris, whereas the total network length is longer. Here we recall the concept of economies of network density. The relative size of demand with respect to the total length of the network plays a key role in the resulting network quality. Smaller demand means that the total cost of water production is smaller in Lyon compared to Paris; which also means that the total cost of water loss is also smaller. However, the fact that the total network length is greater in Lyon implies that the trade off between the total cost of good quality mains and the total cost of water loss is greater than in Paris. Thus, it is less cost-efficient for Lyon to have a quality index as high as Paris. In other words water loss reduction is less beneficial (in terms of cost efficiency) for the given values of ρ and α_0. These factors could explain why we observe similar results for Lyon and Tencin in Figure 1.4. Moreover, Lyon extracts water from a water basin that is one of the largest in Europe. It can provide up to 420,000 m^3 water daily, which is greater than the current daily demand (220,000 m^3). Hence, Lyon is in a situation of water abundance which lowers the cost of the presence of leakage.

We now show in Figure 1.5 the impact of price elasticity of demand on the resulting optimal water main quality index. We take Sainte-Lizaigne and Lyon as examples of a rural utility and an urban utility. As the price elasticity of demand rises, the network quality index falls; this is because higher elasticity implies that quantity demand is more reactive to prices. The higher the elasticity, the quantity demanded is lower for the same price of water. This further implies that the total water production is smaller as well; hence in terms of cost, the cost of water loss falls. This means that the trade off between the cost of water loss and the cost of good quality mains falls, reducing the need for higher network quality. In other words, at higher levels of elasticity it becomes less cost efficient to have higher network quality. But again, we see that in an urban utility, the impact of elasticity is not felt for weak levels of elasticity (until about 0.25 for Lyon). This is because the trade of between the cost of water loss and the cost of good quality mains is initially very large compared to a rural utility.

Overall these results depict the significance of regional differences. Moreover, they give an indication of the likelihood of each utility attaining the recommended limit of the rate of water loss enforced under the Law of “Grenelle 2” of 2010: 15% for urban regions and 20% for rural regions. Our results clearly show that a more urbanized region is more likely to achieve a low level of water loss than a rural region. A large reduction in water loss should be enforced in urban utilities while the limit should be less constrained in rural utilities.

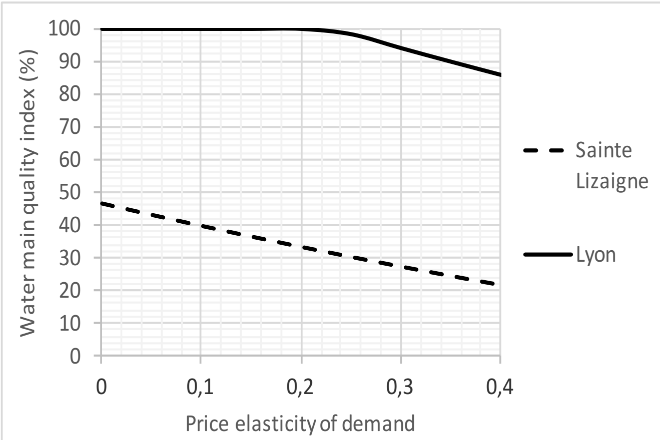

Figure 1.5: The impact of the **price elasticity of demand** (θ) on the quality index for Sainte Lizaigne and Lyon $\alpha_0 = 0.6$ and $\beta = 1$.

U.S. utilities

Now we turn to the United States' regional water utilities. We chose two water utilities from Wisconsin and two water utilities from California. Wisconsin is a state that has access to an abundant source of water while California is an arid region which relies mostly on imported and surface water supply. Table 1.3 shows the calibrated values of the parameters and their quality indices.

We set α_0 as the average value of the U.S., which we later vary in our sensitivity analyses. The quality index for the two utilities in Wisconsin (Madison and Milwaukee) is significantly smaller than the quality index for the two utilities in California (EBMUD and San Diego). The principal reason is the difference in water production cost (ρ). The water production cost in EBMUD and San Diego is at least 10 times greater than in Milwaukee and Madison. Such a difference stems from the difference in the source of the water supply. Water extracted in Milwaukee and Madison mainly originates from groundwater, while in San Diego 80% is imported. Moreover, in EBMUD most of the water extracted is from surface water, hence treatment costs are higher. This implies that regions faced with the uncertainty of water availability are more likely to reflect the value of water in the cost of water extraction which leads to a higher quality index. With the given scenario of parameter values, the reduction in water loss is not

	Madison, WI	Milwaukee, WI	EBMUD, CA	San Diego, CA
α_0	0.8	0.8	0.8	0.8
M	1,368	3,154	6,759	5,314
q_0	33,552,421	115,682,086	244,846,219	294,174,942
ρ	0.066	0.06	0.66	0.75
$\overline{p}$	0.74	0.74	1.03	1.29
r	18,500	10,400	15,850	18,500
θ	0.33	0.33	0.33	0.33
Density (inhabitant per km of main)	183	272	192	244
Percentage of Urbanity	99	41	80	99
Most common extraction method	groundwater	groundwater	surface water	imported water
Current rate of water loss (%)	10	14	7	9.3
quality index $\frac{\overline{M}}{M}$ (%) (with $\beta = 0$)	**8**	**26**	**100**	**100**
quality index $\frac{\overline{M}}{M}$ (%) (with $\beta = 1$)	**9.4**	**27**	**100**	**100**

Table 1.3: Calibration of U.S. water utilities.

cost-efficient for the utilities of Milwaukee and Madison. However, the current rate of water loss is 10% for Madison and 14% for Milwaukee, which suggests that the actual state of the water main network is not that bad. Figure 1.6 shows that if Madison and Milwaukee had the same cost of water production as EBMUD, the quality index would be 100% for Milwaukee and about 75% for Madison, which shows that the type of water and water abundance are major factors that drive the quality index. Although both Milwaukee and Madison have similar water production costs, Milwaukee has more than three times the demand and the cost of good quality mains is cheaper than for Madison, which explains why we observe a higher quality index in Milwaukee than in Madison.

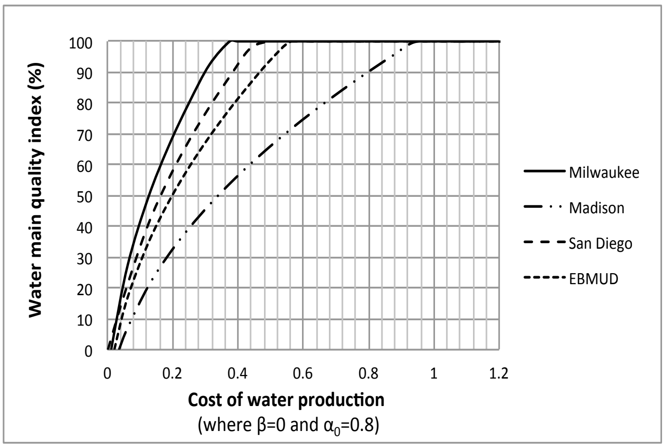

Figure 1.6: The impact of the **cost of water production (ρ)** on the quality index for the US utilities with $\alpha_0 = 0.8$.

Moreover, EBMUD and San Diego are both faced with a larger demand, which implies higher total water production costs and hence greater incentives to reduce leakage. As previously simulated with values of French utilities, we show in Figure 1.7 the impact of α_0 on the quality index. Due to very low water production cost in Madison, there is no incentive for the network to have good quality mains for any level of α_0 below 0.7 (i.e., 70% water loss when all mains are bad quality mains), while San Diego, a utility in a region with scarce water resources, needs 100% good quality mains for any level of α_0 above 0.5.

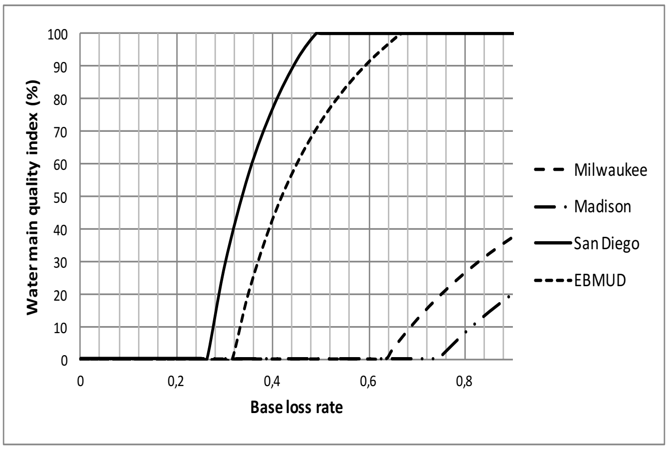

Figure 1.7: The impact of the **base loss rate** (α_0) on the quality index for the four utilities in the U.S. given $\beta = 0$.

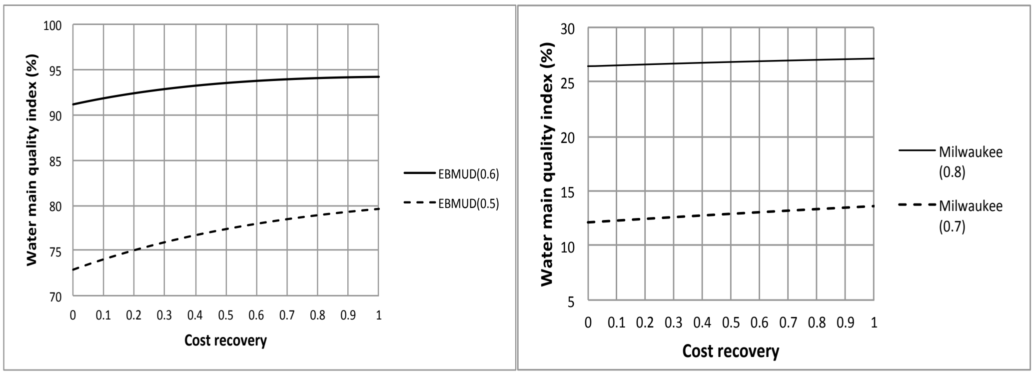

Figure 1.8: Left: The impact of the **cost recovery** (β) on the quality index for EBMUD with $\alpha_0 = 0.6$ for the solid curve and $\alpha_0 = 0.5$ for the dotted curve. Right: The impact of the **cost recovery** (β) on the quality index for Milwaukee with $\alpha_0 = 0.8$ for the solid curve and $\alpha_0 = 0.7$ for the dotted curve.

1.4.4 Cost recovery analysis

From Figures 1.2, 1.3 and 1.7, we can see that for a larger α_0 the quality index is higher, which means that the total cost of good quality mains ($r\overline{M}$) is greater. Given a high total cost, a higher β implies a bigger increase in prices, which in turn results in a bigger negative impact on demand. In this case, there is less further increase in the quality index (represented by the slightly flatter slope of the solid curve compared to the dotted curve in Figure 1.8) since a lower demand lowers the total cost of water production for the utility, leading to a lower incentive for improving mains quality. Moreover, a lower demand may imply a reduction in revenue. According to Brandes et al. (2010), when cost recovery is applied, the price of water rises, which lowers demand, leading to lower revenue and financial struggle. This means that an attempt to recover costs to pay for quality improvement only aggravates the financial situation for the utility; in other words, cost recovery can lead to a vicious cycle. However, our results show the contrary. We observe an increase in revenue as the utility shifts from zero cost recovery to full cost recovery. In the case of French utilities, we compute revenue by multiplying the portion of the price of water that reflects the cost of potable water service by the total demand[24]. In the case of U.S. water utilities, the price of water charged to consumers only reflects the water service's charges; hence, we multiply the observed price by the demand to obtain the revenue. Although demand falls, the rise in price leads to a net increase in revenue. For example, in Tencin, with $\alpha_0 = 0.6$ and $\rho = 1$, demand falls by about 2%; however price increases by 12%. As a result, revenue increases. Similarly, in Milwaukee demand falls by about 3%, but price rises by about 11%, which results in an increase in revenue. In other words, the reduction in demand is compensated for by the rise in price. This result is consistent with the simulation results based on French empirical data conducted by Rinaudo et al. (2012). Furthermore, the total cost, which comprises the total cost of water production and the total cost of good quality mains falls by about 1% in Tencin and 2% in Milwaukee. We then denote the "utility's gain", by the difference between the revenue and the total cost. We show in Figure 1.9 the "net gain" that the utility acquires as they shift from zero cost recovery to full cost recovery. This net gain is the difference between the utility's gain at $\beta = 0$ and $\beta = 1$.

Given the costs of water production, the greater the α_0, the more beneficial it is for the utility to apply full cost recovery for quality improvement. Given the level of α_0, if the cost of water production rises, the more beneficial it is for the utility to enforce full cost recovery. There is a maximum level of net gain, which is attained when the quality index reaches 100%. We make sure that the demand doesn't fall below the "minimum"

[24] In Tencin, about 51% of the price reflects the costs associated with potable water services; hence, to obtain the revenue, we take 51% of the price multiplied by the total demand.

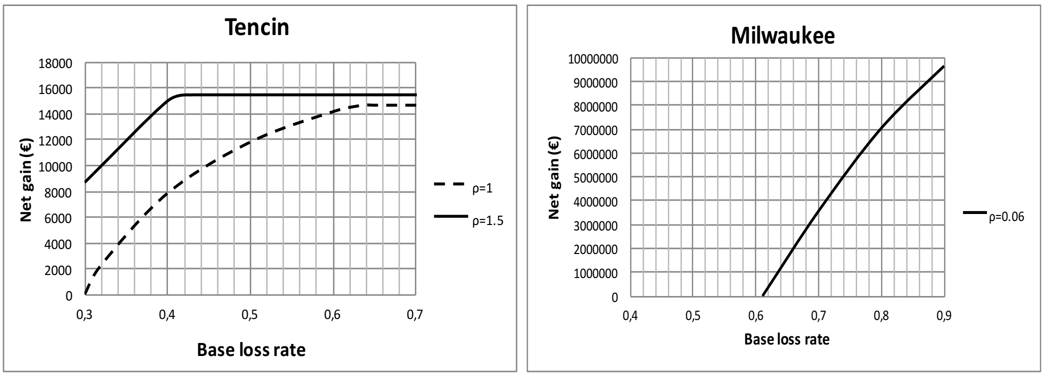

Figure 1.9: Left Figure: The impact of the **critical rate of water loss** (α_0) on the "net gain" of Tencin over different levels of ρ. Right Figure: The impact of α_0 on the "net gain" of Milwaukee when $\rho = 0.06$. The "net gain" is computed as the difference of *revenue* - *total cost* at $\beta = 0$ and at $\beta = 1$.

volume necessary (defined by the WHO), which is 100 litres per day per person, which translates to about 36 m^3 per year per person. For $\rho = 1$, demand when $\beta = 1$ is about 44 m^3 per year per person in Tencin, which is largely above the minimum threshold. Similarly, in Milwaukee, when $\beta = 1$ the demand is about 130 m^3 per year per person, which is lower than the country average, although far above the required minimum. Although cost recovery does not much alter the level of the quality index, it has an unequivocally positive impact on the utility. It could be argued that this benefit is gained at the cost of the rise in price that consumers face; however, the difference in the price is only 46 cents per m^3 (when $\alpha_0 = 0.6$ and $\rho = 1$) in Tencin. Taking the French average consumption per person per year (which is about 50 m^3 per year), the additional annual expense would be about 23 euros per person, or less than 2 euros per month; it is objectively quite small. Similarly in Milwaukee the rise in price is a mere 8 cents. Moreover, in Paris the rise in price is smaller than the French national average; it is about 10 cents. The bigger the demand (the bigger the density), the smaller the rise in price, which again explains why we obtain high quality indices for utilities with urban characteristics.

1.5 Conclusion

In the first part of this chapter, we developed a static cost minimization model of a water utility that faces water loss from water mains. We conducted simulations using French and American data to obtain cost-minimizing water mains quality indices. Our quality index represents the proportion of mains younger than 50 years in the entire main network. This index illustrates the minimalist scenario in which negative environmental externalities and maintenance costs are left out. Hence the values we obtain are in fact the "minimum" quality index that water utilities should achieve. The quality index we obtain for average values for France is close to the actual value we observe today. However, the current average age of most of the water mains in France is over 40 years already; hence in the very near future, these water mains will reach the end of their useful life and begin to degrade rapidly, increasing the rate of water loss. This means that the current quality index will begin to fall and given the current annual replacement rate of water mains in France, which is 0.6%, raising the quality index will be a challenge. Similarly, in the U.S. the annual rate of replacement is about 0.5%, which means that mains are expected to last for about 200 years (Morrison et al., 2013). Although mains installed today could last for about 100 years, a majority of the mains that are in operation today have expected lifetimes of 50 years. Hence, there should be more awarness of the necessity for water mains renewal.

Our results show that regional characteristics have a large impact on the quality index. In particular, the degree of network density which is reflected by the relative size in demand in comparison to the total network size, the difference in main material, the difference between rural and urban areas and geographical differences in water abundance and type, all impact the cost of water production. For example, the greater the demand, the greater the pressure on water loss reduction; hence a higher quality index. Conversely, the cheaper the cost of water production, the lower the incentive to reduce water loss; hence a small quality index is obtained. In addition, we show that the material of the mains has a large impact on the index. The more corrosion-resistant the mains, the lower the leakage from old mains; hence the lower the need for young mains in the network. Moreover, our results revealed the benefits of "cost recovery" for the utilities. Although moving from zero cost recovery to full cost recovery has little impact on the quality index, the utilities' are better off financially. The reason why the quality index is not affected is due to the characteristic of our objective function. In this part of the chapter we defined a cost minimization problem; hence the optimal quality index to the solution of the minimization problem is based on the cost efficient trade off between the cost of water loss and the cost of good quality mains; therefore cost recovery has only a weak indirect effect through quantity demand. We show in the second part under profit maximization that cost recovery has a direct and significant effect through revenue. It is often stated that the rise in prices could trigger a vicious circle by causing a reduction in water demand which would lower revenues and cause further financial distress (Brandes et al., 2010). However, our results show that cost recovery would actually raise revenues for the utility. The increase in prices compensates for the reduction in demand and results in higher revenues for the utilities. Moreover, the utilities benefit the most from full cost recovery when the mains are made of corrosion-prone material and when water resources are costly. However, rural utilities would face a bigger increase in prices than urban ones, due to the fact that the total cost per m^3 of water produced is much greater in small utilities than in bigger ones. Hence, local authorities may set a price cap which may be lower than the full cost recovery level. Hence as Janzen et al. (2016) writes, these small municipalities face the biggest challenge in recovering water supply costs. Solutions such as funding or low-interest loan programs should be available for utilities that struggle to meet replacement needs due to exceeding price thresholds when cost recovery is applied. Overall, our simple model provides important insights into the determinants of mains leakage reduction. Various parameters play a key role in making the decision to reduce leakage. The values assigned to these parameters are essential in determining the cost-effective quality index. An accurate valuation of these parameters (for example reflecting the intrinsic value of water in the water extraction cost) would allow the utility to realize a low leakage level while remaining cost-efficient. In the next part of this chapter we develop a profit maximization problem. In this framework the utilities' decisions to engage in network renewal would depend on profits. Under profit maximization the positive impact of cost recovery on revenue will affect the optimal water main network quality. We further explore the effect of price caps, leakage detection activities and the effect of organizational structures of water provision (private vs public vs outsourcing).

1.6 Appendix

1.6.1 Appendix 1

The following is the comparative statics of the first order condition:

When the price of water extraction increases

$$\frac{d\overline{M}}{d\rho} = \frac{\alpha'_{\overline{M}} q\left(\overline{M}\right) + q'_{\overline{M}}\left(1 - \alpha\left(\frac{\overline{M}}{M}\right)\right)}{\left(2(r-m)\left(1 - \alpha\left(\frac{\overline{M}}{M}\right)\right)\alpha'_{\overline{M}} - \rho\alpha''_{\overline{M}} q\left(\overline{M}\right) - \rho q''_{\overline{M}}\left(1 - \alpha\left(\frac{\overline{M}}{M}\right)\right)\right)} \geqslant 0$$

$$\frac{dW^l}{d\rho} = \frac{\alpha'_{\overline{M}} q\left(\overline{M}\right)}{\left(1 - \alpha\left(\frac{\overline{M}}{M}\right)\right)}\left(1 + \frac{\alpha\left(\frac{\overline{M}}{M}\right)}{\left(1 - \alpha\left(\frac{\overline{M}}{M}\right)\right)} + \frac{\alpha\left(\frac{\overline{M}}{M}\right) q'_{\overline{M}}}{\alpha'_{\overline{M}} q\left(\overline{M}\right)}\right)\left(\frac{d\overline{M}}{d\rho}\right) \leqslant 0$$

When the cost of bad quality mains (maintenance cost) increases:

$$\frac{d\overline{M}}{dm} = \frac{\left(1 - \alpha\left(\frac{\overline{M}}{M}\right)\right)^2}{\left(\rho q\left(\overline{M}\right)\alpha''_{\overline{M}} + q''_{\overline{M}}\left(1 - \alpha\left(\frac{\overline{M}}{M}\right)\right)\rho - 2(r-m)\left(1 - \alpha\left(\frac{\overline{M}}{M}\right)\right)\alpha'_{\overline{M}}\right)} \geqslant 0$$

$$\frac{dW^l}{dm} = \frac{\alpha'_{\overline{M}} q\left(\overline{M}\right)}{\left(1 - \alpha\left(\frac{\overline{M}}{M}\right)\right)}\left(1 + \frac{\alpha\left(\frac{\overline{M}}{M}\right)}{\left(1 - \alpha\left(\frac{\overline{M}}{M}\right)\right)} + \frac{\alpha\left(\frac{\overline{M}}{M}\right) q'_{\overline{M}}}{\alpha'_{\overline{M}} q\left(\overline{M}\right)}\right)\frac{d\overline{M}}{dm} \leqslant 0$$

When the cost of good quality mains increases:

$$\frac{d\overline{M}}{dr} = -\frac{\left(1 - \alpha\left(\frac{\overline{M}}{M}\right)\right)^2}{\left(\rho q\left(\overline{M}\right)\alpha''_{\overline{M}} + q''_{\overline{M}}\left(1 - \alpha\left(\frac{\overline{M}}{M}\right)\right)\rho - 2(r-m)\left(1 - \alpha\left(\frac{\overline{M}}{M}\right)\right)\alpha'_{\overline{M}}\right)} \leqslant 0$$

$$\frac{dW^l}{dr} = \frac{\alpha'_{\overline{M}} q\left(\overline{M}\right)}{\left(1 - \alpha\left(\frac{\overline{M}}{M}\right)\right)}\left(1 + \frac{\alpha\left(\frac{\overline{M}}{M}\right)}{\left(1 - \alpha\left(\frac{\overline{M}}{M}\right)\right)} + \frac{\alpha\left(\frac{\overline{M}}{M}\right) q'_{\overline{M}}}{\alpha'_{\overline{M}} q\left(\overline{M}\right)}\right)\frac{d\overline{M}}{dr} \geqslant 0$$

1.6.2 Appendix 2

The first order condition implies

$$\rho q\left(\overline{M}\right)\alpha'_{\overline{M}}+\rho q'_{\overline{M}}\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)+\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)^{2}(r-m)=0$$

with

$$q\left(\overline{M}\right)=\frac{q_0}{\left(\left(\frac{r\overline{M}}{q_0}\right)\beta+\overline{p}\right)^{\theta}}$$

and

$$\alpha\left(\frac{\overline{M}}{M}\right)=\alpha_0\left(1-\frac{\overline{M}}{M}\right)$$

The derivative of the implicit function with respect to $\overline{M}$ and β gives

$$\left[\rho q\left(\overline{M}\right)\alpha''_{\overline{M}}+\rho q''_{\overline{M}}\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)+2\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)\alpha'_{\overline{M}}(r-m)\right]d\overline{M}+\left[\rho q'_{\beta}\alpha'_{\overline{M}}+\rho q''_{\overline{M}\beta}\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)\right]$$

According to the functions we have specified, we have

$$\begin{aligned}
\alpha'_{\overline{M}} &= -\frac{\alpha_0}{M}<0\\
\alpha''_{\overline{M}} &= 0\\
q'_{\overline{M}} &= -\frac{\theta r\beta}{\left(\left(\frac{r\overline{M}}{q_0}\right)\beta+\overline{p}\right)^{\theta+1}}<0\\
q'_{\beta} &= -\frac{\theta r\overline{M}}{\left(\left(\frac{r\overline{M}}{q_0}\right)\beta+\overline{p}\right)^{\theta+1}}<0\\
q''_{\overline{M}} &= \frac{\theta\left(\theta+1\right)r\beta^{2}\left(\frac{r}{q_0}\right)}{\left(\left(\frac{r\overline{M}}{q_0}\right)\beta+\overline{p}\right)^{\theta+2}}>0\\
q''_{\overline{M}\beta} &= -\theta r\frac{\overline{p}-\theta\beta\left(\frac{r\overline{M}}{q_0}\right)}{\left(\left(\frac{r\overline{M}}{q_0}\right)\beta+\overline{p}\right)^{\theta+2}}<0\Longleftrightarrow\overline{M}<\frac{\overline{p}q_0}{\theta\beta r}
\end{aligned}$$

and

$$\frac{d\overline{M}}{d\beta} = -\frac{\rho q'_{\beta}\alpha'_{\overline{M}} + \rho q''_{\overline{M}\beta}\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)}{\rho q''_{\overline{M}}\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right) + 2\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)\alpha'_{\overline{M}}r}$$

The denominator and the numerator can be either positive or negative depending on the level of $\overline{M}$. However, in our simulations, we see that the derivative is always positive (sometimes very close to zero).

Finally the demand reaction is given by

$$\frac{dq}{d\beta} = \frac{\partial q}{\partial \beta} + \frac{\partial q}{\partial \overline{M}}\frac{\partial \overline{M}}{\partial \beta}$$

1.6.3 Appendix 3: Figures

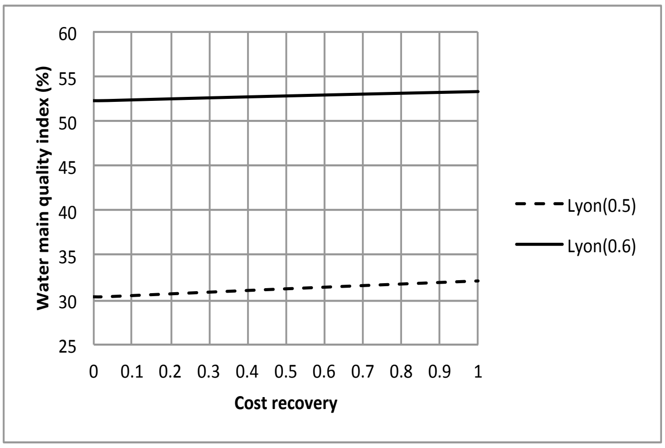

Figure 1.10: The impact of the **cost recovery** (β) on the quality index for Lyon with $\alpha_0 = 0.6$ for the solid curve and $\alpha_0 = 0.5$ for the dotted curve.

Part II

Profit maximizing water main quality index

In this section we develop a profit maximization problem which complements the analysis based on the cost minimization approach which was presented in Part I. The reason why we analyze both cost minimization and profit maximization is because cost minimization reveals the minimum water main quality index that utilities should achieve based on the trade off between the cost of water loss and the cost of good quality mains; whereas profit maximization takes into account the revenue generated by the utility which reflects a different decision making process for network renewal. Previously we have seen that cost recovery had almost no impact on the resulting quality index. Here we show that cost recovery can have a large impact on the resulting quality index through its direct effect on revenue. If water demand is assumed to be perfectly inelastic, higher prices have no impact on the quantity demanded, which means that higher prices would only imply higher revenue. We study both perfectly inelastic demand and inelastic demand.

Results show that profit maximization objectives lead to quality indices that are excessive, which are no longer cost efficient in terms of the trade off between the cost of water loss and the cost of good quality mains. However, we remind the readers that the cost efficient quality index we obtained in the first part is a minimalist scenario. Hence, quality indices above the cost efficient level is not "bad news", on the contrary the higher the quality, the lower the water loss. However high quality comes at the expense of unnecessary rise in prices which effect consumers negatively. As we have already mentioned in the previous section, cost recovery can lead to large price hikes in small utilities compared to large ones. In large utilities cost recovery has very little impact on the price per m^3 of water. We further show that this price rise becomes constraining for rural utilities due to price caps. Results show that lowering water loss and recovering costs can be incompatible in rural utilities.

1.7 Theoretical Model

We consider a fully public, fully private and an outsourced utility. Under pure in-house provision and private provision, the decision to engage in network renewal is taken by the same entity that operates the service provision; whereas the delegated firm in charge of water provision does not make decisions concerning network renewal. Their responsibility concerning network quality depends on the objective specified in the contract. This situation illustrates the water industry in France. Ownership of the water infrastructure remains under the state; however service provision could take several forms which can be generalized as in-house provision, outsourced provision or fully private provision. In order to distinguish fully private provision to fully public provision, we set different price caps. Public utilities would be influenced by local electoral results; hence, the opinion of the voters is important concerning the prices (Chong et al., 2015). In other words, higher prices would have an influence on the popularity of local authorities; hence price caps are lower in public utilities. This difference has already been shown in many empirical papers that analyze the effect of organizational structures on water price. Moreover, we introduce the "efficiency" of the network quality. In other words, $\frac{\overline{M}}{M}$ could have a different impact on the overall water loss $W^l = \alpha\left(\frac{\overline{M}}{M}\right)W^{in}$ depending on the efficiency of the good quality mains ($\overline{M}$). Not all old mains have the same degree of leakage as one another; hence, the resulting network quality would only be optimal if the worst (most leaky pipes) are selected for renewal. Utilities that do not engage in leakage detection activities may achieve inefficient network quality. Most utilities are aware of the proportion of old mains in their network; however, prioritizing and pin-pointing those that are the most problematic is the challenge. High network quality may not necessarily be associated with the minimum water loss. Therefore, we integrate this efficiency factor in our water loss function.

The variables and parameters are represented with the same labels and symbols as in the cost minimization problem. Moreover, we remain in a static framework; hence we do not use the term "investment" or "replacement" concerning water mains network renewal. Instead, we use "network quality" to represent a given state of the network representing a proportion of non-replaced mains (bad quality mains) and replaced mains (good quality mains).

The profit of the utility is defined as:

$$\Pi(\overline{M}, \underline{M}, W^{in}, q) = pq - \rho W^{in} - r\overline{M} - m\underline{M} \tag{1.14}$$

where p is the price per unit of water paid by users and q is the total volume of water demanded. ρ, r and m are fixed parameters that represent the cost per unit of water production (W^{in}), the cost per unit of good quality mains ($\overline{M}$) and the cost per unit of bad quality mains ($\underline{M}$). Here m reflects the cost of leakage detection and temporary repair activities of bad quality mains.

As in Part I, water loss is defined as a fraction of the water supply:

$$W^l = \alpha\left(\frac{\overline{M}}{M}, m\right) W^{in}, \tag{1.15}$$

where $\alpha\left(\frac{\overline{M}}{M}, m\right)$ is the fraction of water lost through the water distribution system. It could also be interpreted as the "conveyance loss rate" specified in the article by Chakravorty et al. (1995). Moreover $\alpha'_{\overline{M}}(\cdot) \leq 0$ and $\alpha''_{\overline{M}}(\cdot) \geq 0$, in other words the greater the network quality, the smaller the water loss. Furthermore, $\alpha'_m(\cdot) \leq 0$ and $\alpha''_m(\cdot) \geq 0$ which implies that the greater the leakage detection cost, the lower the water loss. The efficiency of leakage detection is reflected by the cost because leakage detection activities with high performance have higher costs. We present further details later when we specify this function. In general, for the same level of water main quality, utilities that invest in leakage detection achieve lower water loss volumes.

As we have specified in the cost minimization problem, the total amount of water delivered should satisfy the total demand (q). Although the elasticity is very small, we define demand as a function of prices. Moreover, these prices vary depending on good quality mains since costs are covered in the price. Therefore we define demand as $q(p(\overline{M}))$ where $q'(\cdot) \leq 0$ and $q''(\cdot) \geq 0$.

The program of profit maximization writes as follows:

$$\max \quad \Pi(\overline{M}, \underline{M}, W^{in}, q)$$

$$\begin{aligned}
\text{subject to:} \quad & W^{in} - W^{l} \geqslant q\left(p\left(\overline{M}\right)\right) \\
& W^{l} = \alpha\left(\frac{\overline{M}}{M}, m\right) W^{in} \\
& \overline{M} + \underline{M} = M \\
& W^{in} > 0 \\
& \overline{M}, \underline{M}, W^{l} \geqslant 0 \\
& 0 \leqslant \alpha\left(\frac{\overline{M}}{M}, m\right) < 1
\end{aligned}$$

where the constraints are the same as in the cost minimization program. After substituting the constraints, we obtain the following profit function as a function of the good quality mains.

$$\Pi(\overline{M}) = p(\overline{M})q(\overline{M}) - \frac{\rho q(\overline{M})}{1 - \alpha\left(\frac{\overline{M}}{M}, m\right)} - r\overline{M} - m(M - \overline{M}) \tag{1.16}$$

The first order condition is given by:

$$\frac{\partial\Pi}{\partial\overline{M}} = p'(\overline{M})q(\overline{M}) + p(\overline{M})q'(\overline{M}) - \frac{\rho q'(\overline{M})}{\left(1-\alpha\left(\frac{\overline{M}}{M},m\right)\right)} - \frac{\rho q(\overline{M})\alpha'\left(\frac{\overline{M}}{M},m\right)}{\left(1-\alpha\left(\frac{\overline{M}}{M},m\right)\right)^2} - (r-m) \tag{1.17}$$

When an interior solution exists, the optimal proportion of good quality mains is the solution to $\frac{\partial\Pi}{\partial\overline{M}} = 0$.

The following second order condition confirms that the optimal quantity $\overline{M}$ indeed maximizes profits.

$$\frac{\partial^2\Pi}{\partial\overline{M}^2} = p''(\overline{M})q(\overline{M}) + 2p'(\overline{M})q'(\overline{M}) + p(\overline{M})q''(\overline{M}) - \frac{\rho q''(\overline{M})}{\left(1-\alpha\left(\frac{\overline{M}}{M},m\right)\right)} \tag{1.18}$$

$$-\frac{2\rho q'(\overline{M})\alpha'\left(\frac{\overline{M}}{M},m\right)}{\left(1-\alpha\left(\frac{\overline{M}}{M},m\right)\right)^2} - \frac{\rho q\alpha''(\frac{\overline{M}}{M},m)}{(1-\alpha\left(\frac{\overline{M}}{M},m\right)^2)} - \frac{2\rho q(\overline{M})\left(\alpha'\left(\frac{\overline{M}}{M},m\right)\right)^2}{\left(1-\alpha\left(\frac{\overline{M}}{M},m\right)\right)^3} \leqslant 0 \tag{1.19}$$

The implicit form of the optimal solution is given as follows:

$$p'(\overline{M})q(\overline{M}) + p(\overline{M})q'(\overline{M}) - \frac{\rho q'(\overline{M})}{\left(1-\alpha\left(\frac{\overline{M}}{M},m\right)\right)} - \frac{\rho q(\overline{M})\alpha'\left(\frac{\overline{M}}{M},m\right)}{\left(1-\alpha\left(\frac{\overline{M}}{M},m\right)\right)^2} = (r-m) \tag{1.20}$$

The water loss function is defined as:

$$\alpha\left(\frac{\overline{M}}{M},m\right) = \alpha_0 \cdot \left(\frac{1-\frac{\overline{M}}{M}}{\sqrt{1+\frac{m}{m_{max}}}}\right) \tag{1.21}$$

where α_0 is the base loss rate, when the network has zero good quality mains, m_{max} is the maximum cost of leakage detection. High performance leakage detection tools and methods have higher costs, such as electronic acoustic devices; whereas a mechanical acoustic device may cost much less with lower precision. We can see that if the entire main network is composed of good quality mains ($M = \overline{M}$), $\alpha(1,m) = 0$ no matter the amount of leakage detection. On the other hand, if the entire network is composed of bad quality mains ($M = \underline{M}$) and leakage detection costs are high ($m = m_{max}$), $\alpha(0, m) = \alpha_0 \frac{1}{\sqrt{2}} < \alpha_0$, which means that even with no good quality mains, thanks to leakage detection activities which include temporary repair or water pressure control, water loss can be lowered. Furthermore, for example if the quality index $\left(\frac{\overline{M}}{M}\right)$ is 0.5 and $\frac{m}{m_{max}} = 0$, $\alpha = \alpha_0 \cdot 0.5$; whereas if $\frac{m}{m_{max}} = 1$ then $\alpha = \alpha_0 \cdot 0.35$ which shows that leakage detection improves the efficiency of the network quality in terms of water loss reduction.

The quantity demand function is defined as previously in equation (1.11):

$$q(p) = \frac{q_0}{p\left(\overline{M}\right)^{\theta}}$$

where q_0 is the unconstrained demand, the annual average quantity desired by households and θ is the price elasticity of demand.

The price function is defined as following:

$$p\left(\overline{M}\right) = \min\left[\left(\frac{r\overline{M}}{q_0}\right)\beta + \overline{p}\ ,\ p_{max}\right]$$

where $\left(\frac{r\overline{M}}{q_0}\right)\beta + \overline{p}$ is the same as the price equation (1.12), where β is the cost recovery parameter. If $\beta = 1$, the total cost of good quality mains is recovered by the price of water paid by users. The cost of leakage detection is considered as operational costs which should be included in $\overline{p}$. This price has a threshold level defined by p_{max}.

The comparative statics (derivative of $\overline{M}$ with respect to ρ, r, m) are presented in the Appendix. The marginal effect of these key parameters on the quantity of good quality mains has the same sign as in Part I but with different magnitudes. We discuss in depth these differences in the next section where we present our simulation results.

1.8 Simulation

We calibrate our parameters using data from SISPEA, the same source used in the first part of the chapter. In addition to the four utilities presented in Table 1.2 in Part I, we selected few other utilities in order to take into account the different organizational structures. We set higher price caps (p_{max}) for private utilities and in order to reflect the cost of good quality mains on the price, we set $p_{max} > \overline{p}$. The value of $\overline{p}$ is the total price that users pay for water supply. It includes the cost of water distribution, taxes and the cost of wastewater services. It does not include the cost of good quality mains; hence in order to observe the impact of cost recovery via the rise in prices on the quality index, we set p_{max} to a value that is higher than $\overline{p}$. Here, we set $\alpha_0 = 0.4$ instead of $\alpha_0 = 0.6$ since the simulated quality indices for all the utilities are 100% under $\alpha_0 = 0.6$. The aim of our analysis is to be able to detect variations in the optimal quality index based on the utility-specific characteristics; hence we simulate with $\alpha_0 = 0.4$[25] which allows more variation in resulting quality indices. As we have shown in Part I Figure 1.4, network quality is very sensitive to the unit cost of water production (ρ). However, we do not have precise information of ρ for each utility; hence, as a close estimate, we used the price of water distribution as an approximate value for this cost. In practice, the total price of water is composed of taxes, wastewater services and water distribution costs. We decomposed the part of the price that only reflects the cost of water production by removing taxes and any other fees that are associated with other costs. We are aware that this is an approximation; however, it gives an idea of the difference in the cost of water production among the utilities. It is much more informative than setting the same value of ρ for all the utilities. We set higher price caps for private and outsourced utilities compared to public utilities. It has already been shown in the empirical studies such as that of Chong et al. (2015) that private utilities tend to set higher prices. Private utilities or private provision are associated with higher water quality; which is reflected by larger unit costs of water production. Indeed we can see this in Table 1.4 as well.

[25] This means that when the entire water main network consists only of bad quality mains ($M = \underline{M}$), the water loss reaches 40% of the total water supply.

The unit cost of water production (ρ) is generally higher in outsourced and private utilities. We provide two indicators of water loss; one is in terms of the proportion of total water production and the second one is an index that shows the volume of water loss per length of main. We can see that large percentages do not necessarily imply that the volume of water loss is high. Percentage values alone could be misleading to the readers since it only depends on the total volume produced. Water loss could appear to be very small if the total volume of water production is large. We also indicate the number of communes that the utility supplies water to. Large intercommunal utilities may be able to benefit from economies of scale by sharing the burden of costs.

We present two sets of results. The first set is based on the assumption that all six utilities have set network renewal as their principal objective. This means that they are all engaged in leakage detection activities. Therefore, we set m (cost of leakage detection) to its maximum value. Information and precise values of m are difficult to obtain for the case of France; therefore we estimated using information assembled principally from Uni-Bell (2011), which has already been presented in Part I. Conerning leakage detection activities in France, the website of *wikiwater* presents information on the cost of leakage detection tools which could range from 300 euros to 12,000 euros; the cheapest with the lowest performance level (the basic acoustic detection) and the most expensive one with the highest performance level. Maintenance costs on average based on North American data is about \$1,500 per miles of mains; hence for rural utilities, we simulate over a range of 0 to 1000 Euros per kilometer of mains and for an urban utility (parallel to the fact that replacement costs could be four times greater than in rural utilities), we vary the cost between 0 to 4000 Euros per kilometer. The results in Table 1.4 and 1.5 are based on the maximum value of m; however, we vary m from minimum to maximum in the sensitivity analysis presented later. In the same Tables, we also present results based on the assumption that network renewal is not specified in the contract signed by the outsourcing firms. This set of results does not concern the fully public or fully private utilities. Local authorities could set objectives other than network renewal; such as water quality improvement. In this case the delegated firm will not engage in leakage detection; hence we set $m = 0$. The results in Table 1.4 reveals the optimal quality index for large urban utilities and results in table 1.5 reveals the optimal quality index for rural utilities.

	(A)[26]	(B)	(C)	(D)	(E)	(F)
Operator type	public	public	delegated	delegated	private	private
M (km)	2097	415	3074	605	914	375
q_0 (m^3)	221,632,479	12,032,353	79,967,392	11,801,896	10,077,390	8,256,215
ρ ($Euros/m^3$)	1.1	0.9	1.6	1.4	1.8	1
$\overline{p}$ ($Euros/m^3$)	3.28	2.83	3.35	4.13	5.67	4.09
p_{max} ($Euros/m^3$)	4	4	4	5	6	5
Density (inhabitant per km of main)	1084	374	371	264	181	314
Current rate of water loss (%)	8.3	12.3	20	22	21	9.34
Water loss index ($m^3/km/day$)	21	9.6	15.9	18.1	6.96	6.3
Number of communes	1	1	33	4	20	1
	Network renewal objectives defined: $m = m_{max} = 4000Euros/km$ for all utilities					
$\overline{M}/M$ (%) ($\beta = 0$, $\theta = 0.2$)	**100**	**52**	**100**	**48**	**0**	**17**
$\overline{M}/M$ (%) ($\beta = 1$, $\theta = 0.2$,)	**100**	**100**	**100**	**100**	**67** ($\beta = 0.45$)	**100**
$\overline{M}/M$ (%) ($\beta = 0$, $\theta = 0$)	**100**	**86**	**100**	**94**	**43**	**58**
$\overline{M}/M$ (%) ($\beta = 1$, $\theta = 0$)	**100**	**100**	**100**	**100**	**100**	**100**
	Network renewal objectives not defined for delegated utilities[27]					
$\overline{M}/M$ (%) ($\beta = 0$, $\theta = 0.2$)	·	·	**0**	**0**	·	·
$\overline{M}/M$ (%) ($\beta = 1$, $\theta = 0.2$,)	·	·	**100**	**80**	·	·
$\overline{M}/M$ (%) ($\beta = 0$, $\theta = 0$)	·	·	**16**	**0**	·	·
$\overline{M}/M$ (%) ($\beta = 1$, $\theta = 0$)	·	·	**100**	**100**	·	·

Table 1.4: Profit maximizing water main quality indices of urban utilities with different organizational structures. The base loss rate is set to $\alpha_0 = 0.4$, and the cost of good quality mains is $r = 12,000 Euros/km$

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[26] The calibrated values are based on data of certain selected utilities from 2013 in the database of SISPEA which could be found online on the website of Observatoire national des services d'eau et d'assainissement. Utility (A): Paris, (B): Aix-en-Provence, (C): Lyon, (D): Dijon, (E): Syndicat des eaux du Valenciennois, (F): Orleans

[27] Leakage detection cost is set to $m = 0$ and the base loss rate is set to $\alpha_0 = 0.2$.

Cost recovery effect

We begin with the analysis of the first set of results in Table 1.4. We can see that under full cost recovery ($\beta = 1$), the optimal water main quality index is 100% for 5 out of 6 utilities. We notice that most of them reach a quality index of 100% without fully recovering the costs of good quality mains. At elasticity $\theta = 0.2$, utility (B) reaches 100% quality index at 25% cost recovery ($\beta = 0.25$) with a resulting price of 2.94 Euros, utility (D) reaches 100% at 30% cost recovery ($\beta = 0.3$) with a resulting price of 4.32 Euros and utility (F) reaches 100% at 45% cost recovery ($\beta = 0.45$) with a resulting price of 4.34 Euros. This implies that without full recovery of the costs of good quality mains, it is profit maximizing to have 100% water main quality index. These results reveal a particular characteristic of urban utilities in the sense that water loss reduction is clearly a priority and it is beneficial for the utility. However, we can see that utility (E) does not match this criteria. We see that 100% quality index is not possible for (E) because price exceeds the price cap ($p_{max} = 6$) at 67% quality index. We notice that the unit cost of water production (ρ) is the highest and the density is the lowest among the others. Moreover, the relative size of the network (total length of mains) to the size of demand is the largest for (E); reflecting a lack of economies of network density (Mizutani and Urakami, 2001). This means that the relative cost of water loss to the cost of good quality mains is smaller compared to utilities that have economies of network density. A smaller trade-off of cost of water loss to cost of good quality mains imply that the reduction of water loss represents a large cost burden to the utility. Overall, the fact that the cost of water production is high implies that the cost of water loss is high as well, hence it creates an incentive for water loss reduction (more good quality mains). However, due to small economies of network density, cost recovery has a larger marginal effect on price rise. Hence, price reaches the price cap faster. This creates a dilemma; the utility needs high quality index but the price cap constrains the index to a certain limit. As a note to the readers, the fact that value of density is the smallest does not imply that density by itself is an indicator for quality index. We show later that although in rural utilities, density is on average smaller than in large urban utilities, quality indices could reach 100% for some of them. While density is highly associated with the volume of water loss per length of mains, the quality indices are influenced by a combination of the utility-specific characteristics, in particular the cost of water production and the relative size of the length of network to demand which reflects potential economies of network density.

The quality indices without full cost recovery ($\beta = 0$) corresponds to the cost-efficient quality index. In other words, the simulated quality index essentially depends on the trade off between the cost of water loss and the cost of good quality mains. We can see that utilities (B), (D), (E) and (F) have quality indices less than 100%. This means that in terms of cost efficiency, 100% quality index is unnecessary. We have shown in Part I that cost recovery had almost no impact on the quality index; whereas, here we show that the optimal quality index rises to 100% for a very small increase in cost recovery ((B), (D) and (F)). This is because under profit maximization, higher cost recovery implies higher revenue, therefore raising the network quality beyond the (minimum) cost efficient level is beneficial for the utility. Moreover due to the predominance of economies of network density in large cities, the marginal effect of cost recovery on prices is small; hence the demand reacts little; which means that there are two forces that drive up the quality index for $\beta > 0$. On the one hand, the drop in demand is negligible, hence water loss does not vary much; on the other hand revenue rises due to higher prices; hence, both forces have a positive impact on the quality index.

Effect of cost of water production

We see in Table 1.4 that the quality index for utility (A) and utility (C) is always at 100%. Although the density in (A) is a third that of (C), the optimal quality index reaches 100% in both cases. The cost of water production is one of the reasons why the quality index in (C) is as high as in (A). Higher cost of water production implies that the cost of water loss is also high ($\rho W^l = \rho(\alpha W^{in})$); therefore, water loss reduction is profitable for (C). But this also depends on the relative cost of good quality mains. Overall, it is beneficial for (C) to have 100% water main quality index.

Current water loss vs simulated optimal water mains quality index

Although our simulation results show that in some cases 100% network quality is optimal in terms of cost efficiency or profit maximization or both for the utility; we may not observe such results in reality. The current water loss rates and water loss indices in Table 1.4 reveal that actual network quality is lower than 100%. For instance, the current observed water loss rate of (A) is 8.3%, which is the smallest among the six utilities which should imply a high quality index in reality (if we consider that in reality there are minimum unavoidable water loss in water networks); however, in terms of water loss index ($21m^3/km/day$), it is the highest. It is shown that where there is high density, water loss tend to be high as well due to numerous service connections that are connected to the water mains. These service connections is one of the main sources of fragility and aging of mains. However, in reality utilities may reason by the fact that 8% water loss is quite small, that replacement is not worth it. On the other hand, utility (E) has a current rate of water loss of 21% which implies lower network quality index; however, in terms of water loss indices, it is about $7m^3/km/day$, which is a third that of (A). Hence, relatively speaking, it is difficult to judge which utility has a better water main network quality than the other based on observed percentages. The optimal index that we obtain is based on the trade off between the total cost of water loss *volume* and the total cost of good quality mains; hence, the resulting simulated index does not depend on the reported water loss rate based on the size of water production. This is why water loss threshold guidelines may be misleading; such as the Grenelle II[28], which specifies thresholds of 15% water loss for urban utilities and 20% for rural utilities.

[28] It is a law on environmental regulation put in place in 2010 in France.

The effect of outsourced provision

The second set of results in Table 1.4 shows the situation in which network renewal is not specified in the contract signed by the outsourcing firm (utilities (C) and (D)). The fact that network renewal is not specified, we assume that the utility does not engage in leakage detection ($m = 0$) and the utility behaves as if the network is in a very good condition; which could be represented by a very small value of α_0, which we set to 0.2. In this case, the quality index could be 0%. This type of situation does not imply that the utilities are underperforming; it is simply due to the underlining structure of outsourcing. Outsourced utilities are not required to take part in network quality management unless specified in the contract since they are remunerated for what they are asked for in addition to the fees collected by the users. Therefore if the contract specifies water quality objectives, there is no incentive for the delegated firm to exert effort on leakage reduction activities; instead invest in water treatment methods. Moreover, the delegated firm has all the information concerning the condition of the network; hence, even if water loss is high, if they're earnings do not depend on the volume of water loss, there is no need for altering the objective of the contract.

Effect of price elasticity of demand

We analyse both perfect inelastic demand ($\theta = 0$) and inelastic demand ($\theta = 0.2$). If demand is perfectly inelastic, households would consume more than if they were somewhat responsive to prices, which means that the utility would be confronted with greater water production. As we already mentioned previously, higher water production raises the proportion of water lost through leakage, which raises the incentive to raise water main quality indices. Therefore, quality indices increase even when $\beta = 0$. Furthermore, we can see that for utility (E), under inelastic demand ($\theta = 0.2$), the maximum quality index achievable was 67% (limited to 45% cost recovery due to price cap); however, under perfect inelasticity, this index can reach 100%. This is because there is no longer a negative impact of price hikes on the quantity demanded. In other words, higher revenue and larger water production both effect positively the quality index.

We now present the results for rural utilities in Table 1.5.

	(G)[29]	(H)	(I)	(J)	(K)	(L)
Operator type	public	public	delegated	delegated	private	private
M (km)	15.1	55	13.94	27.9	77.91	12.88
q_0 (m^3)	37,197	170,834	86,075	69,456	262,047	48,110
ρ $(Euros/m^3)$	1.25	0.9	1.9	2	1.2	2
$\overline{p}$[30] $(Euros/m^3)$	3.5	3.6	3.82	4.2	4.7	3.9
p_{max} $(Euros/m^3)$	4	4	5	5	5	5
Density (inhabitant per km of main)	48	27	105	47	41	44
Current rate of water loss (%)	33	9.8	6	30	27	25
Water loss index $(m^3/km/day)$	2.89	0.71	0.83	2.42	2.58	2.75
Number of communes	1	9	1	1	1	1
	Network renewal objectives defined: $m = m_{max} = 1000 Euros/km$ for all utilities					
$\overline{M}/M$ (%) $(\beta = 0, \theta = 0.2)$	**0**	**0**	**100**	**3.5**	**0**	**64**
$\overline{M}/M$ (%) $(\beta = 1, \theta = 0.2,)$	**65** $(\beta = 0.6)$	**63** $(\beta = 0.65)$	**100**	**100**	**61** $(\beta = 0.55)$	**100**
$\overline{M}/M$ (%) $(\beta = 0, \theta = 0)$	**0**	**0**	**100**	**43**	**14**	**100**
$\overline{M}/M$ (%) $(\beta = 1, \theta = 0)$	**100**	**98** $(\beta = 0.4)$	**100**	**100**	**100**	**100**
	Network renewal objectives not defined for delegated utilities[31]					
$\overline{M}/M$ (%) $(\beta = 0, \theta = 0.2)$	·	·	**0**	**0**	·	·
$\overline{M}/M$ (%) $(\beta = 1, \theta = 0.2,)$	·	·	**74** $(\beta = 0.5)$	**28**	·	·
$\overline{M}/M$ (%) $(\beta = 0, \theta = 0)$	·	·	**42**	**0**	·	·
$\overline{M}/M$ (%) $(\beta = 1, \theta = 0)$	·	·	**100**	**95** $(\beta = 0.7)$	·	·

Table 1.5: Profit maximizing water main quality indices of rural utilities with different organizational structures. The base loss rate is $\alpha_0 = 0.4$ and the cost of good quality mains is $r = 3,000 Euros/km$.

[29] The calibrated values are based on data of certain selected utilities from 2013 in the database of SISPEA which could be found online on the website of Observatoire national des services d'eau et d'assainissement. Utility (G): Rimaucourt , (H): SIAEP de Frucourt, (I): Tencin, (J): Sainte Lizaigne, (K): Uzerche, (L): Chailley

[30] We could not obtain the specific prices for all rural utilities; hence, $(\overline{p})$ values are set to average prices of the *departement* that the utility belongs to.

[31] Leakage detection cost is set to $m = 0$ and the base loss rate to $\alpha_0 = 0.2$.

Cost recovery effect

Table 1.5 shows that in the case of rural utilities, 100% quality index is difficult to achieve; especially if the price elasticity of demand is $\theta = 0.2$. This is essentially due to the trade off between the cost of water loss relative to the cost of good quality mains reflected by the lack of economies of network density which is further reflected on the marginal effect of cost recovery on prices. If $\overline{p}$ is already quite high, there is little room for recovering costs through raising prices before reaching the price cap. Rural utilities in general have a much greater impact of cost recovery on price per m^3 of water than in urban utilities; hence, the difference between $\overline{p}$ and p_{max} is much more constraining. This is typically the case in fully public utilities; which set lower price caps. However, utility (K), which is a fully private one, also faces the same dilemma. We notice that the length of their network is the largest in comparison to others. Very large networks could be a reason for huge price hikes if not met with a relatively large demand since the costs are reflected on the price per m^3 of water paid by users. Moreover in comparison to the urban utilities, utility (J) and (L) reaches 100% quality index at $\beta = 0.55$ and $\beta = 0.2$ respectively. The price rises to 4.95 Euros for utility (J); which is very near the price cap. On the other hand, the price of utility (L) reaches 4.06 Euros, which is quite far from the price cap. Utility (L) reflects a similar characteristic of an urban utility, where 100% quality index can be reached at low degrees of cost recovery accompanied by a small rise in prices. This is because economies of network density is present. Similarly to typical urban utilities, the trade off between the cost of water loss relative to the cost of good quality mains is larger. The cost of water loss is high in (L) due to the cost of water production; moreover, the length of their network is the shortest. The length is most closely relatable to that of utility (I); however, their demand is twice the size of (L); hence in terms of pure cost efficiency, the quality index of (L) is 64%; whereas it is 100% for (I). However, with a small rise in cost recovery the quality index of (L) reaches 100%; essentially due to the positive effect on revenue from higher prices.

Impact of cost of water production

As we have seen previously for urban utilities, the unit cost of water production has a large impact on the network quality index. For example utility (G) and (L) have quite similar characteristics in terms of the size of the network and volume of demand; however the cost of water production is much higher in (L). Under zero cost recovery ($\beta = 0$), the optimal quality index is 0% for (G); whereas, it is 64% for (L). This shows that in terms of cost efficiency, (L) should have a much higher quality index in order to reduce water loss, which is costly for the utility.

Effect of outsourcing

As we have seen in the results for urban utilities, by recreating a scenario of utilities that are outsourced but without network renewal objectives, we obtain similar results. The optimal quality index could drop to 0% for utilities (I) and (J) due to the absence of network renewal objectives in their contract.

Effect of price elasticity of demand

As we have already seen with urban utilities, price elasticity of demand can have a large impact on the optimal quality index. Taking zero cost recovery ($\beta = 0$), by altering the assumption of inelastic demand to perfect inelastic demand, the optimal quality index jumps to 43% for (J) and 100% for (L). This is because quantity demanded is higher by construction when $\theta = 0$ regardless cost recovery. Hence, larger demand implies larger total water production; hence water loss is also greater. This automatically has a positive impact on the network quality index in terms of pure cost efficiency. Now if we add cost recovery into the picture, the quality index rises even further. This is essentially due to the fact that price hikes due to cost recovery no longer have a negative impact on demand; only a positive effect on revenue. Hence, higher quality indices are profit maximizing. This result shows that models based on perfect inelasticity could overestimate the potential network quality attainable.

These results reflect the challenges faced by rural utilities. Many of them face difficulty improving network quality due to the inevitable price hikes from cost recovery. Utility (I) has the lowest water loss in terms of percentages and is the second lowest in terms of volume; coincidentally it is cost efficient regardless the degree of cost recovery to have a 100% quality index. The fact that we obtain 100% quality under zero cost recovery shows that the cost of water loss relative to the cost of good quality mains is high; hence, even without recovering the costs; it is beneficial for the utility to have 100% good quality mains.

We also observe that utilities (G), (J) and (K) have high current water loss rates. The simulated quality indices for these utilities are either 0% or near 0%. This means that in terms of cost efficiency, having high network quality indices are not cost efficient. However, as cost recovery is applied, high network quality does become beneficial for the utility; of course at the cost of higher prices. Here we set the price caps to a hypothetical level; it is possible that in reality it is lower; which would explain the high water loss rates (low network quality). As argued previously, we should not forget the objectives of the utility: in some cases network renewal is not their priority but water quality improvement is. For instance, even under zero cost recovery, the quality index is quite high for utility (L); however, the current observed water loss is 25%. This may imply that their are other priorities than network renewal. Similarly, utility (J) also have high current water losses but with high cost of water production. But unlike (L), (J) has more than twice the length of water mains, which raises the cost of having a high quality network index.

1.8.1 Impact of leakage detection activities on the optimal quality index

We now turn to the efficiency of the water main quality index. In both Tables (1.5 and 1.4), we assumed that all utilities engaged in the highest level of leakage detection. Figure 1.11 shows the impact of varying levels of leakage detection activities on the optimal quality index. 100% leakage detection means that the utility engages in the highest performance of leakage detection methods. The smaller the cost of leakage (m), the less efficient; meaning there is smaller probability to detect the problematic mains precisely. In such cases, higher network quality indices are required to achieve a level of water loss that corresponds to the highest level of leakage detection.

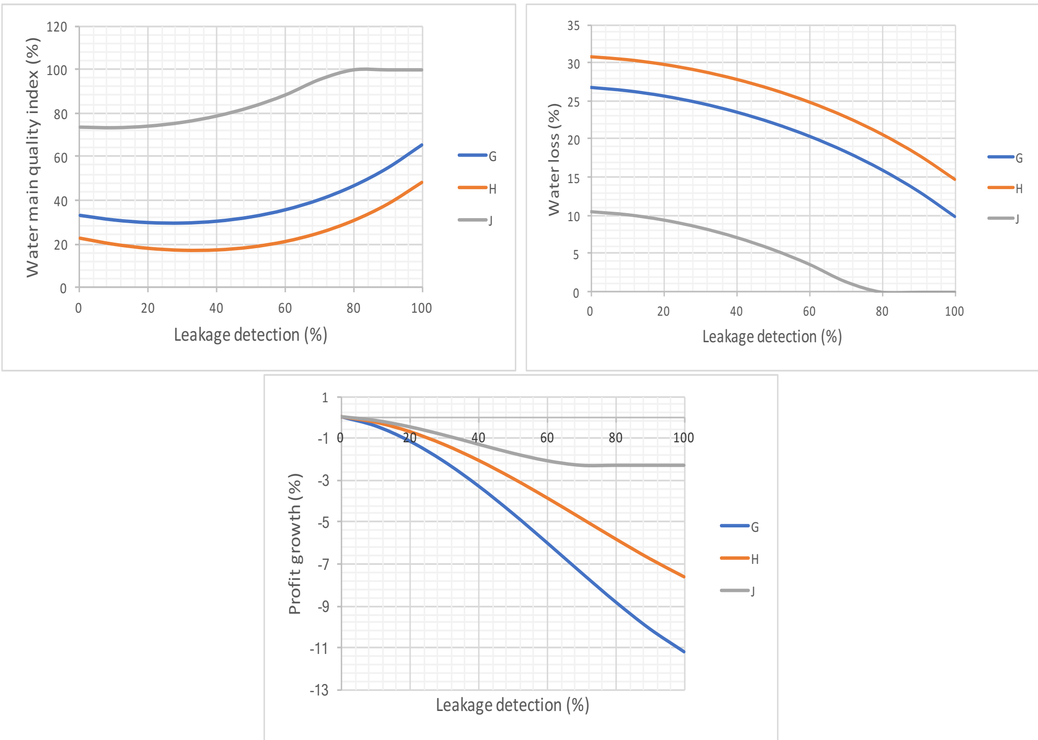


Figure 1.11: The impact of **leakage detection** ($\frac{m}{m_{max}}$) on the quality index (top left) and on the water loss rate (top right) for rural utilities at $\beta = 0.6$, $\alpha_0 = 0.4$ and $\theta = 0.2$. The bottom graph shows the impact of leakage detection on the growth of profits. We set $\beta = 0.6$ because beyond that point the price exceeds the price caps for utility (G) and (H).

We see in Figure 1.11 that for utilities (H) and (G) the greater the leakage detection activities, the more efficient the quality index. In other words, for the same level of quality index, if leakage detection activities consist of high performance devices, water loss can be lowered. For (H), the quality index is 20% when leakage detection is at 0% and at 60%. However, in terms of water loss, at 60% leakage detection, the corresponding water loss is reduced to 25% from 31%. This means that for the same level of quality index, because higher performance leakage detection activities allowed the utility to identify the most problematic mains with precision, the resulting water loss is lower than if the utility had not invested in leakage detection. And we can see that the gain in efficiency is much greater when the quality index is initially small (large initial water loss). For instance, the quality index of (J) is already high at 0% leakage detection. Hence in order to lower further the water loss, the utility is obliged to raise the quality index. Moreover, at 100% leakage detection the optimal quality index for (H) is about 48% with an associated water loss of 14%. Such a level of water loss without leakage detection activities would have required a quality index of 65%, which reveals the efficiency gain of leakage detection.

However the profit for (H) corresponding to 60% leakage detection quality is clearly lower than the profit associated with zero leakage detection activities. This is because leakage detection costs are additional costs that are deducted from the water sales. As a note to the readers, each level of optimal quality index simulated solves for a profit maximizing quality index; therefore each point on the curve is where profits are maximized; however, when we compare these individual points with each other, the larger the cost of leakage detection activities, the maximum profits are smaller. We also notice that the difference in profits is the smallest for (J), which is characterized as a utility with an initial water loss that is quite small compared to the others. We have already mentioned that due to the high costs of water production it is beneficial for (J) to have a high quality index even with low cost recovery. Hence, although leakage detection raises costs and dampens the profits compared to zero leakage detection, the reduction in water loss compensates the costs more than (G) and (H). In other words, too much investment in leakage detection is also costly for the utility which in turn incentives further water loss reduction to compensate for the higher costs due to leakage detection activities. In general, small leakage detection activities maintain high levels of water loss; whereas too much leakage detection hurts profits and dampens the positive effect it had on the efficiency of the network quality. This means that meeting water loss thresholds while being able to recover costs, assure financial sustainability and maximize the efficiency of network quality is a challenge for rural utilities.

We now turn to the analysis with urban utilities. In order to observe the impact of different costs of leakage detection activities on the water main quality index, we set $\beta = 0$; otherwise the quality index for most urban utilities remain at 100% for all values of leakage detection costs. We remind the readers that the leakage detection costs are estimates inspired by a source based on North American data; hence, the results could be different depending on the value of leakage detection costs. For instance, if d_{max} is set to 10,000 Euros per kilometer instead of 4000 Euros, we could observe a similar result as that of rural utilities. This is because leakage detection becomes a cost burden relatively to the cost of water loss; therefore, the greater the expenditure of the utility on leakage detection, the greater the benefit of water loss reduction due to surging costs. When costs of leakage detection are relatively small compared to water loss reduction, we could observe a scenario such as the following shown in Figure 1.12.

At 100% leakage detection, the utility spends 4000 Euros per km of bad quality mains to detect (and repair if necessary) leakage. As we have seen previously with rural utilities, the utility with the highest gain from leakage detection is the one with the highest initial water loss (F). With 0% leakage reduction, the quality index should be around 36%; whereas with maximum leakage detection, the quality index is reduced to 18%. The corresponding water loss is reduction is from 26% to 23%. The reason why we do not observe further reduction in water loss is because $\beta = 0$, which means the optimal quality index is based on the pure trade off between the cost of water loss and the cost of good quality mains. Overall we can see that leakage detection allowed the utility to drastically lower their quality index without aggravating water loss.

Concerning the impact on profits, we can see that until 70% leakage reduction, the change in profits is positive. This is due to the fact that quality indices fall sharply initially accompanied by a rise in leakage detection costs. In terms of cost efficiency, due to the additional cost of leakage detection, the optimal quality index is lower; hence

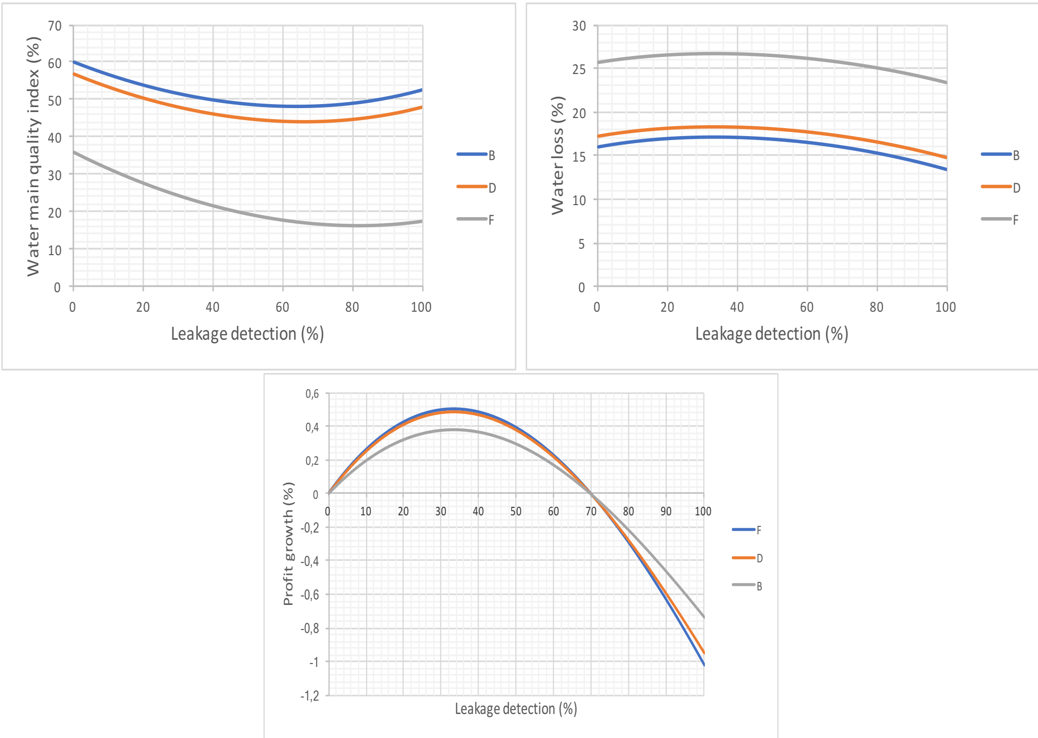


Figure 1.12: The impact of **leakage detection** ($\frac{m}{m_{max}}$) on the quality index (left) and on the water loss rate (right) for urban utilities at $\beta = 0$, $\alpha_0 = 0.4$ and $\theta = 0.2$. The bottom graph shows the impact of leakage detection on the growth of profits. We set $\beta = 0$ because urban utilities reach Indices of 100% for very small values of β.

water loss is also slightly higher; however, when leakage detection is high, the efficiency is high as well; hence even if the quality index drops, water loss could also be lowered as well. At 70% leakage detection, water loss is about the same as 0% leakage detection; however, the corresponding quality index of (F) drops from about 35% to around 18%; with the same level of profits. However, beyond 70%, there is less advantage in terms of profits compared to the marginal gain in water loss reduction. The fact that leakage detection could lower the quality indices significantly for urban utilities (especially those with higher trade offs between cost of water loss and cost of good quality mains) is beneficial since in urban utilities, mains replacement can be very disruptive in terms of roadworks and water service interruptions compared to rural utilities. Hence, efficient network renewal is worth the cost in urban utilities.

Here we show mathematically the impact of leakage detection on the optimal quality index:

$$\frac{d\overline{M}}{dm} = \frac{\frac{\rho q'_{\overline{M}}\alpha'_m+\rho q(\overline{M})\alpha''_m}{\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)^2}+\frac{2\rho q(\overline{M})\alpha'_{\overline{M}}\alpha'_m}{\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)^3}-1}{p''_{\overline{M}}q\left(\overline{M}\right)+2p'_{\overline{M}}q'_{\overline{M}}+p\left(\overline{M}\right)q'_{\overline{M}}-\frac{\rho q''_{\overline{M}}}{1-\alpha\left(\frac{\overline{M}}{M}\right)}-\frac{\left(2\rho q'_{\overline{M}}\alpha'_{\overline{M}}+\rho q(\overline{M})\alpha''_{\overline{M}}\right)}{\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)^2}-\frac{2\rho q(\overline{M})\left(\alpha'_{\overline{M}}\right)^2}{\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)^3}} \tag{1.22}$$

where $p'_{\overline{M}} > 0$, $p''_{\overline{M}} < 0$, $q'_{\overline{M}} < 0$, $q''_{\overline{M}} > 0$, $\alpha'_{\overline{M}} < 0$, $\alpha''_{\overline{M}} > 0$, $\alpha'_m < 0$, and $\alpha''_m > 0$.

The sign of $\frac{d\overline{M}}{\partial m}$ depends on the sign of the numerator since the denominator is negative.

If $\frac{\rho q'_{\overline{M}}\alpha'_m+\rho q(\overline{M})\alpha''_m}{\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)^2} + \frac{2\rho q(\overline{M})\alpha'_{\overline{M}}\alpha'_m}{\left(1-\alpha\left(\frac{\overline{M}}{M}\right)\right)^3} > 1 \Rightarrow \frac{d\overline{M}}{dm} < 0$ and $\frac{d\overline{M}}{dm} > 0$ otherwise.

If α'_m is large and $\alpha\left(\frac{\overline{M}}{M}\right)$ is large, it is likely that $\frac{d\overline{M}}{dm} < 0$. This means that, as we have already seen in Figure 1.11 and 1.12, utilities with a low cost efficient quality index (cost of water loss relative to the cost of good quality mains is smaller) benefit more from leakage detection activities. In other words, the greater the leakage detection, water loss could be reduced with a smaller water main quality index.

1.8.2 General discussion and political implication of the results

The first thing we notice in our results is that water main quality indices could reach 100% under full cost recovery in comparison to Part I results. This is because under profit maximzation, higher cost recovery leads to higher revenue; hence, higher quality indicies are "profitable" for the utility. This positive effect on the quality indices is accentuated under the assumption of perfect inelastic demand. If demand does not react to price hikes, the revenue rises with the marginal increase in prices. In Part I, under cost minimization, cost recovery had almost no impact on the quality index since we did not include revenue. Here, under zero cost recovery, the quality index coincides with this cost efficiency quality index. Hence, we can see that in some cases, in terms of cost efficiency, low quality indices are optimal; however, under high cost recovery, due to the positive effect on revenue, high network quality is optimal.

The optimal water main quality indices presented in Tables 1.4 and 1.5 and Figures 1.11 and 1.12 reveal a common point that rural utilities face the largest difficulty in achieving high water main quality indices. We showed that the optimal water main quality index could be 0% in rural utilities. This is due to their common characteristic regarding the trade off between the cost of water loss and the cost of good quality mains. Compared to urban utilities, the size of the water network (total length of the water mains) is relatively bigger than the size of demand (total volume of water consumed), which is characterized by the concept of economies of network density. This in turn is reflected on the trade off between the cost of water loss and the cost of good quality mains. The cost of water loss depends on the unit cost of water production and the total volume of water loss. In general, the total volume of water loss is much greater in urban utilities due to the large volume of water production (which is driven by large demand). This implies that in terms of cost efficiency, the total cost of water loss in terms of the total cost of good quality mains is smaller in rural utilities; hence, having 0% good quality mains could be cost efficient in rural utilities. We take the example of utility (G) to further reveal the potential challenges that rural utilities could face. The current reported rate of water loss is 33% in (G). This means that if regulations on water loss thresholds are enforced, (G) must raise its quality index. Moreover, if the principle of full cost recovery is enforced as well; the utility should recover the cost of good quality mains by raising prices. Table 1.5 shows that (G) can only recover 60% of the costs because beyond that level, prices exceed the price cap. Hence, even if the quality index permits water loss reduction; the utility cannot satisfy full cost recovery. The marginal increase in prices due to cost recovery is much larger in rural utilities, which means that prices can exceed the price caps before achieving full cost recovery. Furthermore, in some cases, the maximum quality index that these types of utilities could reach through self financing may coincide with a water loss that is greater than the regulated limit. If full cost recovery is not feasible, this means that these utilities would have to continuously finance their network renewal through debt or reduce expenditure on other activities. Now, if we assume perfect inelastic demand, the results from our table show that full cost recovery can be achieved without exceeding the price cap and water main quality indices could be raised to 100%. This difference illustrates the importance of price elasticity assumptions. Decisions based on perfect inelastic demand may undermine the challenge faced by rural utilities.

One solution to overcome the lack of economies of scale could be intercommunal utilities. Utilities (C), (D), (E) and (H) are examples of intercommunal utilities, where several small communes merge their water distribution management. However in line with Martins et al. (2006), our results show that simply by merging neighboring communes does not solve the problem unless the relative size of the network to the volume of demand is taken into account. Even if we merge several small communes, if the relative size of the network remains large in terms of the size of demand, cost efficiency may not improve. Merging could even increase the burden of costs on the utility. We also see this in urban utilities. The water main quality indices that satisfy cost efficiency is the lowest for (E), which consists of 20 communes merged together. Clearly, the relative size of the network and the demand size correspond to a small cost efficient water main quality index. Whereas, (C) which has 33 communes, have 100% index. Hence, intercommunal utilities may present conflicting results regarding the degree of economies of network density.

Furthermore, we studied the impact of leakage detection activities on the optimal network quality. Higher performance leakage detection devices (which is reflected by high costs) could allow efficient network quality. In other words, we showed in Figure 1.11 that water loss could be lowered with the same level of quality index if the utility engaged in leakage detection. Moreover we showed in Figure and 1.12 that for the same level of water loss, quality index could be lowered significantly. Overall, leakage detection activities allow less good quality mains for the same or better result (in terms of water loss reduction). However, we show again that the benefit generated differs between urban and rural utilities. As we have already mentioned, in terms of cost efficiency, water loss reduction is not a priority in rural utilities; therefore, adding leakage detection activities may simply translate as an additional cost burden. Whereas, in urban utilities, water loss reduction IS a priority in terms of cost efficiency; hence, leakage detection activities turn out to be beneficial since lower quality indices could be achieved without aggravating water loss. Minimizing roadworks and construction sites are beneficial for an urban city since it is much more disruptive for the community.

And lastly we showed that utilities that are outsourced could have lower network qualities than if they had been fully public or private. This is due to the division of the responsibilities concerning water service provision. Local utilities can outsource their service provision to external firms in order to gain in efficiency and benefit from specialization. However, these firms follow certain objectives that are defined by the local authority; such as network quality improvement and water quality improvement. They are remunerated based on what they are asked for and also through customer receipts. If network quality improvement is not specified as an objective, there is no incentive for the outsourced firm to exert effort on water loss reduction, such as partaking in leakage detection activities. Hence, we may observe high water loss in these utilities due to the underlining structure of the service. This subject will be dealt in depth in the third chapter.

1.9 Conclusion

In this part of the chapter we developed a profit maximization problem to solve for the optimal water main quality index. In Part I of the chapter we studied the optimal water main quality index based on the pure trade off between the total cost of water loss and the total cost of good quality mains. The simulated quality index revealed the cost efficient network quality. The results showed that water loss reduction was indeed beneficial in the context of urban utilities due to their large demand. Part II allowed to investigate further the incentives beyond cost efficiency for network renewal. Under profit maximization, utilities now decide on the optimal network quality based on profits; hence, the principle of full cost recovery plays a key role. Higher cost recovery of good quality mains lead to higher revenue; hence, the optimal quality index can reach excessive levels compared to the cost efficient quality index. Furthermore, similarly to Part I, the results reveal that water loss reduction is particularly beneficial for urban utilities. On the other hand rural utilities face the largest challenge for meeting threshold water loss rates. We also reflect the differences among public, private and mixed operators of water utilities in our model by assigning price caps. And finally, we include an efficiency factor that improves the efficiency of network quality. Utilities that engage in high performance leakage detection methods could lower water loss by selecting the mains that have the most problems. We show that this is particularly beneficial for urban utilities.

1.10 Appendix

1.10.1 Effect of Cost recovery

$$\frac{d\overline{M}}{d\beta} = \frac{\rho q'_{\beta}\alpha'_{\overline{M}} - (1-\alpha(\cdot))\left(p''_{\overline{M}_{\beta}}q + p'_{\overline{M}}q'_{\beta} + p'_{\beta}q'_{\overline{M}} + pq''_{\overline{M}_{\beta}} - \rho q''_{\overline{M}_{\beta}}\right)}{2(1-\alpha(\cdot))\alpha'_{\overline{M}}\left(r-m-p'_{\overline{M}}q-pq'_{\overline{M}}\right) + (1-\alpha(\cdot))^2\left(p''_{\overline{M}}q + 2p'_{\overline{M}}q'_{\overline{M}} + pq''_{\overline{M}}\right) - (1-\alpha(\cdot))\rho q''_{\overline{M}} - \rho q\alpha''_{\overline{M}}} \tag{1.23}$$

where $\alpha(\cdot) = \alpha\left(\frac{\overline{M}}{M}, m\right)$, $q'_{\beta} < 0$, $\alpha'_{\overline{M}} < 0$, $p''_{\overline{M}_{\beta}} > 0$, $p'_{\overline{M}} > 0$, $p'_{\beta} > 0$, $q'_{\overline{M}} < 0$, $q''_{\overline{M}} > 0$ and $p''_{\overline{M}} < 0$. In the first part we assumed that $q''_{\overline{M}_{\beta}} < 0$ if $\overline{p} > \frac{\theta r \overline{M}\beta}{q_0}$, which we apply here as well.

If the numerator and the denominator of 1.23 are both negative or positive at the same time, $\frac{d\overline{M}}{d\beta} > 0$.

$$\frac{d\overline{M}}{d\rho} = \frac{(1-\alpha(\cdot))q'_{\overline{M}} + q\alpha'_{\overline{M}}}{2(1-\alpha(\cdot))\alpha'_{\overline{M}}\left(r-m-p'_{\overline{M}}q-pq'_{\overline{M}}\right) + (1-\alpha(\cdot))^2\left(p''_{\overline{M}}q + 2p'_{\overline{M}}q'_{\overline{M}} + pq''_{\overline{M}}\right) - (1-\alpha(\cdot))\rho q''_{\overline{M}} - \rho q\alpha''_{\overline{M}}} \tag{1.24}$$

where the numerator is always negative. In Part I we saw that the greater the cost of water production, the greater the good quality mains; hence, the derivative should be positive (it is also what we observe in our results), which implies that the denominator should be negative. This means that the denominator of (1.23) is also negative because it is the same expression. Hence, the fact that we observe $\frac{d\overline{M}}{d\beta} > 0$ in our results implies that the numerator of (1.23) is also negative. We should also mention that with our function specifications, certain terms disappear. $p''_{\overline{M}}$ and $\alpha''_{\overline{M}}$ are zeroes.

$$\frac{d\overline{M}}{dr} = \frac{-(p''_{\overline{M}_r}q+p'_{\overline{M}}q'_r+p'_rq'_{\overline{M}}+pq''_{\overline{M}_r}-1)(1-\alpha(\cdot))^2-\rho q''_{\overline{M}_r}(1-\alpha(\cdot))-\rho q'_r\alpha'_{\overline{M}}}{2(1-\alpha(\cdot))\alpha'_{\overline{M}}\left(r-m-p'_{\overline{M}}q-pq'_{\overline{M}}\right)+(1-\alpha(\cdot))^2\left(p''_{\overline{M}}q+2p'_{\overline{M}}q'_{\overline{M}}+pq''_{\overline{M}}\right)-(1-\alpha(\cdot))\rho q''_{\overline{M}}-\rho q\alpha''_{\overline{M}}} \quad (1.25)$$

From the Expressions (1.23) and (1.24), we deduced that the denominator of (1.25) is negative. Since the numerator of (1.25) is positive, $\frac{d\overline{M}}{dr} < 0$ which is intuitive. The greater the cost of good quality mains, the smaller the quantity of good quality mains.

Chapter 2

Optimal switching time for water main replacement

2.1 Introduction

Water main replacement is an on-going issue around the world. Today, municipalities and water utilities are faced with the question whether to renew their aging water mains or not. For instance, in France the required amount of annual replacement amounts to about 1.5 billion euros; of which, not even half is being met today (Salvetti, 2013).

Foremost, the consequence of aging water mains is leakage of potable water resulting from mains breaks and cracks. Water lost through the form of leakage is not only a waste of water resources, but also a waste of energy and resources put into the production of potable water at treatment plants. This implies that the benefit of reducing leakage by network renewal leads to the "reduction of energy consumption and greenhouse gas emissions" (Xu et al., 2014). Moreover, leakage reduction can reduce the need for supply expansion when faced with growing demand.

"So if high leakage is so harmful, why is more not done to reduce it? The answer is complex and relates to a lack of awareness, knowledge and priority within Water Utili-

ties." Rogers and Calvo (2015)

In this chapter we develop a theoretical model that solves for the *optimal timing* of replacement of water mains that are obsolete. The model is representative of **one section** of the water main network. Replacement does not happen in one shot; but one section at a time. This section produces a certain volume of water loss until it is replaced. In order to deal with water loss management, utilities can divide their network into several sections, or the so-called District Metering Area (DMA). It is one of the methods to tackle water loss reduction presented by Rogers and Calvo (2015).[1]

2.1.1 Background literature on pipe replacement models

One of the earliest papers that deal with optimal pipe replacement models dates back to 1979 developed by Shamir and Howard (1979). Their model is based on the trade-off between the cost of maintenance of failing water infrastructure versus the cost of replacement. They propose an optimum replacement time by minimising this cost function.

The model developed by Walski and Pelliccia (1982) builds on the framework of Shamir and Howard (1979) which is adjusted and modified to enable practical use by engineers in the field. They incorporate a pipe failure model that is more rigorous, taking into account the physical properties of the pipe, which allows them to predict the cost and the timing to replace or to repair a pipe.

Later studies are adaptations of the aforementioned canonical models with prime focus on the development of the technical aspect of pipes and the mathematical representation of their failure rates; hence practical to water infrastructure engineers (such as Roshani and Filion (2013); Mailhot et al. (2003)). These models allow a global picture of the optimal water main replacement in a given water utility. In line with Shamir and Howard (1979), the optimum takes place if maintenance costs surpass replacement

[1]Further information on DMA can be found on the website http://www.waterloss-reduction.com

costs (Nafi and Kleiner, 2009)

Some studies such as Walski et al. (1987) and more recently Cobacho and Cabrera Sr (2009) incorporate the cost of water loss in these replacement models. They are the first to integrate water production costs as an influential factor on the timing of pipe replacement. They show the sensitivity of the cost of water loss (such as production, environmental and energy costs) and the leakage rate on the optimum renovation period. The results we obtain are consistent with their work as well.

What is different about our model?
The issue of optimal water mains replacement is quite sparse in the economic literature. The replacement models that exist estimate a replacement cycle such as those presented by Hritonenko and Yatsenko (1999). In other words, these models solve for an optimum lifetime of a "machine" which would be replaced at the end of its lifetime. Our approach differs significantly from this replacement cycle model. The objective of our model is to solve for the optimal "timing" of replacement of mains that are obsolete today. We focus on a small section of the network that requires renewal. In other words, these mains have already reached their expected lifetime; but has not been replaced yet. Clearly, one of the major issues today concerning water mains network is that renewal is behind schedule. Our model shows that the optimal timing of replacement depends heavily on the utility-specific characteristics such as the urbanity of the utility and the corrossivity of the mains.

We showed in Chapter 1 that based on key parameters such as cost recovery, demand elasticity, cost of water production and the presence of economies of network density, the decision of network renewal can be heavily altered. Similarly, in this chapter we examine the effect of these parameters on the optimal timing of replacement. Moreover we depart from a static framework and move to a dynamic one. In addition to the key parameter already studied in the first chapter, we study the effect of rehabilitation on the optimal timing. Because rehabilitation costs are much cheaper than replacement costs, it may be attractive to utilities to choose rehabilitation as a temporary solution before replacing these mains. The results show that the effect of rehabilitation is not that straightforward.

Our model is most closely relatable to the simplicity of the canonical form developed by Shamir and Howard (1979). In line with the literature of optimal main replacement, the aim of our model is to study the optimal timing of renewing obsolete mains. Our model includes the revenue generated from water consumption, cost of water production, cost of rehabilitation and the cost of replacement(in line with Cobacho and Cabrera Sr (2009)). Moreover, our model is continuous, unlike most other replacement models which are discrete. This allows us to use standard optimization techniques and establish qualitative properties (Hritonenko and Yatsenko, 1999).

As Walski et al. (1987) writes, the switching time proposed by our model is not definitive but an "indicator" for a potentially optimal moment for main replacement.

This paper is organized as follows. The second section presents the theoretical model, section three presents the functions used in the simulations. Furthermore, the calibration and simulation results are presented in section four and five. Finally, section six concludes.

2.2 Theoretical Model

The theoretical model that we develop here is inspired by the canonical model of optimal pipe replacement by Shamir and Howard (1979) and the "two-stage optimal control approach" developed by Tomiyama (1985) and later applied by Boucekkine et al. (2004). We consider three regimes defined by profit functions with old, rehabilitated and new water mains. The first regime is associated with the old mains, the second one with the rehabilitaed mains and the third regime with the new ones. Utilities can skip directly to new mains which would reduce the number of regimes to two. We consider new mains as ideally HDPE-type mains, since they are the least corrosion-prone and water loss-prone[2]. Our aim is to find the switching time t^* at which the water utility switches from "old" to "new" mains given the current state of the network characterised by the initial level of water loss. We would like to investigate the impact of the size of demand, the cost of replacement, the rehabilitation of old mains, the cost of water production, the degree of cost recovery and the elasticity of demand on the optimal switching time.

Our model is representative of a small group of mains that face renewal needs. We do not solve for a replacement schedule which defines the expected lifetime of a main. We study the optimal timing of replacement of a given set of leaky mains that need to be replaced. These mains share the same characteristics (age and material). In the first chapter, we considered the entire network of a utility and solved for the quality index representing the proportion of new mains to old mains. We did not talk about replacement since it was a static framework. In this chapter, we focus on certain pipes that need to be replaced in a network. We would like to observe the impact of different factors already discussed in the first chapter on the decision to replace today or in the near future. The issue we face today in France (and in other developed countries), is that water mains network renewal is behind schedule. Certain mains have not been replaced yet (for financial reasons, cost efficiency issues). Hence, we develop a simple model that shows the optimal timing which is profit-maximizing for the utility.

2.2.1 The water utility's decision

Consider a water utility that provides potable water to households. This utility is faced with the "obligation" to replace obsolete mains at some time t^*. Replacement decisions are made for a given section of mains at a time.

Consider a certain section of the water distribution network that requires renewal due to obsolescence (represented by large water loss). The question is, when is it in the interest of the utility to renew those mains? Utilities have different options to deal with water main renewal. Rehabilitation of mains is a common way to fix leakage and corroded

[2] HDPE mains are used today widely since it is considered as the cost-efficient, corrosion-prone material (ARTELIA, 2014; Solutions, 2016; Kuffer, 2008).

pipes instead of replacement. For example pipe-lining methods are oftentimes cheaper than pipe replacement (Roshani and Filion, 2014). If water utilities decide to rehabilitate their mains instead of replacing them, water loss is reduced; hence postponing the timing of replacement. The following profit function reflects the profit generated over the obsolete section of the network:

$$\Pi(t) = \underbrace{\int_0^{t^*-n} (p\overline{q} - \rho\overline{q} - \rho\overline{\alpha q}e^{\delta t})e^{-\gamma t}dt}_{\text{Regime I}} + \underbrace{\int_{t^*-n}^{t^*} (p^R q^R - \rho q^R - \rho\alpha^R q^R e^{\delta t} - R)e^{-\gamma t}dt}_{\text{Regime II}} + \underbrace{\int_{t^*}^{t^*+a} (p^A q^A - \rho q^A - \rho\alpha^{min} qA - A)e^{-\gamma t}dt}_{\text{Regime III}} \tag{2.1}$$

where time 0 is today, $t^* - n$ is when the utility repairs the problematic mains by rehabilitating them. At t^* the utility replaces the obsolete mains with new non-corrosive mains. a is the number of years of amortization. At $t^* + a$, the utility has paid off the total cost of replacement that occurred in t^*. Accordingly; we can construct three different periods. The first regime consists of the profit generated by the revenue of water sales minus the cost of total water production. The second regime consists of the profit generated by the revenue of water sales minus the cost of total water production and the cost of rehabilitation. Finally, the third regime consists of the profit generated by the revenue of water sales minus the cost of total water production and the cost of replacement.

2.2.2 First regime

In the first regime, the profit of the utility is defined as the difference between the revenue ($p\overline{q}$) and the total cost of water production ($\rho\overline{q}$ and $\rho\overline{\alpha q}e^{\delta t}$). $\overline{q}$ is the water demand and $\overline{\alpha q}e^{\delta t}$ is the water loss. For the sake of simplicity, the only time variant component is water loss. At the rate of δ, water loss grows. Hence the total cost of water production in regime I grows due to the increase in water loss. At time $t = 0$, the volume of water loss corresponds to $\overline{\alpha q}$; which is the initial total volume of water loss in that particular section of the network. Until the mains are either rehabilitated or replaced, this volume increases with a rate of δ. This rate reflects the physical characteristics of the mains, such as the material and size. For instance, a corrosion-prone material will have a higher δ than a corrosion-resistant material. It can also reflect the surrounding environment of the pipes, such as soil condition. Hence, the first regime characterizes the scenario where water loss grows over time.

2.2.3 Second regime

In the second regime, the utility rehabilitates the leaky mains. Rehabilitation of mains is a common way to fix leakage and corroded pipes instead of replacement. For example pipe-lining methods are oftentimes cheaper than pipe replacement (Roshani and Filion, 2014). If the utility applies cost recovery, prices would increase ($p(R^+)$); hence, we now denote price as p^R where $p^R_R > 0$. Moreover, if demand is inelastic but not perfectly inelastic, it would react to the rise in prices ($q(R^-)$). Hence, we now denote demand as q^R where $q^R_R < 0$. Thanks to the rehabilitation of the mains, water loss is reduced to its minimum level which we denote as $\alpha^R q^R$ where $\alpha^R_R < 0$. However, since the main is not completely renewed, water loss grows over time again at rate[3] δ. The main purpose of rehabilitation is to extend the longevity of the mains and allow the utility to postpone replacement. Hence, in regime II the profit is defined as the revenue from water sales ($p^R q^R$) minus the total cost of water production ($\rho q^R + \rho \alpha^R q^R e^{\delta t}$), which consists of water consumed and water loss minus the cost of rehabilitation (R). This period lasts for n years. In other words, the utility decides to rehabilitate n years before replacement. This means that the utility seeks to postpone replacement for at least another n years starting from today ($t = 0$).

[3] Although δ is possibly smaller once the mains are rehabilitated, we keep the same δ for two reasons: (1) the simulation results do not differ much (less than 1 year difference in the t^*). (2) No explicit solution with two different δs. An explicit solution allows more in-depth analysis. Matlab simulation results could be obtained upon request.

2.2.4 Third Regime

In the third regime, the utility decides to replace entirely the obsolete mains. We consider mains such as HDPE-type mains which are highly recognized for its non-corrosive properties and longevity. Once the mains are replaced, the water loss drops to its minimum unavoidable volume, which we denote as α^{min}. Since we consider cost recovery, price and demand react to the cost of replacement (A) in the following manner: $p^A = p^A(A^+)$ and $q^A = q^A(A^-)$; hence, the new prices and demand are denoted as p^A and q^A where $p^A_A > 0$ and $q^A_A < 0$. This period lasts until $t^* + a$; which is the end of the expected lifetime (a) of the new mains. Water loss does not grow anymore in this regime since we consider replacement with HDPE pipes which are known for extremely small risks of breaks or leaks. The profit is defined as the water sales ($p^A q^A$) minus the total cost of water production ($\rho q^A + \rho\alpha^{min} q^A$) minus the cost of replacement (A). And finally, γ is the discount rate.

There exists a certain time t^* that is profit maximizing for the utility to switch from Regime II to Regime III or directly from Regime I to Regime III. For simplicity, we assume that this section of mains is replaced at t^* and the cost is paid during Regime III until the end of the amortized period (for example $t^* + 100 = T$)[4]. In line with AWWA (2012), the cost is funded via an increase in prices, which is divided equally over a m^3 of volume demanded. Replacement depends on the trade-off between the cost of water loss and the cost of replacement[5]. We consider that there is no capacity expansion, hence the unit cost of water production (ρ) is constant for all m^3 units pumped into the system.

[4]We assume that the utilities fund their investments via cost recovery. The European water framework directive enforces full cost recovery - Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy, Article 9 and Appendix 1.

[5]For example, a PVC main is expected to last for about 50 years; however, they are not necessarily replaced at the end of their useful time due to the cost of replacement.

First order condition

We maximize the function (2.1) with respect to t^*. We obtain the following optimal timing of replacement which we refer to as the optimal switching time t^*:

$$t^* = \begin{cases} \frac{1}{\delta}\ln\left(\frac{e^{\gamma n}(p\overline{q}-\rho\overline{q})-(e^{\gamma n}-1)(p^R q^R-\rho q^R-R)-(1-e^{-\gamma a})[p^A q^A-\rho q^A-\rho\alpha^{min}q^A-A]}{\rho\alpha^R q^R-e^{-n(\delta-\gamma)}(\rho\alpha^R q^R-\rho\overline{\alpha q})}\right) > 0 & \text{if (2.3)} \\ 0 & \text{otherwise}^6 \end{cases} \quad (2.2)$$

$$e^{\gamma n}(p\overline{q}-\rho\overline{q}-e^{n\delta}\rho\overline{\alpha q})-(e^{\gamma n}-1)(p^R q^R-\rho q^R-R)-\rho\alpha^R q^R(1-e^{-n(\delta-\gamma)}) \quad (2.3)$$
$$> -(e^{-\gamma a}-1)(p^A q^A-\rho q^A-\rho\alpha^{min}q^A-A)$$

Since $e^{-\gamma a} < 1$ and $p^A q^A - \rho q^A - A > 0$ (which represents the per period profit generated in Regime III), The righthand side of the inequality is positive. Hence the lefthand side of the inequality must be positive as well. The difference between the magnitude of δ and γ could have a large influence on assuring that the lefthand side is positive. A smaller δ means slower corrosion, or smaller evolution of water loss. A large δ on the other hand, implies that water loss grows faster in Regime I, and this could be reflected by a large cost of water loss ($e^{n\delta}\rho\overline{\alpha q}$); hence, the lefthand side may not be positive anymore, which means that $t^* > 0$ does not exist. In other words, the switch (replacement) should have occurred already.

If $R = 0$, we switch from Regime I to Regime III immediately:

$$t^* = \begin{cases} \frac{1}{\delta}\ln\left(\frac{p\overline{q}-\rho\overline{q}+(e^{-\gamma a}-1)[p^A q^A-\rho q^A-\rho\alpha^{min}q^A-A]}{\rho\overline{\alpha q}}\right) > 0 & \text{if } \textit{see below} \\ 0 & \text{otherwise}^7 \end{cases} \quad (2.4)$$

[6] We do not consider the negative part of t^* since it only means that replacement should have already occurred (Walski et al., 1987).

if $p\overline{q} - \rho\overline{q} - \rho\overline{\alpha q} > -(e^{-\gamma a} - 1)[p^A q^A - \rho q^A - \rho\alpha^{min} q_A - A]$. This condition means that the profit generated in Regime I must be greater than the profit generated in Regime III; otherwise, the switch would have already occurred and $t^* \not> 0$.

Second order condition

The following second order condition shows that $t^* > 0$ maximizes profits iff:

$$(p^R q^R - \rho q^R - R)(e^{\gamma n} - 1) + (p^A q^A - \rho q^A - \rho\alpha^{min} q^A - A)(1 - e^{-\gamma a})$$
$$< (p\overline{q} - \rho\overline{q})e^{\gamma n} + \tfrac{(\delta-\gamma)}{\gamma} e^{\delta t^* - n(\delta-\gamma)}(\rho\overline{\alpha q} - \rho\alpha^R q^R) + \tfrac{(\delta-\gamma)}{\gamma}\rho\alpha^R q^R e^{\delta t^*}$$

This condition is always satisfied in our simulation results because $(p^R q^R - \rho q^R - R)(e^{\gamma n} - 1) + (p^A q^A - \rho q^A - \rho\alpha^{min} q^A - A)(1 - e^{-\gamma a})$ is less than $(p\overline{q} - \rho\overline{q})e^{\gamma n}$. This condition roughly implies that the profit generated in Regime I (without water loss) is greater than the profits generated in Regime II and III. If it were the contrary, the switching time would have already occurred since it is not profitable to remain in Regime I.

Comparative Statics

- The impact of Rehabilitation (R) on the switching time:

  Is it profit-maximizing for the utility to rehabilitate before replacement? If $\frac{dt^*}{dR} < 0$, means that rehabilitation does not extend the longevity of the mains. Whereas if $\frac{dt^*}{dR} > 0$ then rehabilitating is beneficial for the utility since it allows replacement to take place later. The solution depends on the elasticity of demand, cost recovery and the corrosivity of the mains.

[7] Footnote 6.

$$\frac{dt^*}{dR} = \tag{2.5}$$
$$\left(\frac{1}{\delta}\right)\frac{-(e^{\gamma n}-1)(p_R^R q^R + p^R q_R^R - \rho q_R^R - 1)}{e^{\gamma n}(p\overline{q}-\rho\overline{q}) - (e^{\gamma n}-1)(p^R q^R - \rho q^R - R) - (1-e^{-\gamma a})[p^A q^A - \rho q^A - \rho\alpha^{min} q^A - A]}$$
$$-\left(\frac{1}{\delta}\right)\frac{(\rho\alpha_R^R q^R + \rho\alpha^R q_R^R)(1-e^{-n(\delta-\gamma)})}{\rho\alpha^R q^R - e^{-n(\delta-\gamma)}(\rho\alpha^R qR - \rho\overline{\alpha q})}$$

The denominator of the first term in Equation (2.5) corresponds to the numerator of the expression t^* (Equation 2.2) and the denominator of the second term is the denominator of the expression t^* (Equation 2.2). And from the Expression 2.3, we know that these terms are positive. Hence, the sign of 2.5 depends on the sign of the numerator of both terms and their relative magnitudes.

If the first term is positive this means that the positive effect of cost recovery on revenue dominates the negative effect on quantity demanded. Regardless the sign of the second term, if the first term is sufficiently large, $\frac{dt^*}{dR} > 0$. However if the first term is negative, $\frac{dt^*}{dR} < 0$. This means that the negative effect of cost recovery of rehabilitation costs on quantity demand dominates the positive effect on revenue; hence, the greater the cost of rehabilitation, the more beneficial it is to replace. Moreover, if δ is greater than γ, the second term is always positive because the numerator of the second term is negative ($\alpha_R^R < 0$ and $q_R^R < 0$). Large δ implies large corrosion rate. This means that regardless the sign of the first term, if the main is corrosive (leakage increases faster), the effect of rehabilitation on t^* is positively impacted. In other words, it postpones replacement. In our results we discuss further this point in detail.

- The impact of the cost of replacement (A) on the switching time:

$$\frac{dt^*}{dA} =$$
$$\frac{-(1-e^{-\gamma a})(p'_A q_A + p_A q'_A - \rho q'_A - \rho\alpha^{min} q'_A - 1)}{\delta\left(e^{\gamma n}(p\overline{q}-\rho\overline{q}) - (e^{\gamma n}-1)(p_R q_R - \rho q_R - R) - (1-e^{-\gamma a})[p_A q_A - \rho q_A - \rho\alpha^{min} q_A - A]\right)} > 0$$

We know that the denominator is positive from Equation (2.2). If $p_A^A q_A + p_A q_A^A - \rho q_A^A - \rho \alpha^{min} q_A^A < 1$, then $\frac{dt^*}{dA} > 0$, which means that the greater the cost of replacement, the further away the switching time. This result is quite intuitive since the greater the cost of replacement, utilities are less incentivized to replace mains. The cost of having water loss becomes relatively "cheap".

- The impact of the initial level of water loss ($\overline{\alpha}$):

$$\frac{dt^*}{d\overline{\alpha}} = -\frac{1}{\delta}\left(\frac{e^{-n(\delta-\gamma)}\rho\overline{q}}{\rho\alpha^R q^R - e^{-n(\delta-\gamma)}(\rho\alpha^R qR - \rho\overline{\alpha q})}\right) < 0$$

The greater the level of water loss today, the earlier the switching time. Large water loss at $t = 0$ (today) means that the state of the main network is already quite poor. Mains with high leakage compared to lower ones have a larger incentive to switch regimes since the opportunity cost of water loss is larger. Hence replacing mains become more and more imminent as the initial state worsens.

- The impact of the rate of corrosivity (δ) on the switching time:

$$\frac{dt^*}{d\delta} = -\frac{1}{\delta}\left(t^* - \frac{ne^{-n(\delta-\gamma)}(\rho\alpha^R q^R - \rho\overline{\alpha q})}{\rho\alpha^R q^R - e^{-n(\delta-\gamma)}(\rho\alpha^R qR - \rho\overline{\alpha q})}\right) < 0 \qquad (2.6)$$

The greater the rate of corrosion, the earlier the switching time. A higher rate of leakage could reflect bad quality mains, badly installed mains or mains that have specific corrosive properties depending on the surrounding soil condition. Replacement would be in the favor of the utilities if their network consists of mains that are rapidly degenerating since the cost of water loss could become a burden quite rapidly.

- The impact of the cost recovery (β) on the switching time:

$$\frac{dt^*}{d\beta} = \tag{2.7}$$
$$\left(\frac{1}{\delta}\right)\frac{-(e^{\gamma n}-1)(p_\beta^R q^R + q_\beta^R(p^R-\rho)) - (1-e^{-\gamma a})(p_\beta^A q^A + q_\beta^A(pA-\rho-\rho\alpha^{min}))}{e^{\gamma n}(p\overline{q}-\rho\overline{q}) - (e^{\gamma n}-1)(p^R q^R - \rho q^R - R) - (1-e^{-\gamma a})[p^A q^A - \rho q^A - \rho\alpha^{min} q^A - A]}$$
$$-\left(\frac{1}{\delta}\right)\frac{(\rho\alpha^R q_R^R)(1-e^{-n(\delta-\gamma)})}{\rho\alpha^R q^R - e^{-n(\delta-\gamma)}(\rho\alpha^R q^R - \rho\overline{\alpha q})}$$

$\frac{dt^*}{d\beta}$ could be positive or negative depending on the sign of the first term of (2.7). If $\delta > \gamma$, the second term is always positive. As we already know from Equation (2.2), the denominator of the first term in (2.7) is always positive. The sign of the first term depends if the positive effect of cost recovery on prices dominates the negative effect on demand. Cost recovery has a positive effect on the price ($p_\beta^R > 0$ and $p_\beta^A > 0$) which raises revenue; however, has a negative effect on quantity demanded ($q_\beta^R < 0$ and $q_\beta^A < 0$) which lowers revenue. Hence, the difference in the magnitude of the two effects determines the sign of the first term. In general, if the positive effect dominates, $\frac{dt^*}{d\beta} < 0$.

2.3 Defining functions

2.3.1 Quantity demand function

We apply the same demand function proposed in the first chapter:

$$q^R = \frac{Q_0}{(p^R)^\theta} \tag{2.8}$$

$$q^A = \frac{Q_0}{(p^A)^\theta} \tag{2.9}$$

$$\overline{q} = \frac{Q_0}{\overline{p}^\theta} \tag{2.10}$$

where q^R and q^A reflect the quantity demand that depends on cost recovery of the rehabilitation costs (R) and the replacement costs (A). The third quantity demand equation ($\overline{q}$) reflects the quantity demand in the first regime where there are no rehabilitation and replacements. The price function p^R is the price function that depends on the cost of rehabilitation (R) in regime II and p^A is the price function that depends on the cost of replacement (A) in regime III:

$$p^R = \left(\frac{R}{Q_0}\right)\beta + \overline{p} \tag{2.11}$$

$$pA = \left(\frac{A}{Q_0}\right)\beta + \overline{p} \tag{2.12}$$

where Q_0 is the unconstrained demand, $\beta \in [0, 1]$ reflects the degree of cost recovery and $\overline{p}$ is the price that reflects the cost of water production and the other fees (taxes, etc).

2.3.2 Water loss function

Water loss in Regime II can be reduced thanks to rehabilitation. The rate of water loss function is defined as follows:

$$\alpha R = \alpha^{min} + (\overline{\alpha} - \alpha^{min})\left(1 - \frac{R}{R^{max}}\right) \tag{2.13}$$

where α^{min} represents the minimum water loss rate and $\overline{\alpha}$ corresponds to the initial level of water loss rate in Regime I. When the utility rehabilitates their mains, the rate of water loss falls. At R^{max} water loss is reduced to its minimum level. Moreover, if there is no rehabilitation (R=0), then the corresponding rate of water loss level is equal to the one in regime I ($\overline{\alpha}$).

With our function specifications and our calibration values, we always obtain $\frac{dt^*}{dR} > 0$ because the first term of Equation 2.5 is always positive. This is because $p^R_R q^R < 1$.

Furthermore, $\frac{dt^*}{d\beta}$ is always negative. The greater the cost recovery, the earlier the switching time. This means that for the utility, replacement becomes profitable to be executed earlier if the recovery of replacement costs increase.

2.4 Calibration

We select two French utilities from the the 2013 SISPEA database, the same database used in the first chapter for calibrating the parameters. The data is available online on the website of l'Observatoire National des Services d'Eau et d'Assainissement. The two utilities represent the characteristics of an utility in a rural and an urban region. We take the utility of Lyon as reference for an urban region and the utility of Sainte-Lizaigne as reference for a rural region.

Not all values for the parameters in the model are found in the database; hence, for the missing values we select approximate values or a range of values that are justified by the references that we cite. For the calibration of ρ, we take 45% of the price of water ($\overline{p}$) charged to users. There are many possible values for the calibration of the discount rate (γ). According to the current report on the discount rate in France[8] the rate is about 2.5% for short term investments and 1.5% for the long term (Quinet, 2013). However, it is recommended in the report to apply the unique discount rate of 4.5%, since the new rates proposed are yet to be applied in reality. Moreover, 3% is a rate commonly used in dynamic models (Gastineau and Taugourdeau, 2014). For our simulations we select 3%.

We assembled information available online to estimate the total cost of replacement of mains. According to Radisson (2014), replacing one kilometer of mains costs around 400,000 to 800,000 EUR, which means on average, 600,000 EUR. Moreover, in a rural area, the cost of replacement per kilometer is around 100,000 to 200,000 EUR[9], which means on average, 150,000 EUR. According to Majdouba et al. (2011), the amortization period depends on the expected "useful" life of the mains. Since in Regime III we assume that mains are replaced by HDPE-type (water loss-prone material), the expected useful life is 100 years and therefore we set a to 100 years. The exact total length of this small section does not impact the final switching time since the other parameter values adjust

[8] Another report from 2005,Lebègue et al. (2005), reports 4% for short term investments and investments exceeding 30 years have discount rates that gradually decline until 2%.

[9] Sciences et Avenir, "Eau: il y a de la fuite dans le réseau", 20 mars 2014.

proportionally as well. In other words, a large total length implies larger A, but also a larger volume of water supply, hence the model is not sensitive to absolute values but to proportional change. In our simulations, we consider 10 kilometers for an urban utility and one kilometer for a rural utility. There is evidence that 1 kilometer of mains can be replaced during a period of 2 months; hence, 10 kilometers of replacement is feasible[10].

The cost of rehabilitation is not available in the database so we set an approximate value, inspired by an example from the United States which we refer to in the first chapter concerning maintenance costs (Uni-Bell, 2011). However this time we set the costs higher than for simulations in Part II chapter 1 since we consider rehabilitation costs. Rehabilitation costs could be significantly greater than repair costs. The initial proportion of water loss ($\overline{\alpha}$) is set according to the level of water loss we observe today which is found in the database. We calibrate the unconstrained demand (Q_0) by estimating the total volume of m^3 of water consumed per km of mains[11]. The base price ($\overline{p}$) reflects the cost of pumping and treating water, which is provided in the data. We also constrain this price with a price cap that we have applied in Part II of chapter 1 as well. It limits the rise in the price increase due to cost recovery. The calibration of the price elasticity of demand (θ) is in reference to the first chapter as well. For the corrosion rate (δ), we try a range of values from 0.03 to 0.1 since there are no data available concerning the corrosion rate. We also set an arbitrary number of years n as the duration of Regime II. A different n may lead to a different switching time; however it would not impact the interpretation of the results. This argument also holds concerning the corrosion rate; the precise switching time may differ according to the values assigned; however, the resulting analytical implication of the results remain consistent.

We present the calibration for our parameters in Table 2.1. In the following section, we present our simulation results.

[10]South west water. "Newton Poppleford water main replacement completed ahead of schedule", 12th of Dec. 2013https://www.southwestwater.co.uk/index.cfm?articleid=11275

[11]We multiply the population density per kilometer of mains by the number of kilometers in the section of mains considered. We further multiply by the volume of water in m^3 demanded per inhabitant per year.

Parameter	Description	Units	Urban utility	Rural utility
ρ	Cost of water production	€$/m^3$	1.6	2
γ	Discount rate	N/A	[0.015, 0.045]	[0.015, 0.045]
$\overline{\alpha}$	Initial rate of water loss	[0,1) proportion	0.2	0.3
Q_0	Unconstrained demand	$m^3/year$	255,000	2,500
$\overline{p}$	Base price	€$/m^3$	3.35	4.2
p_{max}	Price cap	€$/m^3$	4	5
θ	Price elasticity	N/A	[0, 0.2]	[0, 0.2]
δ	Rate of corrosion	N/A	[0.03, 0.1]	[0.03, 0.1]
a	Years of amortization	years	100	100
β	Cost recovery	N/A	[0,1]	[0,1]
n	rehabilitation period	years	10	10
A	Unit cost of replacement per period	€/km	6,000	1,500
R	Unit cost of rehabilitation per period	€/km	[0, 1,000]	[0, 100]
	Approximate size of DMA	km	10	1

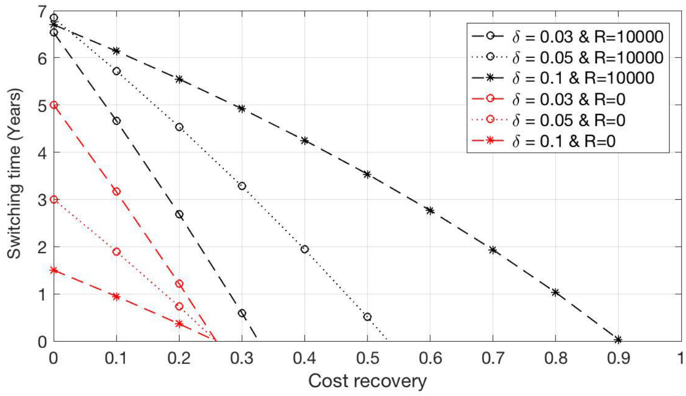
Table 2.1: Calibration of parameter values

2.5 Simulations

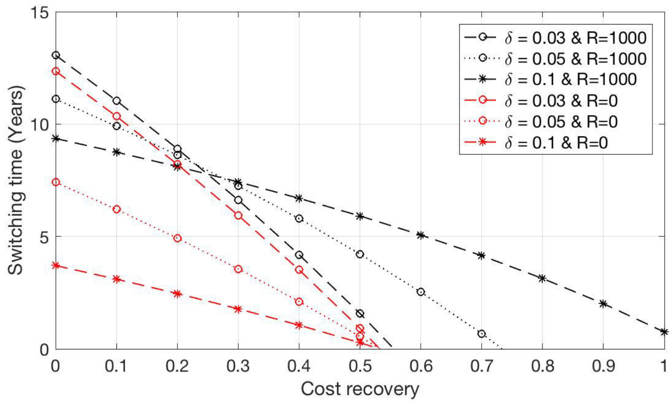
The effect of Rehabilitation on the optimal switching time

We have set $n = 10$ in our simulations, which reflects the moment the mains are rehabilitated before the switching time (t^*). We suppose that the utility decides to rehabilitate at $t^* - 10$ and expect that the longevity of the mains are extended for at least another 10 years from today ($t = 0$). Our results show that in certain cases, the optimal switching time is before 10 years; which means that postponing replacement beyond 10 years is not profit maximizing for the utility. We can see that this is the case for an urban utility for all values of cost recovery (β) and for all values of corrosion rates (δ). As we have shown in the comparative statics (2.5), rehabilitation postpones switching time; however, in this particular case, switching time is before 10 years.

On the other hand, in a rural utility, rehabilitation could extend the longevity of the mains beyond 10 years only if the corrosion rate is $\delta = 0.05$ for very small values of cost recovery. The switching time is also greater than 10 years for $\delta = 0.03$; however, it is not exclusive to the case with rehabilitation. In other words, the optimal switching time without rehabilitation is already beyond 10 years. Rehabilitation extended the switching



(a) Urban utility



(b) Rural utility

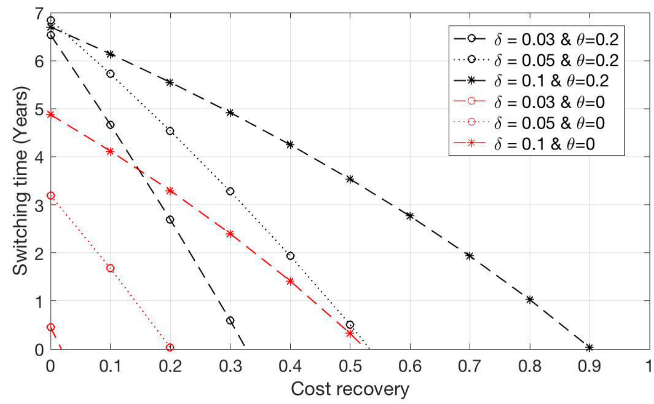
Figure 2.1: The impact of cost recovery (β) and the Rehabilitation (R) on the switching time with $\gamma = 0.03$, $\theta = 0.2$.

time for only an additional year. On the other hand, in terms of the difference in the optimal timing of replacement, we observe that the effect of rehabilitation is the greatest for large corrosion rates such as $\delta = 0.1$.

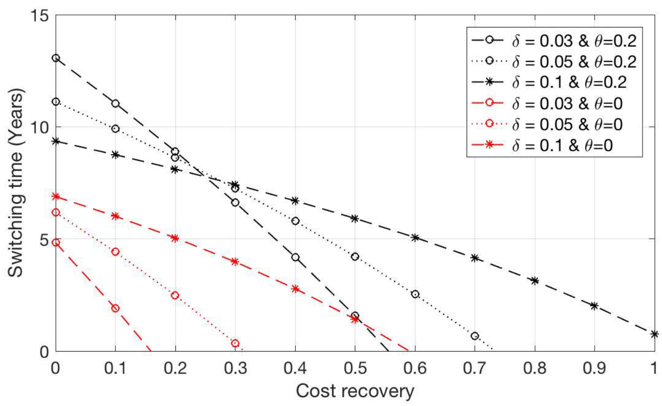
We can further notice in Figure 2.1b that cost recovery has a different effect on the switching time depending on the corrosion rate. If rehabilitation takes place ($R = 1000$), for very small values of cost recovery, the switching time is earlier for higher corrosion rates. Whereas, for higher values of cost recovery, the switching time is earlier for smaller values of corrosion rates. First of all, from Expression (2.2) we can see that for very small values of δ and β, t^* is greater than for larger values of δ. However, as we increase β, for large values of δ (the curve with $\delta = 0.1$), the marginal effect of β on t^* in Expression (2.7) is weaker; hence the downward slope is flatter. On the other hand, if δ is small (the curve with $\delta = 0.03$), the marginal effect of β on t^* is stronger; hence the downward slope is sharper. Small δ means that the mains age slowly; hence, rehabilitation has little impact on extending the longevity; this means that the positive effect of cost recovery dominates the effect on optimal switching time. The smaller the δ, the behavior of $\frac{\partial t^*}{\partial \beta}$ is closer to the case with zero rehabilitation. Whereas, a larger δ implies that the mains age faster (water loss increases faster); hence, rehabilitation could have a large impact on extending the longevity of the mains; hence, if costs are sufficiently recovered, the optimal switching time can be postponed much later in comparison to the case with zero rehabilitation.

Overall the switching time is earlier in an urban utility. We can see that although the initial rate of water loss ($\overline{\alpha}$) is greater for the rural utility, utilities face different degrees of trade off between the total cost of water loss relative to the cost of replacement. The relative cost of water loss to the cost of replacement is greater when the demand is greater. At zero cost recovery ($\beta = 0$), the optimal switching time corresponds to the cost efficient switching time. Taking $\delta = 0.1$ (the highest corrosion rate), characterizing the worst condition of the mains; without rehabilitation ($R = 0$), the optimal switching time for a rural utility is around 4 years from today. Whereas, for an urban utility, the optimal switching time is in less than 2 years. It is more cost efficient to replace mains earlier in an urban utility than in a rural utility. Switching time is less sensitive to cost recovery for urban utilities. Even with less than a third of costs recovered, it is beneficial for utilities to replace immediately since water loss reduction is worth it. Whereas, for replacement to occur immediately in rural utilities, at least half of the costs should be recovered.

In general, the main message that we convey from this result is that the benefit of rehabilitation depends on the the corrossivity of the mains, the degree of cost recovery and the relative trade off between cost of water loss and the cost of replacement. In our simulations, we assume that the utility plans on extending the longevity of the mains for at least 10 years by rehabilitation. We show that if the mains are highly corrosive, waiting 10 years (even with rehabilitation) is not beneficial for the utility. If the mains are less corrosive, it could indeed allow the utility to postpone replacement for more than 10 years; however, if the rate of corrosion is very small, there is little difference in the optimal timing with or without rehabilitation. We definitely see that rehabilitation benefits the most when the corrosion rate is the highest by comparing the difference in the switching time with and without rehabilitation; however, it is lower than 10 years. Moreover, for high levels of cost recovery, the optimal timing of replacement approaches $t^* = 0$, which implies an immediate replacement. This is because under profit maximization, cost recovery has a positive effect on revenue; hence, the earlier the switching time. And finally, we see a clear difference in the switching time between an urban utility and a rural utility. As we have already seen in Chapter 1, the typical characteristic of an urban utility is the fact that the cost of water loss relative to the cost of replacement is larger than in a rural utility. This is essentially due to the size of demand. Hence, the switching time is about twice as early for an urban utility than for a rural one.



(a) Urban utility



(b) Rural utility

Figure 2.2: The impact of cost recovery (β) and the price elasticity of demand (θ) on the switching time with $\gamma = 0.03$ and with rehabilitation.

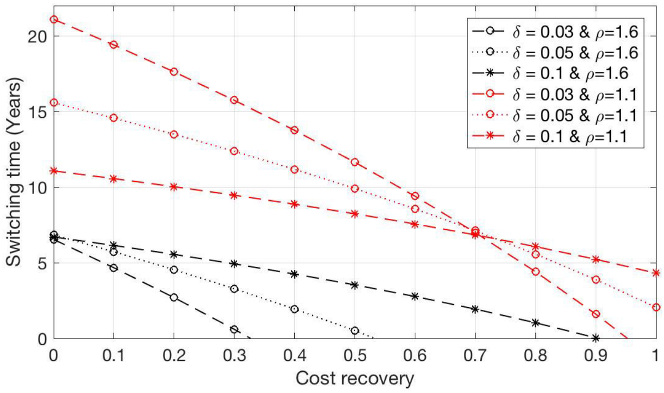
Effect of price elasticity of demand on the optimal switching time

Figure 2.2 shows the impact of price elasticity of demand on the optimal switching time. The price elasticity of demand is a highly debated topic in the literature of water economics. Some studies show that it is almost perfectly inelastic, whereas some studies show that there is indeed an elastic behavior. We show here that the optimal timing of replacement could be quite different depending on the assumption of elasticity. Here we assume that the utilities rehabilitate their mains. In both types of utilities, the optimal switching time is earlier under perfect inelastic demand. Under perfect inelasticity, cost recovery only affects the price; which means that revenue is greater than under inelastic demand.

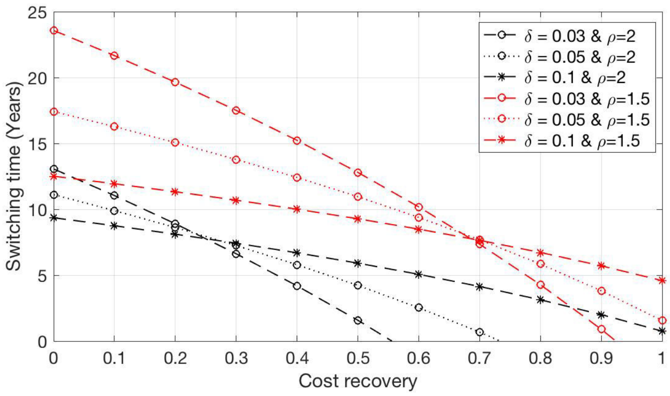
We can see that at $\beta = 0$ and $\delta = 0.03$, there is a 7 year difference in the switching time for an urban utility when $\theta = 0$ and $\theta = 0.2$. We can see that this difference is the smallest when the corrosion rate is the largest ($\delta = 0.1$). The higher the corrosion rate, the greater the need for renewal; however with rehabilitation, replacement is postponed and we have seen earlier that the marginal effect of cost recovery is the smallest with large δ which also captures the effect of elasticity. On the other hand, with smaller corrosion rates, rehabilitation has little effect on the reduction in water loss; hence the marginal effect of cost recovery on the optimal timing dominates. This in turn means that the smaller the $\theta = 0$ the larger the positive effect of β on revenue; hence, in terms of profits, the sooner the replacement, the sooner the better for small δ.

Cost recovery and the unit cost of water production

Figure 2.3 shows that the greater the unit cost of water production (ρ), the earlier the switching time. This is because the total cost of water loss increases. For an urban utility, at $\beta = 0$ and $\delta = 0.03$, the difference in the switching time could amount to 15 years. Similarly, for a rural utility, at $\beta = 0$ and $\delta = 0.03$, the difference could amount to about 11 years. We recall that under zero cost recovery, it captures the pure trade off between the cost of water loss and the cost of replacement. We further note

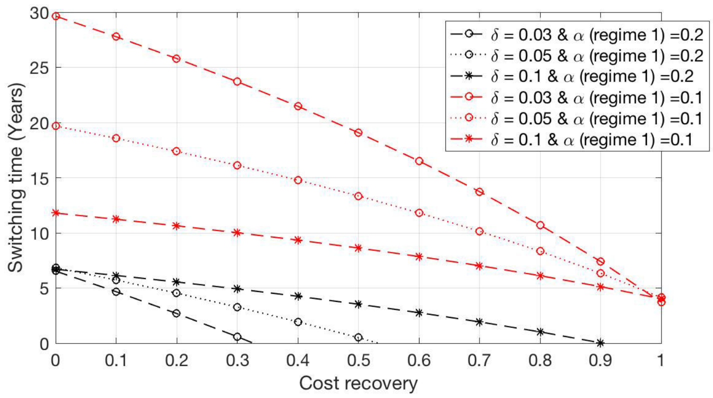


(a) Urban utility

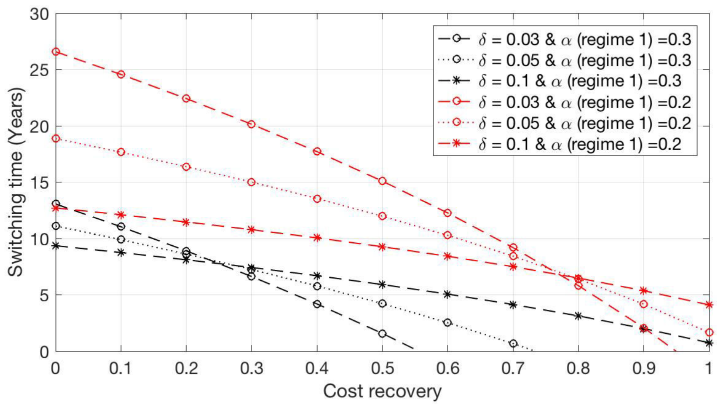


(b) Rural utility

Figure 2.3: The impact of cost recovery and the unit cost of water production (ρ) on the switching time with $\gamma = 0.03$, $R = R_{max}$ and $\theta = 0.2$.



(a) Urban utility



(b) Rural utility

Figure 2.4: The impact of cost recovery and the initial water loss rate ($\overline{\alpha}$) on the switching time with $\gamma = 0.03$, $R = R_{max}$ and $\theta = 0.2$.

that the difference in the optimal timin is the smallest when the corrosion rate is the largest. This shows that even if the cost of water loss is smaller but the mains are highly corrosive, the optimal switching time is barely affected.

Cost recovery and the initial rate of water loss

As we can see in Figure 2.4, the smaller the initial level of water loss, the further away the switching time. Again, we assume that the utility engages in rehabilitation at $t^* - 10$. If the corrosion rate is $\delta = 0.03$ and the cost recovery is $\beta = 0$, the optimal switching time for an urban utility is 30 years from today ($t = 0$) compared to 6 years if $\overline{\alpha}$ had been 0.2.

However, at full cost recovery, the optimal switching time is reduced to less than 5 years from today. As we have already mentioned in chapter 1 Part II, profit-maximization could result in excessive renewal under full cost recovery; especially in urban utilities where the price hikes are small due to large demand. We also notice that the difference in the switching time is the smallest for the highest corrosion rate ($\delta = 0.1$). These results show that the timing of rehabilitation on the eventual switching time depends a lot on the current state of the network (which we represent with the current rate of water loss). If the current rate of water loss is already quite high, rehabilitating at $t^* - 10$ has hardly any impact on the optimal switching time for very small corrosion rates (we have seen this in Figure 2.1). Whereas, if the current rate of water loss is not yet excessive, rehabilitation at $t^* - 10$ can have a significant effect on mains with a small corrosion rate (acts as a preventive strategy); whereas, for higher corrosion rates, the longevity of the mains cannot be extended much. These results suggest that rehabilitation can be beneficial (profit-maximizing) if the mains have a weak corrosive characteristic and if the current state of the mains is not yet obsolete. If the current state has already reached obsolescence, only for highly corrosive mains, rehabilitation could allow the utility to postpone replacement for a few more years; however, there is very little benefit for mains that age slowly. Hence, direct replacement is recommended on the basis of profit maximization.

2.6 Conclusion

In this chapter we developed a profit maximizing optimal switching-time model for water mains replacement. The question of main replacement is a prevalent issue in water utilities around the world, especially today, since a large proportion of the mains in use are already obsolete or are reaching the end of their expected useful life. One of the reasons why utilities postpone replacement is due to the financial burden and the lack of awareness of the public on the importance of water distribution infrastructure. This chapter focuses on the optimal timing of replacement of a small section of mains that are considered obsolete today (due to large volumes of water loss); in other words, we do not solve for the optimal replacement rates of the water main network, instead we solve for the optimal timing at which the utility decides to replace a subset of their mains that are obsolete. Is it optimal for the utility to replace them today ($t^* = 0$) or in the future ($t^* > 0$)?

Although optimal replacement schedules are theoretically estimated for each type of mains; depending on the utility-specific characteristics, the actual date of renewal could vary significantly. In our model, obsolescence of mains are represented by the volume of water loss. The longer replacement is postponed, the greater the water loss. We show that this optimal timing depends on key parameters such as cost recovery, price elasticity of demand, corrosion rate of mains, the cost of water production and rehabilitation. Our main contribution of this chapter concerns the effect of rehabilitation of obsolete mains and the degree of cost recovery. Rehabilitation is a cheaper way to temporarily fix the water loss problem; hence, utilities may prefer to rehabilitate instead of replacing. Moreover, in big cities where roadworks are disruptive, rehabilitation of mains are less cumbersome than replacement. We show that the optimal switching time indeed can be postponed in certain cases. In general, if the mains are already obsolete, rehabilitation has very little impact on the optimal timing of replacement. This impact is particularly clear in an urban utility, where replacement is preferable to rehabilitation. This is because rehabilitation is only a temporary solution in terms of water loss reduction. An urban utility is characterized by the fact that the total cost of water loss is large relative to the total cost of replacement; hence, the optimal switching time is earlier for an urban utility than for a rural one. In addition, we also show that in most cases; when all the costs (related to replacement and rehabilitation) are recovered in the price of water paid by users, the optimal switching time is reduced significantly; in some cases, replacement should have already occurred ($t^* \not> 0$). This result is comparable to what we have already observed in Part II of the first chapter; that too much cost recovery could lead to excessive investment. This is because cost recovery raises the revenue of the utility; especially, if the price elasticity of demand is low.

Chapter 3

Water mains replacement and the role of outsourced water provision: A case study of French water utilities

3.1 Introduction

In the first and second chapters we developed theoretical models that focused on the trade off between the cost of water loss and the cost of replacement of mains for explaining water distribution network quality. The analysis was based on utility-specific characteristics such as the length of mains, the material of mains, the size of demand, the cost of water production and the cost of replacement.

In this chapter, we investigate the effect of organizational structures of water utilities on network renewal. We have briefly explained in Part II of chapter 1 that in outsourced utilities, network quality could be significantly different from the optimal network quality (simulated by our model) due to the particular characteristic of outsourcing that had been pointed out by Christophe Audouin[1] during an interview regarding the decisions on network renewal taken by water utilities. In France, the water infrastructure remains under public ownership; however, the service (distribution of potable water to users) could remain public, be outsourced to a private firm or entirely privatised. Outsourcing is characterised by the fact that decisions concerning investments are left to the municipality, whereas fully privatised utilities can decide on their own. In theory, outsourcing should allow specialization of the staff working in the water industry; hence water distribution management should be more efficient, which means smaller water loss (González-Gómez et al., 2012). Indeed several papers by Chong et al. (2015), Ruester and Zschille (2010), Chong et al. (2006) and Carpentier et al. (2006) show that outsourcing (public-private-partnerships (PPP)) has a positive impact on performance, which is reflected by higher prices paid by users. According to Chong et al. (2015), high prices can be justified by the fact that outsourced water provision is accompanied with higher water quality in terms of water treatment. However, González-Gómez et al. (2012) show that there is a positive relationship between outsourcing and water losses, which could imply a negative relationship between outsourcing and water infrastructure quality. However, they write that this could be due to a selection bias of water utilities that originally were in bad shape that self selected into outsourcing. This reasoning could be justified by the fact that they observe a negative relationship between water loss and outsourced utilities with longer contracts. In other words, utilities that have been outsourced for a longer time have lower water losses than those that have been outsourced for only a short period of time.

González-Gómez and García-Rubio (2008) presents a summary of the main literature concerning the relationship between ownership type and the efficiency of urban water utility management. Efficiency is usually measured by estimating cost functions (nowadays by techniques such as the Data Envelopment Analysis). They conclude that there is no evidence which points to a causal relationship between management ownership and efficiency. The reason why privatisation or municipalisation may not reveal clear

[1]Personal communication with Christophe Audouin on the 10th of October 2016.

effects on efficiency is due to the nature of the industry which restricts the possibility of creating competitive environments. However, in the case of France and Spain, where services are often delegated to the private sector, a pseudo-competitive environment can be generated; hence the interest of studying their impact on water distribution network quality.

In line with González-Gómez et al. (2012), there is very little work in the economic literature that studies the issue of water loss (in general, infrastructure quality) in urban water utilities in relation to utility-specific factors and service operator type. Therefore, their work is the closest reference that we can draw concerning the aim of this chapter. Most analysis based on water network renewal focus on the technical and physical aspects of the mains themselves; such as the diameter, material, soil condition and age - studies that are practical to water engineers (such as Majdouba et al. (2011); Le Gat and Eisenbeis (2000); Demouy (2003)).

The contribution of this chapter is to show the effect of outsourcing on network renewal. After controlling for the factors that are specific to the utility, such as the size of the network; we would like to see if there is any specific impact of outsourcing on the rate of water mains replacement. If network renewal only depends on the utility characteristic such as demand, length, cost of replacement, etc.- factors studied in the theoretical models - there shouldn't be any difference between outsourcing or in-house provision. However, according to Audouin, water utilities that are outsourced may have smaller water mains replacement rates due to the nature of their contracts. Each water utility sets specific "objectives" concerning the distribution of potable water. It may focus particularly on quality aspects of the water itself, leakage reduction or price structures. Sometimes these "objectives" may leave out entirely the aspects of network renewal.

We differ significantly in the estimation method of González-Gómez et al. (2012). They conduct a simple weighted least squares regression model based on the weights defined by the length of mains. However, the rate of main replacement is not included in their model, which clearly affects the level of water loss. On the other hand, age of mains is included as one of the explanatory variables; which also is affected by the level of replacement. Indeed the authors observe that the effect of age is positive and then negative beyond a certain threshold value; which they reason by the presence of replaced pipes. There is definitely a problem of endogeneity that is present; which is treated in our regression model. We conduct an instrumental variable regression for positive replacement rates and an instrumental probit regression model to take into account replacement rates with zeros. Then we conduct a Heckit and a Two-Part regression to obtain the overall marginal effect. Furthermore in order to test any selection bias of water utilities self-selecting into outsourcing provision due to initial network quality conditions, we conduct a switching regression in reference to Chong et al. (2006).

Furthermore, we use open metadata of French water utilities. We obtain this data from the website of the *Observatoire national des services d'eau et d'assainissement*, where we can also find annual reports published based on analyses of these data, for example the one by Dequesne and Brejoux (2015) which we draw reference to when discussing the results. However, a multivariate analysis has not been conducted yet with a focus on water network renewal.

Estimation results show that water loss, prices, type of service provider, network length, urbanity and intercommunality have the strongest influence on the rate of replacement. We particularly focus on the significance of service provider type. Results show that globally, mains replacement is higher under in-house provision. This is partly because the majority of in-house provision is found in small networks and that smaller networks in general have higher replacement rates. The reason why rates are high is due to the fact that the length of mains replaced relative to the total length of the network is greater compared to larger networks. In addition, water loss is much lower in outsourced utilities in smaller networks. However, in very large cities, rates are significantly higher for in-house provision for the same level of water loss. This difference may be due to the difference in the objectives defined by the municipalities regarding the priorities on network renewal and potable water quality. A focus on network renewal represents a long run vision of network management. The problem with network renewal is that the benefit is not appreciated directly by the users - it is most of the time a source of nuisance due to the roadworks and the service interruptions. On the other hand, focusing only on user experience, which is primarily through water quality management, represents a short run vision of network management. Although maintaining high-quality water is primal to water distribution services, postponing replacement of obsolete mains could have large repercussions in the long run. First of all, highly treated water gets wasted through leakage and the longer the mains are left in use, more and more mains will reach its replacement age. Consequently, the burden of replacement falls on the future generations.

To our knowledge this is the first empirical paper that conducts a regression analysis on the rate of replacement of mains over a sample of French utilities.

This paper is organised into seven sections. The second section is devoted to the background information on water mains replacement and its influential factors, the third section presents and describes the data and the fourth section presents the empirical models. The results are presented in the fifth section and the discussion and political implications are included in the sixth section. Finally, the seventh section concludes.

3.2 Background: Factors that influence water mains replacement

Studies that focus on water mains replacement are abundant in the engineering literature (Shamir and Howard, 1979; Walski and Pelliccia, 1982; Majdouba et al., 2011); however quite sparse in the economics literature. Water mains network renewal is both an engineering problem but also an economic one. Mains that have exceeded their expected lifetime and have become obsolete have economic consequences - water loss, flooding due to main breaks, water quality reduction and of course costly intervention borne by the citizens. Therefore, in this chapter we investigate qualitative factors that may have impact on the water mains replacement of French water utilities.

The physical presence of water leaks is one of the main reasons behind water mains replacement; however, the actual decision to replace depends on several factors which comprise of financial, geographical, social and political aspects. Renaud et al. (2012) observe that reduction in water loss is disproportionate to the amount of mains replaced. The direct cost of replacing a main must be compared to the benefit generated, which again depends on what is considered "costs" and "benefits". The cost not only includes the cost of new pipes and the cost of installation, it also includes welfare loss caused by temporary interruption of water supply service. On the other hand, the benefit of replacing today and not tomorrow includes cost-saving of future intervention costs and prevention of further water loss. According to Arjun Thapan[2], recovering non-revenue water (which includes water lost from leakage) costs less than investments in supply augmentation (Frauendorfer and Liemberger, 2010). In other words, repairing leaks costs less than the cost of alternative options to compensate for leakage. The factors that impact the cost of leakage depends on characteristics that differ from utility to utility. For instance, "cheap" water - essentially groundwater - would imply a lower cost of leakage than "expensive" water such as surface water or desalinated water. If the opportunity cost of leakage is small, replacement is not an immediate concern. Furthermore, some utilities are less equipped in leakage detection than others. For instance, larger cities are more active in network renewal and leakage detection because they have more access to funding and hiring technicians and experts. Hence, urbanity should be taken into consideration. Moreover, the decision for utilities to outsource, privatise or remain in-house can also be a key in explaining the differences in water mains replacement. In this section we provide detailed information on all these factors already mentioned and many others that can have an impact on water mains replacement. In the next section we present the factors that can be found in the database that is used for the estimations. Some of the factors presented here are not available in the database; hence we use proxies if possible.

[2]The Chair of Expert Advisory Group of the International Hydrologic Programme at UNESCO

3.2.1 Water leaks

A network with large volumes of water leaks could signal a poor state of mains, meaning obsolete mains or poorly installed mains. Water lost through leakage is quite literally *money poured down the drain*. Production of potable water is not free of charge; it consists of extraction and treatment costs. Therefore, higher water loss should incite utilities to replace leaky mains. However, oftentimes replacement costs are greater than the cost of increasing water production, hence utilities would rather pump more water to compensate for leakage than to replace the leaky main (Garcia and Thomas, 2001; Renaud et al., 2012). The cost of water loss depends on the production cost of water; hence, with large demand and large costs, main replacement becomes a favorable option (Cousin and Taugourdeau, 2016).

3.2.2 Age and material of pipes

Old networks have a higher probability of water leaks and eventual main breaks. However, age by itself does not determine the state of the network. The material of the mains and geographic characteristics of the region are equally important. Younger mains may require imminent replacement due to its material or soil condition. For instance, the same aged mains, whether it is made of cast iron or PVC could have aged very differently. In addition, whether these mains are located under a busy road or under a pedestrian could have different impact on the state of the mains in terms of physical damage. Moreover in some cases, such as lead pipes have properties that are harmful when ingested by humans. These pipes do not necessarily have leakage, however, due to sanitary reasons, must be replaced.

3.2.3 Network size and customer base

A large network implies that the utility provides water to large agglomerations instead of small rural villages. This means that the cost of replacement is larger (Chauveau, 2014). However, at the same time, large utilities tend to benefit from economies of scale through larger demand size. The greater the demand, the investment cost associated with the replacement of mains can be shared over a large customer base through a small amount of increase in prices. In other words, cost recovery is easier with a large demand base. Hence, the network size could have a positive or negative impact on the replacement depending on the factor that is dominant. We also showed in Chapter 1 and 2 that water utilities with economies of network density should prioritize water loss reduction due to the large demand base. Therefore, based on our theoretical results we should expect higher replacement rates where network size is large (with the presence of network density economies).

3.2.4 Type of service provider

While the water infrastructure remains under the ownership of the state, the distribution of water could either be managed in-house or delegated to a private entity or fully privatized. In France there are several types of operators: direct public management (*régie*), two hybrid public management (*régie avec une prestation de services* and *régie intéressée*), and three forms of public-private partnerships (*affermage*, *concession* and *gérance*). In theory, as Chong et al. (2006) point out, "PPPs could harness the benefits of both public and private solutions" but franchise-bidding could lead to suboptimal results depending on the nature and the length of the contract. Moreover, the involvement of a private firm will influence decisions that satisfy minimization of cost of production which could result in low levels of costly replacement activities (González-Gómez et al., 2012). However, this is only in the case where the investment decisions are shared between the local authority and the private company. The majority of the water utilities in France are either operated in the form of direct management (régie) or outsourced in the form of lease (affermage) contracts[3]. Under a lease contract, the operator's responsibility is specified by the local authority which could include water quality management, maintenance or network renewal. It is often possible to have con-

[3]In our sample less than 5% consists of the rest of management types. Hence, we analyse the effects of the two dominant management types.

tracts that do not specify network renewal. Moreover, the local authority is in charge of decisions concerning investments (network renewal). The operator is remunerated directly by customer receipts which exposes them only to operational risk (Chong et al., 2006). This means that depending on the objective of the local authority, the operator in charge could be expected to engage in network renewal or not. Hence, the mere fact that a utility is outsourced or not should not have a direct impact on the level of main replacement; it depends on the objective defined by the municipality. However, the choice of outsourcing or not is not taken randomly by the municipalities. This non-randomness of the choice of each municipality may reflect upon the rate of replacement. As we can see in the paper by Chong et al. (2015), large utilities benefit more from the positive aspect of outsourcing (through efficiency gains) than small utilities. The “abusive” behaviour can be observed among those that operate in small networks because they have less power to “discipline” the outsourced firms. They observe that larger utilities are more capable of switching back from outsourcing to in-house provision than smaller ones; therefore, the incentive of maintaining high-quality performance levels varies among utilities. Such structural difference could reflect on water mains replacement.

3.2.5 Objectives of the utility

Utilities that sign outsourcing contracts with a private firm specify in their contracts the objective of the municipality. Network renewal does not necessarily appear in the objectives. In that case there will be no impact of outsourcing on mains replacement. According to Audouin’s experience, he observed certain outsourced utilities that lowered prices during their contract duration since network renewal was not included in the contract.

3.2.6 Groundwater, surface water or imported water

A utility that extracts groundwater faces lower costs of water production than a utility that extracts surface water. Groundwater is cheaper since there is less treatment needed. The greater the cost of producing potable water, the greater the cost of leakage which should incite utilities to replace leaky mains (González-Gómez et al., 2012; Renaud et al., 2012). Moreover, utilities that import their supply of water are dependent on external sources of water. Imported water is more expensive than direct supply since they are charged for the delivery service. If a utility is located far from the source, the cost of delivery will be much higher. Hence, greater the dependence on imported water, the greater the cost of water loss (Renaud et al., 2012).

3.2.7 Soft water or Hard water

Depending on the geographical region, water could be either hard or soft. Soft water is known to accelerate corrosion of pipes and favor the apparition of leaks (CNRS, 2000). Therefore, depending on the type of water, the replacement rates could vary. Soft water is particularly present in the North West (ex. Bretagne) and in the lower regions of the center of France. Therefore, where soft water is abundant, replacement of corrosive mains could be observed. However, the corrosivity depends also on the material of the pipes. Even if the water is soft, if the network is mainly composed of PVC or HDPE, there would be little corrosion compared to cast iron mains.

3.2.8 Price/tariff of water

The price charged per m^3 of water in France is divided into three parts. About 45% of the price represents the cost of water supply, about 40% reflects the cost of wastewater collection, and about 15% represents taxes (ONEMA, 2012). The European Water Framework Directive enforces the principle of full-cost recovery, which means that prices should reflect the cost incurred by the utility. As Egenhofer et al. (2012) writes, cost-recovery "is a tool to obtain the necessary funds to run the public water supply system and cover the investments needs." He further states that "appropriate cost recovery mechanisms are essential to ensure the financial viability of water management." Moreover, according to Renaud et al. (2012), France no longer receives subsidies; therefore, they are faced with strict budget constraints which accentuates the importance of cost-recovery. Hence, the higher the price charged to consumers, the larger the financial feasibility of the utility to engage in costly investments.

3.2.9 Knowledge of the state of network

The awareness of the state of the water distribution network is not guaranteed by all utilities. It highly depends on the pertinence of leakage detection technology and the knowledge of the operational condition of their mains. The less an utility is aware of potential main breaks or leakage in their pipe system, the less the utility would meet investment requirements. The lack of knowledge that persists among utilities concerning the state of their network is a significant obstacle to replacement. Less than 20% of the utilities had reported a detailed description of their network in 2012 (Radisson, 2014). Since 2013, the *Grenelle II* enforces the utilities to provide detailed description of their state of network. According to Audouin, bigger utilities tend to be more knowledgeable of their network. This is because they have better access to technicians and experts compared to small/rural utilities.

3.2.10 Geographical effects

Depending on the geographical aspects that are specific to the regions in France, the structure of the water utility could be different and consequently water network management could be influenced. For instance, a mountainous region may have different costs of main replacement compared to a flat region. Transporting new pipes into towns that are located in higher altitudes should be more cumbersome than transporting through plain fields. Moreover, due to potential difficulties in water network management, water utilities may tend to resort to economies of scale solutions such as regrouping the management of several networks together. Overall, the regional specific effects could have an indirect effect on the decisions concerning network renewal. For instance, in France, the Rhone-Alpes region of France captures the mountainous geography, as well as the policies adapted to its geographical characteristics. Whereas, the region of Ile-de-France which includes Paris would capture the urbanity and its associated political environment of the region.

3.2.11 Financial situation

Although the cost of water production should be covered by the price of water paid by the users (according to the principle of "l'eau paie l'eau"(water pays water)), oftentimes the receipts itself do not suffice to cover the entire cost of investment. Since subsidies are no longer available to utilities for infrastructure investment and since raising prices faces resistance, utilities require funding from other sources, such as debt issuance(Renaud et al., 2012). Hence, those that already have a large debt burden will have difficulty increasing debt, leading to low investment.

3.2.12 Average revenue of the region

The level of prosperity in an area where the utility is in charge of water distribution could have an influence on the ultimate decision of water network renewal. Since replacement of mains implies a rise in prices for the purpose of recovering costs, areas that are struck hard by low average revenues may tend to postpone such costly activities. According to Audouin, the region of the North of France during the industrial period was much wealthier than today. During the industrial period, many large mains were installed; hence, today, they face large costs of renewal which do not correspond to the current revenue level of the inhabitants.

3.2.13 Political incentive in public utilities

In favor of being reelected, the municipal authority would avoid actions that are unpopular to the citizens size as price hikes (Chong et al., 2015). Hence, raising prices to reflect the cost of main replacement may raise voices among citizens and in turn negatively impact network renewal (González-Gómez et al., 2012). Although the elasticity of demand is quite weak for water, "evidence suggests that users alter their water consumption patterns in response to water charges" (Egenhofer et al., 2012). According to Dore et al. (2004), the public water services had maintained water prices heavily underpriced for a long period that it is not adapted to recover costs of infrastructure renewal. However, adjusting to the current need of network renewal would require huge price increases in some utilities which would face resistance from households (AWWA, 2012). Moreover, utilities anticipate the risk that higher prices may reduce consumption levels, eventually hurting their revenues. Therefore, depending on the political orientation of the incumbent and their plan of action, replacement rates could vary. However, according to González-Gómez et al. (2012), the political ideology in the local government had no effect on the level of water loss.

3.3 Data Description

We collected municipal-level data from the 2014 SISPEA database[4] on the performance variables of water utilities. Some of the factors that are mentioned in section 3.2 are not available in the database, such as data on the age of pipes, material, financial situation and utility objectives. The sample we obtained represents 45% of the utilities in France. Although all the utilities in France are required to submit complete information of their network, due to various reasons[5] the database remains incomplete, hence we are confronted with missing values. We present in Table 3.1 the summary statistics of

[4]The data sheets are available on this page: http://www.services.eaufrance.fr/base/telechargement. The data sheets are updated on average every 6 months. Therefore, the actual 2014 data sheets may not correspond to the version used in this paper.

[5]For example, some utilities may find difficulty filling out certain information that lack precision in their definitions or simply due to lack of data (Brochet et al., 2015).

the variables before removing outliers, missing values and applying log-transformations. The variables listed do not include the interaction terms and generated variables. They will be mentioned in the next section.

As we can see in Table 3.1, the total number of potential observations (total number of utilities) is 13,339; however, the number of observations left for our estimations without missing values ranges from about 1000 to about 3500 observations depending on the choice of the model and the choice of variables.

3.3.1 Pre-estimation analysis of the explanatory variables

In this section we study each explanatory variable that we include in our estimations.

Water loss

We can see in Table 3.1 that the values of `water loss` vary among utilities. Due to misreported values of the length of the network, `water loss` is affected since it is calculated as the volume of loss per km of mains. On the other hand, it is possible that utilities have reported `water loss` in terms of percentages instead of volume per km of mains. In order to detect potential outliers, we have converted `water loss` to a percentage value. We observe that about 10% of the utilities that have reported the values of `water loss` correspond to percentage leakage greater than 40%; furthermore, about 18 observations exceed 100% due to error inputs of either the volume of water produced or the total length of mains. These observations are considered as outliers. In line with Dequesne and Brejoux (2015), we expect a positive impact of water loss on the rate of replacement since water loss signals problematic mains. However, if in the past, many mains have been replaced, we would observe smaller water loss today. Hence, this signals an endogeneity problem. We will deal with this variable in the next section by introducing an instrumental variable.

Furthermore, the reason why we do not represent water loss in percentage form is due to the fact that percentages are misleading. Water loss indices as a form of

Table 3.1: Summary statistics

Variable	**Mean**	**Min.**	**Max.**	**N**	**Units**
rate of replacement	0.761	0	94.040	5220	%
water loss	3.768	0	169.479	5477	$m^3/km/day$
tariff2014	2.01	0	7.1	5719	€$/m^3$
regie	0.68	0	1	12562	dummy
length	322.446	0	456351	5558	km
knowledge	75.342	0	120	5797	index
ratio of produced to imported	0.749	0	1	5302	ratio
soft water	0.245	0	1	13339	dummy
groundwater	130.95	0	110517	4497	%
revenue group 1	0.09	0	1	13339	dummy
revenue group 2	0.31	0	1	13339	dummy
revenue group 3	0.29	0	1	13339	dummy
revenue group 4	0.29	0	1	13339	dummy
Nord Pas de Calais	0.021	0	1	13339	dummy
Picardie	0.051	0	1	13339	dummy
Champagne Ardennes	0.076	0	1	13339	dummy
Lorraine	0.071	0	1	13339	dummy
Alsace	0.023	0	1	13339	dummy
Ile de France	0.041	0	1	13339	dummy
Haute Normandie	0.017	0	1	13339	dummy
Basse Normandie	0.026	0	1	13339	dummy
Bretagne	0.032	0	1	13339	dummy
Pays de Loire	0.016	0	1	13339	dummy
Centre	0.069	0	1	13339	dummy
Bourgogne	0.052	0	1	13339	dummy
Franche Compté	0.062	0	1	13339	dummy
Poitou Charentes	0.012	0	1	13339	dummy
Aquitaine	0.034	0	1	13339	dummy
Midi Pyrenées	0.052	0	1	13339	dummy
Limousin	0.025	0	1	13339	dummy
Auvergne	0.037	0	1	13339	dummy
Languedoc Roussillon	0.088	0	1	13339	dummy
PACA	0.056	0	1	13339	dummy
Rhone Alpes	0.115	0	1	13339	dummy
Corse	0.024	0	1	13339	dummy

network performance indicator has been preferentially used over percentage forms by water professionals (Lambert et al., 1999). As Winarni (2009) writes, water loss rates are strongly influenced by the volume of demand; hence the same volume of water loss can take different percentage values depending on the volume of demand. Let us take an example with a rate of water loss of 20%. If the total production of utility A is $1000m^3$, while for utility B it is $100m^3$, the total water loss for utility A is $200m^3$, while for utility B it is $20m^3$. In percentage form, the water loss is equivalent for these two utilities. However, in terms of water loss indices, we could differentiate them. Suppose that utility A has 10km of mains and utility B has 2 km of mains in total. The water loss index would be $20m^3/km$ for utility A and $10m^3/km$ for utility B. On the other hand if utility A had 5 km in total, the water loss index would become $40m^3/km$[6]. Hence, the water loss index not only takes into account the production level but also the length of the main which reflects the size of the utility. If total water production is sizeable, the percentage loss could be quite small, which underestimates its severity. In terms of relative cost, if water demand is sufficiently large, the absolute volume of water loss could be neglected by the utility. The water loss index allows a comparison of the volume of loss relative to the size of the utility which helps reveal the quality of the network. Although utility A and B may have the same percentage of water loss, in terms of $waterloss/km$, utility A has a larger volume of loss relative to the size of its network.

Knowledge

Knowledge is evaluated in the form of *scores* that range from 0 to 120. On average the utilities we have in our sample score around 75 points out of 120. According to SISPEA, this knowlege index can be divided into three components. 15 points are given if the utility has an updated map of their main network, 30 points are given if detailed inventory of their network is available including information on the material of the pipes and their installation date. Finally, 75 points are given to information available on the

[6]A similar example is given in the paper by Winarni (2009).

rest of the aspects of the network; for example the location of the service connections and an updated information on the replacement schedule. We observe that the knowledge index is greater among the utilities that report positive rates. Moreover, although weak, there is a positive correlation between the knowledge index and the positive rates for utilities that are outsourced. Outsourced utilities are in the hands of private entities whom are specialised in various areas concerning water supply management.

Tariff

The `water tariff` (measured in €$/m^3$) is the price charged to users that consume up to 120 m^3 including taxes. This price only concerns one part of the entire tariff paid by users. As we have already mentioned previously, the price associated with the distribution of potable water reflects on average 45% of the entire price charged to consumers. We can see in the Table that the minimum price is zero. Indeed, there are 8 utilities that report zeroes, which we consider as outliers.

The effect of price is difficult to estimate since it is endogenous. Current prices could reflect past, current or future investment costs. Moreover, for outsourced utilities, prices are determined upon the signing of the franchise contract. We elaborate on this issue in section 3.4.1. In both cases, scatterplots do not reveal a clear correlation between the rate and the price. However in line with Chong et al. (2015), we observe a link between the price and the population and the operator type. Depending on whether the utilities are outsourced or not, the relationship between price and population is different. Utilities that distribute water to municipalities with greater than 10,000 inhabitants tend to set lower prices than in municipalities with less than 10,000 inhabitants. Whereas, under in-house provision there is barely a difference in prices between the two. In their paper they explain that "while cities with populations exceeding 10,000 residents tend to discipline franchisees that overprice by not renewing their contracts, the renewal pattern of towns with 10,000 or fewer residents is not influenced by franchisee overpricing." Although on average prices are higher in outsourced utilities, depending on the size of the utility, some utilities benefit less from the gain in efficiency expected form private firm participation. They also mention that the quality of water and infrastructure is in general better under private provision than in-house provision. We compare the average water loss index in utilities that are operated in-house and those outsourced. Indeed, the average volume of water loss per km of mains in an outsourced network is about 3.16 m^3 whereas the average volume is about $4.18m^3$ for utilities that are operated in-house. This may imply that although outsourced utilities set higher prices, it is justified by a better network quality with smaller water loss. Moreover this could imply that higher prices and outsourcing are associated with higher network renewal.

Ratio of Produced and Imported water

We expect rates to be greater for utilities that depend largely on imported water due to higher costs. We can see that on average, the majority of the utilities self-produce their water. On average 75% of the production is supplied directly by each individual utility. Although there is very little difference based on the size of the utilities, utilities that are 100% self-sufficient tend to be a little smaller than those that depend on imported water. Where there is larger demand, it is more likely that utilities need to import from other utilities. Moreover we also observe regional disparities. Utilities in the Northwest depend more on imported water than in the Southeast of France. There is perhaps a difference in the abundance of water. Moreover in the Southeast regions of France we observe more smaller utilities, whereas in the Northwest, we observe a larger number of intercommunal utilities. Merging of communal-level utilities could be a sign of cost-sharing and in search for scale economies. However, the impact of imported water on replacement depends on the state of the network. Utilities with very small volumes of water loss or with good quality water infrastructure are not concerned with imminent mains replacement. But if the utility faces large volumes of water loss, those that depend heavily on imported water may be inclined to invest more in mains replacement.

We remove observations with zeroes since it means that there is zero water production.

There are 4 utilities that report zeroes, which we consider as outliers and leave them out of the estimations.

Groundwater

We can see in Table 3.1 that `groundwater` has some obvious outliers. Since it is measured in percentages, the maximum value should be 100 but we see that it exceeds 100. There are four observations that correspond to these outliers. Without them, the mean is 88%. This means that, the majority of French water utilities depend mainly on groundwater resource (whether it is imported or produced in-house). According to Dequesne and Brejoux (2015), regions in the North and the West of France depend more on surface water. Surface water requires more treatment in the potabilisation process and therefore, water production costs could be larger in these regions compared to the Southeast of France. We also observe that there are more intercommunal utilities where there is less groundwater available, perhaps reflecting the necessity to share the cost burden. The impact on replacement rates would depend on the difference between the cost of potabilisation of groundwater and surface water.

Soft water

We can see in Table 3.1 that about a quarter of the water resources in France is composed of soft water. This type of water is more corrosive than hard water. Hence, networks with a large proportion of corrosive mains may face a larger need for replacement. Moreover, soft water also requires more quality management since they are more likely to have water quality problems. Hence, we may observe higher rates of replacement for utilities that are faced with soft water. However, if in these regions the network is fairly recent and is composed of recent material, we would expect to see very little impact of soft water on the rate of replacement.

Revenue

We include dummy variables for four categories of revenue level. We obtained the data from an INSEE report[7] that maps out the difference in median revenue level for each department in France. They have created four categories where the first category represents revenues between 17350 to 20360 euros, which we denote as `rev1`, the second category from 15766 to 17350 euros, which we denote as `rev2`. The third category from 14820 to 15766 euros, which we denote as `rev3` and the fourth category from 13740 to 14820 euros, denoted as `rev4`. Although the report dates back to 2004, we used this report as a reference point since we end up with the same grouping of departments from another report in 2013 (but they are subdivided into 8 categories). We recall the reason why the average income level may matter on the decision to replace mains. Due to the fact that municipalities may be reluctant to allow price rises in relatively low income areas, investments such as network renewal may occur less frequently. We observe a positive correlation between tariffs and revenue levels. The average tariff for the group `rev1` is around 2.15 euros while for `rev4`, the average tariff is 1.94 euros. However, the two other revenue groups in between have a reversed order. `rev3` has an average tariff of 2.07 euros while the `rev2` has an average tariff of 1.96 euros. This discrepancy may be also influenced by the difference in the type of water used in the corresponding regions.

Regions

Although today the number of regions in France (main land) have shrunk to 13, the data we use is from 2014; when there were still 22 regions. The summary statistics show that the observations are fairly equally distributed over France. The left map in Figure 3.1 shows the distribution of utilities around France. Each value represents the percentage of utilities in the specific region. For instance, there are around 4% of the total number of utilities in France that operate in the region of Ile de France. Furthermore the right map

[7]The link to the INSEE report 2004 https://www.insee.fr/fr/statistiques/1280669

in Figure 3.1 shows the distribution of our sample. The values in each region represents the percentage of utilities that have reported either zero or positive replacement rates. We can see that where the percentage of reported rates are higher, the percentage of utilities is also high as well; hence, we do not observe any major accumulation of data in one particular region. These regional dummy variables could help capture effects that are specific to the region.

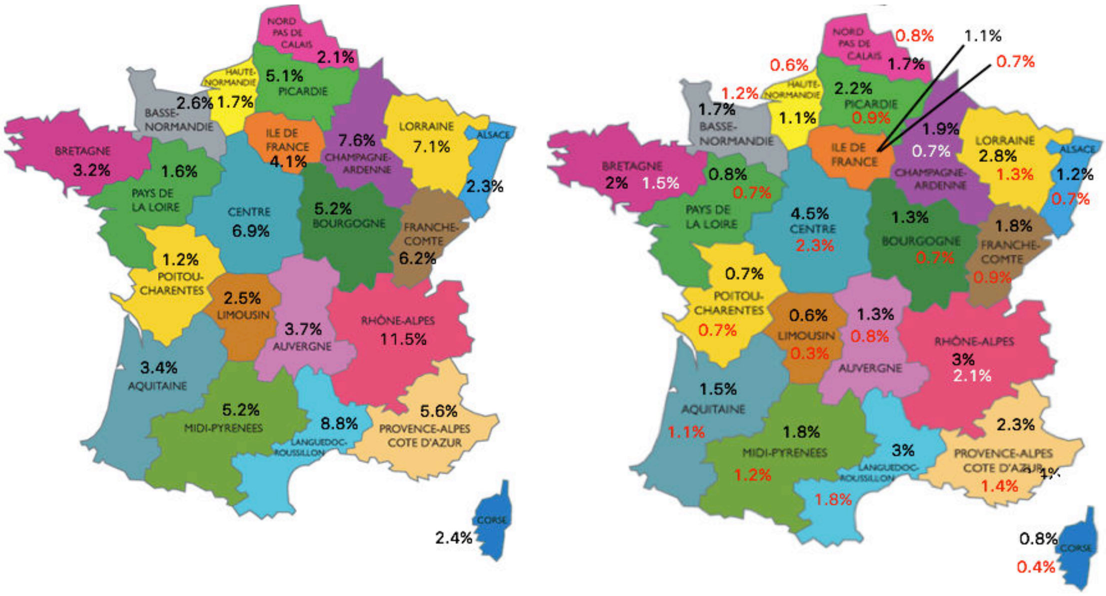


Figure 3.1: On the left: The distribution of utilities around France out of the total 13339 utilities. On the right: Proportion of utilities in each region out of the total number of utilities in France (13339) that have reported the rate of replacement. In black, the percentage of utilities that have reported zero or positive rates. In red or white, the percentage of utilities that have reported positive rates.

We can see that Rhone-Alpes and Centre have many utilities; hence, naturally we have a large proportion of those observations in our sample. The reason why some regions have more utilities is because they have many small municipal utilities which are in-house operated (as we can see in Figure 3.2). Each individual commune is in charge of the supply of water; and there are many small communes in these regions. For instance, in the region of Centre and Rhone-Alpes, the median size of the utility is less than 2000 inhabitants; while in Bretagne and Pays de la Loire the median size of the utility exceeds 5000 inhabitants.

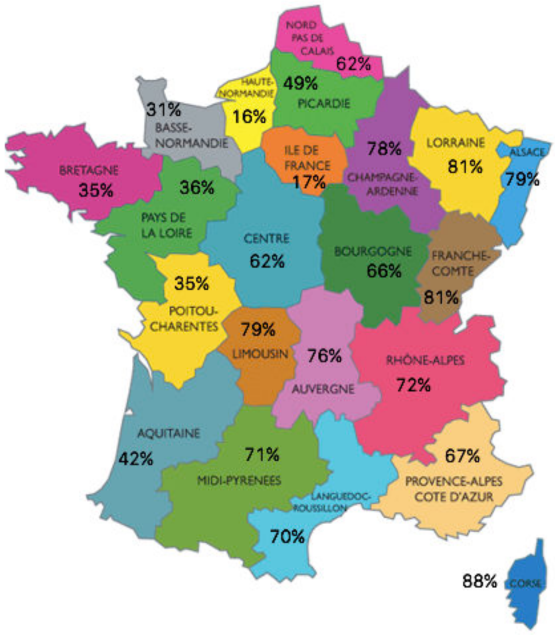


Figure 3.2: The proportion of utilities operated in-house (régie) in each region of France in 2014

3.3.2 Pre-estimation analysis of Replacement rates with network size and operator type

In this section we examine the relationships among the network length, the replacement rate and the operator type. We analyse separately the positive replacement rates and zero replacement rates since there is a large proportion of observations with zero rates. This is taken into account in the choice of the model which is presented in the next section. The statistical analysis conducted in a recent report by Dequesne and Brejoux (2015) published on the ONEMA website only include observations with positive rates. According to them, including observations with zero rates could bias their results since these observations could reflect utilities that do not have annual updated information on their water mains. Moreover, utilities that are unaware of the actual rate of replacement may simply report zero values. However, by analyzing only positive rates, we may be ignoring a major selection problem. In our estimations we use both zero rates and positive rates to deal with this possible selection bias. The utilities that reported zero may be systematically different from the utilities that reported positive rates.

Replacement rates and Length of network

The values of the `rate of replacement` found in the database is presented as an average rate over the past 5 years. It ranges from 0 to 94%. As we can see in the table, the average rate of replacement is about 0.76%, which clearly hints the presence of outliers and skewness. There are 17 observations with replacement rates greater than 20%. This does not mean that all observations with large values are outliers. A typical outlier we encounter is incorrectly reported values by the utilities. For instance, there are utilities that report the total length of mains in terms of meters instead of kilometers. We observed this anomally by comparing values from previous years (if they were reported). For example the water utility of Bligny-sur-ouche had reported 11.9 km in 2013; however in 2014 they had reported 11799 km; which indicates an input error. On the other hand, utilities with small networks (total length less than 10km) could have rates that exceed 20% without it being an error. For example, Lougres, which has 3 km of mains in total reported a rate of 70%. This corresponds to 2 km of mains, which is not an unrealistic scenario. However, the fact that we are dealing with an average rate of replacement calculated over 5 years, 2km of mains replaced annually for a utility with a total of 3 km of mains does not seem right. Hence, extremely large rates are most probably due to an input error or an accounting problem.

We observe a negative relationship between the total length of the network and the positive rates of replacement. However, for very large utilities, we no longer see a strong negative relationship between size and the rate of replacement, as shown in Figure 3.3. In order to capture this nonlinearity, we include a quadratic term of the length in our estimations.

We consider the length of the network to represent the size of the network. Since

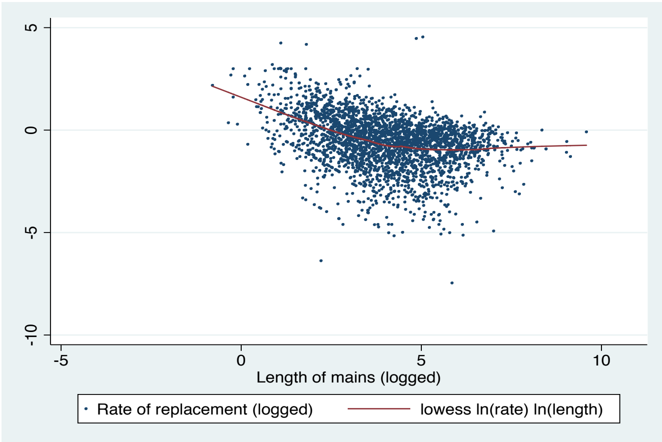


Figure 3.3: Correlation between the rate of replacement and the length of mains.

it is highly correlated with the number of inhabitants, we do not include population in the estimation. The term becomes omitted due to severe collinearity. We can see this in Figure 3.4.

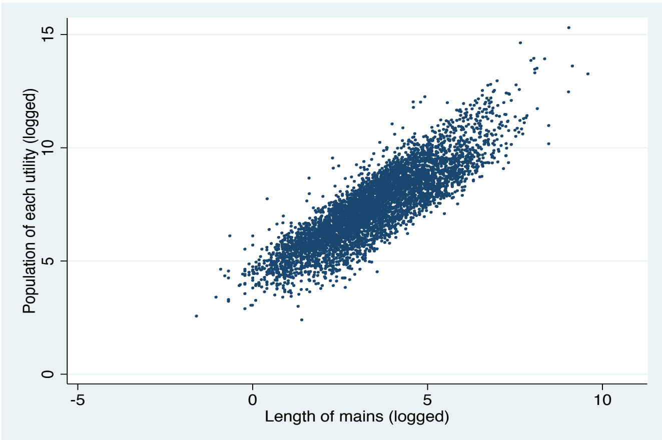


Figure 3.4: Correlation between the population and the length of mains.

3.3.3 Operator type and rate of replacement

The `regie` variable takes value 1 if the utility is operated in-house (regie) and takes value 0 if the utility is outsourced to a private entity (affermage), which represents Public-Private-Partnership (PPP). We only consider these two operator types since they represent the majority. Only about 5% of the utilities have other types of organizational forms (mentioned in section 3.2).

Looking only at positive replacement rates (greater than zero), we observe a positive relationship between utilities that are operated in-house (*régie*) and the rate of replacement. This would imply that in-house operated utilities are more actively engaged in network renewal. However, we also observe that among the positive rates, in-house operated utilities tend to report larger replacement rates compared to outsourced ones. This could be explained by the fact that in-house operated utilities tend to be smaller in size in terms of total length of the network. We can see this in Figure 3.5.

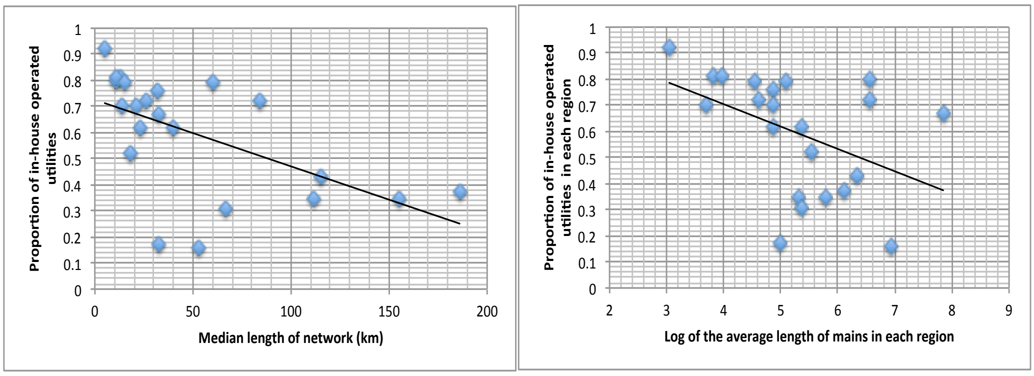


Figure 3.5: Correlation between in-house operated utilities and the size of the network. Each point represents a different region in France. On the left, we plot over the median length of the network due to skewness. On the right we plot over the logged average length of the network. Both plots show a negative relationship.

Small utilities are represented by short total network length, which means that the percentage of replaced mains would naturally be greater compared to a longer network. Furthermore, small utilities mostly represent rural utilities which can undergo replacements more easily than large utilities due to the fact that replacements can be done simultaneously with other roadworks. Pearson (2002) writes that urban areas face more difficulty in locating and repairing leaks. Furthermore, Figure 3.6 shows a positive relationship between utilities operated in-house and the proportion of zero replacement rates.

In other words, zeroes are reported more often by utilities that are operated in-house than those outsourced. However, the fact that small utilities have zero replacement is

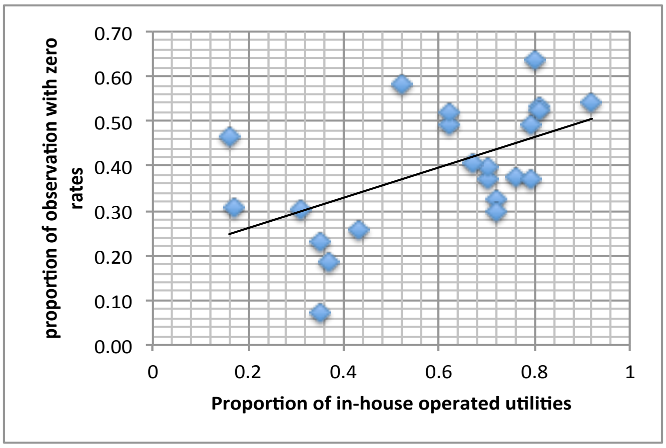


Figure 3.6: Correlation between the proportion of in-house operated utilities and the proportion of zero replacement rates. Each point represents a different region in France.

not absurd since their network tends to be younger. As we have already mentioned, rural utilities (mostly operated in-house) tend to have younger mains. We control for this difference in our estimations.

3.3.4 Generated variables

We generate several interaction and dummy variables to be able to control some of the effects discussed previously. We present here the summary statistics of these variables. Since the value of rate of replacement is an average value of the rates from the past 5 years, in order to control for the utilities that terminated or renewed contracts with an outsourcing firm, we include a dummy variable that identifies utilities that have had a contract since at least 5 years. We name this variable `contract since 2010`.

As previously mentioned, we include a control variable, *pop10000*[8] that captures the difference between rurality and urbanity. This distinction is also used in the paper by Chong et al. (2015), where they consider municipalities with inhabitants greater

[8]For utilities that consist of several communes, we divided the population of the utility by the number of communes so that it represents the average size of each commune. Hence, this dummy variable represents the size of each commune and not the population of each utility.

than 10,000 people as large towns or cities. 10,000 is a number often used by INSEE to conduct population census. Communes with less than 10,000 inhabitants receive an exhaustive census; whereas they conduct a random sampling in communes with inhabitants greater than 10,000 for the population census. Hence, we use this value to distinguish between rurality and urbanity (Dumont, 2016). The purpose of controlling for the difference between urban and rural areas is to reflect the difference in the age and material of the water networks. In urban areas, networks tend to be older and consist more of materials from older times, whereas in rural areas, water networks are much younger.

In addition, we create a dummy variable that captures the impact of very large intercommunal utilities. Utilities that are made of several communes reflect the need for cost sharing and the preference towards joint management compared to provision on an individual communal scale. We chose the utilities that exceed the 95 percentile; utilities that provide service to more than 14 municipalities. We name this variable: `commune14`.

As we have mentioned previously, in order to capture the relationship between the size of the water network and the tariff, we create an interaction term that we denote by `lengthtariff`.

We also observed the nonlinearity of the size of the network on the replacement rates; hence we create a quadratic term of the total length of the network which we denote as `lengthsq`.

As we have already thoroughly explained in the previous section, the majority of observations with zero replacement rates tend to be operated in-house. On the other hand, among them that have positive replacement rates, the rates tend to be quite high. This is highly linked to the fact that the utilities are small. Hence, in order to control for this interaction between operator type and the size of the utility (the nature of the utility), we introduce an interaction variable which we call `regielength`[9].

And finally, since we observed a difference in average prices between the operator type, we generate an interaction term that we denote by `regietariff`.

As a final note, some variables that we have generated were dropped from the regression due to severe collinearity such as: the interaction term between knowledge and length of the network, dummy variable that represents the quality of water and a dummy variable that represents the political orientation of the *departement* where utilities belong.

3.3.5 Variable transformation

We transform the groundwater variable into a dummy variable which we denote by `ground100`. Utilities that depend 100% on groundwater takes value 1 and it takes value 0 for the others. The reason why we applied this transformation is due to the fact that bootstrap simulations for estimating marginal effects in the Two Part model failed to produce correct estimates. This is because the groundwater variable is unbalanced. Around 85% of the utilities depend 100% on groundwater; hence, the distribution of the variable becomes quite unbalanced, affecting the coefficient estimates. Hence, we transform the variable into a binary term. As we can see in table 3.2, this transformation has very little impact on the average proportion of groundwater usage by utilities.

Table 3.2: Groundwater variable transformation

variable	**N**	**mean**	**p50**	**sd**	**skewness**	**kurtosis**	**unit**
groundwater	4493	87.93	100	31.253	-2.324	6.5554	percentage
ground100	4493	.85	1	.3571	-1.96	4.8426	ratio

[9]To avoid severe multicollinearity among variables that appear in interaction terms, we center (de-mean) each variable.

As we can see in Table 3.1, there are several variables that are heavily skewed. Skewness in a linear model can lead to poor prediction results (Cameron and Trivedi, 2010). They are: `rate of replacement`, `water loss` and `length`. Table 3.3 shows the before and after of applying log transformation to these variables once we remove the outliers. As mentioned previously, we removed observations with values of groundwater exceeding 100 since the unit is in percentages. We removed two observations with rate of replacements 94% and 87% due to input error of length of mains and the inconsistency with the previous years' rates. We also left out a few observations with error inputs in the length. We were able to identify these outliers by comparing values from previous years (if they were available). Moreover, we left out observations where tariffs were equal to zero. And finally, we left out observations of water loss that corresponded to percentage of water loss greater than 100%.

Table 3.3: Skewed variables

variable	**N**	**mean**	**p50**	**sd**	**skewness**	**kurtosis**
rate	3676	.7349445	.1781756	2.298305	16.19588	415.6905
lnrate	2179	-.5683475	-.4813823	1.278281	-.4289137	4.343869
water loss	3676	3.730004	2.183098	5.587759	10.00018	230.5154
lnloss	3651	.7262934	.7914516	1.168984	-.7390946	6.169913
length	3676	116.9331	29.425	430.2429	18.50661	485.4903
lnlength	3676	3.467143	3.381845	1.548126	.2294084	2.79586

A normally distributed variable should have zero skewness; hence, by taking the log of the skewed variables we are able to reduce the skewness to a fairly acceptable level (Cameron and Trivedi, 2010). As we can see from the difference in the number of observations, the `rate` variable consists of many zeros, hence we apply a corner-solution model: the Heckit and the two-part model, elaborated in the next section.

3.4 The Empirical Model

3.4.1 Endogenous variables

We have several potentially endogenous variables. The most clear endogeneity can be detected in the water loss variable in relation to the rate of replacement. Water loss from time $t-1$ influences the decision to invest in network renewal which could have an impact on replacement in time t. Moreover, the replacement of time t affects the volume of water loss in time t. In general, past replacements of mains have an influence on the current replacements as well as current volume of water loss, which is a clear case of endogeneity where the error terms are not independent with the explanatory variables.

Our second problematic variable is water tariff. Although the endogeneity and probable reverse causality are not evident as in the previous case with water loss, it possesses potential endogeneous properties. The choice of prices and the investment level in network renewal is essentially determined in the contract where the objective of the municipality is defined (depending on whether the utility is outsourced or not). In the case of utilities that are outsourced, the price and the investment decisions are specified at the signing of the contract. For example Audouin explained that a contract that has been signed in $t-5$ where $t=2014$, all prices and replacements that follow are linked to the content of the contract. If the contract does not specify network quality as an objective of the utility for the duration of the contract, then the price that is set may be in relation to past investment costs that must be recovered. Hence it is possible to observe in that particular period a stagnant rate of replacement accompanied by an increase in prices. However there is also a possibility to observe higher prices that are set in $t-5$ along with a rise in replacement rates as well. In order to analyze these temporarl variations, we require a panel regression. However, many observations are missing for each utility over time; hence, the only option is a pseudo-panel with department-level cohorts or a cross-section. In order to observe utility-level impact on the replacement rates, we decided to estimate cross-sectional models. We must keep in mind that the replacement rates obtained in the database is an average value over the past 5 years (assuming utilities have inputted correctly these values). This means that we could observe large differences in replacement rates for contracts that have expired during those 5 years. In order to control for this effect, we created a dummy variable called `contract since 2010` which identifies utilities that have signed or had a contract already signed in 2010. Unlike for the water loss variable, we could not identify a credible instrumental variable candidate for prices; hence, we decided to test a lagged tariff variable. For instance tariff from 2010. However, this may not eliminate the endogeneity completely due to the existence of potential temporal dynamics in the unobservables - the unobservables being the objective of the contract. According to Bellemare et al. (2015), introducing a lagged variable may even worsen the estimations in the presence of temporal dynamics. Sometimes, we may be better off simply ignoring the endogeneity. We will conduct regressions with both and compare the results. Another issue we encounter when using the lagged price variable is the large number of missing values. If we use prices from 2014, the sample size in the linear regression estimations for positive rates is 2006; however, if we use prices from 2010, the sample size shrinks to 1062. We lose almost 1000 observations, which could have a big impact on the estimated coefficients. We present in Table 3.4 the lagged tariff variable with and without outliers:

Table 3.4: Summary statistics for 2010 tariff

Variable	**Mean**	**Min**	**Max**	**N**
tariff2010	1.996	0	172.18	1907
tariff2010	1.85	0.63	4.39	1904

As we can see from table 3.4, there are evident outliers. We observe two observations with tariffs that are above 100 Euros. Hence, we remove them. In addition, there is one observation with 0 Euros; hence, we remove it as well. The second row shows the statistics without the outliers.

Another variable that may have problems is `regie`, an indicator variable that shows whether a utility is outsourced or operated in-house. In the Appendix we include a switching regression that tests for potential "self-selection" bias caused by utilities that choose in-house provision or outsourcing based on the expectations of the need for network renewal. However, the coefficient that reflects selection bias is insignificant; hence, we proceed with the assumption that there is no selection bias of operator type on the replacement rates. As mentioned in the previous section, the in-house provision is more often observed in small networks; hence we generate the interaction term between operator type and size of network. We also include an interaction term between operator type and tariff since tariffs are in general lower in in-house utilities.

Choice of instrumental variable for water loss

`Water loss` is an endogenous variable since past levels of main replacement could influence both current replacement `rate` and `water loss`. Hence; $E(\beta_1 u) \neq 0$ which will lead to inconsistent estimators. In order to solve this problem, we instrument `water loss` with an exogenous variable which we call `density`. This variable is computed by dividing the population of a certain utility by the length of the mains. In the literature on water leakage, it is said that leakage levels are high where there are many customer service connections (González-Gómez et al., 2012; AWWA, 2008; Renaud et al., 2012; Pearson, 2002). In particular, PVC mains experience leakage at the joints, hence the greater the number of service connections the greater the probability of leakage. Furthermore, Pearson (2002) shows that indeed there is a positive relationship between higher density and higher leakage. In addition, the greater the number of outlets from a given length of mains, the more susceptible is the durability of the main due to higher water flow present in a short distance. We can see in Figure 3.7 that leakage is greater where the volume of water demanded per length of main is greater.

For certain types of mains, such as cast iron, strong water flow can aggravate corrosion and weaken the lining of the mains. Moreover the regression results by González-

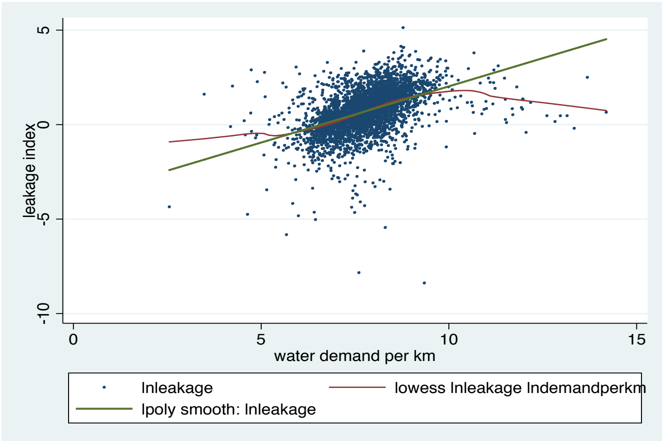


Figure 3.7: The correlation between water loss index and volume of water demanded per km of main length. The green line indicates the linear correlation and the red line is the spline.

Gómez et al. (2012) show a significant positive relationship between water loss and density. Our first stage regression supports this point as well: the greater the density, the greater the leakage. Ideally, the number of service connections is more suitable for the instrument, however for the lack of data, we substitute it with the density of inhabitants per length of mains. Although the number of inhabitants over a km of mains is not equal to the number of service connections, higher density of inhabitants per km of mains implies higher proportion of residential units, hence, more service connections. The reason why `density` is a feasible instrumental variable is because it satisfies the following requirements:

- **Non-exclusion:** We can see in Figure 3.8, there is barely any relationship between the rate of replacement and density. Large density does not necessarily imply that there are more people for a given length of mains. It could also imply that the total length of mains is short for a given population size. We saw in Chapter 1 that regardless the value of density, depending on the difference between total length and total demand, the network quality could be high or low. Furthermore, we observe that the average density does not vary much whether the utility is large or small in terms of network length. Utilities with very small total network length could have a large density as well as utilities with a very large total network: it depends on population and length of network. Nevertheless, as we saw in Chapter 1 and Chapter 2, density could be quite large in very large urban utilities; hence, we cannot say that density and the urbanity of the utility is independent of each other; therefore we control for the difference between rurality and urbanity in our estimations with the dummy variable `pop10000`.

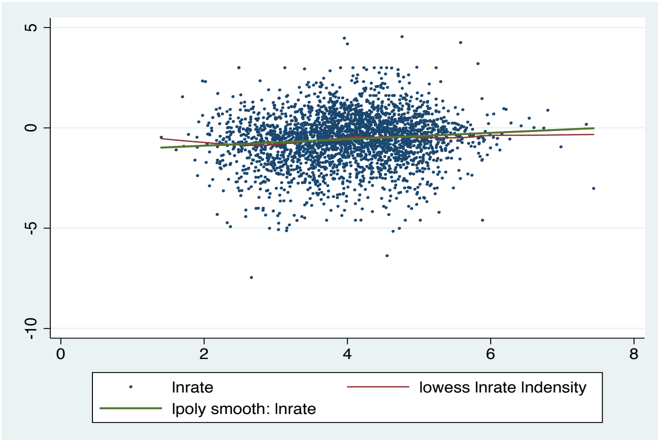


Figure 3.8: The correlation between the rate of replacement and density.

- **Uncorrelated with** u **(the error term):** We do not detect any clear correlation with density and the unobservables that affect replacement rates that are not included in the covariates such as financial situation of the utility and political will. As we have already mentioned, density is exclusively highly correlated with water loss. Moreover, there are no noticeable collinearity issues (in terms of VIF) with the other covariates.

- **Correlated with `water loss`:** Along with Figure 3.9, the first stage regression shows that density is highly correlated with `water loss`.

We present in Table 3.4.1 the summary statistics and the log transformation of the density variable without outliers.

Now we present our regression model. We would like to estimate the following least squares regression as show in 3.4.1:

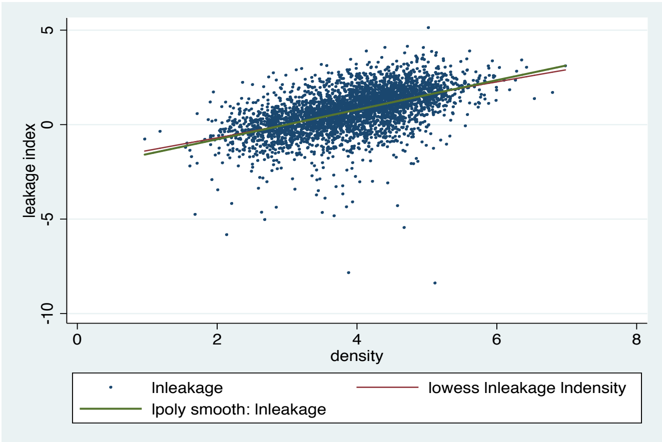


Figure 3.9: The correlation between the water loss index and density.

Table 3.5: Log transformation of density without ouliers

variable	**N**	**mean**	**p50**	**sd**	**skewness**	**kurtosis**
density	3676	68.86533	53.3299	62.29923	4.018072	40.20548
lndensity	3676	3.917226	3.976497	.8134062	-.1611211	2.758163

$$\begin{aligned} \texttt{rate}_i &= \beta_0 + \beta_1 L_i + \beta_2 M_i + \beta_3 M_i^2 + \beta_4 MT_i + \beta_5 O_i + \beta_6 OM_i + \beta_7 OT_i + \beta_8 C_i \\ &+\beta_9 G_i + \beta_{10} K_i + \beta_{11} T_i + \beta_{12} I_i + \beta_{13} S_i + \beta_{14} P10_i + \beta_{15} COM_i \\ &+\beta_{16} R1_i + \beta_{17} R2_i + \beta_{18} R3_i + \rho_j RFE_i + u \end{aligned} \tag{3.1}$$

Where i indicates the ith water utility, L stands for water loss measured in $m^3/km/day$, M stands for main length measured in kilometers (km), M^2 for the quadratic term of the main length, MT for the interaction term between main length and tariff, O for the type of service provider (taking 1 if operated in-house), OM for the interaction term between the type of operator and the length of mains, OT for the interaction term between operator type and tariff, C for the dummy variable that controls for the duration of the contract since 5 years, G for ground100 which indicates 100% reliance on groundwater or not, K for knowledge of the state of water network, T for tariff,

I for the ratio of produced to imported water, S for soft water, $P10$ for the dummy that controls for utilities that serve communes greater than 10,000 inhabitants which reflects urbanity, COM for the dummy variable of utilities composed of more than 14 communes, R1, R2 and R3 as different levels of average revenue and RE for Regional Effects which may capture the unobservables that are associated with the political orientation of the region, the geographical factors and regulations that are imposed on water related issues. Moreover, ρ_j contains 22 dummy variables of the different regions in France and u is the error term.

However, we cannot conduct ordinary least squares regression with this set-up since we encounter two econometric problems. Water loss is endogenous and the large number of zero replacement rates implies a "corner solution" problem.

3.4.2 Corner solution

Since a large proportion of the observations on the replacement rate are equal to zero, estimating least squares only on positive values will bias the estimates of β. Moreover, including the entire sample will also result in inconsistent estimates since $E(y|x)$ is nonlinear in x, β_i and the variance, σ. We conduct the Tobit-type 2 model or the so-called *Heckit* model along with the Two Part model. We do not estimate the standard Tobit type 1, since this type of model consists of a single mechanism that determines the selection between zero rates and positive rates ($P(rate > 0)$). In other words the effects of the explanatory variables are identical on the probability that rates would be zero or positive ($P(rate > 0)$) and on the linear estimates of the expected value of rates ($E(rate|x, rate > 0)$), given the positive rates (Jeffrey, 2002). It is natural to expect that certain variables have different degrees of influence on $P(rate > 0)$ and $E(rate|x, rate > 0)$, given positive rates. In the next section we present the Heckit and Two-Part models.

3.4.3 Heckit model and Two Part model

Both the Heckit and the Two Part model consist of two steps. The first part which estimates the probability of observing positive observed outcomes ($Pr(rate{>}0|x)$) and the second part which estimates the expected outcome conditional on positive values ($E(rate|x, rate{>}0)$). In the Heckit model, we include the Inverse Mills Ratio (IMR) which captures the selection bias that could potentially be present by that fact that utilities with zero rates may systematically be different from utilities with positive rates. On the other hand the Two Part model treats the two parts independently of each other. According to Dow and Norton (2003) "As long as the zero expenditures are true zeroes - not missing data - then there is no selection problem to address", where expenditures refer to medical expenditures that are true zeros or positive values. However, concerning latent variables, they write that "if those with missing values differ systematically from those with observed values, then 2PM (Two Part) will suffer from selection bias". They refer to the example of the difference between women who work and women who do not. They are most probably systematically different from each other; hence the Heckit model is more appropriate in taking into account the selection problem that arises from the unobserved wages of women who do not work. We believe that this situation is not exclusive to missing (latent) values. There is a possibility that the utilities with zero replacement rates may be systematically different from the utilities with positive rates (after controlling for covariates). Hence, for the sake of robustness, we estimate both models. Both models enable us to estimate the following:

$$\begin{aligned} E(r|x) &= Pr(r = 0|x) \times 0 + Pr(r{>}0|x) \times E(r|x, rate{>}0) \\ &= Pr(r{>}0|x) \times E(r|x, r{>}0) \end{aligned} \tag{3.2}$$

where r is the rate of replacement and x is the vector of regressors. The first part of the model, $Pr(r{>}0|x)$, is estimated by a binary outcome model over the entire sample. We create a binary variable which takes value 1 if $r > 0$ and takes value 0 if $r = 0$. Then we use the probit model for estimating the probability of a positive outcome, $r > 0$. Formally represented as:

$$Pr(r>0|x) = \Phi(x\omega, \epsilon) \tag{3.3}$$

where x is a vector of regressors, ω is the final estimated coefficients using maximum likelihood estimation which produces the marginal changes in the z-score, ϵ is the error term and Φ is the cumulative distribution function of the standard normal distribution. For the Two Part model we conduct the instrumental variable probit regression by instrumenting water loss with density. However, for the Heckit model we use the simple probit model by including an exclusion restriction. This means that the first part (selection model) should have at least two variables that are correlated with the selection process but not with the outcome variable. According to Jeffrey (2002), the instrumental variable (density) counts as one. Without proper exclusion restrictions, the coefficient on the Inverse Mills Ratio (IMR) generated via the probit estimation may be imprecise or nonsignificant. This is because without the exclusion restriction, severe collinearity arises between the IMR and the covariates. If too much information in the IMR is correlated with the variables included in the outcome model, the IMR would no longer have any meaning.

The second part of 3.2, $E(r|x, r>0)$ is also estimated differently for the Two Part and the Heckit model. The Heckit model is defined as follows: $E(r|x, r>0) = x\beta_2 + E(\epsilon_2|y > 0, x)$ where $E(\epsilon_2|y > 0, x)$ is estimated by the inverse mills ratio $\lambda(x\beta_1) = \phi(x\beta_1)/\Phi(x\beta 1)$ calculated from the probit estimation, the term that captures the selection bias. On the other hand, the Two Part model assumes no selection bias; hence, $E(r|x, r>0) = x\beta_2$.

For the Two Part model, $E(r|x, r>0)$ is estimated with the instrumental variable least squares regression[10] over a subset of the sample where $r > 0$. Recall equation 3.1,

[10]We use the 2SLS (two stage least squares) since it is equivalent to the IV estimator in "just-

our structural equation:

$$\texttt{rate}_i = \beta_0+\beta_1 L_i+\beta_2 M_i+\beta_3 M_i^2+\beta_4 MT_i+\beta_5 O_i+\beta_6 OM_i+\beta_7 OT_i+\beta_8 C_i+\beta_9 G_i+ \beta_{10}K_i+\beta_{11}T_i+\beta_{12}I_i+\beta_{13}S_i+\beta_{14}P10_i+\beta_{15}COM_i+\beta_{16}R1_i+\beta_{17}R2_i+\beta_{18}R3_i+\rho_j RFE_i+u$$

The reduced form equation is then defined as follows:

$$\begin{aligned} L_i &= \delta_0 + \delta_2 M_i + \delta_3 M_i^2 + \delta_4 MT_i + \delta_5 O_i + \delta_6 OM_i + \delta_7 OT_i + \delta_8 C_i + \delta_9 G_i \\ &+\delta_{10} K_i + \delta_{11} T_i + \delta_{12} I_i + \delta_{13} S_i + \delta_{14} P10_i + \delta_{15} COM_i + \delta_{16} R1_i + \delta_{17} R2_i \\ &+\delta_{18} R3_i + \delta_{19} RFE_i + \theta_1 D_i + \zeta \end{aligned} \tag{3.4}$$

where D stands for density, the instrumental variable. Given $\theta_1 \neq 0$, $E(\zeta) = 0$ and that ζ is uncorrelated with the explanatory variables. Substituting (3.4) into (3.1), we obtain the following:

$$\begin{aligned} \texttt{rate}_i &= \alpha_0 + \alpha_1 M_i + \alpha_2 M_i^2 + \alpha_3 MT_i + \alpha_4 O_i + \alpha_5 OM_i + \alpha_6 OT_i + \alpha_7 C_i \\ &+\alpha_8 G_i + \alpha_9 K_i + \alpha_{10} T_i + \alpha_{11} I_i + \alpha_{12} S_i + \alpha_{13} P10_i + \alpha_{14} COM_i \\ &+\alpha_{15} R1_i + \alpha_{16} R2_i + \alpha_{17} R3_i + \alpha_{18} RFE_i + \mu_1 L_i + v \end{aligned} \tag{3.5}$$

where $\alpha_i = \beta_i + \beta_1\delta_i$ and $\mu_1 = \beta_1\theta_1$ and $v = \beta_1\zeta + u$. The error term u follows a Normal distribution with mean 0 and variance σ^2.

We apply a lognormal transformation to our model, hence $r|r > 0$ becomes $\ln(r|r > 0)$ with an independent and identically normally distributed error term. Finally we can rewrite (3.2) as:

$$E(r|x) = \Phi(x\omega, \epsilon) \times exp\left(x\omega + \frac{\sigma^2}{2}\right) \tag{3.6}$$

identified" models.

where $x\omega$ is the mean and σ is the standard deviation, $\Phi(x\omega, \epsilon) = Pr(rate{>}0|x)$ and $exp\left(x\omega + \frac{\sigma^2}{2}\right) = E(r|x, rate{>}0)$.

The associated marginal effect is then calculated as follows:

$$\begin{aligned} \frac{\partial E(r|x)}{\partial x_k} &= [\beta_{(ivreg)k} + \beta_{(probit)k} \times \lambda(x\beta_{probit})] \times E(r|x) \\ &\text{where } \lambda(x\beta_{probit}) = \phi(x\beta_{probit})/\Phi(x\beta_{probit}) \end{aligned} \tag{3.7}$$

where $\beta_{(ivreg)k}$ is the *kth* coefficient estimated by the linear instrumental variable regression and $\beta_{(probit)k}$ is the *kth* coefficient estimated by the instrumental probit regression. ϕ is the probability density function and $E(r|x)$ is the expression we obtained in 3.6.

For the Heckit model, the first part is estimated using a probit model with exclusion restriction. The probit model is estimated using the covariates mentioned above except for water loss. We instead apply the exclusion restriction by adding density and an additional exogenous variable that has an influence only on the probability of observing positive rates but not on the expected rate of replacement. We include an indicator variable `leakage detection` that reflects the effort of the utility on leakage detection and network maintenance. This indicator variable takes value 1 if the utility is engaged in detecting leakage and if the utility keeps an updated report on the leaks that have been repaired. This variable, although small, has a significant positive effect on the selection process; whereas, it has no significant effect on the outcome process. If this indicator is 0, it means that the utility is not engaged in leakage detection; which directly affects the probability of the utility replacing mains or not. Perhaps due to the weak influence of the exclusion variable, the collinearity of the IMR with the covariates may be high which results in imprecise estimation results. We estimate the second part similarly as shown in (3.5) however we add the inverse mills ratio (IMR) term. We show in (3.8) the additional term IMR with coefficient λ. If this coefficient is significant, the sample suffers from a selection problem.

$$\begin{aligned}\texttt{rate}_i &= \gamma_0 + \gamma_1 M_i + \gamma_2 M_i^2 + \gamma_3 MT_i + \gamma_4 O_i + \gamma_5 OM_i + \gamma_6 OT_i + \gamma_7 C_i \\ &+\gamma_8 G_i + \gamma_9 K_i + \gamma_{10} T_i + \gamma_{11} I_i + \gamma_{12} S_i + \gamma_{13} P10_i + \gamma_{14} COM_i \\ &+\gamma_{15} R1_i + \gamma_{16} R2_i + \gamma_{17} R3_i + \gamma_{18} RFE_i + \xi_1 L_i + \lambda \texttt{IMR}_i + \nu\end{aligned} \tag{3.8}$$

3.5 Results

We begin with estimations of the instrumental variable ordinary least squares (IVOLS). Table 3.6 shows the results of the z-score coefficients of the instrumental variable probit model and the first stage estimations of the IVOLS estimations. It reveals that *density* has a large and significant impact on water loss. Furthermore, we can reject the null hypothesis of exogeneity at the 1% level.

	(First stage ivregress with tariff2010)	(First stage ivprobit with tariff2010)	(First stage ivregress with tariff2014)	(First stage ivprobit with tariff2014)
	lnloss	lnloss	lnloss	lnloss
	b/se	b (z-score) /se	b/se	b (z-score) /se
lndensity	.7590***	.7561***	.7611***	.8167***
	(.0381)	(.0314)	(.0323)	(.0254)
tariff2010	-.145	-.0809		
	(.0874)	(.0685)		
tariff2014			.0029	.0188
			(.0744)	(.0571)
regie	-.0189	.1240**	.1148*	.1976***
	(.0763)	(.0620)	(.0633)	(.0502)
regietariff2010	-.0999	-.0797		
	(.106)	(.0918)		
regietariff2014			-.1193	-.1061
			(.0903)	(.0738)
lnlength	.0720	.1507***	.1335***	.1932***
	(.0396)	(.0313)	(.0351)	(.0269)
lnlengthsq	-.0226*	-.0219***	-.0348***	-.0321***
	(.0101)	(.0084)	(.0083)	(.0067)
regielength	-.0127	-.0982***	-.0492	-.1039***
	(.0395)	(.0337)	(.0345)	(.0285)
lengthtariff2010	.0122	-.0215		
	(.0413)	(.0330)		
lengthtariff2014			-.0465	-.0352
			(.0293)	(.0234)
knowledge	.0003	.0003	-.0003	-.0007
	(.0008)	(.0006)	(.0006)	(.0005)
contract since 2010	-.0070	-.0731	.0103	-.0548
	(.0633)	(.0559)	(.0598)	(.0513)
ratio produced imported	.2041***	.1164**	.1635***	.1264***
	(.0706)	(.0586)	(.0595)	(.0480)
rev1	-.0749	-.0354	.0544	-.0290
	(.1556)	(.1419)	(.1221)	(.1109)
rev2	-.0764	-.1160	-.0375	-.0729
	(.0815)	(.0745)	(.0726)	(.0633)
rev3	-.0346	-.0476	.0151	.0122
	(.0806)	(.0723)	(.0710)	(.0616)
soft water	-.0273	-.1212	-.0862	-.1529**
	(.0834)	(.0738)	(.0722)	(.0614)
pop10000	-.0772	-.0198	-.0426	-.0755
	(.0919)	(.0907)	(.0882)	(.0875)
commune14	-.0009	-.0495	.0252	-.0235
	(.0889)	(.0897)	(.0858)	(.0860)
ground100	.0981	.0682	.2562***	.2459***
	(.0655)	(.0610)	(.0577)	(.0520)
Languedoc Rousillon	.4112***	.3820***	.4456***	.3272***
	(.1473)	(.1333)	(.1275)	(.1134)
Midi Pyrenees	.3533**	.2380*	.4379***	.4226***
	(.1480)	(.1351)	(.1321)	(.1215)
Limousin	-.2899	-.1341	-.2337	-.1743
	(.3313)	(.2786)	(.2113)	(.1723)

	(First stage ivregress with tariff2010)	(First stage ivprobit with tariff2010)	(First stage ivregress with tariff2014)	(First stage ivprobit with tariff2014)
	lnloss	lnloss	lnloss	lnloss
	b/se	b (z-score) /se	b/se	b (z-score) /se
Poitou-Charentes	-.0329	.0095	.0154	.0822
	(.1793)	(.1712)	(.1676)	(.1637)
Bourgogne	-.1171	.2074	.1440	.3002**
	(.1812)	(.1554)	(.1566)	(.1302)
Franche Compte	.1827	.3022**	.2740**	.4144***
	(.1505)	(.1308)	(.1345)	(.1147)
Alsace	-.3127*	-.2547*	-.3415**	-.1890
	(.1740)	(.1538)	(.1617)	(.1438)
Lorraine	.0890	.1713	.1172	.1547
	(.1402)	(.1216)	(.1271)	(.1091)
Champagne Ardenne	.1119	.1398	.1285	.1458
	(.1900)	(.1668)	(.1554)	(.1264)
Corse	.2169	.5289	.3151	.5553***
	(.3600)	(.3465)	(.2011)	(.1739)
Centre	-.4103***	-.4041***	-.3514***	-.3345***
	(.1169)	(.1027)	(.1091)	(.0972)
Pays de la Loire	-.5569***	-.4750***	-.5252***	-.4382***
	(.1596)	(.1478)	(.1468)	(.1390)
Ile de France	-.1570	-.1278	-.0839	.0191
	(.3061)	(.2515)	(.1938)	(.1695)
Haute Normandie	.2021	.2879	.0088	.0053
	(.2271)	(.2047)	(.1731)	(.1495)
Basse Normandie	-.2981**	-.3104**	-.2297*	-.2525**
	(.1435)	(.1341)	(.1317)	(.1209)
Bretagne	-.2243	-.1340	-.1830	-.0629
	(.1594)	(.1459)	(.1475)	(.1372)
Auvergne	.2057	.3010**	.4211***	.5039***
	(.1598)	(.1424)	(.1478)	(.1317)
Rhone Alpes	.2034	.2627**	.2924**	.4347***
	(.1427)	(.1278)	(.1224)	(.1105)
Picardie	-.1938	-.0706	-.1525	-.1023
	(.1588)	(.1367)	(.1381)	(.1173)
Nord pas de calais	.0857	-.0370	.0328	.0434
	(.1663)	(.1418)	(.1465)	(.1245)
PACA	.5212***	.5193***	.5577***	.5805***
	(.1536)	(.1408)	(.1297)	(.1187)
Constant	-2.386***	-2.4094***	-2.593***	-2.8453***
	(.2206)	(.1885)	(.1911)	(.1580)
athrho				
Constant		-.3185***		-.4015***
		(.0667)		(.0480)
lnsigma				
Constant		-.2376***		-.0774***
		(.0169)		(.0121)
Observations	1138	1753	2006	3414
F-test	28.48		35.87	

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3.6: First stage regression of ivregress and ivprobit

Now we present three estimations: the first column of Table 3.7 shows the estimates using 2010 tariffs, the second column shows the estimates with 2014 tariffs over the same observations available in the first estimation, and the third column shows the estimates with the full number of observations available using 2014 tariffs. As we have mentioned previously, the problem with using 2010 tariffs is the large number of missing values. Ideally, we should estimate with the lagged tariff variable to minimise the endogeneity in tariff2014. However, the number of observations in the estimations drop by almost half when we switch to 2010 tariffs (from 2006 to 1062 observations).

	IVOLS with tariff2010	IVOLS with tariff2014	IVOLS with full sample from 2014
	lnrate	lnrate	lnrate
	b/se	b/se	b/se
water loss index	.3183***	.3437***	.3206***
	(.0749)	(.0755)	(.0564)
tariff2010	.0905		
	(.1311)		
tariff2014		.2038	.3021***
		(.1244)	(.0988)
regie	.8792***	.8440***	.8138***
	(.1104)	(.1081)	(.0837)
regietariff2010	.3497**		
	(.1536)		
regietariff2014		.3142**	.1529
		(.1475)	(.1197)
lnlength	-.1842***	-.1899***	-.2842***
	(.0578)	(.0582)	(.0468)
lnlengthsq	.0370**	.0398***	.0597***
	(.0147)	(.0143)	(.0111)
regielength	-.1875***	-.1916***	-.1486***
	(.0575)	(.0563)	(.0459)
lengthtariff2010	.0773		
	(.0604)		
lengthtariff2014		.0378	-.0014
		(.0560)	(.0391)
knowledge	.0034***	.0034***	.0035***
	(.0011)	(.0011)	(.0008)
contract since 2010	.1962**	.1646*	.1823**
	(.0917)	(.0928)	(.0794)
ratio produced imported	-.1107	-.0917	-.0283
	(.1029)	(.1029)	(.0788)
rev1	.0403	.0343	-.0386
	(.2337)	(.2339)	(.1625)
rev2	.2051*	.2187*	.1931**
	(.1199)	(.1201)	(.0961)
rev3	.0506	.0463	-.0650
	(.1196)	(.1195)	(.0944)
soft water	.1557	.1837	.0949
	(.1257)	(.1257)	(.0962)
pop10000	.1870	.1914	.2300**
	(.1313)	(.1317)	(.1162)
commune14	.1159	.1212	.1109
	(.1289)	(.1291)	(.1139)
ground100	-.0325	-.0400	-.0320
	(.0966)	(.0966)	(.0765)

	IVOLS with tariff2010	IVOLS with tariff2014	IVOLS with full sample from 2014
	lnrate	lnrate	lnrate
	b/se	b/se	b/se
Languedoc Roussillon	-.1031	-.1305	-.0676
	(.2256)	(.2263)	(.1755)
Midi Pyrenees	.3034	.2786	.2248
	(.2190)	(.2194)	(.1755)
Limousin	.2734	.2416	.2781
	(.4727)	(.4728)	(.2819)
Poitou-Charentes	.3218	.3585	.2619
	(.2572)	(.2570)	(.2226)
Bourgogne	.4142	.4200	.1813
	(.2693)	(.2694)	(.2089)
Franche Compte	.2690	.1869	.0816
	(.2238)	(.2243)	(.1812)
Alsace	.3564	.3383	-.0060
	(.2458)	(.2461)	(.2125)
Lorraine	-.0009	-.0341	-.1625
	(.2085)	(.2083)	(.1701)
Champagne Ardenne	-.0399	-.0130	-.0884
	(.2754)	(.2747)	(.2073)
Corse	.1533	.1250	.3044
	(.5136)	(.5145)	(.2701)
Centre	-.0778	-.0338	-.1774
	(.1732)	(.1738)	(.1466)
Pays de la Loire	.1718	.2312	.2326
	(.2384)	(.2388)	(.1977)
Ile de France	.1476	.1362	-.4307*
	(.4561)	(.4559)	(.2567)
Haute Normandie	.3057	.3366	.0860
	(.3323)	(.3301)	(.2300)
Basse Normandie	.5045**	.5277**	.3925**
	(.2107)	(.2107)	(.1754)
Bretagne	.0021	.0228	.1941
	(.2347)	(.2331)	(.1963)
Auvergne	.3452	.3584	.2976
	(.2344)	(.2343)	(.1959)
Rhone Alpes	.1822	.1706	.1507
	(.2106)	(.2108)	(.1651)
Picardie	-.1042	-.1092	-.0746
	(.2289)	(.2285)	(.1819)
Nord pas de calais	-.0969	-.0862	-.1546
	(.2421)	(.2408)	(.1951)
PACA	-.0986	-.0833	-.2352
	(.2248)	(.2246)	(.1773)
Constant	-1.7711***	-1.8055***	-1.7238***
	(.2526)	(.2530)	(.1955)
Observations	1062	1062	2006

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3.7: IVOLS estimations with tariffs from 2010 and 2014 from different periods. Aquitaine is left out as the reference term for the regional effects. rev4 is left out as the reference term for the revenue effect.

Aside from the tariffs, we can see that the coefficients obtained in the three estimations are very similar to each other. Comparing the first model to the third one, we can see that the coefficient on tariff2010 is not significant; whereas tariff2014 is significant. This may be due to the difference in the number of observations; hence, we estimate with tariff2014 and remove the missing values associated with tariff2010. We can see that tariff2014 is no longer significant (column 2). Since we cannot verify the significance of the tariff2010 over the same observations available for the tariff2014, we cannot confirm fully the actual effect of tariff on the rate of replacement but it is safe to assume that the difference in the significance levels is due to the difference in the number of observations. Nevertheless, we do not reason in terms of causality concerning prices. In the case of outsourced utilities, tariffs and investment activities are determined simultaneously in the contract that is signed between the municipality and the firm. On the other hand, if the utility remains in-house, they would also decide on the price levels in association with the level of investment in network renewal. Hence, tariffs could be set in accordance with the level of anticipated replacement of mains or it may also be set to recover past investment costs or it may be set entirely independent of the investment activities. What is interesting to note is the significance of the `regietariff2010` variable. Although tariff2010 itself has no significance, higher 2010 prices in utilities with in-house provision have higher average replacement rates over the following 5 years. This interaction term is no longer significant in the full sample with 2014 tariffs. Aside from the tariffs, the coefficients on the other variables are similar in all three estimations, except for pop10000. Over the full 2014 regression, the coefficient is positive and significant. Again, this may simply be due to the difference in the number of observations.

In all three results, the coefficients on the regional effects of Basse Normandie is significant and positive (compared to the reference region: Aquitaine). With the information at hand, it is not evident to conclude on the significance of this regional effect. Again, we suppose that due to a small number of observations, the significance of the regional effect of Ile de France is not captured in the estimates with 2010 tariffs.

In Table 3.8 we present the results from the Heckit (Tobite type-2) estimations. Again, we compare coefficients between models using 2010 tariffs and 2014 tariffs. Similarly to the case with the IVOLS alone, we see that *tariff2010* and *tariff2014* are not significant; whereas, in the full sample (without missing values corresponding to tariff2010) *tariff2014* becomes significant. The Probit estimations show that the length variable has different significance level if the model is estimated using tariff2010 or tariff2014. Length variables (*length* and *lengthsq*) are significant when we use tariff2014, whereas for tariff2010, they are not significant. These differences arise due to the slight differences in the estimated coefficients obtained in the probit model. We can see that small differences in the standard error affects these results. Nevertheless, in all three scenarios, the coefficient on the Inverse Mills Ratio (IMR) is insignificant; meaning there is no selection problem to address in this set-up. However, the precision of the IMR depends heavily on the choice of the exclusion restriction variable - *leakage detection*. Hence, as mentioned previously, weak exclusion restriction variables may lead to imprecise estimation results. Therefore, although the coefficient is insignificant, we do not ignore the possibility of selection bias.

	Probit 2010	Heckit 2010	Probit 2014	Heckit 2014	Probit 2014 Full	Heckit 2014 Full
	rate	lnrate	rate	lnrate	rate	lnrate
	b/se	b/se	b/se	b/se	b/se	b/se
tariff2010	-.0197	.0522				
	(.1314)	(.1300)				
tariff2014			-.0566	.1750	.0337	.2791***
			(.1274)	(.1234)	(.0917)	(.1018)
regie	.2531**	.8389***	.2385**	.7957***	.3811***	.8312***
	(.1195)	(.1188)	(.1161)	(.1154)	(.0798)	(.0963)
regietariff2010	.3307*	.3738**				
	(.1891)	(.1581)				
regietariff2014			.4879***	.3059**	.2596**	.2321*
			(.1854)	(.1546)	(.1248)	(.1269)
lnlength	.4196***	-.1221	.4134***	-.1791*	.4714***	-.2240***
	(.0680)	(.0909)	(.0683)	(.0918)	(.0499)	(.0776)
lnlengthsq	.0367	.0261	.0497**	.0346**	.0296**	.0535***
	(.0225)	(.0169)	(.0221)	(.0162)	(.0145)	(.0123)
regielength	.1558*	-.1503**	.1416	-.1533***	.0217	-.1511***
	(.0875)	(.0593)	(.0862)	(.0580)	(.0595)	(.0494)
lengthtariff2010	.2875***	.0959				
	(.0831)	(.0650)				
lengthtariff2014			.2543***	.0514	.0760	.0125
			(.0774)	(.0584)	(.0466)	(.0404)
knowledge	.0004	.0036***	.0004	.0034***	.0015*	.0038***
	(.0012)	(.0012)	(.0013)	(.0012)	(.0008)	(.0009)
contract since 2010	-.0094	.2437***	-.0222	.2197**	-.0561	.2022**
	(.1103)	(.0935)	(.1101)	(.0937)	(.0823)	(.0829)
ratio produced imported	.0406	-.1091	.0517	-.0786	.0403	-.0195
	(.1113)	(.1030)	(.1124)	(.1026)	(.0749)	(.0813)
rev1	.1599	.0335	.1830	.0429	.3381*	.0378
	(.2955)	(.2292)	(.2960)	(.2280)	(.1852)	(.1681)
rev2	-.0702	.1896	-.0560	.2197*	-.0492	.1874*
	(.1445)	(.1193)	(.1447)	(.1190)	(.0981)	(.0990)
rev3	.0224	.0536	.0191	.0416	.1713*	-.0390
	(.1470)	(.1201)	(.1469)	(.1194)	(.0988)	(.0998)
softwater	.1850	.1734	.2046	.1785	.0598	.0935
	(.1446)	(.1226)	(.1445)	(.1220)	(.0963)	(.0979)
pop10000	.6092**	.2403*	.6087**	.2314*	.2171	.2346*
	(.2770)	(.1348)	(.2774)	(.1346)	(.1881)	(.1200)
commune14	.4918**	.1965	.4371*	.1672	.3591**	.1480
	(.2453)	(.1334)	(.2452)	(.1323)	(.1781)	(.1194)
ground100	-.0400	-.0349	-.0470	-.0355	-.0953	-.0764
	(.1330)	(.0951)	(.1330)	(.0946)	(.0881)	(.0814)

In Table 3.9 we present all the estimations conducted with different models using tariff2014. In order to obtain coefficients for the Two-Part model, we were obliged to use tariff2014 due to the number of observations. Bootstrap simulations would fail when estimating the marginal effects with the number of observations corresponding to tariff2010. We believe that it is due to the large number of missing values.

	Probit 2010	Heckit 2010	Probit 2014	Heckit 2014	Probit 2014 Full	Heckit 2014 Full
	rate	lnrate	rate	lnrate	rate	lnrate
	b/se	b/se	b/se	b/se	b/se	b/se
Languedoc Roussillon	.2994	-.1495	.3295	-.1695	.1661	-.0170
	(.2626)	(.2235)	(.2633)	(.2231)	(.1835)	(.1810)
Midi Pyrenees	.1440	.2667	.1764	.2480	.0210	.1943
	(.2692)	(.2143)	(.2699)	(.2137)	(.2030)	(.1808)
Limousin	-.4544	.1864	-.4466	.2029	-.2612	.2718
	(.5277)	(.4785)	(.5328)	(.4759)	(.2625)	(.2865)
Poitou-Charentes	.1903	.2916	.2770	.3247	.2144	.2892
	(.3794)	(.2587)	(.3828)	(.2579)	(.3141)	(.2264)
Bourgogne	-.2027	.3468	-.1584	.3564	-.4774**	.1452
	(.2921)	(.2602)	(.2914)	(.2586)	(.2049)	(.2232)
Franche Compte	-.0120	.2938	.0134	.2281	-.0346	.1149
	(.2542)	(.2288)	(.2554)	(.2278)	(.1861)	(.1895)
Alsace	.0311	.4160	.0344	.3696	-.1784	.1199
	(.2986)	(.2542)	(.3001)	(.2532)	(.2351)	(.2216)
Lorraine	-.2776	-.1215	-.2442	-.1244	-.2098	-.1519
	(.2329)	(.2076)	(.2334)	(.2056)	(.1771)	(.1779)
Champagne Ardenne	.0219	-.1042	.0963	-.0765	-.0902	-.0331
	(.3084)	(.2843)	(.3085)	(.2824)	(.1998)	(.2169)
Corse	-.0592	.1803	-.0601	.1661	.3856	.3948
	(.7375)	(.5191)	(.7325)	(.5174)	(.2652)	(.2764)
Centre	-.2068	-.1369	-.1464	-.0925	-.1689	-.1658
	(.1925)	(.1710)	(.1925)	(.1701)	(.1557)	(.1498)
Pays de la Loire	-.2537	.1286	-.1977	.1787	-.1758	.2785
	(.3002)	(.2328)	(.3006)	(.2322)	(.2398)	(.2013)
Ile de France	-.5900	.1698	-.5362	.1965	-.5185*	-.4470
	(.4614)	(.4423)	(.4632)	(.4390)	(.2774)	(.2735)
Haute Normandie	-.2996	.2067	-.2625	.2661	-.3041	.0621
	(.3919)	(.3389)	(.3884)	(.3341)	(.2338)	(.2398)
Basse Normandie	-.0360	.3967*	.0268	.3971*	-.0496	.4215**
	(.2675)	(.2090)	(.2666)	(.2081)	(.1952)	(.1786)
Bretagne	-.0833	-.0002	-.0325	.0158	.0272	.2435
	(.2871)	(.2309)	(.2857)	(.2284)	(.2298)	(.2004)
Auvergne	-.0185	.2859	.0302	.3207	.2900	.2752
	(.2737)	(.2342)	(.2748)	(.2325)	(.2140)	(.2022)
Rhone Alpes	.1002	.1945	.1296	.1711	.2895	.1953
	(.2475)	(.2089)	(.2479)	(.2080)	(.1792)	(.1687)
Picardie	-.4197*	-.2509	-.3692	-.2152	-.3256*	-.1037
	(.2535)	(.2328)	(.2540)	(.2305)	(.1860)	(.1908)
Nord pas de calais	-.5361**	-.1328	-.4819*	-.0624	-.3689*	-.1541
	(.2692)	(.2591)	(.2694)	(.2548)	(.1986)	(.2091)
PACA	.6465**	.0305	.7076**	.0108	.2756	-.1789
	(.2781)	(.2334)	(.2793)	(.2338)	(.1951)	(.1839)
lndensity	.3869***		.3839***		.3810***	
	(.0596)		(.0601)		(.0397)	
leakage detection	.2853***		.2856***		.2266***	
	(.0838)		(.0840)		(.0568)	
water loss index		.3417***		.3273***		.3710***
		(.0896)		(.0878)		(.0776)
IMR		.3688				
		(.2826)				
IMR2				.1602		
				(.2809)		
IMR3						.3134
						(.2505)
Constant	-1.5551***	-1.9786***	-1.5872***	-1.8569***	-1.6509***	-1.9759***
	(.3651)	(.3339)	(.3684)	(.3329)	(.2518)	(.2916)
No. of Observations	1664	1082	1664	1082	3276	1914
R^2		.1808		.1882		.2141
F-test						
log(likelihood)	-809.1790		-808.2718		-1.73e+03	

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3.8: Heckit estimations with tariff2010 and tariff2014

	(IVOLS without regions)	(IVOLS)	(IVPROBIT)	(TWO-PART)	(PROBIT)	(HECKIT)
	lnrate	lnrate	rate	$E(lnrate \mid rate > 0)$	rate	lnrate
	b/se	b/se	b (dydx) /se	b/bootstrap se	b/se	b/se
water loss index	.2645***	.3206***	.1344***	.5536***		.3710***
	(.0494)	(.0564)	(.0105)	(.0932)		(.0776)
tariff2014	.2840***	.3021***	.0084	.3039**	.0337	.2791***
	(.0986)	(.0988)	(.0250)	(.1258)	(.0917)	(.1018)
regie	.8216***	.8138***	.0803***	.9250***	.3811***	.8312***
	(.0787)	(.0837)	(.0213)	(.1197)	(.0798)	(.0963)
regietariff2014	.1616	.1529	.0946***	.3203**	.2596**	.2321*
	(.1171)	(.1197)	(.0341)	(.1478)	(.1248)	(.1269)
lnlength	-.2631***	-.2842***	.0991***	-.0889*	.4714***	-.2240***
	(.0430)	(.0468)	(.0135)	(.0529)	(.0499)	(.0776)
lnlengthsq	.0592***	.0597***	.0117***	.0785***	.0296**	.0535***
	(.0094)	(.0111)	(.0040)	(.0160)	(.0145)	(.0123)
regielength	-.1486***	-.1486***	.0235*	-.0985	.0217	-.1511***
	(.0418)	(.0459)	(.0161)	(.0555)	(.0595)	(.0494)
lengthtariff2014	.0057	-.0014	.0275**	.0493	.0760	.0125
	(.0369)	(.0391)	(.0127)	(.0453)	(.0466)	(.0404)
knowledge	.0034***	.0035***	.0008***	.0048***	.0015*	.0038***
	(.0008)	(.0008)	(.0002)	(.0010)	(.0008)	(.0009)
contract since 2010	.1914**	.1823**	-.0001	.1738**	-.0561	.2022**
	(.0760)	(.0794)	(.0225)	(.0836)	(.0823)	(.0829)
ratio produced imported	-.0290	-.0283	.0049	-.0179	.0403	-.0195
	(.0774)	(.0788)	(.0205)	(.0928)	(.0749)	(.0813)
rev1	.0132	-.0386	.0880*	.1251	.3381*	.0378
	(.1048)	(.1625)	(.0506)	(.2181)	(.1852)	(.1681)
rev2	.2369***	.1931**	-.0110	.1642	-.0492	.1874*
	(.0673)	(.0961)	(.0272)	(.1200)	(.0981)	(.0990)
rev3	.0096	-.0650	.0284	-.0097	.1713*	-.0390
	(.0656)	(.0944)	(.0270)	(.1005)	(.0988)	(.0998)
soft water	.2361***	.0949	.0306	.1469	.0598	.0935
	(.0670)	(.0962)	(.0269)	(.1053)	(.0963)	(.0979)
pop10000	.2040**	.2300**	.0391	.2915**	.2171	.2346*
	(.0960)	(.1162)	(.0488)	.1435	(.1881)	(.1200)
commune14	.1248	.1109	.1149**	.3174**	.3591**	.1480
	(.0973)	(.1139)	(.0488)	(.1423)	(.1781)	(.1194)
ground100	-.0615	-.0320	-.0635***	-.1474	-.0953	-.0764
	(.0717)	(.0765)	(.0241)	(.1031)	(.0881)	(.0814)

In the first two columns we present the instrumental variable ordinary least squares (IVOLS) without and with regional effects, in the second column the instrumental variable Probit (IVProbit), in the third column the Two-Part model, in the fourth column the Probit regression and in the last column the Instrumental variable Heckit (IVHeckit) estimation results. The marginal effects of the Two-Part model are obtained according to the procedure explained in section 3.4.3 [11] and the Heckit results are obtained following the procedure explained in section 3.4.3.

We recall that the Two-Part model treats the "selection" process (probability of observing positive or zero replacement rates) independent of the outcome process (the rate of replacement given positive rates). On the other hand, the IVHeckit model takes into account the possible selection bias generated when we take into account only the positive rates. Utilities that have zero rates may be systematically different from those that have reported positive values. However, the coefficient on the IMR term is insignificant; hence, either the selection problem does not exist or that the variable used for the exclusion restriction is too weak, resulting in imprecise IMR.

The reason why we do not conduct a Tobit type-1 model is due to the fact that the covariates have different influence on the selection process and the outcome process. We can see in Table 3.9 that the signs on some of the coefficients on the covariates in the least squares estimation are different compared to the IVProbit estimates. For example, the length variable has a positive effect on the selection process and a negative effect on the outcome process. Moreover, the magnitude of each covariate varies between the IVOLS and IVProbit results.

Although IVOLS estimates may suffer from selection bias (unconfirmed by Heckit), we can draw certain interesting conclusions on the variables that influence mains replacement. We can be certain that *water loss* has a significant positive effect on replacement. A one percent increase in water loss increases the replacement rate by about 30%. Furthermore, we observe a significantly positive impact of in-house (*regie*) operated utilities

[11] The estimates from the IVOLS and IVProbit are used to compute the marginal effects. The standard errors of these coefficients are bootstrapped. The bootstrap simulation code could be provided by the author upon request.

	(IVOLS without regions)	(IVOLS)	(IVPROBIT)	(TWO-PART)	(PROBIT)	(HECKIT)
	lnrate	lnrate	rate	$E(lnrate \mid rate > 0)$	rate	lnrate
	b/se	b/se	b (dydx) /se	b/bootstrap se	b/se	b/se
Languedoc Roussillon		-.0676	.0042	-.0568	.1661	-.0170
		(.1755)	(.0511)	(.2079)	(.1835)	(.1810)
Midi Pyrenees		.2248	-.0309	.1578	.0210	.1943
		(.1755)	(.0557)	(.1788)	(.2030)	(.1808)
Limousin		.2781	-.0562	.1620	-.2612	.2718
		(.2819)	(.0742)	(.3747)	(.2625)	(.2865)
Poitou-Charentes		.2619	.0651	.3699	.2144	.2892
		(.2226)	(.0870)	(.2794)	(.3141)	(.2264)
Bourgogne		.1813	-.1525***	-.1078	-.4774**	.1452
		(.2089)	(.0568)	(.2415)	(.2049)	(.2232)
Franche Compte		.0816	-.0491	-.0125	-.0346	.1149
		(.1812)	(.0513)	(.1913)	(.1861)	(.1895)
Alsace		-.0060	-.0145	-.0325	-.1784	.1199
		(.2125)	(.0635)	(.2591)	(.2351)	(.2216)
Lorraine		-.1625	-.0776	-.2981	-.2098	-.1519
		(.1701)	(.0486)	(.1911)	(.1771)	(.1779)
Champagne Ardenne		-.0884	-.0379	-.1542	-.0902	-.0331
		(.2073)	(.0553)	(.2399)	(.1998)	(.2169)
Corse		.3044	.0231	.3332	.3856	.3948
		(.2701)	(.0759)	(.4023)	(.2652)	(.2764)
Centre		-.1774	.0032	-.1635	-.1689	-.1658
		(.1466)	(.0433)	(.1582)	(.1557)	(.1498)
Pays de la Loire		.2326	.0273	.2724	-.1758	.2785
		(.1977)	(.0659)	(.2501)	(.2398)	(.2013)
Ile de France		-.4307*	-.1173	-.6274*	-.5185*	-.4470
		(.2567)	(.0752)	(.3228)	(.2774)	(.2735)
Haute Normandie		.0860	-.0914	-.0861	-.3041	.0621
		(.2300)	(.0647)	(.3058)	(.2338)	(.2398)
Basse Normandie		.3925**	.0320	.4337	-.0496	.4215**
		(.1754)	(.0541)	(.1824)	(.1952)	(.1786)
Bretagne		.1941	.0323	.2447	.0272	.2435
		(.1963)	(.0633)	(.2228)	(.2298)	(.2004)
Auvergne		.2976	.0285	.3367*	.2900	.2752
		(.1959)	(.0586)	(.1921)	(.2140)	(.2022)
Rhone Alpes		.1507	.0135	.1688	.2895	.1953
		(.1651)	(.0500)	(.1781)	(.1792)	(.1687)
Picardie		-.0746	-.0786	-.2160	-.3256*	-.1037
		(.1819)	(.0510)	(.2024)	(.1860)	(.1908)
Nord pas de calais		-.1546	-.1088**	-.3480	-.3689*	-.1541
		(.1951)	(.0542)	(.2155)	(.1986)	(.2091)
PACA		-.2352	.0287	-.1716	.2756	-.1789
		(.1773)	(.0540)	(.1976)	(.1951)	(.1839)
lndensity					.3810***	
					(.0397)	
leakage detection					.2266***	
					(.0568)	
IMR						.3134
						(.2505)
Constant	-1.7066***	-1.7238***			-1.6509***	-1.9759***
	(.1352)	(.1955)			(.2518)	(.2916)
Observations	2006	2006	3414	3666	3276	1914

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3.9: Estimation results

on the rates. Rates are about 80% higher under regie. In the regression with 2010 tariffs, this percentage is even higher, with 88%. However taking into account the full effect of regie on the rate of replacement; $0.82 - 0.15 lnlength$[12], for very large networks, the rate of replacement is reduced. For instance, length of network at the 90th percentile would reduce this positive effect to about 50%. Nevertheless, this result implies that replacement rates of in-house utilities are on average higher than in outsourced utilities. Indeed the average rate of replacement in larger networks remain greater for utilities that are operated in-house. We looked at the utilities with greater than average total network length and saw that the rate of replacement in in-house provision is about 0.7%, whereas for outsourced utilities it is 0.5%.

Concerning the effect of in-house provision on the probability of observing positive rates, we expected to observe a negative impact; however, the IVProbit results show that observing positive rates is higher for in-house operated utilities that set higher prices. The probability increases by about 8 percentage points. Moreover, if we consider significance levels at the 10% level, *regielength* is also positive and significant. Which implies that although the difference is quite small, the probability of observing positive rates is *greater* for in-house operated utilities than outsourced ones in larger networks.

These results confirm our initial analysis on the size of the network that explains the relationship between in-house operated utilities and the rate of replacement. Higher rates are observed among in-house utilities since the majority of them operate very small networks. However, the results reveal that even for larger networks, utilities operated in-house have larger replacement rates.

We also notice that the probability of observing positive rates is higher for in-house provision that set higher prices. In both estimations with tariff2010 and tariff2014, the interaction term between tariff and regie is positive and significant. This means that replacement rates are higher under in-house provision for higher tariffs. Since we cannot ignore the potential endogeneity problem associated with tariffs, we do not reason in

[12]The interaction terms are centered (demeaned); therefore the mean value of lnlength is 0. Hence, at average values, the effect of regie is 0,82.

terms of causality but that higher tariffs and higher rates reveal a positive correlation. This relation is in favor of the full cost recovery principle enforced by the European water framework directive. Ideally prices should reflect the cost of delivery of water services.

The IVOLS estimates reveal a negative impact of network length on the rate of replacement. A one percent increase in the length of network lowers the rate of replacement by about 28%. The effect is smaller with 2010 tariffs; perhaps due to the smaller number of observations available. However, this negative effect does not persist in very large networks, represented by the variable *lnlengthsq* (the quadratic term of length). The full effect of length on the replacement rate for in-house utilities is $-0.28 + 2 * 0.06 lnlength - 0.15$; whereas for outsourced utilities the marginal effect is $-0.28 + 2 * 0.06 lnlength$. If we take the 90th percentile length of network, the average marginal effect is almost null (-0.04) for outsourced utilities. Whereas the negative impact persists for in-house utilities (-0.19). This implies that the marginal effect of the size of the network has a greater negative impact on the rates in in-house provision. Replacement of mains drops more rapidly in in-house provision. Although on average, rates tend to be higher for very large networks under in-house provision, our results show that in-house operated utilities are more "sensitive" to network size. Overall, the nonlinearity of the impact of network length on rates reflect the differing degrees of network renewal needs. It makes sense that the larger the network, the percentage of replaced mains shrinks; however, very large networks are more likely to face larger replacement needs since these networks could consist of a larger variety of mains in terms of material and age.

As anticipated, *knowledge* of the network has a positive impact on the rates. It is quite intuitive that utilities well aware of the state of their network have higher replacement rates. However, this knowledge score includes various factors which does not only include the aspect of network renewal. We also observe that outsourced utilities with the contracts that are still active (have not expired during the period 2010 to

2014) is associated with higher rates; about 18% higher. Since the replacement rate is an average rate over the past 5 years, contracts that have specified network renewal objectives should reflect a higher replacement rate on average compared to expired contracts within the past five years. The fact that this term is significant may imply that these contracts include network renewal objectives[13].

We also observe higher rates where utilities provide water to large cities (utilities composed of greater than 10,000 inhabitants in each commune that receives water), which is reflected by the term *pop10000*. Rates are about 23% higher in these utilities. Mains tend to be older in larger cities and where there is larger demand, water loss could be higher. Indeed, we observe that on average water losses are about $7m^3/km/day$ in networks with municipalities that have greater than 10,000 inhabitants. Whereas, the average is about $3.5m^3/km/day$ in communes with less than 10,000 inhabitants.

The impact of groundwater is only observable in the IVProbit model. The probability of observing positive rates is lower for utilities that depend 100% on groundwater resources. It is coherent with the fact that groundwater is cheaper in terms of treatment costs compared to surface water. Hence, the presence of water loss is less costly. Similarly, the coefficient on *commune14* is only significant in the IVProbit model. Utilities with more than 14 municipalities grouped together raises the probability of observing positive rates by about 12 percentage points.

We also observe in the linear regression that the revenue group *rev2* has a positive impact on the rate of replacement compared to the lowest revenue group (*rev4*).

Moreover, the results of IVOLS without regional effects show that *soft water* has a positive effect on rates. We believe that this effect is absorbed by the regional effects once included and that *soft water* alone loses its explanatory power.

The final column shows the Heckit estimates; however, as we have mentioned previously, the IMR coefficient is insignificant which means that either the model is misspecified (due to the weak exclusion restriction) or that indeed there is no strong selection

[13]These contracts are quite recent so network renewal issues may be prioritized.

bias. Hence, we analyse the Two-Part model which assumes no selection bias.

3.5.1 Analysis of the Total Marginal Effects of Two-Part Model

The total marginal effects is obtained by solving Equation (3.7). The computed results are shown in the fourth column of Table 3.9. The associated standard errors are bootstrapped (Belotti et al., 2015). As we can see, the marginal effects of water loss, tariff, regie, regietariff, length, lengthsq, knowledge, contract, pop10000 and commune14 are significant. The Two Part model allows the marginal effects to be "readjusted" by taking into account the observations with zero rates. For instance, water loss has a larger impact on rates than the coefficient estimated by IVOLS, which estimates only over positive rates. Moreover, the coefficients with the same signs in the IVProbit estimation and the IVOLS estimations results in a much larger impact on the rate compared to the estimates in IVOLS. Whereas, coefficients that have different signs in the two parts have a smaller total marginal effect on the rate. Moreover, the interaction term between regie and length is no longer significant. This means that on average, regardless the size of the network, in-house utilities have a much larger replacement rate than outsourced utilities. Regarding the effect of the size of the network (ceteris paribus), the total marginal effect is now: $-0.09 + 2 * 0.08 lnlength$. At average network length, a one percent increase in the length lowers the rate by 9%; however, length at the 90th percentile raises the rate by 23%. On the other hand, the IVOLS results would correspond to about -2%. Taking into account the positive impact of network size on the probability of observing positive rates raises the overall impact of length on the expected rate of replacement. Furthermore, the positive impact of *knowledge* is preserved as well. And finally, the positive effects of urbanity (pop10000) and intercommunal utilities (commune14) on the rates are captured in the total marginal effect. Both coefficients are larger compared to IVOLS and IVPROBIT estimates (first, second and thrid columns of Table 3.9).

3.6 Discussion of Results and Political Implication

The main conclusion that we draw from our results is that the replacement of mains are on average higher under in-house (regie) provision. Technically, we should not see much difference in the replacement rate based on the difference between in-house or outsourced utilities since network renewal is a part of investment activities which are decided and paid by the municipality. However, since local municipalities decide to delegate their services to private entities in favor of improved efficiency in terms of superior technical and management knowledge and access to funds[14] it could be reasonable to expect higher network quality to be seen in outsourced utilities (Garcia and Reynaud, 2004). As we have mentioned at the beginning of the chapter and in Part II Chapter 1, the underlining objectives of the contract signed by outsourcing utilities could be directed towards water quality improvement instead of network renewal. Or, in line with González-Gómez et al. (2012), water utilities that have been outsourced for a longer period exhibit higher quality (reflected by lower water loss in their study). Indeed, we see that utilities that have been contracted out since at least 5 years, exhibit higher replacement rates on average. This could also imply that due to aging networks, recently signed contracts may include network renewal objectives as priorities. Nevertheless the overall average replacement rates are greater under in-house provision. Given that a majority of utilities in France are small rural utilities, we can draw reference to the results presented in the paper by Chong et al. (2015). According to their results, small rural utilities that delegate their provision to private entities have difficulty "disciplining" the performance of the firm due to their weak bargaining power compared to larger utilities. This may imply that rural utilities that are outsourced may particularly be associated with lower network quality due to similar reasons.

Overall, does this imply that network renewal is more effective under in-house provision? Results also showed that rates are particularly higher in urban areas. Hence, we compared the average water loss and the corresponding average rate of replacement

[14]Information concerning the management of water distribution in France *http : //www.cnrs.fr/cw/dossiers/doseau/decouv/france/07$_e$au.htm* Reports by Bernard Barraqué.

between in-house provision and outsourced provision. In urban areas (large cities with more than 10,000 inhabitants), the average water loss is almost the same under both types of service providers. However, replacement rates are much greater in in-house operated utilities than outsourced ones (0.5% vs 0.9%). On the other hand, in less urban areas (smaller cities), water loss is much smaller in utilities that are outsourced. Consequently, replacement rates are smaller in these outsourced utilities. In general, in-house utilities outperform outsourced utilities in terms of replacement rates; however, network conditions (water loss) are better in outsourced utilities that provide water in smaller cities, which justifies smaller rates. The fact that network renewal is smaller under outsourced provision in large cities (facing similar volumes of water loss) makes us wonder why? Theoretically, private participation should lead to better results in general - lower prices and higher quality. According to Chong et al. (2015), private firms excel in the provision of high quality water compared to in-house providers. This may imply that the objectives of the utilities are focused on different priorities. For instance some may prioritize the quality/taste of water which justifies the higher prices of outsourced utilities; whereas, some may prioritize network renewal in favor of water loss reduction. However, lack of replacement would lead to waste of highly-treated water which ultimately translates into higher costs. In addition, our results showed that in-house operated utilities are more sensitive to the change in the size of the network. We see very little impact of the marginal increase in the length of network on the replacement rates in an outsourced utility. This may reflect the impact of higher financial burden on public utilities regarding network renewal in larger networks.

Furthermore, our results show that the probability of observing positive rates is higher for intercommunal utilities. Today in France, more and more communes are merging to create large intercommunal organisations, which was also mentioned by Audouin. Since the implementation of the law NOTRe, individual communal level local authorities are merging into larger entities. The benefit of merging communes is for easing the account balance problems and to improve the efficiency of the implementation of decisions that are taken by the local authorities. If there are less layers of authorities, the implementation of a decision will be executed more rapidly. Moreover, in the case of bulky water network management, economies of scale applies once individual communes merge. A group of communes that share the same characteristics, such as high water production costs and high leakage may find it beneficial to merge.

Figure 3.10 shows that certain regions have larger proportions of intercommunal utilities. We see that it is particularly the case in the North and West of France. According to Dequesne and Brejoux (2015) this is due to the difference in raw water quality. Utilities in this area of France depend heavily on surface water. Hence, we observe individual communes joining hands with others to share the cost burden. On the other hand, we see less communal-integration in the East and the South-East of France. The reason may be due to the fact that cheap water is more abundant.

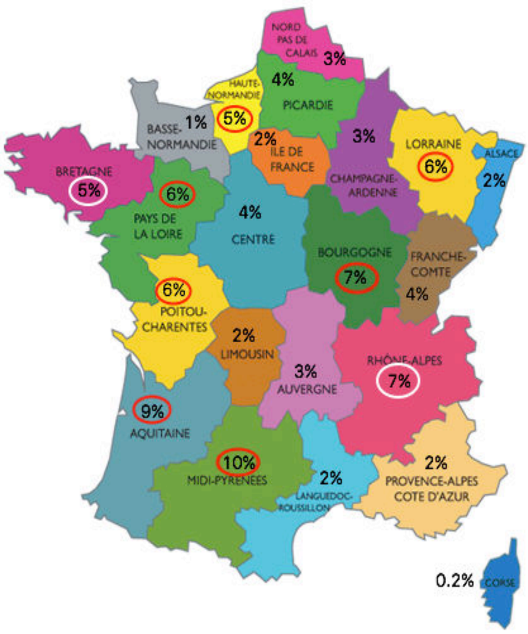


Figure 3.10: Proportion of utilities that is composed of more than 14 communes (percentages are rounded). Greater than 5% is indicated with a red or a white circle around them.

However, Table 3.10 shows that intercommunality does not only depend on groundwater abundance. There are certainly other factors that explain why we observe high intercommunality in the East of France as well. For example mountainous regions and highly rural areas coincide with regions that have high intercommunality. However, as we have shown in Part II of chapter 1 and in reference to Martins et al. (2012), merging neighboring utilities does not guarantee scale economies; the relative size of the network to the volume of demand must be considered.

	(1) Regions	(2) Groundwater (%)	(3) Mountains	(4) Rural
1.	Picardie	100	–	–
2.	**Haute Normandie**	**98**	–	–
3.	Nord Pas de Calais	97	–	–
4.	Centre	97	–	–
5.	**Aquitaine**	**95**	–	–
6.	Alsace	95	–	–
7.	**Rhone Alpes**	**92**	Yes	–
8.	Basse Normandie	92	–	–
9.	**Lorraine**	**92**	–	Yes
10.	Franche Compte	92	–	–
11.	PACA	89	–	–
12.	**Bourgogne**	**89**	–	Yes
13.	Champagne Ardenne	89	–	–
14.	Auvergne	87	–	–
15.	Languedoc Roussillon	87	–	–
16.	Ile de France	82	–	–
17.	Corse	81	–	–
18.	Limousin	76	–	–
19.	**Pays de la Loire**	**70**	–	–
20.	**Midi Pyrénées**	**63**	Yes	–
21.	**Bretagne**	**59**	–	–
22.	**Poitou Charentes**	**47**	–	–

Table 3.10: In bold are the regions with high intercommunality (greater than 14 communes per utility). Those with higher groundwater percentages are associated with regions corresponding to mountainous and/or rural areas.

3.7 Conclusion

In this chapter we estimated the effect of several factors that influence the water mains replacement rates of water utilities in France. The reason why we study the rate of replacement is because obsolete water networks could have serious consequences regarding water loss from leakage, quality reduction of water and the risk of main breaks. The current rate of replacement in France is about 0.6%, which means pipes are expected to last for about 200 years. Yet in reality, pipes only last for about 50 to 100 years. Hence this implies that network renewal is falling behind in France. The main contribution of this chapter was to highlight the impact of the difference between in-house provision and outsource provision. In the economic literature studies that are based on the impact of the governance of water service provision on the "network quality" rarely exists. For out empirical method, we used corner-solution models such as the Heckit and the Two Part model due to the large number of zero replacement rates. Moreover, we estimated instrumental variable models since water loss suffers from endogeneity. Overall, the results from the different models show that water loss, tariff, network size, type of service provider, urbanity, type of water, knowledge of the network and communal integration have significant influence on the rate of replacement. Water loss, service provider and urbanity have the largest impact on the replacement rates. Our results show that replacement rate in general are greater under in-house provision. This could be explained by the fact that on average, water loss is smaller where private participation exists. According to Chong et al. (2015) the quality of water and infrastructure is better under outsourced provision. However our results show a nonlinear effect of the size of the network on the replacement rates. In particular, rates are higher in very large networks under in-house provision. Indeed, water loss is smaller for smaller networks for outsourced utilities compared to in-house operated utilities; which justifies lower rates for outsourced utilities in smaller networks. However, in large urban cities, water loss does not vary much between service providers but the replacement rate is noticeably higher under in-house provision. This may reflect the difference in the priorities specified by the municipalities regarding water quality and network renewal. However, postponing network renewal can aggravate leakage, which wastes away highly-treated water.

To further understand the impact of the variables on the rate of main replacement over time, we should study the evolution over time. However, this requires a panel data analysis, which is currently unavailable due to missing observations over time for each utility. Our next step is to conduct a pseudo-panel by generating cohort groups defined by the *departement* of France.

3.8 Appendix

3.8.1 Selection bias due to operator type

In line with the study carried out by Chong et al. (2006) and Ruester and Zschille (2010), we test the possibility that utilities self-select into in-house provision or outsourcing regarding the state of their water mains network. An utility that has difficulty investing in network renewal may prefer to seek private participation in water provision. Although the difference is quite small, we observe lower average water loss in utilities with a lease contract (affermage); however, we observe higher rates of replacement for utilities that operate in-house. However, since investment activities such as main replacements is decided by the local authorities and not by the delegated providers under a lease contract, selection bias may be weak. In order to test the existence of this bias, we follow the same procedure as that of Chong et al. (2006) and Ruester and Zschille (2010), known as the switching regression model. In this type of model, we need a variable that has influence only on the *regie* variable and not on the replacement rate. Similar to Chong et al. (2006), we chose the variable that indicates the type of service provider for wastewater services (affermage vs regie). The following results show that the coefficient of `regieWaste` is significant; which implies that utilities that choose to provide waste water services in-house will also likely choose in-house provision for potable water services. We then reestimated the instrumental linear regression with the inverse mills ratio (IMR) that captures the potential selection bias. The coefficient on the IMR turns out to be insignificant; hence we cannot conclude for an existence of selection bias caused by utilities self-selecting operator types depending on the network renewal needs. As we have shown in Chapter 1, the “need” for network renewal depends primarily on the trade-off between the cost of water loss and the cost of replacement. The choice to remain in-house or delegate service provision depends more on other factors such as expertise dedicated towards water treatment (in reference to Chong et al. (2006)). After all in-house or outsourcing, network renewal decisions are in the hands of the local authority.

We estimate with a lagged tariff from 2010 and tariff from 2014. Since organisational choice and price levels are shown to be endogenous, we substitute price from 2014 with price from 5 years back, 2010. However, by doing so we lose almost half of our observations due to missing values. Hence, we conduct estimates with both tariffs and compare the results. In both cases, the coefficient on the IMR is insignificant. The only variables that behave the same way in the regression of replacement rates and the probit regression of operator type is the length variable.

	Probit with tariff2010	Switching regression with tariff2010	Probit with tariff2014	Switching regression with tariff2014
	regie	lnrate	regie	lnrate
	b/se	b/se	b/se	b/se
leakage index		.2674***		.2774***
		(.0982)		(.0760)
lndensity	-.2926**		-.1568*	
	(.1433)		(.0853)	
regie		.5039***		.5067***
		(.1454)		(.1225)
tariff2010	-1.1402***	.1427		
	(.1851)	(.1295)		
tariff			-.7626***	.3276***
			(.1115)	(.0865)
lnlength	-.1959*	-.2857***	-.2541***	-.4140***
	(.1044)	(.0568)	(.0629)	(.0422)
lnlengthsq	.1066***	.0483**	.0666***	.0778***
	(.0408)	(.0203)	(.0232)	(.0155)
lengthtariff2010	-.0163	-.0222		
	(.1426)	(.0893)		
lengthtariff			.1240	-.0256
			(.0804)	(.0580)
knowledge	-.0062**	.0032**	-.0095***	.0038***
	(.0027)	(.0015)	(.0019)	(.0012)
contract since 2010	-2.9178***	.3767*	-2.2768***	.3600**
	(.2805)	(.1953)	(.1838)	(.1766)
ratio produced imported	.4906**	-.1595	.3428**	-.0632
	(.2462)	(.1429)	(.1518)	(.1123)
rev1	.6067	-.1461	.1984	-.1264
	(.6518)	(.3128)	(.3800)	(.2294)
rev2	-.5632*	-.0290	-.3864*	.0692
	(.3150)	(.1593)	(.2137)	(.1360)
rev3	-.2632	-.0055	-.2845	-.1076
	(.3105)	(.1537)	(.2042)	(.1297)
soft water	.0967	.0737	.0305	.1162
	(.2945)	(.1644)	(.1939)	(.1346)
pop10000	.4735	.0418	.3389	.2537
	(.3868)	(.1765)	(.2515)	(.1584)
commune14	.1899	.0077	.2303	-.0059
	(.4886)	(.2339)	(.3109)	(.2002)
ground100	.1321	-.0692	-.0287	-.0373
	(.2489)	(.1317)	(.1622)	(.1087)

Ideally, tariff2010 is preferable than tariff2014. By using tariffs from previous years, the causality could be reflected. Tariff from the same year is problematic since tariffs are usually determined in the contract that is signed with the outsourcing firm. Hence if we include 2014 tariffs, we will not establish a causal relationship but simply a correlation. tariff at $t = 2014$ would have been already agreed upon at the time of outsourcing which could be any time t. However, including lagged tariffs (2010), we may be able to establish causality since utilities that are not satisfied with the contract signed, associated with the price level, would perhaps switch to in-house (Chong et al., 2015). Contracts since 2010 that have not expired yet are controlled for. However, we have a technical problem which is severe missing values. Hence, it is difficult to compare the significance of the tariff variables between the two models.

	Probit with tariff2010	Switching regression with tariff2010	Probit with tariff2014	Switching regression with tariff2014
	regie	lnrate	regie	lnrate
	b/se	b/se	b/se	b/se
Languedoc Roussillon	.2653	-.3118	.6167*	-.0707
	(.4794)	(.2630)	(.3191)	(.2212)
Midi Pyrenees	.2296	-.0350	.3116	.0649
	(.5331)	(.2881)	(.3477)	(.2434)
Limousin	.3064	.6061	.5776	.1752
	(.9952)	(.7871)	(.4902)	(.3586)
Poitou-Charentes	.8706	-.0240	.8029*	.0947
	(.6643)	(.3513)	(.4329)	(.2956)
Bourgogne	.4950	.0733	.2505	.2368
	(.6372)	(.3537)	(.3472)	(.2732)
Franche Compte	-.7660	.3562	-.0289	.2472
	(.5126)	(.2933)	(.3362)	(.2446)
Alsace	1.3685	.6466	1.6156*	-.0397
	(1.1814)	(.4289)	(.8587)	(.3268)
Lorraine	.2301	-.1028	.4326	-.1164
	(.4780)	(.3045)	(.3296)	(.2489)
Champagne Ardenne	1.2295*	.0736	.7924*	-.1614
	(.7040)	(.3808)	(.4083)	(.3123)
Corse	.0000		1.1153	.0771
	(.)		(.7409)	(.3478)
Centre	.8202**	-.1064	.6094**	-.1073
	(.4000)	(.2226)	(.2737)	(.1951)
Pays de la Loire	.9071	.1671	.8377**	.3708
	(.5617)	(.3153)	(.4169)	(.2976)
Ile de France	.9331	.2704	.1826	-.5906
	(1.0669)	(.5257)	(.5535)	(.3811)
Haute Normandie	.1594	.1875	.1012	.1131
	(.8787)	(.4294)	(.4270)	(.2785)
Basse Normandie	.2314	.1284	.8771*	.4052
	(.6693)	(.3508)	(.4948)	(.3012)
Bretagne	.6470	.0157	.3645	.2633
	(.5190)	(.2958)	(.3662)	(.2559)
Auvergne	1.0807	.3825	1.0322**	.2382
	(.6936)	(.2966)	(.4961)	(.2549)
Rhone Alpes	.4305	-.0401	.6841**	.0825
	(.4626)	(.2717)	(.2989)	(.2201)
Picardie	.8746	-.2084	.8251*	-.0250
	(.6319)	(.3509)	(.4662)	(.2965)
Nord pas de calais	-.4054	-.0209	-.3608	.1985
	(.5975)	(.3585)	(.4286)	(.3202)
PACA	1.2734**	-.2115	.6008*	-.2505
	(.5876)	(.2685)	(.3147)	(.2185)
regieWaste	2.8965***		2.4480***	
	(.2362)		(.1406)	
leakage index		.2674***		.2774***
		(.0982)		(.0760)
IMR1		-.0708		
		(.0615)		
IMR2				-.1067
				(.0695)
Constant	-.6118	-1.2037***	-.2689	-1.3899***
	(.7996)	(.3329)	(.5011)	(.2806)
Observations	878	557	1749	1065
No. of observations				
Overall-R^2				
R^2		.1505		.2046
F-test				
log(likelihood)	-155.3664		-353.0973	

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3.11: Switching models to test “self-selection” bias

Conclusion

In this dissertation, I have developed two theoretical models based on cost efficiency and profit maximization to solve for the optimal water main quality index and I have also developed a optimal switching time model that solves for the optimal timing of water mains replacement. Lastly, I have conducted an empirical analysis on the water main replacement rates observed in France. I recall in the conclusion the purpose of this dissertation. Many developed countries are facing a deteriorating quality of water infrastructure; in particular the water mains that carry potable water to our taps. The main reason is because replacement of mains have been neglected and postponed, mostly due to the fact that replacement costs are pricy and water prices are very cheap. The main consequence of obsolete water mains is leakage. Water lost through leakage is not only a waste of water resources but it is also an economic loss. This is because the resources (labor, chemicals and energy) that have been put into the process of potabilization is being wasted through leaks. Therefore, the main purpose of this dissertation was to try an investigate the reasons why water mains are not being replaced. Engineering papers on water main life expectancies estimate clearly the longevity of the mains; however, depending on other various factors that are specific to the water utility, it may not be "optimal" to replace right at the moment when the mains reach theoretical obsolescence. The results in the first chapter sheds light on the reason why in some utilities even with very high water loss, it may not be "optimal" to replace mains. This "optimality" is based on the cost efficient network quality. Results show that having a high network quality (implying replacing obsolete mains) is a cost efficient solution for a typical large urban utility; whereas, that is rarely the case in rural utilities. This is because the cost efficient criteria evaluates the trade off between the cost of water loss and the cost of water mains renewal. In very large urban utilities, the volume of demand is extremely large compared to a typical rural utility. Since water loss is a proportion of water production, if demand is large, water loss is large as well. Hence in relative terms, the cost of water loss is very large in large urban utilities compared to the cost of mains replacement. On the other hand, in rural utilities, because the relative size of demand in relation to the total length of the network is much smaller than in an urban utility, the trade off of the cost of water loss and the cost of replacement is small; hence, in terms of cost efficiency our results often showed 0% network quality (implying no replacement necessary). In comparison, the estimation results in Chapter 3 showed that replacement rates are much higher in small rural utilities. However, this is particularly the case for very small utilities (less than 10 km of mains) because naturally, even with very short lengths of replacement, the resulting proportion could be quite large. Moreover, in practice mains are often replaced alongside other roadworks. On the other hand, the fact that replacement rates are large in large urban utilities is coherent with the estimation results which show that on average replacement rates are larger in large urban utilities in France characterized by more than 10,000 inhabitants in each commune. In this empirical exercise, we also observed the positive impact of in-house provision on replacement rates. Contrary to the economic theory that private participation could bring efficiency and lower prices; in the water industry there are conflicting results. This is mainly due to the fact that the water industry is characterized by a natural monopoly where there is no room for competition. The estimation results show that on average in-house operated utilities have larger replacement rates than outsourced utilities. Furthermore, this is visible in very large urban utilities as well. However, according to Christophe Audouin, a water professional that I interviewed, this is actually quite a natural observation. The fact that outsourced utilities may be associated with small replacement rates does not imply that outsourced utilities perform badly. This is because outsourced utilities are only responsible for what is specified in the contract signed with the local authority. If network renewal is not one of them, there is no incentive or obligation to exert effort on network renewal. This reveals a problem of asymmetric information. Since, the local municipality that is in charge of the investment activities may be less aware of the current state of their network due to the fact that the outsourced firm may not be actively overseeing the state of the network. The firm is remunerated for the responsibility specified in the contract along with the receipts paid by users. A recent study on outsourced utilities in France revealed that they often manifest higher prices accompanied with higher water quality. This means that an outsourced utility that has high levels of water loss and simultaneously investing in high quality water may be wasting away precious resources through leaks (highly cost inefficient). Hence, it is essential to accompany high network quality with high water quality in terms of cost efficiency.

Furthermore, in the theoretical models, I showed that the cost recovery principle has a significant impact on the resulting optimal network quality if implemented. In other words, even if lowering water loss is not optimal in terms of cost efficiency, if the costs of replacement are recovered in the price paid by users, it becomes beneficial for the utility to replace mains and reduce water loss. This is because cost recovery raises prices and has a direct impact on revenue. As long as prices do no reach the price caps set under regulations, water mains replacement raises revenue and lowers cost (by lowering the cost of water loss). This positive effect of cost recovery on network quality is also observed in the results obtained in the second chapter where the optimal timing of replacement is analyzed. The greater the recovery of costs, the more profitable it is for the water utility to replace mains and reduce water loss. However, we observe again a discrepancy between rural and urban utilities and public and private utilities. In rural utilities that are operated in-house (public management), price caps are oftentimes set lower than in private utilities; therefore, prices could reach the limit before achieving full cost recovery. This situation generates a dilemma in terms of water loss reduction and full cost recovery. Low water loss thresholds and the enforcemement of full cost recovery may not be compatible in rural utilities. Hence, before enforcing regulations, it is important to study the compatibilities of different regulations concerning water distribution management in rural utilities. Moreover, these results could be highly influenced by the sensitivity of demand towards prices. If analyses are based on perfect inelastic demand assumptions, we may overestimate the benefit of cost recovery on water utilities. In Chapter 1, results show that with perfect inelastic demand the dilemma faced by rural utilities disappears and water loss could be reduced to its minimum. This is mainly because demand remains high (unconstrained demand) regardless the price increase; hence, water loss reduction becomes more beneficial compared to the case with inelastic demand. Moreover, cost recovery no longer has a negative effect; hence it can be raised higher than under inelastic demand. In the theoretical models I also showed that network quality is extremely sensitive to the unit cost of water production (cost of pumping and treating water). This means that in arid regions or where water is costly (due to lack of groundwater), the presence of water loss becomes costly. In the U.S., water scarcity is a serious issue; especially in the west coast due to climate change and the aridity of the region. Network renewal to save water loss is definitely a priority. I further showed the benefit of engaging in leakage detection activities to maximize the "efficiency" of the network quality. Water mains replacement can be highly disruptive in terms of roadworks and water service interruptions in large urban cities; hence, by detecting and identifying the "worst" condition mains and replacing them would be beneficial for the community and for the water utility. And finally, if water mains have already reached obsolescence (characterised by a threshold level of water loss), rehabilitating them in order to be able to postpone replacement is not beneficial (in terms of profit maximisation) for the utility. Rehabilitation of water mains should be considered BEFORE the mains have reached obsolescence, which reflects a preventive measure. As we have mentioned in the conclusion of Chapter 3, the next step in this area of research would be to conduct panel data regression to observe the evolution of water mains replacement over time.

Résumé en français

Cette thèse s'intéresse au problème du renouvellement des infrastructures des services de distribution d'eau potable. Nous observons aujourd'hui dans les pays développés qu'une grande partie des canalisations atteint un état d'obsolescence avancée. La principale conséquence de cette obsolescence est l'apparition de fuites d'eau conséquentes. L'eau perdue dans ces fuites entraîne des pertes économiques et ce, pour plusieurs raisons. Tout d'abord, les pertes en eau représentent une source de gaspillage des ressources investies dans la production d'eau potable comme par exemple la main-d'oeuvre, les produits chimiques utilisés dans la potabilisation d'eau ou les ressources en énergie liées à l'extraction de l'eau. Les fuites engendrent également une baisse de la qualité de l'eau dûe à l'infiltration des contaminants dans les canalisations par les fissures. Dans la majorité des cas, les canalisations qui ont atteint leur état d'obsolescence peuvent casser et créer des dégâts significatifs dans un périmètre assez vaste. Les inondations résultant d'une rupture de canalisation peuvent entrainer une interruption de la distribution d'eau aux citoyens. Enfin, les pertes d'eau représentent aussi une perte financière pour les services de distribution de l'eau. Par conséquent, dans cette thèse j'explore les raisons pour lesquelles le taux de renouvellement des réseaux de distribution d'eau est si faible comparé aux besoins manifestes. Cette thèse est composée de trois chapitres. Le premier chapitre développe un modèle théorique qui propose un indice de qualité du réseau d'eau. Le deuxième chapitre étudie la date optimale de remplacement des canalisations. Enfin le troisième chapitre propose une étude empirique des facteurs influençant les taux de remplacement des réseaux d'eau dans les services de distribution de l'eau en France.

Le premier chapitre est composé de deux parties. Dans la première partie, je présente un modèle statique de minimisation des coûts pour obtenir un indice de qualité qui est "cost-efficient". Cet indice est défini comme une proportion des canalisations "neuves" âgées moins de 50 ans (que nous appelons les "canalisations de bonne qualité") par rapport à la longueur totale du réseau. La solution optimale dépend de l'arbitrage entre le coût des pertes en eau par rapport au coût des canalisations de bonne qualité. Le coût des pertes en eau dépend du coût de la production de l'eau. Une augmentation du volume de fuite engendre une augmentation de la production d'eau et en conséquent, augmente le coût total de la production d'eau. De plus, lorsque le volume total de l'eau consommé par les habitants est très important, la proportion d'eau perdue dans les fuites est aussi importante. Ainsi, lorsque des économies d'échelle liées à la densité du réseau existent, comme dans les services urbains, les pertes en eau représentent un coût important et la réduction des pertes en eau par une augmentation de la qualité du réseau est une solution bénéfique pour les services d'eau. Cependant, les résultats de la simulation du modèle basés sur les données Françaises et Américaines montrent que l'indice de qualité est particulièrement bas dans les milieux ruraux. Cela peut être expliqué par l'absence fréquente d'économies d'échelle liées à la densité. En termes d'arbitrage des coûts, le coût associé aux canalisations de bonne qualité pèse plus lourdement pour les services ruraux que pour les services urbains. Autrement dit, en terme de coût-bénéfice, la réduction des pertes d'eau est moins bénéfique dans les services ruraux. A contrario, les données empiriques que j'étudie dans le troisième chapitre montrent que les "taux de remplacement annuels des canalisations d'eau" sont en moyenne supérieure dans les services ruraux que dans les services urbains. Ceci est justifié par le fait que la proportion des canalisations renouvelées dans les services ruraux de petite taille (caractérisé par la longueur totale du réseau) est grande. Par exemple, un remplacement de 500 mètres sur un réseau total de 2km traduit à un taux de remplacement important. Cela montre que l'économie d'échelle liée à la densité est présente dans les très petites services (petit réseaux) comme dans les très grands services urbains ou la densité du réseau est très élevés due à la taille de la population. Dans la deuxième partie de ce chapitre je présente un modèle de maximisation des profits pour obtenir un indice de qualité comme dans la première partie. Le modèle de maximisation des profits prend en compte la recette générée par le service d'eau. De ce fait, les résultats de la simulation montrent que l'indice de qualité du réseau augmente avec le niveau du recouvrement des coûts des canalisations de bonne qualité. Un niveau de recouvrement des coûts élevés engendre une augmentation du prix du mètre cube de l'eau, qui engendre une augmentation de la recette. Cependant, le prix de l'eau est régulé avec un "price-cap", par conséquent dans les services ruraux en absence d'économie d'échelle liée à la densité, le niveau du recouvrement des coûts ne correspond plus au niveau d'indice de qualité optimal. Autrement dit, les services d'eau dans les milieux ruraux font face à de plus grandes difficultés, à la fois pour pouvoir assurer une réduction des pertes en eau et pour répercuter le coût de renouvellement dans les prix.

Dans le deuxième chapitre, je présente un modèle de "optimal switching time" qui étudie la date optimale de renouvellement des infrastructures déterminée à partir d'un modèle de maximisation des profits des services d'eau. Dans ce modèle, nous analysons le choix entre la réhabilitation et le remplacement des canalisations. Cela signifie que les services d'eau peuvent choisir une option moins coûteuse caractérisée par la réhabilitation des vielles canalisations ou le remplacement immédiat qui entraîne un coût nettement supérieur. La réhabilitation permet aux services de décaler le moment du remplacement mais ne résout pas le problème d'obsolescence des canalisations en question. Les résultats nous montrent que le remplacement direct est un choix plus raisonnable puisque les gains associés à la réduction temporaire des pertes en eau et au prolongement de la durée de vie des canalisations ne compensent pas le coût supplémentaire associé à la réhabilitation. Ceci est particulièrement visible dans le cas des services d'eau en milieu urbain. De plus, les résultats nous montrent que le choix de la réhabilitation est préférable en mesure de prévention et non pas une mesure de prolongation de renouvellement. Le bénéfice généré par la réhabilitation dans les réseaux pré-obsolescence permet de prolonger la durée de vie de la canalisation significativement.

Dans le troisième chapitre, je présente une étude empirique concernant le taux de remplacement des canalisations dans les services d'eau en France. L'objectif de ce chapitre se focalise sur l'effet de la mode de gestion des services d'eau sur le taux de remplacement des canalisations. Le modèle théorique présenté dans le premier chapitre nous a montré que l'économie d'échelle liée à la densité et le recouvrement des coûts sont des facteurs explicatifs de la renouvellement des réseaux d'eau. Cependant, les données de SISPEA révèlent que le taux de remplacement des canalisations peut varier selon le mode de gestion. Les résultats empiriques nous montrent que les taux de remplacement sont en moyenne plus élevés dans les services gérés par des régies qu'en affermage. Cela peut être justifié par le fait que les services en régie sont majoritairement présents dans les services de petite taille. Par conséquent, des taux de remplacement élevés sont souvent associés à des réseaux de petite taille (faible kilométrage de canalisations). De plus, dans les petits services ruraux, les travaux de remplacement sont souvent réalisés en parallèle d'autres travaux. Néanmoins nous observons également dans les services de grande taille des taux de remplacement plus élevés dans les services en régie que dans les services en affermage. Ceci peut être expliqué par une différence d'objectif précisé par les services en régie et les services en affermage : les services en affermage ne sont pas responsables du renouvellement des canalisations à moins que ceci soit spécifié dans leurs contrats. De plus, nos résultats montrent que même s'il existe un effet négatif de la taille des services sur les taux de remplacement, dans les très grandes villes, les taux de remplacement sont plus élevés. Ceci est cohérent avec les résultats théoriques obtenus dans les deux premiers chapitres.

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Titre : Trois Essais sur l'économie de l'eau

Mots clés : Eau potable ; Canalisations ; Fuite d'eau ; Investissements d'infrastructures ; Gestion des réseaux d'eau

Résumé :

Cette thèse s'intéresse au problème du renouvellement des infrastructures des services de distribution d'eau potable. Nous observons aujourd'hui dans les pays développés qu'une grande partie des canalisations atteint un état d'obsolescence avancé. La principale conséquence de cette obsolescence est l'apparition de fuites importantes. L'eau perdue dans ces fuites entraîne des pertes économiques liées au gaspillage des ressources investies dans la production d'eau potable, une baisse de qualité de l'eau et des pertes financière. Dans cette thèse j'explore les raisons pour lesquelles le taux de renouvellement des réseaux de distribution d'eau est si faible comparé aux besoins manifestes. Cette thèse est composée de trois chapitres.

Dans le premier chapitre, je présente un modèle statique de minimisation des coûts pour obtenir un indice de qualité qui est « cost-efficient ». Cet indice est défini comme une proportion des canalisations de « bonne qualité » par rapport à la longueur totale du réseau. La solution optimale dépend de l'arbitrage entre le coût des pertes en eau par rapport au coût des canalisations de bonne qualité. Lorsque des économies d'échelle liées à la densité du réseau existent, comme dans les services urbains, les pertes en eau représentent un coût important et la réduction des pertes en eau par une augmentation de la qualité du réseau est une solution bénéfique pour les services d'eau. Cependant, nous montrons que les services d'eau dans les milieux ruraux font face à de plus grandes difficultés, à la fois pour pouvoir assurer une réduction des pertes en eau et pour répercuter le coût de renouvellement dans les prix.

Dans le deuxième chapitre, je présente un modèle de « optimal switching time » qui étudie la date optimale de renouvellement des infrastructures déterminée à partir d'un modèle de maximisation des profits des services d'eau. Dans ce modèle, nous analysons le choix entre la réhabilitation et le remplacement des canalisations. Cela signifie que les services d'eau peuvent choisir une option moins coûteuse caractérisée par la réhabilitation des vielles canalisations ou le remplacement immédiat qui entraîne un coût nettement supérieur. Les résultats nous montrent que le remplacement direct est un choix plus raisonnable puisque les gains associés à la réduction temporaire des pertes en eau et au prolongement de la durée de vie des canalisations ne compensent pas le coût supplémentaire associé à la réhabilitation. Ceci est particulièrement visible dans le cas des services d'eau en milieux urbain.

Dans le troisième chapitre, je présente une étude empirique concernant le taux de remplacement des canalisations dans les services d'eau en France. Les résultats nous montrent que les taux de remplacement sont en moyenne plus élevés dans les services gérés par des régies qu'en affermage. Ceci peut s'expliquer par le fait que les services en régie sont majoritairement présents dans les services de petites tailles. Par conséquent, des taux de remplacement élevés sont souvent associés à des réseaux de petite taille (faible kilométrage de canalisations). De plus, dans les petits services ruraux, les travaux de remplacement sont souvent réalisés en parallèle d'autres travaux. Néanmoins nous observons également dans les services de grande taille des taux de remplacement plus élevés dans les services en régie que dans les services en affermage. Ceci peut s'expliquer par une différence d'objectif défini par les services en régie et les services en affermage : les services en affermage ne sont pas responsables du renouvellement des canalisations à moins que ceci soit spécifié dans leurs contrats. De plus, nos résultats montrent que même s'il existe un effet négatif de la taille des services sur les taux de remplacement, dans les très grandes villes, les taux de remplacement sont plus élevés. Ceci est cohérent avec les résultats théoriques obtenus dans les deux premiers chapitres.

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Title: Three Essays on Water Economics

Keywords: Potable water ; Water mains ; Water leakage ; Infrastructure investments ; water network management

Abstract:

This dissertation focuses on the issue of water infrastructure renewal in potable water distribution networks. I investigate the reasons why water infrastructure in certain water utilities are not renewed. This dissertation is divided into three chapters. The first chapter is based on theoretical models that solve for the optimal water main network quality index. The second chapter studies the optimal timing of water mains replacement. And finally, the third chapter is based on an empirical study on the factors that influence the water main replacement rates in French utilities.

In the first chapter I present a static cost minimisation model to solve for the cost-efficient water main quality index. This quality index is defined as the proportion of ``new" mains (which we denote as "good quality mains") to the total length of mains. The solution depends on the arbitrage between the cost of water loss and the cost of good quality mains. Where economies of network density are present such as urban utilities, water loss represents a cost burden to the water utility; hence water loss reduction (high network quality) is beneficial. Furthermore, we show that rural utilities face the largest difficulty in achieving both water loss reduction and cost recovery of network renewal.

In the second chapter I present a two-stage optimal switching timing model that solves for the profit-maximising timing of water mains replacement. This model considers the option between rehabilitation and replacement. Water utilities may be inclined to rehabilitate old mains to extend their longevity since rehabilitation costs are much lower than replacement costs. We show that it is beneficial for the utilities to replace mains that are already obsolete than to rehabilitate since the generated benefit from temporary water loss reduction and the postponement of replacement is not worth the cost of rehabilitation. This is particularly noticeable in large urban utilities that face large costs of water loss.

In the third chapter, I present an empirical study on the water mains replacement rates observed in French water utilities. The empirical results based on cross sectional data show that publicly operated utilities on average have higher replacement rates than outsourced utilities. This is because most of the public utilities have short total network length (very high replacement rates are associated with small network length). Moreover, small rural networks tend to conduct replacement of mains alongside other roadworks. However, results also show that public utilities have higher replacement rates over outsourced ones in very large urban utilities. This result reflects the difference of priorities defined by in-house operated utilities and outsourced utilities. This difference does not imply that outsource utilities neglect network renewal; instead it reveals the nature of the structure of outsourced utilities. The responsibility of outsourced utilities are defined in the contract signed with the local authority. If network renewal is not specified, there is no incentive for replacing mains. Moreover, in practice, outsourced utilities often manifest higher prices which are accompanied by higher water quality. Furthermore, the results show that the size of the network has a large impact on replacement rates. The longer the length, the proportion of replaced mains are smaller; however, for very large utilities the negative effect disappears. The results show that replacement rates are indeed greater in very large urban utilities. This result is coherent with the theoretical models presented in the first chapter that shows the urgent need for high network quality in large urban utilities.