Inventory, condition assessment and diagnosis of water supply and sewage systems

by

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INVENTORY, CONDITION ASSESSMENT AND DIAGNOSIS OF WATER SUPPLY AND SEWAGE SYSTEMS

ABSTRACT

This project describes a methodology for developing a digitized GIS-based inventory of underground municipal utilities, and recommends an approach for developing a database, which will assist with considerably improved management of buried systems and effective use of limited available resources. The study also discusses the water and sewer infrastructure debt and the total infrastructure debt in Canada. Some other issues related to the Canadian water infrastructure, such as water pricing and consumption patterns, along with the deterioration mechanisms of the underground services, are also discussed. The study focuses on the main services of water supply and sewage systems in any Canadian municipality, which presently are in an advanced state of deterioration. The steps required to develop such an inventory are reviewed and suggestions are made for condition assessment of the system using non-destructive techniques, employing simple methods, as well as more sophisticated tests in critical sectors, where further investigation is required. These methods are also summarily revised.

The underground infrastructure of the McGill Downtown Campus is summarily described; it comprises the various underground features which exist in a small community, e.g. water supply and sewage system, electrical lines, gas pipelines, telecommunication networks, etc., which are similar with Montreal's underground services, in terms of age, materials employed, workmanship and technologies available over the past 175 to 200 years. The framework for the underground infrastructure inventory is proposed for implementation in a small community such as the McGill Downtown Campus.

The long-term goal of the project is to extrapolate the McGill "model", and to enhance it such that the municipalities in Canada can implement it as a basis for development of GIS-based inventories and condition assessment, and prioritization for effective management of underground services, which include scheduling, financing and implementation of repair, rehabilitation and replacement of underground and other infrastructure.

INVENTAIRE, ÉVALUATION ET DIAGNOSTIC DES RÉSEAUX D'AQUEDUCS ET D'ÉGOUTS

RÉSUMÉ

Ce projet décrit une méthodologie pour développer un inventaire numérisé SIG (Geographical Information System) pour les utilités municipales souterraines, et recommande une approche pour développer une base de données, qui aidera avec une meilleure gestion des systèmes enterrés et utilisera efficacement les ressources limitées disponibles. L'étude discute également la dette d'infrastructure d'eau et d'égout, et la dette totale d'infrastructure au Canada. Quelques autres aspects liés à l'infrastructure canadienne de l'eau, telle que le prix et la consommation de l'eau, et les mécanismes de détérioration des services souterrains, sont également discutées. L'étude vise les services d'aqueduc et d'égout qui sont présentes dans toutes les municipalités canadiennes, et actuellement, la plupart d'entre eux sont dans un état de détérioration avancé. Les étapes exigées pour développer un tel inventaire sont revues et des suggestions sont faites pour l'évaluation de la condition du système en utilisant des techniques non destructives simples, aussi bien que des tests plus sophistiqués dans les secteurs critiques.

L'infrastructure souterraine du campus du McGill est sommairement décrite; elle comporte les diverses utilités souterrains qui existent dans une petite communauté, i.e., réseaux d'aqueduc et d'égout, lignes électriques, réseaux de gaz, réseaux de télécommunication, etc., qui sont semblables avec les services souterrains de Montréal, en termes d'âge, des matériaux utilisés, d'exécution et des technologies disponibles au cours de 175 à 200 dernières années. La méthodologie pour développer un inventaire numérisé d'infrastructures souterraines est proposée pour la mise-en-point dans une petite communauté telle que le campus du centre du McGill.

Le but à long terme du projet est d'extrapoler le modèle de McGill, et le développer tels que les municipalités au Canada peuvent le mettre en application comme une base pour le développement des inventaires numérises SIG, l'évaluation de la condition, et la prioritization pour la gestion efficace des services souterrains, qui incluent l'établissement du programme, le financement et l'exécution de la réparation, de la réhabilitation et du remplacement des infrastructures souterraines et/ou autres infrastructures.

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CHAPTER 1

INTRODUCTION

A well functioning infrastructure is essential for sustained productivity and economic growth, international competition and overall quality of life in a country. It is difficult to imagine urban life without access to potable water, clean and effective sewage and storm sewage and storm water disposal, electrical energy, travel facilities such as roads, railways, airports and navigation, telecommunications, and others.

Infrastructure is the medium connecting the social and economic activities of a society to the natural environment. Since the Middle Ages, infrastructure tended to embrace different forms, to support the diverse social and economic human activities, ranging from communication and transportation means, i.e., streets and roads, bridges, to public water wells, fountains and public baths, to markets for goods exchange and trade, and arenas for recreational purposes. Its need was recognized early in supporting the community goals and prosperity.

It is hard to rank the infrastructure facilities based upon their importance, since each category has a well defined role for the community it serves. However, these infrastructure assets and the services provided through them are sometimes in a close interdependency, therefore a system cannot be singularly conceived, i.e., a water filtration plant will need access to a waterway for the intake, electrical power for pumps and operation, communication systems, etc. Therefore, infrastructure can be regarded as a single unit which contributes to the achievement of a society's needs and goals.

These services provided by infrastructure are vital for urban dwellers and their disruption in one form or another has influenced the society adversely; these have resulted in serious disruptions to the society, and have been manifested in direct and indirect socio-economic, environmental and other costs to the society, occasionally involving unacceptable loss of life. It is therefore essential to be aware of the importance of our infrastructure, to undertake the necessary steps and to ensure all necessary provisions such that it is well maintained and that its state of health will have no significant negative effect on the community it serves, and will not affect the human activity, safety and life.

1.1. Value of Water Infrastructure

Awareness for water infrastructure dates back to the Egyptians and Romans (Sewerhistory, 2006). The Romans acknowledged the importance and value of their water infrastructure. Their water works for certain cities sometimes comprised 30-40km aqueducts, used for water transportation from the source. Furthermore, the concept of reusing and recycling was of considerable concern, so that the wastewater from the public bath facilities was used as flushing water, and eventually conducted to the sewer system to dispose it away from the city. In 2000 - 500 BCE, several aristocrats in Egypt/Palestine had their homes outfitted with copper pipes, used to carry hot and cold water. Public baths were constructed in Palestine during that era to assist with many religious ceremonies, included bathing. But the oldest testimony of a water infrastructure system seems to be as early as 4000 BCE, in Babylonia, where clay pipes and tees and angle joints were discovered. The pipes were moulded, supposedly using potter' wheel, and then baked to gain their final strength. Some cities were equipped with storm water disposal systems, which were built of clay-bricks or stone. In some instances, homes were connected to the network to enable the proper disposal of human wastes.

The human interest in having the water closely available to satisfy one's daily needs dates back thousands of years ago, a fact which emphasizes how valuable the water is for the society. Nowadays, urban life is unconceivable without the availability of running water at the tap; unfortunately, sufficient attention is not given to the infrastructure that provides this fundamental service; only when it is interrupted, when there is water contamination due to the system drawbacks, it comes to the attention of the responsible officials. It is, therefore, not the case of water infrastructure to be "taken for granted", a service which will be provided forever, without an appropriate effort. It needs careful provision of material and financial resources and human implication to make it effective, since it is essential for the human being.

1.2. First Cities with Centralized Water Systems

The need for centralized water systems in Canadian municipalities dates back to the early 1800's (James, 1998) when their tremendous benefits were recognized for fire fighting. In addition, the urban population soon became conscious of the multiple advantages in terms of health, economic progress and, eventually, comfort and quality of life of all citizens. The City of Montreal was the first beneficiary of a water supply system in Canada. The water pipelines were constructed and administrated by the private sector, beginning in 1801, and finally sold to the City in 1845. Saint Johns' water system was built in 1837 and it was the first Canadian public-owned water system. Subsequently, other cities followed the model of Saint Johns, such as Toronto (1841) and Halifax (1848).

The public interest in centralized systems for clean and potable water increased considerably during the mid 1800's, when the North American Cities were devastated by cholera and typhoid epidemics. In 1834, in Halifax, with a population less than 15000 at that time, people were dying at alarming rates (e.g. 18 deaths/day) from Asiatic cholera (Halifax Water Commission, 1995). Scientists recommended the daily wash down of streets with water, since they believed that epidemics were coming from the waste deposited on the city streets. In 1854, the City of Hamilton, Ontario, lost 500 lives to cholera. To obviate any future catastrophes, the city built its own water supply system. Several other Canadian municipalities followed the lead and had their public-owned water systems by the early 1900's.

The sewage disposal systems were built during same period in most of the Canadian municipalities.

1.3. Design Principles and Materials Used along Years

Since the construction of the earlier urban water and sewer systems, a number of materials have been employed, ranging from wooden pipes, clay pipes and brick sewage lines to the presently well known ductile cast iron, or plastic pipes. Each era had its innovations and discoveries, leading to the development of more efficient materials for the construction of water supply and sewer disposal systems, or, sometimes, to the improvement, or advances in fabrication technologies, or installation techniques.

In earlier years, wood was the most popular material employed in water and even sewer systems, because it was inexpensive and abundantly available. It was used extensively for sewers systems, in conjunction with bricks, stone or slate for large diameter lines, thus forming a 'combined' system (Sewerhistory, 2006). The choice of materials was governed by their availability and cost, resulting in the use of a wide variety of materials.

Vitrified clay pipe appeared as a ducting material in the mid 1800's, with applications in small diameter sewers. Cement mortar was also used for the same applications. At the beginning of the 20th century, clay pipes were the choice for large diameter sewer lines. The concept of 'lining' arose from the need for the protection of concrete pipes against corrosion, and clay tile lining was used for this purpose. However, the mostly employed material employed mostly in sewer systems in the late 1800's remains brick since it permitted construction of a variety of section shapes of varying dimensions. The cross-sectional shapes of the sewers evolved from simple circular or rectangular ones to elliptical or egg-shaped (with the vertical dimension larger than the horizontal one), to ease the access of inspection personnel. The egg-shaped section, discovered and first employed in France, was considered an innovation while it provided a high water velocity even at a low flow. Large dimensions brick sewers sometimes required piling for their support and were constructed on a solid cradle of wood. Internal lining with Portland cement mortar was usually used, because of its higher resistance to abrasion. Figure 1 presents the most common shapes and cross-sectional dimensions for the sewer system used for the city of Boston, during the late 1800's (Clarke, 1885).

Cast iron pipes were manufactured in the United States in early 1800's. It was an excellent choice for situations where high structural capacity was required. Soon, other benefits of cast iron pipes were observed, such as the capacity to withstand higher internal pressures, longevity, etc., and, within a short time, it was adopted for water supply systems by several municipalities in North America.

Cellulose fibers, impregnated with coal-tar pitch emerged as water and sewer pipe material in the early 1900's. With a reasonable service life of 60 years, it was utilized extensively until the early 1970's.

Plate VII

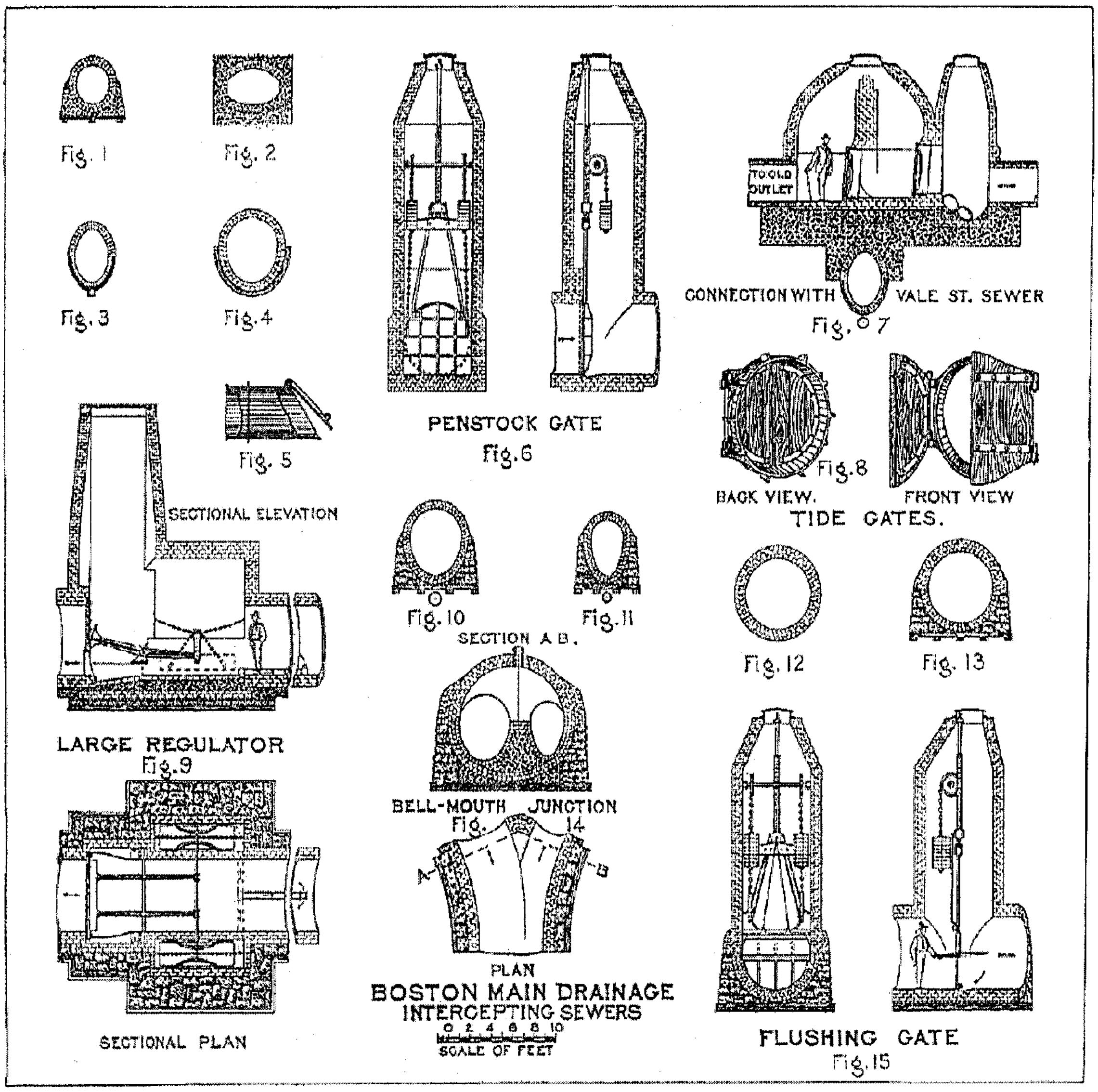


Figure 1. Main Drainage Works of the City of Boston, 1885 (Clarke, 1885)

The preoccupation for more reliable materials in water and sewer construction led to the development of plastic pipes, which were used first in Holland, about 50 years ago. Because of its many advantages, the polyvinyl chloride (PVC) pipe was introduced in North America in the late 1960's. Since then, significant developments have occurred in this area, making the plastics and ductile iron the most desirable materials in water infrastructure works.

It is interesting to note that old materials, such as cast iron (which changed into ductile cast iron three decades ago), are still in use and their assembly technology is based on the same bell-and-spigot joint principle which dates back to 1785 (Sewerhistory, 2006). A similar jointing system was adopted for plastic pipes and composite fibre pipes. Internal lining for existing or new pipes was initiated about 100 years ago. Even the concept of fibre pipe (developed about 100 years ago) is used presently to produce composite pipes (i.e. Hobas type) with glass fibre and quartz sand internal and external linings.

While some materials such as wood, slate, brick, etc., failed to fulfill their long-range use for water and sewer infrastructure construction, a number of technological advances and new design theories have evolved recently and they constitute the basis of our present knowledge.

1.4. Catastrophes due to Waterborne Diseases

The concept of design had evolved since the early age of water and sewage systems in urban communities. As an example, the sewage system was conceived initially to have no joints between the component parts to allow the underground water to enter the system and to improve the flow in the conduits, since different sorts of debris were transported through the system, without any concern for contamination of the underground water.

Presently, such situations are considered accidents and arise because of deteriorated sewage pipelines. In some cases, besides the underground water contamination, the phenomena may be accompanied by contamination water supply systems, which may have weak points in the vicinity of the sewers, resulting in water pollution. Although such accidents can be prevented, they still happen, resulting sometimes in loss of human lives, for example, three deaths in Battleford, Saskatchewan (2001, water contamination-cryptosporidium parasite), seven deaths and 2300 cases of sickness in Walkerton, Ontario (2000, infected water- e-coli bacteria) with many residents still suffering from hypertension and liver diseases. The worst waterborne eruption of disease, causing 100 deaths and 400,000 sickness cases occurred in Milwaukee (1993) due to contamination of water with cryptosporidium parasite, basically due to the maintenance and inspection neglect of the water supply system. The crisis led to an expenditure of $ 75 million on improvement of the water treatment plants.

Recently, terrorist threats of the water supply systems, i.e. cyanic threat, have been received the attention of civil and environmental engineers. In a study of the safety of the American water supply systems (Luthy, 2001), their vulnerability has been attributed to chemical and biological agents. Even if the monitoring of contaminants is usually performed before the water reaches the treatment plant, it does not consider the whole spectrum of threatening agents. Therefore, hazardous chemicals might not be detected in most instances, until they enter the treatment plant, or worse still, in the distribution system. Recommendations to improve the security of the water supply systems against chemical or biological threats are to install multiple barriers to act as safeguards, form the treatment plants to the distribution system, reservoirs, and to the domestic tap. Of course, the essential barriers should be installed at the treatment plant, where the conversion of raw source water into potable water is performed. A secondary source of potable water should be another solution, so that the water supply system can be by-passed in case of an emergency.

Presently, the state of buried underground utilities throughout Canada is rather poor. As mentioned earlier, these services were constructed, commencing in the early 1800's, and occasionally, municipal engineers discover old operating pipes dating back to those years. Traditionally, these services were provided by the municipalities, however, due to poor or no record keeping, municipalities are generally unaware of their "ancient" infrastructure and its state of health, resulting in confusion and an incomplete picture for effective management purposes.

1.5. Present Trends and Needs in Water Infrastructure Industry

Soon after 1900, most of Canadian cities completed the construction of their own water and sewer systems. The demand for new water infrastructure ceased for the following decades, but an increased need was observed during 1960's due to the "baby-boom" generation, when Canada extensively expanded most of its infrastructure. As the majority of the infrastructure was relatively new, the need for repair was almost inexistent and maintenance was not considered an issue requiring attention at that time. This trend has unfortunately continued even after some decades, and presently it constitutes the basic philosophy adopted in the Canadian infrastructure management practices, which is the well-known principle of design-build-operate. Recently, some attempts were made to introduce a new philosophical concept, to deal with the maintenance of the facility during its service life. De Sitter proved that one dollar spent at the right time for the maintenance of a given asset will result in tremendous savings which could be used in key points to address the infrastructure system's drawbacks (CEB, 1992). This philosophy is oriented more towards the present needs, because the infrastructure facilities are not new anymore and the demand for new infrastructure across Canada is relatively small (excepting for some scattered examples with increased development rates, i.e., Edmonton and Calgary due to the expansion of gas industry). Therefore, more attention should have been paid to the maintenance of the infrastructure assets during the last decades, to avoid the crisis caused by the long-term deferred maintenance and advanced ageing.

The water supply and sewer systems are not exceptions. The Montreal water supply and sewer system is used in the following to illustrate the age of the buried services, which is comparable to most of Canadian municipalities (Figure 2) - a fact that will be discussed later.

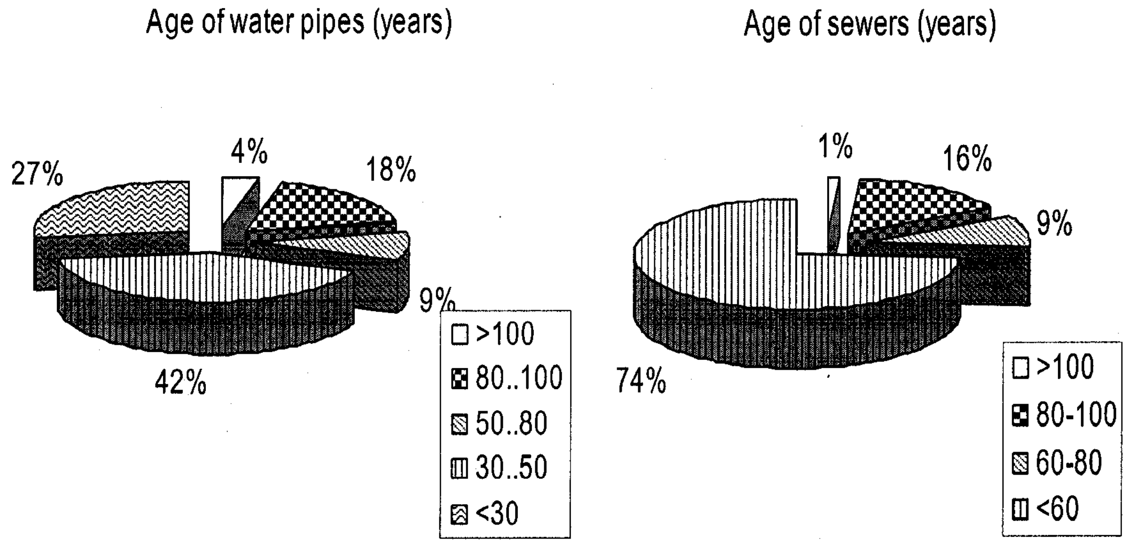


Figure 2. The Age of the Water Supply and Sewage Systems in Montreal (SNC-Lavalin/ Dessau-Soprin, 2002)

A low percentage of construction and/or replacement (27%) of the water supply system have taken place during the last 30 years. The most of this infrastructure has an age between 30 and 50 years, corresponding to the urban infrastructure expansion of the 1960's.However, the rest of the water infrastructure is even older. About three quarters of the component elements of Montreal sewer system are up to 60 years old, showing again the advanced aging of our underground infrastructure.

Presently, engineers have to deal with an old water supply and sewer infrastructure, weakened by deferred maintenance, poor management and neglect. It is obvious that the needs of this infrastructure have also changed and require more resources to keep it operational, effective, and safe. For instance, the maintenance needed 10 years ago for a particular infrastructure element and which was either deferred or not performed, is not applicable anymore since the given element may be in need of rehabilitation, or even replacement.

As emphasized by Mirza, 2005a (Figure 3), the performance of an asset can be expressed at any point during its lifetime in terms of its age and the remaining service life, the latter being influenced by regular maintenance, repair or rehabilitation. Curve 1 shows the results of proper maintenance of the asset throughout its entire lifespan, which results in the highest performance, the longest life and requires a minimum of resources to be invested. Curve 2 represents several rehabilitations during the life of the asset, to bring it back to the required performance each time. The worst case scenario, Curve 3, accounts for no maintenance or rehabilitation works, which results in the premature failure of the structure to fulfill its requirements, with a performance below the minimum required, and with a very high cost to rehabilitate it; at some point this cost may become very expensive and technically difficult and it would be necessary to replace the asset.

Based on the majority of current infrastructure management practices which are guided by the old "design-build-operate" principle, with no inclusion of the maintenance in the life-cycle cost of the assets, and which led to the continuous degradation of the Canadian infrastructure, the water supply and sewer systems across the Canadian municipalities can be assumed to be best represented by the situations illustrated by Curves 2 or 3. They lead to a reasonable explanation of the present escalating deficits of the infrastructure.

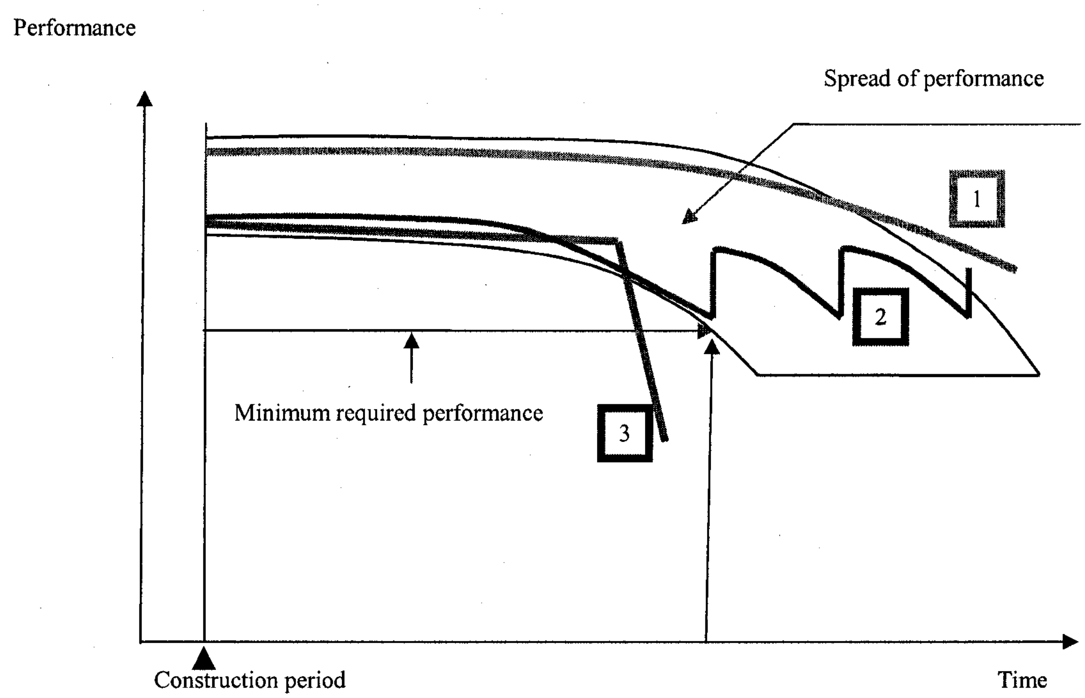


Figure 3. Loss of Performance with Time (Mirza, 2005a)

1.6. Present Developments and Technological Advances: New Materials and Installation Techniques

New materials in water infrastructure industry have emerged during last decades from the increased need to improve the safety of the water infrastructure systems and to overcome the deterioration due to the aggressive environmental exposure(s). Currently, materials such as vitrified clay, grey cast iron or asbestos-cement have become obsolete and are not in use anymore for new water supply, or sewer systems.

The most important advance in the pipe industry represents the introduction of plastics and ductile cast iron systems. Plastics are available in a large variety, from PVC (polyvinyl chloride), PP (polypropylene), PB (polybutylene) to several types of PE (polyethylenes of low, medium or high densities). In some instances, depending on the field of application, plastics are combined with metals (e.g. aluminium inserted reticulated polyethylene for domestic hot and cold water applications), or within them (e.g. the 3-layer unplasticized foam-core PVC pipe used for domestic sanitary sewers, to confer the pipe increased sound-proof characteristics and lower weight). Research for more reliable materials in the water and sewer industry has led to the development of a wide range of plastics, each suitable for a specific application.

Plastics, metallic pipes and accessories have opened a new era for water supply systems. The classical grey-cast-iron pipe has been replaced with the ductile cast iron pipe, an iron/carbon/silicon alloy. The graphite is present in a spheroidal form, rather than in a flake random pattern as in the case of the grey cast iron, giving fewer discontinuities in the material and hence increasing its ductility (Stanton, 1997). This specific graphite pattern formation is due to the addition of a small amount of magnesium (0.01-0.05%), resulting in increased resistance to physical loads, and mechanical and thermal shocks (CG Industrial Specialties LTD, 2006). This material is employed mostly in water pipelines applications (including pipes, valves, hydrants or couplings and adaptors), especially for large diameter pipes, because of its relatively low cost of production (comparable to the grey-cast iron) and its good response in operation. Usually, the ductile-iron pipes and accessories i.e., fittings and couplers, are protected internally by a cement mortar lining and sometimes by exterior bitumen paint. The valves and hydrants are usually epoxy-coated, both internally and externally. Some other applications, with less extended use, are in sewer systems; however, the increased acidity of the medium in a sewer requires better protection of the pipe inner wall and it results in an increased cost of production. Manhole covers and surface boxes production have also been enhanced in the ductile-iron industry, with very good results in exploitation compared to the old grey-cast-iron.

The urban agglomeration of buried services and, in some cases, the impossible service interruption because of the increased costs of service disruption has led to the development of various installation techniques. Whether it is a rehabilitation work, or a new installation in a crowded area, trenchless technologies are often cheaper than the conventional installation methods. In a case study, savings of up to 46% were obtained by employing a HDD (horizontal directional drilling) instead of the classical "open cut" method, for the construction of a 300m long 250mm sanitary sewer in the City of Toronto (Langan, 2005).

Rehabilitation of an old conduit without unearthing is not considered a challenge any more; some of the most known methods, being currently used, are the cured in place pipe (relining with polyester/ epoxy and felt/ glass fibre), the sliplining (immersion of a new pipe in the old one), spot repairs (with grout and seal applied via robots), or spray lining (with cement mortar, epoxy resin, or polyurethane applied via robots). For new installations, pipebursting or horizontal directional drilling method can be employed. In both cases, a drill head is pushed into the soil to drill a pilot hole (or into the old pipe), which is replaced afterwards by a reamer powered by a compressed air installation. The new pipe is connected to the reamer, which pulls it into the ground as it advances. The installed pipe is usually made of polyethylene; however, steel pipes may be installed using the same technique. Also, microtunnelling can be an efficient solution when installing large diameter pipes.

1.7. The Future of Plastics in the Water Supply and Sewage Systems Construction and Rehabilitation

The first ever large diameter PVC pressure pipe produced was in the Dutch City of Zwolle (Wavin, 2006) in 1953. Investigation of the PVC use in water infrastructure emerged from the need of a new piping material capable of withstanding soil movements without breaching and also being able to resist the increased acidity and/or salinity of the microclimate of the buried service. The polyvinyl chloride pipe was produced in the workshop of Zwolle's water company, after numerous experiments. The workshop was turned soon into a small pipe factory, to serve the water boards of the province. Two years later, WAVIN Company was formed (which was contraction of two words- WAter and VINyl chloride), and shortly, the mass production of plastic pipes throughout European countries was started. The integrity of the first installed plastic pipes was proven over a period of time, as they still remain as a testimony showing the material performance over time. It is said that plastics have at least 50 years lifetime, based on their verified functionality, but the forecast life can be considerably higher. It is well known that a usual polyethylene shopping bag, with a thickness of a few micrometres bio-degrades in about 200 years. Therefore, a plastic buried pipe should have a significant service life, because of the larger thickness of the material.

The introduction of thermoplastic pipe materials in water infrastructure applications has produced new flexible structures which have many freely movable joints and high ability to take up strains without failing; this behaviour cannot be compared with the conventional pipes (grey-cast iron, vitrified clay, asbestos-cement pies, etc.). The materials employed are the unplasticized polyvinyl chloride (PVC), the polyethylene of low/medium/high density (LDPE, MDPE, HDPE), and polypropylene (PP). As these materials are relatively new, the experience in water infrastructure covers a shorter period than that of cast iron pipes for instance, and sometimes the classic cast-iron or concrete pipe is regarded by many people to be more convenient, based on the long-term experience with their use and overall behaviour. However, performance of plastics in water supply and sewer applications has been observed for more than 50 years and has been documented; the results have compared well with the theoretical predictions. It has been well proven that properly installed plastic pipes can have a very low life cycle cost (usually close to zero) and fulfill a higher degree of functional requirements than many conventional pipes. A lifetime of at least 100 years is normally estimated.

HDPE pipes are suitable for the transport and distribution of potable water, gas, wastewater and for pressure sewers. Expertise has extended their use in many industrial applications due to their high chemical resistance, high ductility and abrasion resistance. They are also used extensively in trenchless installation techniques.

From the range of thermoplastics, high density polyethylene is the most common material employed presently for water systems. The high reliability and the proven service performance make polyethylene pipes the preferred choice, particularly for buried systems. The material presents a high resistance to low temperatures, permitting the installation and operation in cold conditions (however, its installation is recommended above -5`C, because its ductility decreases with the temperature, and at a certain point it becomes brittle). Based on its ductility, polyethylene exhibits a high impact resistance giving the pipe excellent resistance against surge pressures and fatigue (e.g., a laboratory sample of a pipe designated to withstand a pressure of 6 Bars failed at 36 Bars). The interior wall smoothness of HDPE pipes allows higher flow velocity than in other types of pipes. Over time, deposits (calcareous, sulphates, etc.) are unlikely to form because of this increased smoothness; furthermore, corrosion products cannot be formed, and therefore the water quality is definitely improved. Comparisons have shown that HDPE pipes have a higher abrasion resistance than other materials, therefore they are preferred for slurry transportation systems.

From the chemical point of view, the polyethylene has high resistance to different chemical compounds making it also suitable for many industrial applications. Table 1 represents the chemicals that can be resisted by polyethylene pipes and accessories (Polyprocessing, 2006) for a temperature of up to 40`C.

Chemical agent resisted by polyethylene				
Acetic Acid	Diazo Salts	Hydrochloric Acid	Perchloric Acid	Stanic Salts
Aluminum Salts	Diethyl Carbonate	Hydrofluoric Acid	Phenol<10%	Stannous Salts
Alum	Diethanol Amine	Hydrofluorosilic ic Acid	Potassium Hydroxide	Starch Solutions
Ammonium Hydroxide	Diethylene Glycol	Hydrogen Peroxide<52%	Potassium Salts	Stearic Acid
Ammonium Salts	Diglycolic Acid	Hydrogen Phosphide	Phosphoric Acid	1Sulfuric Acid <80%
Amyl Alcohol	Dimethylamine	Hydroquinone	Photographic Solutions	Sulfurous Acid
Antimony Salts	Dimethyl Formamide	Hypochorous Acid	Propyl Alcohol	Sugar Solution
Arsenic Acid	Ethyl Alcohol	Iodine Solutions	Propylene Glycol	Glucose
Barium Hydroxide	Ethylene Glycol	Lactic Acid	Sea Water	Lactose
Benzene Sulfonic Acid	Ferric Salts	Latex	Selenic Acid	Sucrose, etc.
Bismuth Salts	Ferrous Salts	Lead Acetate	Sewage	Tannic Acid
Boric Acid	Fluoboric Acid	Magnesium Salts	Silicic Acid	Tanning Extracts
Bromic Acid	Fluosilicic Acid	Mercuric Salts	Silver Salts	Tartaric Acid
Butanediol	Formic Acid	Mercurous Salts	Silver Salts	Titinium Acid
Butyl Alcohol	Gallic Acid	Mercury	Soap Solutions	Toluene Sulfonic Acid
Calcium Hydroxide	Gluconic Acid	Methyl Alcohol	Sodium Ferricyanide	Triethanolami ne
Calcium Salts	Hexanol	Methylsulfuric Acid	Sodium Ferrocyanide	Urea
Chromic Acid<50%	Hydrazone<35 %	Michel Salts	Sodium Hydroxide	Vinegar
Citric Acid	Hydrozine Hydrochloride	Nicotinic Acid	1Sodium Hypochlorite<9 %	Wetting Agents
Copper Salts	Hydriodic Acid	Nitric Acid<50%	Sodium Salts	Zinc Salts
Detergents	Hydrobromic Acid	Oxalic Acid	Sodium Sulfonates	

Table 1. Chemical Resistance of Polyethylene Pipes

Polyethylene pipes are produced in lengths up to 16m or, in coils with up to 300m for smaller diameters. Their diameters range from 20mm to 630mm, with pressure classes of 6, 10 and 16 bars, covering the most range of other common material pipes. Some increased diameters of over 630mm are also available, especially, in the case of corrugated pipes used for sewer systems. Their low weight makes them easy to transport and handle.

Polyethylene pipes can be assembled by fusion or by use of mechanical joints. The following methods of welding are available: butt-fusion, electrofusion, and socket fusion. Mechanical installation can be made by push-fit rubber ring, flanged connection, and mechanical compression joints. These methods give the polyethylene pipe systems the flexibility to connect to any other type of pipe and valves.

The mostly used connection in water supply systems is the welded connection. The polyethylene is a material that can be easily brought to its yield temperature, which is around 210-230`C. In the assembling process, two ends of the pipes which have to be welded are heated to the yield temperature and pressed against each other at a controlled pressure of $0.15 N/mm^2$. No additional materials are used. At this stage, the material in the two pipes reacts and reforms its physico-chemical bonds. After cooling, the pressure is released. The main advantage of this technology is that the assembled pipe will have a continuous structure, even in the connected locations. This makes the system leak-free and highly flexible, compared with that of the PVC or cast-iron systems, which are connected through bell and spigot joints. Therefore, a long length can be assembled, outside the open cut, making the installation very simple and cost-effective. This advantage of polyethylene pipes is also used for the unconventional installation techniques i.e., horizontal directional drilling, sliplining, etc. Sliplining takes into account the `elastic memory` of polyethylene after extrusion. The pipe is longitudinally folded to become C-shaped as it exits the extruder and it is rolled on a drum. After sliplining is performed, hot steam at high pressure is introduced in the C-shaped pipe, to permit the pipe to gain its original circular shape through heating. The use of this method presents the high advantage of the reduced folded pipe cross-section which permits to easily reline the older pipes. Polyethylene pipes were also successfully used in projects of submerged or floating water mains due to their high ductility, corrosion proof, easy handling and installation.

Polyvinyl chloride pipe is usually employed for sewer systems. There are some applications in water supply systems, especially well construction, or rehabilitation; however, they employ heavy PVC, which is different. An other innovation in the sewer system is the corrugated polyethylene pipe, which can be produced in large diameters and has an increased resistance to applied external loads. It has the capacity to modify its cross-sectional shape under loads, without being structurally affected (Soleno, 2006), making it more efficient than a conventional rigid pipe. Once the load is released, it regains its initial circular shape.

The use of plastic pipes in the rehabilitation of urban infrastructures can eliminate the problems concerning corrosion which is the most common spread phenomena leading to pipeline breaks, and it also can improve system hydraulic, besides upgrading the water quality. Plastics can be easily recycled. In the case of sewer polyethylene pipes, recycled plastics may be used in manufacturing, since these systems do not have to withstand high pressures and they do not represent any human health threat. The production of water pipes requires employment of new material only, in order to have an adequate resistance to water pressure and to satisfy the requirements of safety and hygiene.

Despite the outstanding advantages of the polyethylene and other thermoplastics pipes, their use is still not as widespread as their techno-economic merits justify. As Europe has already embarked for using plastics for most of the water and sewer infrastructure works, much more reliability in plastics should be expected in North America as well.

CHAPTER 2

INFRASTRUCTURE DEBT IN CANADA

2.1. General. Present Tendencies

The "public infrastructure debt" has received extensive attention in recent years, and scenarios have ranged from bad to worst with up to $125 billion deficit for all of the infrastructure under the jurisdiction of municipal, provincial, territorial and federal governments (Mirza, 2005a). However, the situation will worsen as the deterioration of the assets continues to occur at an accelerated rate and the deficit grows exponentially with time. This trend is specific to most infrastructure assets, and if unchecked, the infrastructure deficit is estimated to reach one trillion dollars in 2065 (Mirza, 2005a).

According to the different reports over the past 20 years, the municipal infrastructure deficit has skyrocketed from 12billion dollars in 1984 to 57billion dollars in 2002, which represents roughly a five- fold increase (Figure 4).

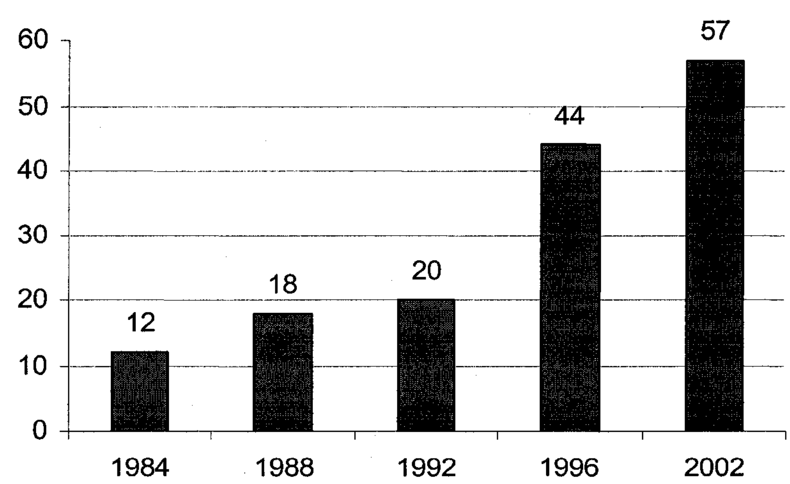


Figure 4. Municipal infrastructure deficit, 2002, in billion dollars (Burleton, 2004)

As the municipal infrastructure represents about 50% of the total infrastructure in Canada, - with an increase of 10% over the last 14 years- it must receive augmented attention from the municipal governments to accommodate this increase. The gap for municipal infrastructure was evaluated at $44 billion (McGill/FCM, 1996) and $57 billion in 2002 (Technology Road Map, 2002), which confirms the percentage of the municipal share when compared with Canada's infrastructure debt of $125 billion. It also emphasizes the rapid asset deterioration over the years and the urgent need for infrastructure rehabilitation.

The debt accrued as a result of the annual shortfall in the financial investment in repair/rehabilitate/replacement the deteriorating infrastructure will increase drastically if no action is taken. This tendency will lead to alarming bills for the infrastructure in the future 15 to 20 years, as emphasized by several authors:

- $110 billion by 2027 (CSCE, 2002);
- $200-300billion by 2015-2020 (Mirza, 2003);
- $400billion by 2015-2020 (Comeau, 2001).

Mirza (2005a) has developed charts to estimate the future infrastructure deficit, based on the current practice of infrastructure management, consisting of simply designing and building the facilities, and operating them with little or no maintenance; in parallel, a very low rate of maintenance was incorporated, within the range of 0.5-2% of the asset value (Figure 5). Significant savings are evident for the cases where maintenance was considered. Conversely, the no-maintenance trend reveals escalating values for the infrastructure deficit, which may lead to as much as one trillion dollars in the next 60years.

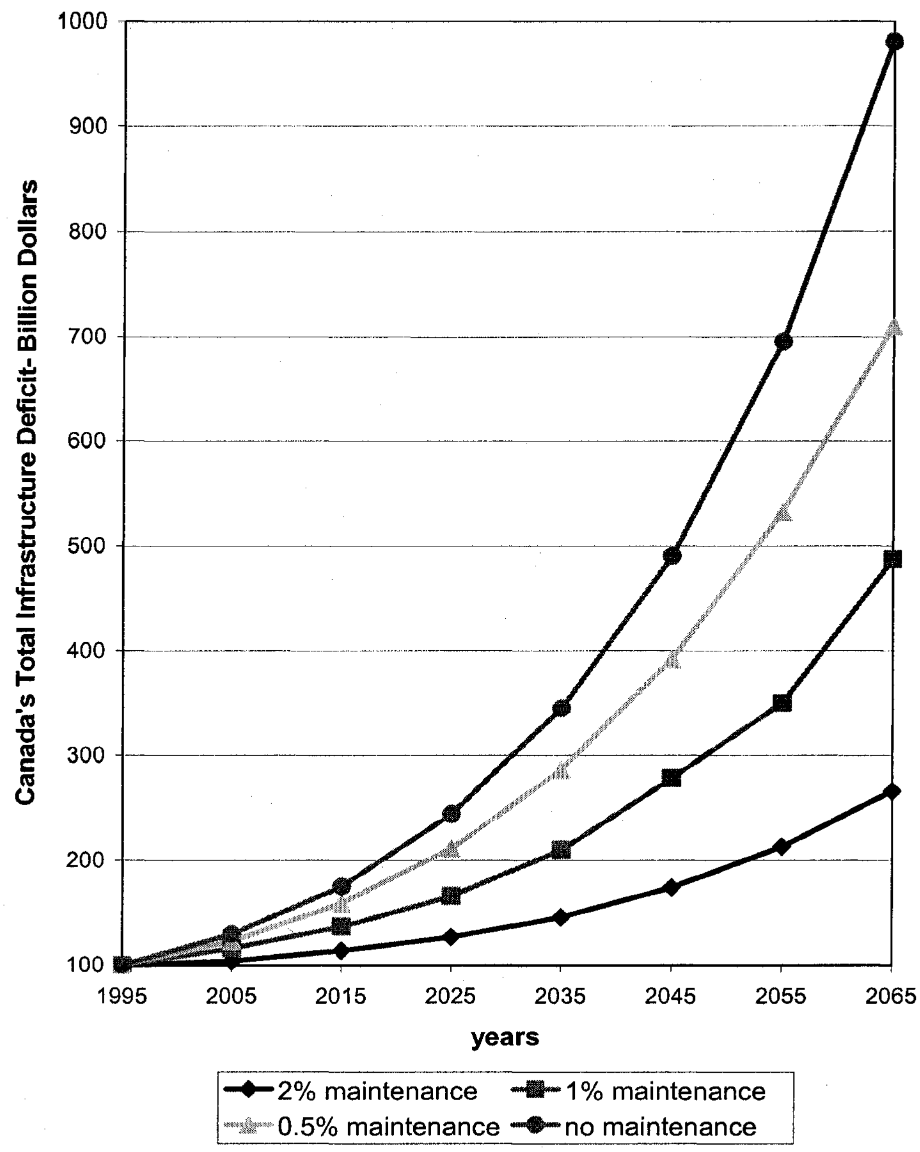


Figure 5. Canada's Estimated Infrastructure Deficit (Mirza, 2005a)

Accordingly, the tendency of the municipal infrastructure share will show a projected deficit of more than $360 billion over the next 60 years if no maintenance is performed; however, this could decrease with appropriate maintenance, to about $100 billion for maintenance implemented at about 2% of the asset cost annually (Figure 6).

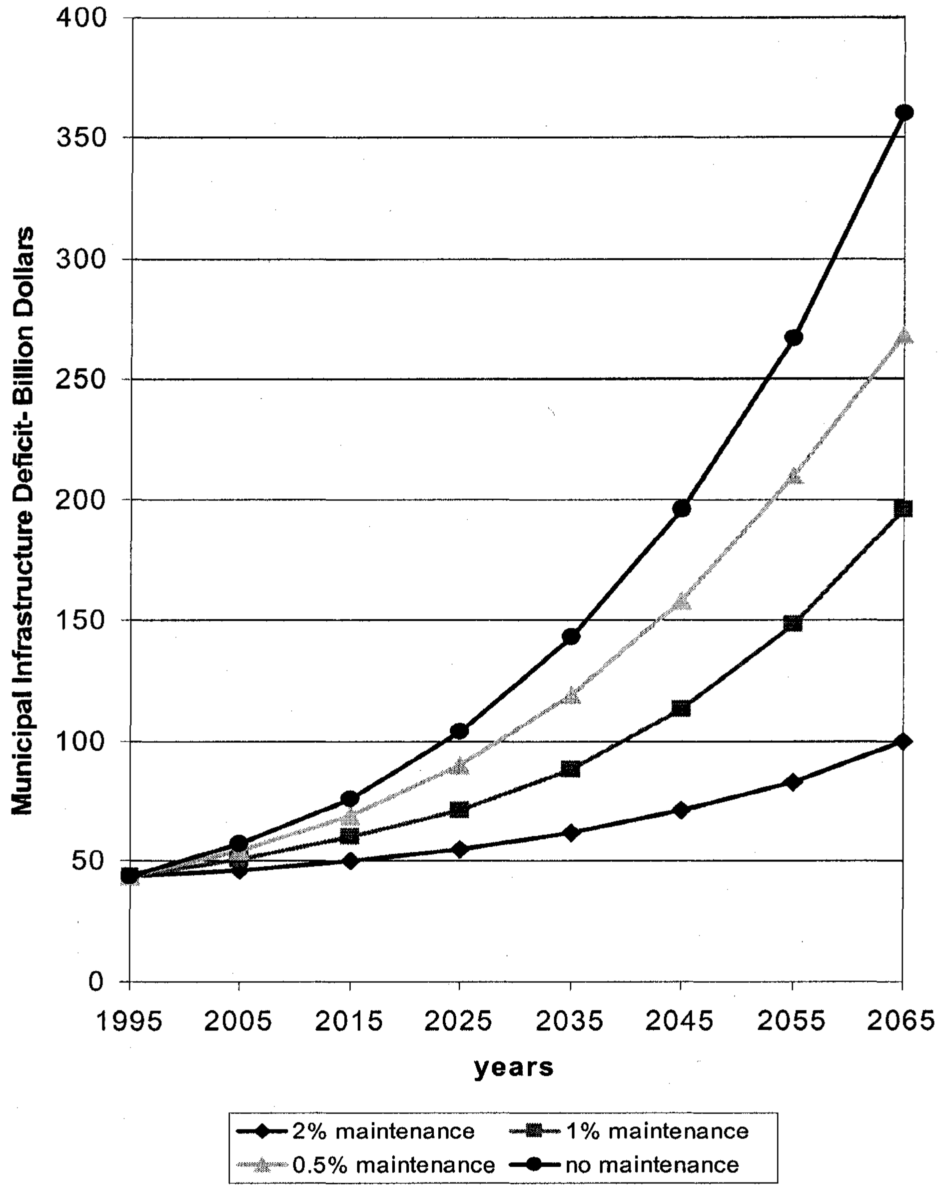


Figure 6. Municipal Estimated Infrastructure Deficit (Mirza, 2005a)

2.2 Strains on Infrastructure- Quick Review

The social and economic activities of a society are strongly dependent on its infrastructure. Canada experienced a steady economic growth during the last decades, which had exerted serious pressures on the infrastructure. Even if most of it was recently constructed after the Second World War period, with a prominence in the 1960's, the urban sprawl and the human-related activities had left their imprint on the relatively new infrastructure. The increased need for new developments to meet the needs of the population increase and to develop the economy- oriented the construction industry towards new assets construction. Consequently, the maintenance of the existing infrastructure assets was deferred, leading to the burden of the infrastructure facilities which were required to continue to provide the same level of services but under the amplified pressure caused by the urban and economic expansion.

The years 1980 and 1990 brought other difficulties caused by the economic recession. The federal and provincial governments faced deficit problems and this impact was also manifested on the nation's infrastructure. The largest obstacle was encountered by the local governments while they were confronted with increased responsibilities due to the urban expansion and considerably reduced resources, which come mainly from the property taxes (e.g., 92.7% of the local tax revenues represent the property tax, according to Kitchen et al., 2003). One notes that, in many instances, the level of property taxes or development charges were below the cost of the delivered service, a trend which is presently continued in all Canadian communities.

To keep the infrastructure well maintained and in a good operating condition requires considerable attention from several parties. A sudden investment will not yield immediate results. This might explain the long-lasting political lack of commitment along the years and the prioritization of other sectors which can show short-term benefits, which is quite convenient for the politicians who are in office for a relatively short tenure. All these issues combined with ineffective and deficient management has contributed to the aggravation of the state of health of the Canadian infrastructure.

The continuous deterioration of water and sewer infrastructure can be attributed to the issues discussed earlier. The deficiencies in funding through governmental programs because of the deficit problems along some years, the lack of political will, and the prioritization of other sectors are the principal factors for the decline of the underground infrastructure. In some instances, location-related issues may add to the serious problems faced. For instance, in the City of Montreal (The Gazette, 1999), megaprojects like the Olympic Stadium or Expo '67 involved the most experienced contractors in the region, leaving the water mains installations in the hands of the less experienced contractors; therefore, the underground infrastructure constructed between 1961 and 1975 might suffer in some cases from "shoddy" workmanship.

The budgetary cuts have also left their imprint on regular inspections and maintenance, which were generally neglected. This might have been considered as a saving initially, however, this was a bad decision because it had a long term impact, leading to the present disastrous state of the water and sewer infrastructure. Unfortunately, the present generation has to pay for the mistakes of the previous generations and has to deal with the actual deteriorated state of the buried utilities across Canada, an issue postponed for years.

2.3. Municipal, Provincial and Federal Infrastructure. Types of Infrastructure under Different Jurisdictions

Over the past four to five decades, the infrastructure capital stock shared by the different levels of governments has changed continuously. The share of the provincial administration encountered a peak in 1979, but it decreased since, stabilizing in 2002 at the same value as in 1961. This is not the case with the local or municipal administration of the infrastructure share which has significantly increased from 26% in 1961 to almost 50% in 2002. Consequently, the federal share recorded a drastic cut from almost 40% in 1961 to 18% in 2002 (Figure 7).

These facts raise the question if the corresponding resources to manage the municipal infrastructure have also been transferred to the new administration. As discussed earlier, the municipal revenue is mostly based on property taxes and user fees, with total "own-source" revenue of 83% (Kitchen et al., 2003). The remaining 17% of the revenue comes from provincial and a very small amount from federal grants, a trend maintained since 1988. As of 2002, the public capital stock in the municipal jurisdiction has almost doubled and the available resources have remained almost constant. Consequently, the maintenance of the infrastructure under the municipal jurisdiction has been continuously deferred on an on-going basis, basically because of the budgetary constraints.

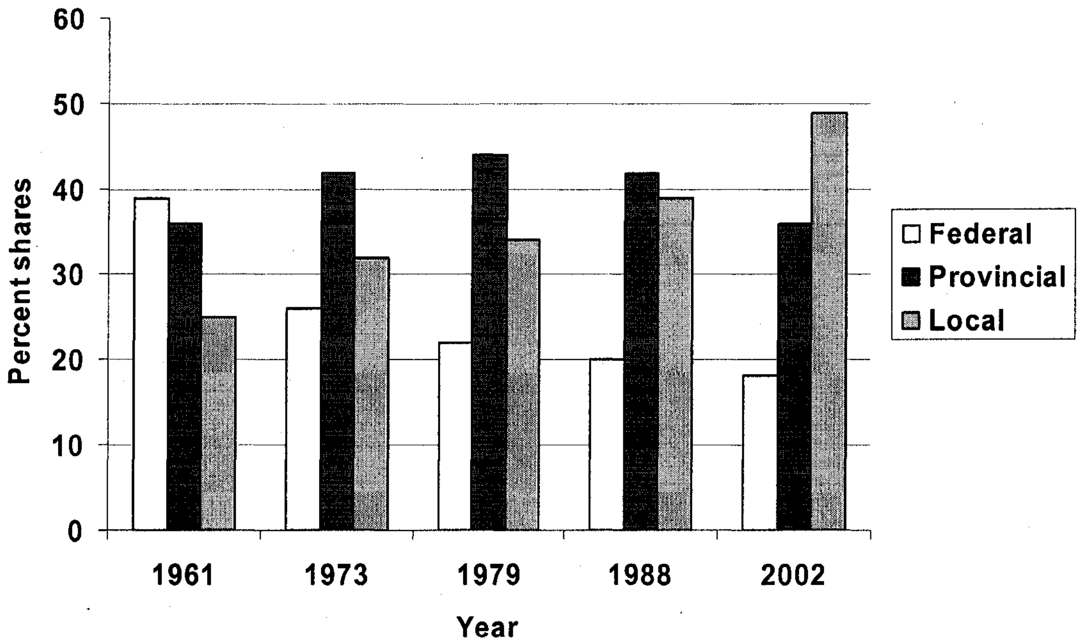


Figure 7. Infrastructure Capital Stock Shares by Level of Government (Statistics Canada, 2003)

The public infrastructure capital stock consists of different categories, which fall awkwardly under the municipal, provincial and federal jurisdictions. It can be easily noted that the services in the municipal jurisdiction are water supply and sewage systems, waste disposal, roads, sidewalks, outdoor recreational facilities, etc., whereas a large part of the highways, roads and bridges belong to the provincial jurisdiction, while rail tracks and harbours and penal facilities fall under the federal control. Figure 8 presents the structure of public infrastructure stock by assets.

In a broader classification, Canada's infrastructure can be divided into a few main categories, such as transportation, with a share of 66% of the total infrastructure, environmental (24%), recreational (3%) and others (7%). Transportation infrastructure comprises roads, bridges, seaways, etc, whereas the environmental infrastructure includes the water and sewage systems along with the corresponding treatment facilities, and the irrigation systems (Burleton et al., 2004). This roughly shows that the water and sewage facilities represent almost a quarter of the nation's infrastructure capital stock.

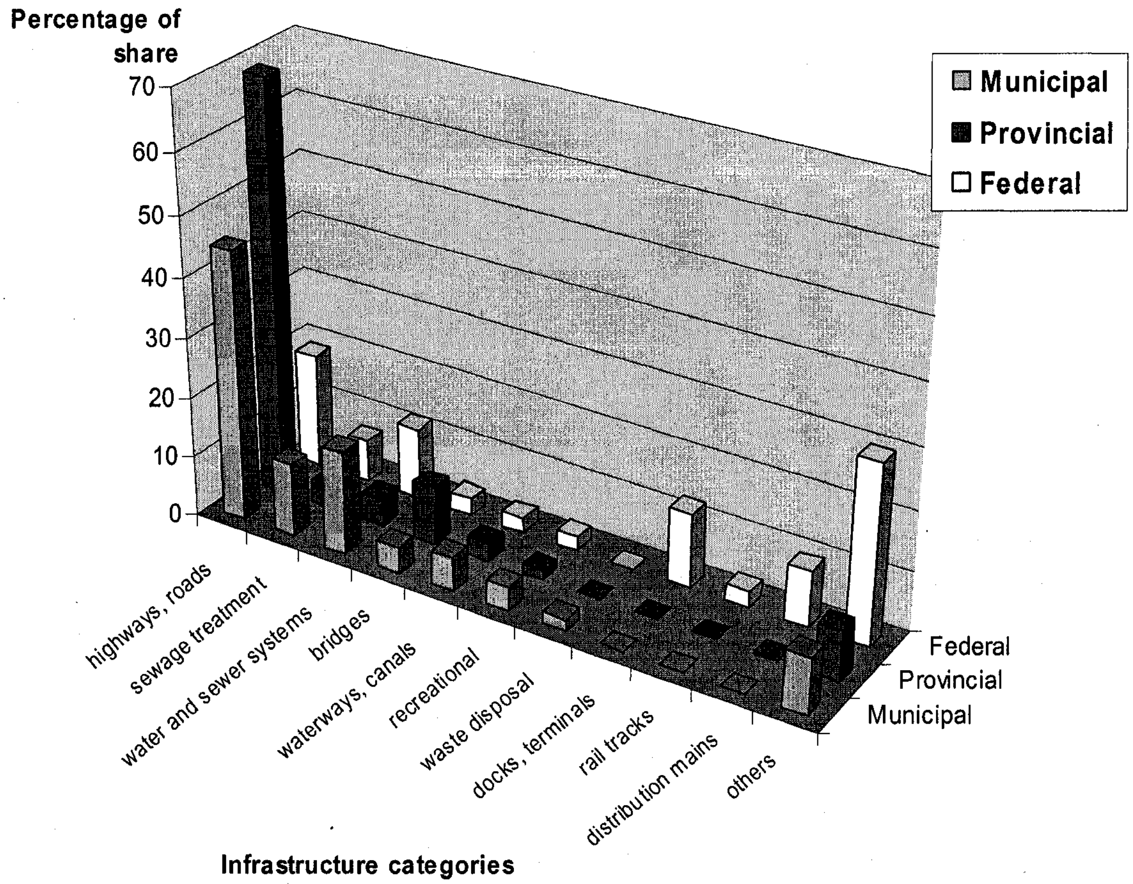


Figure 8. Public infrastructure capital stock by assets -Percentage of share, 2002 (Harchaoui et al., 2003)

2.4. Estimated Deficit- Water Supply and Sewage Systems

Although the infrastructure debt, consisting of repair, rehabilitation or renewal of the infrastructure appears to be quite high, the financial gap becomes more worrisome according to several recent reports which reveal a poorer state-of-health of some specific infrastructure utilities such as water and waste water systems. For example, the Water Strategy Expert Panel (2005) noted an investment need of $30 to $40 billion over the next 15 years to maintain "safe, accessible and affordable water" for the Province of Ontario alone. The report also recommends that the current management practices have to be changed before the investments are made and suggests a new approach towards a long-term sustainability of the water systems.

The City of Montreal had an estimated need of $3.2 billion for the water and wastewater systems in 2002 (SNC-Lavalin and Dessau-Soprin Report, 2002). The needs for financial resources were distributed as follows: $1.95 billion for the water distribution network, $330 million for the sewer systems, $335 million for water production plants and water reservoirs, and $580 million for sewage treatment plants. Recently, the City estimated that the overhauling of water distribution system will cost at least $4 billion over the next 20 years. (The Gazette, 2004).

The above examples exemplify the cases of infrastructure in a province and in a city in Canada. By extending this scenario to all of Canada, and considering that one of the largest municipalities or one province are in need of billions of dollars for only the water supply infrastructure, the currently projected municipal infrastructure deficit of $57 billion in 2005 appears to be considerably underestimated.

A study by the Canadian Water and Wastewater Association (1997) noted an estimated deficit of $ 88.5 billion for water and sewer systems for all of Canada from 1997 to 2012. More specifically, $28 billion were estimated as the need for the municipal water systems and $60.5 billion for wastewater systems (Ploeg, 2003). The study accounted for the maintenance backlog of the existing infrastructure, improvement of the current services and accommodation of the systems to the population growth. The estimate appears to be accurate, since Ontario, which houses about one quarter of Canadian population, is estimated to need $30 billion for the same infrastructure categories. Furthermore, the water infrastructure needs per capita in Montreal (Direction de santé publique de

Montréal, 2001) leads to $4 billion for 1.8 million inhabitants, which is approximately $2,200 per capita. Roughly, for a population of 32,500,000 (Statistics Canada, Demography Division, 2006) the projected future need for the water and sewer infrastructure would be about $72 billion. This reconfirms the estimate envisaged by the study undertaken by the Canadian Water and Wastewater Association in 1997.

One notes that the reports are based on statistical data, trends and/or estimates. No databases of water and sewer infrastructure were available to assess their state of health, and therefore the reports should be treated as being mostly subjective. However, it remains the only way to assess the needs of the present infrastructure assets.

2.5. Comparison to US Water Supply and Sewage Systems- the US Report Card

The American Society of Civil Engineers highlighted the advanced state of infrastructure deterioration in its Report Card for America's Infrastructure (2005) by grading the U.S. infrastructure by categories. The grades ranged from C+ for solid waste to D- for drinking water, wastewater and navigable waterways, and the weighted GPA for America's infrastructure was a low D. (Table 2).

According to the report, drinking water infrastructure experiences an annual shortfall of $11 billion to repair/rehabilitate/replace the old leaking systems and to comply with the safety regulations for potable water. However, the proposed budget for 2006 remained at the same level of $0.85 billion as in 2005, which is lower than 10% of the national need. The wastewater systems were left in the same neglected state. Moreover, the scarce budget was cut for the first time in eight years. A low $0.73 billion budget was proposed for 2006, which is considerably lower than the needs in this sector, estimated at $390 billion over the next 20 years by the US Environmental Protection Agency. One notes that the old American wastewater systems discharge millions of cubic metres of untreated sewage into the surface waters each year. The crisis of water and sewage infrastructure has become evident, starting to cause serious concerns amongst communities, as cited by Jeyapalan (2003): "Fortune magazine wrote: "water promises to be to the 21st century what oil was to the 20th century: the precious commodity that determines the wealth of nations." ".

Infrastructure Category	Grade
Aviation	D+
Bridges	C
Dams	D
Drinking Water	D-
Energy	D
Hazardous Waste	D
Navigable Waterways	D-
Public Parks & Recreation	C-
Rail	C-
Roads	D
Schools	D
Security	I
Solid Waste	C+
Transit	D+
Wastewater	D-
Infrastructure GPA	D
Total Investment Needs	**$1.6Trillion**

Definitions of Grades
A- Exceptional
B- Good
C- Mediocre
D- Poor
F- Failing
I- Incomplete

Table 2. Report Card for America's Infrastructure, 2005.

Unfortunately, Canada does not make an exception. Newspaper headers as "Raw Sewage Headed for River" or "Drain Prompts Pollution Worry" (The Gazette, August 2005) have presently become somewhat common. One knows that Canadian infrastructure faces the same crisis as the US, however, the Canadian infrastructure state was not assessed and therefore it cannot be compared in "real" terms with the United States.

In few instances, such as wastewater infrastructure, Canada owns an insight of its deteriorated infrastructure. The interest to assess the condition of Canada's sewage treatment plants arose in 1994, at the initiative of the Georgia Strait Alliance, Labour and Environmental Alliance Society and Buck Suzuki Environmental Foundation. The last report out of the total three was issued in 2004. The National Sewage Report Card (Sierra

Legal Defence Fund, 2004), graded the sewage treatment of 22 Canadian cities as shown in Table 3:

City	Summary	1999 Grade	+/-	2004 Grade
Brandon	Implemented 100% secondary treatment and UV disinfection. Combined overflow of up to 2.8 million litres per year.	D	+	B-
Calgary	UV disinfection added to 100% tertiary treatment. Additional upgrades in the works ($250 million).	A	+	A+
Charlottetown	Primary treatment only. Volume of discharges not monitored. Plans to upgrade to secondary by 2006.	E	+	E+
Dawson City	Still discharging one billion litres of raw sewage per year. Await funding for upgrade to secondary treatment.	F-	+	E
Edmonton	Upgraded to 100% tertiary treatment and UV disinfection	B+	+	A-
Fredericton	Secondary treatment with UV disinfection. No major improvements since 1999. Low percentage of CSOs.	B	NC	B
Halifax	More than 65 billion litres of raw sewage discharged each year. Regional plants provide secondary or tertiary treatment.	E-/C	+	D
Hamilton	Upgrades to secondary and tertiary treatment. Discharges 5.9 billion litres of raw sewage each year. Only 88% of population served.	C-	+	C+
Montreal	Primary treatment only. No discernible progress made.	F+	-	F
Ottawa	Secondary treatment. Seasonal chlorine disinfection, no dechlorination. Overflow system controls installed.	C	+	B-
Quebec City	Secondary treatment with seasonal UV disinfection. Combined sewer overflow events reduced.	C	+	B
Regina	Enhanced secondary treatment with expanded UV disinfection. Extensive upgrades planned.	B	+	B+
Saint John	Reduction in combined sewers. Primary and secondary treatment. Almost 40% of population still do not receive treatment.	E	+	D
Saskatoon	100 % secondary treatment. Minimal changes since 1999.	C+	NC	C+
St. John's	More than 33 billion litres of raw sewage discharged.Primary sewage treatment plant under construction.	F-	+	E
Toronto	Toughest Sewer-Use Bylaw in country. Secondary treatment. Still discharge 9.9 billion litres of untreated sewage and run-off.	C/B	+	B-
Vancouver	Up to 22 billion litres of combined overflows each year. Upgrades to 100% secondary treatment won't be completed until 2030.	C-	-	D
Victoria	Preliminary screening, no treatment. More than 34 billion litres of raw sewage still discharged each year.	F-	-	Suspended
Whitehorse	Secondary Treatment. Minimal progress since 1999. Efforts under way to reduce volumes of sewage. No raw sewage discharges.	B-	NC	B-
Winnipeg	100% secondary treatment. Reduced number of combined sewers, still one billion litres of combined sewer overflow per year.	C	+	B-
Whistler	100% tertiary treatment.	-		A
Yellowknife	100% secondary treatment with natural UV disinfection. Only minor changes since 1999.	B+	NC	B+

Table 3. Canadian Sewage Treatment Progress, National Sewage Report Card, 2004

The summary in Table 3 shows the progress of the sewage infrastructure health state from 1999 to 2004, with appropriate commentaries. A slight progress is observed in the quality of sewage treatment in most cities, exceptions being the Cities of Montreal, Victoria and Vancouver.

In terms of efficiency, compared to the US wastewater infrastructure, Canada seems to be better prepared, and the national GPA might be within a C and a C+.

The water supply or sewage networks were not included in the report. It is only well known that they are in an advanced state of deterioration and that the number of breaches has exceeded the permissible limit in many cities. For example, the Province of Quebec encounters an intolerable break frequency in 10% of water pipes, with an average number of 30-40 repairs/100km/year. As a result, a considerable amount of potable water (20-30%) is lost into the ground due to the faulty distribution systems. It can, therefore, be assumed with reasonable certainty that the Canadian underground infrastructure is not in a better shape than that in the United States.

CHAPTER 3

WATER AND WASTEWATER INFRASTRUCTURE IN CANADA

3.1. Available Estimates. Water Break Rates and Systems Rating

The state of the Canadian underground utilities has been and will remain a controversial subject in the area of infrastructure. It is obvious that an accurate inventory is invaluable, especially for management purposes, but it also has a positive impact on the final user who pays for the service. A good inventory can assist with good management, which can further minimize the disruption of the service, i.e., the number of breaches in a water supply distribution network. Eventually, this will lead to an increased quality of service delivered to the consumer.

Despite the major benefits such an inventory may offer, there are no reports which assess and/or depict the general state of Canadian water infrastructure. This is due to the poor municipal databases, as a result of inappropriate management accumulated along time. Most of Canadian municipalities do not have a clear picture of their underground infrastructure and, in some instances, it is nonexistent. Even if older plans or records of intervention and repair might exist, they are not readily available and therefore information cannot be retrieved and used.

Presently, the easiest and the most convenient way to assess a water supply system performance is to rate it as a function of the number of breaks per year, per 100km of pipe length. Roughly, the Canadian average is about 20 breaks/100km/year but some cities experience a much higher rate which makes their water distribution systems ineffective. In a survey undertaken by NRC-CNRC (Rajani et al., 1995), the breaks in the water distribution systems of 21 municipalities across Canada were assessed in two consecutive years, 1992 and 1993. The evaluated cities accounted for 11% of the Canadian population and cover different geographical areas; therefore, one can admit that the survey reflects a broader situation which refers to all of Canada. The survey also accounted for the materials mostly employed by the Canadian municipalities in water supply systems which are, in prevailing order, the grey cast iron (GCI), ductile cast iron (DCI), followed by asbestos-cement (ASB-CEM), polyvinyl chloride (PVC) and the prestressed concrete cylindrical pipe (PCCP). Of course, some other materials may also exist in the present Canadian underground infrastructure, but they date from 19th Century (i.e. cellulose fibre impregnated with tar, wooden and ceramic pipes, etc.), and do not represent a significant part of the municipal water network, therefore, these unusual cases were neglected for simplification. The total length of the water distribution systems, for each type of pipe, for the total of 21 cities in the study is summarized in Table 4.

	CITY	GCI (km)	DCI (km)	ASB.-CEM (km)	PVC (km)	PCCP (km)	TOTAL km/TOWN
1	Calgary	1,120.00	1,138.00	68.00	783.00	213.00	3,322.00
2	Edmonton	999.30	3.60	1,060.50	444.40	120.60	2,628.40
3	Ottawa-Carleton	1,062.60	1,069.50	4.60	46.00	117.30	2,300.00
4	Vancouver	1,057.10	318.60	1.45	0.00	5.80	1,382.95
5	North York	828.00	414.00	13.80	82.80	13.80	1,352.40
6	London	723.90	406.40	12.70	63.50	50.80	1,257.30
7	Windsor	765.00	55.80	1.80	43.20	22.50	888.30
8	Regina	15.20	15.20	535.00	147.90	0.00	713.30
9	Burnaby	229.30	150.70	248.90	6.60	0.00	635.50
10	Halifax	290.00	104.00	1.50	0.50	49.00	445.00
11	St. John's	350.00	61.90	0.00	0.00	0.00	411.90
12	Victoria	230.00	120.00	8.50	32.60	0.00	391.10
13	Sherbrooke	182.80	37.30	63.40	85.80	3.70	373.00
14	Peterborough	218.30	93.90	4.10	22.70	18.30	357.30
15	Fredericton	226.20	58.00	0.00	2.90	0.00	287.10
16	Moose Jaw	155.40	2.60	72.50	25.90	0.00	256.40
17	Sydney	115.80	21.70	7.20	0.00	0.00	144.70
18	Corner Brook	84.00	50.40	1.40	1.40	2.80	140.00
19	Mount Pearl	20.00	80.00	0.00	0.00	0.00	100.00
20	Pembroke	51.50	24.80	0.00	10.10	5.50	91.90
21	Summerside	45.00	11.30	0.00	18.80	0.00	75.10
	TOTAL LENGTH	**8,769.40**	**4,237.70**	**2,105.35**	**1,818.10**	**623.10**	**17,553.65**
	Percentage of total length	50.0%	24.1%	12.0%	10.4%	3.5%	

Table 4. Pipe lengths (km) per pipe type in Canadian municipalities (Rajani et al., 1995)

In terms of materials employed, one notes that the grey cast iron was extensively used in the water infrastructure (50%). Even if it is not employed anymore since it was replaced by the ductile cast iron starting in the 1960's, it still accounts for the largest share of the water distribution pipes. This leads to the conclusion that 50% of the water infrastructure of the cities studied in the report was constructed before 1960's. Consequently, this inherited water supply system is mostly prone to breakage because of its advanced age and material's deficiencies. Ductile cast iron is the second category and represents 24% of the total length of the water pipes in the municipalities. Polyvinyl chloride (PVC) pipes came into use later. Even if its production in Canada started in the early 1960's, its employment in water distribution systems began in the late 1970's and constitutes a low proportion of 10.4% of the Canadian water pipes. Asbestos cement pipe is not very common in every municipality. It was used by few cities such as Edmonton, Regina and Burnaby and it is present in Sherbrooke in a lower extent. Finally, prestressed concrete cylinder pipe accounts for 3.5% of the inventory. This pipe is commonly used for water mains of large diameters and therefore it was the choice of larger communities, such as Calgary, Edmonton and Ottawa.

The total number of breaks recorded in 1992 and 1993, for each type of water pipe was noted for each municipality. The accumulated results, for each type of water pipe are summarized in Table 5.

	GCI	DCI	ASB.-CEM	PVC	PCCP	TOTAL
TOTAL km/pipe type	8,769.40	4,237.70	2,105.35	1,818.10	623.10	17,553.65
No of breaks /total length 1992	3078.1	394.1	113.7	16.4	3.1	3,605.33
No of breaks /total length 1993	3218.4	415.3	128.4	9.1	5.0	3,776.17

Table 5. Total number of breaks for different pipe types, for 1992 and 1993 (Rajani et al., 1995)

The evaluation of the breakages for water pipes made of different materials, as a mean of the break rates in the Canadian municipalities considered (Figure 9), shows that the most frequent breaks occur in GCI and DCI pipes, and account for almost 90% of the cases, with an average rate of 36 breaks/ 100km pipe for GCI and 10 breaks/ 100km pipe for DCI pipes.

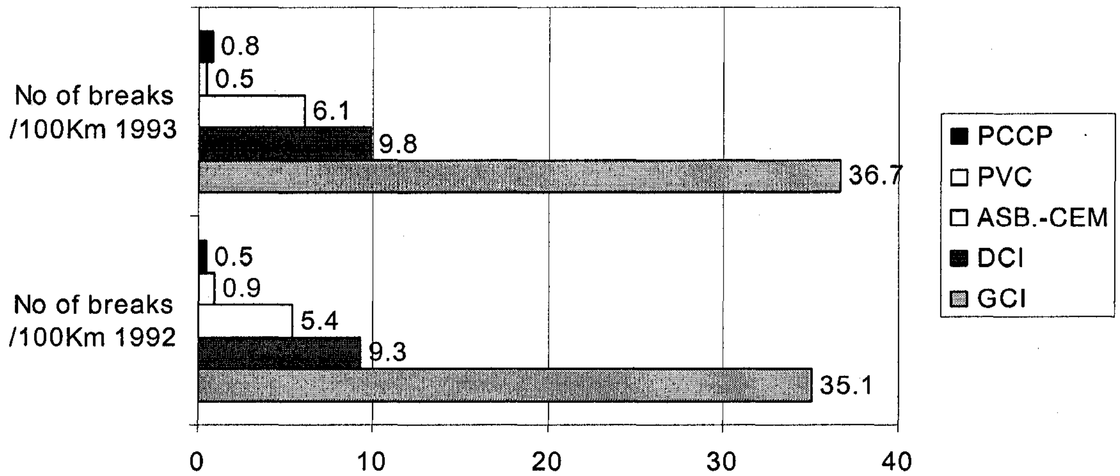


Figure 9. Number of breaks/100km of water pipes in Canadian municipalities in 1992 and 1993 (adapted from Rajani et al., 1995)

At the national level, the results show a rate of 23 breaks/ 100km pipe for the year 1993. This is comparable to the Canadian mean rate of 20 breaks/ 100km pipe (SNC Lavalin/Dessau Soprin, 2002) and therefore seems to be quite accurate. However, this rate might have increased during the last decade in some regions where no improvements were made in the water infrastructure.

According to the Canadian Water and Wastewater Association, the rating of a water supply system can be also performed on a water loss basis. In a broader classification, a water system is considered good if the losses are between 5-10%, average with 15-25% losses; more than 30% losses means that the system is faulty. The leakage problem is not constant throughout the country (Siblin, 1999) i.e., Calgary - 5%, Toronto - 10%, Montreal - 25% or more, which remains a mystery because of the absence of water meters, and a pattern of the phenomenon cannot be established by geographic regions or cities ages, making each municipality unique in its way. However, an increased leakage of the water supply systems is observed in the municipalities with older water infrastructure, mainly comprising of grey cast iron pipes.

Generally, the quality of potable water supplied by the utilities is good; however, several municipalities with less than 5000 inhabitants face problems with the quality of water, for example, the native communities. Accidents of water pollution are more likely to occur especially in the cities with older infrastructure; accidents due to high bursting pressures may also occur and result in major damage to the water systems and occasional contamination of the drinking water, e.g., Dorval 2004, "a pipe may have opened the borough's water system to contamination" (Rocha, 2004). Most of the municipalities do not have a good knowledge of their water distribution system and they make very small investments in works required to improve the state of their water systems.

The sewer systems are less problematic than water distribution systems. This verdict which characterizes most of Canadian municipalities comes from the knowledge that these utilities have not been labelled with problems as frequently as the water systems. However, their state-of-the-art is not known and the assumption that they are generally in a good shape is taken for granted. Sporadic repairs are performed only in emergency cases where deterioration is evident and requires immediate attention. In the Province of Quebec, 2% of the sewers are prone to overflowing and other 4% of the total length of sewers encounters excessive infiltration problems, according to the Quebec Environment Ministry (La Gestion de l'eau au Québec, 1999). The latter phenomenon is noted mostly in the case of older pipes made from less resistant materials such as ceramics, slate and bricks. Inspection of sewers is not normally performed on a systematic basis and their state of health is poorly known.

3.2. Age of Underground Infrastructure

As previously discussed, a majority of Canadian water and sewer infrastructure is in an advanced state of ageing. The water supply systems consist of nearly 50% grey cast iron pipes which were installed starting in the mid-1800, with many pipes still in use. In the

U.S.A., more than 95% of the total cast iron pipes ever installed are still in use, (Cast Iron Soil Pipe Institute, 2006), with a recorded life of over 100 years in some cases. The durability of grey cast iron pipes has been proved over time for underground piping applications, however, this is severely influenced by the condition in which the pipes operate, i.e., cast iron pipes are prone to premature deterioration if exposed to aggressive environments, or accidental operating conditions. Rajani (1996) showed in a study of pipe- soil interaction in the City of Winnipeg, Manitoba, that the number of breaks of grey and ductile cast iron pipes doubles if the temperatures drop below normal. The peak of breakages was recorded during the cold periods, between January and March. The climatic conditions of Winnipeg are comparable to other Canadian cities, and therefore the prolonged life of grey cast iron pipes recorded in U.S. cities should be questioned in the case of Canada. This clearly explains why 37% of the cast iron pipes installed in the City of Montreal between 1940 and 1960, with an average age of about 55 years, present a high risk of breaching (SNC-Lavalin/ Dessau-Soprin, 2002). An examination of the other types of pipes in the Montreal's water supply system, i.e., steel, ductile cast iron and asbestos- cement pipes, and the grey cast iron installed before 1940, clearly shows that more than half of the underground water piping needs immediate consideration for their state improvement.

At the national level the situation might not be far away from that of the City of Montreal. As mentioned previously, about half of the water piping is made of grey cast iron, installed before the 1960's. Some other types of piping materials were employed with prevalence in specific locations of the country, however, the development of communities and the available technologies along the years were somewhat alike across the Canadian Cities, which leads to the conclusion that the pattern of the water infrastructure in terms of materials used and average age could be considered similar throughout Canada.

The SNC-Lavalin/ Dessau-Soprin (2002) estimated the average age of Montreal's sewers to be between 60 and 80 years. Of course, older sewers of more than 100 years exist in the City's underground network and are still in use. Data from other municipalities are not available, however, as in the case of water supply systems, this age pattern would be about the same for other Canadian municipalities.

3.3. Future Trend if no Action is Undertaken

Rajani et al. (1995) synthesized the number of breaks/100km of water pipes across 21 Canadian municipalities, in two consecutive years. An increase of 4.7% in the number of breaks was observed from 1992 to 1993. By simply maintaining this annual breakage rate steady, the projected trend over ten years following 1993 can be easily calculated. The results are shown in Table 6.

CITY	Breaks /GCI	Breaks /DCI	Breaks / ASB.-CEM	Breaks /PVC	Breaks /PCCP	TOTAL breaks	Average break rate /100km, 1993	Average break rate /100km, 2003
Calgary	411	112	4	4	2	532	16	25
Edmonton	367	0	65	2	1	435	17	26
Ottawa-Carleton	390	105	0	0	1	496	22	34
Vancouver	388	31	0	0	0	419	30	48
North York	304	41	1	0	0	346	26	40
London	266	40	1	0	0	307	24	39
Windsor	281	5	0	0	0	287	32	51
Regina	6	1	33	1	0	40	6	9
Burnaby	84	15	15	0	0	114	18	28
Halifax	106	10	0	0	0	117	26	42
St. John's	128	6	0	0	0	135	33	52
Victoria	84	12	1	0	0	97	25	39
Sherbrooke	67	4	4	0	0	75	20	32
Peterborough	80	9	0	0	0	90	25	40
Fredericton	83	6	0	0	0	89	31	49
Moose Jaw	57	0	4	0	0	62	24	38
Sydney	42	2	0	0	0	45	31	49
Corner Brook	31	5	0	0	0	36	26	41
Mount Pearl	7	8	0	0	0	15	15	24
Pembroke	19	2	0	0	0	21	23	37
Summerside	17	1	0	0	0	18	24	37
Montreal	1,192	139	3	1	3	1,338	26	40
							519	821
Canadian average							24	37

Table 6. Estimated trend of the water breaks for 2003

One notes that the deterioration of infrastructure progresses on an exponential scale if remedial actions are not implemented (Figure 5), and consequently this model might be optimistic. The estimation accounts for no maintenance plan, or rehabilitation during the ten years period. For comparison purposes, the City of Montreal was added to the 21 cities incorporated in the study undertaken by Rajani et al., with its shares on each type of water pipe. Accordingly, the number of breaks was deducted for each type of pipe in the system and an annual average breakage rate was calculated. The increased breakage rate from 26/100km/year in 1993 to 40/100km/year in 2003 seems to be quite accurate for the City of Montreal since a rate 30-40 repairs/ 100km/ year was noted by SNC-Lavalin/ Dessau-Soprin (2002), in the report regarding the state of Montreal's water supply system.

The estimate is not very accurate since the situation might have been improved over the last decade in several municipalities; however, based on a Canadian average, it shows a significant deterioration of the water infrastructure if no action is undertaken.

3.4. Non-Technical Issues Promoting Infrastructure Deterioration

The financial neglect during the past three decades has led to deferred or complete lack of maintenance, repair, rehabilitation and replacement of the water supply and sewage disposal infrastructure. It is unfortunate that the evidence revealing the state of the underground infrastructure was not maintained in most cases, therefore, the municipalities are unaware of their assets and their deteriorated condition. The 2002 report on the water supply and sewer systems in the City of Montreal (SNC-Lavalin and Dessau-Soprin, 2002) reveals that a few municipalities (being under the jurisdiction of the City of Montreal) have an idea in terms of "what they have" in the ground. Furthermore, the water losses from the leaking pipes are unknown and interventions are made only in emergency cases. This lack of knowledge of the existence and condition of the underground infrastructure prevents "good" management of the infrastructure with limited resources.

Referring again to the City of Montreal in 2002, 33% of the buried water network had reached its service life and another 34% would follow by 2020. The projected 15 years picture shows a city in which 70% of the distribution system is extremely inefficient with considerable expenditures required to patch the old leaking system. The need to "overhaul" the water and sewer infrastructure will increase considerably in the future, and it will cost more than the current estimate of $4 billion. The water losses will obviously increase and there will be a corresponding need to produce extra potable water, placing pressure on the water production plants, besides increasing the price of the water production.

The example of Montreal is not singular amongst the Canadian municipalities, but it shows the extent to which the underground infrastructure has been neglected. The causes of continuous neglect are, nevertheless, similar for different municipalities. Finally, the task of overhauling the infrastructure assets throughout the country has been transferred from generation to generation but the present one has to pay for it since future delay is not acceptable anymore.

3.5. Assessment of Needs to Address the Present Underground Infrastructure Crisis

Water and sewer services are vital for urban dwellers and their disruption in one form or another can influence the society adversely; these have resulted in serious disruptions to the society, and have been manifested in direct and indirect socio-economic, environmental and other costs to the society, occasionally involving an unacceptable loss of life.

As stated in a few recent reports, e.g., McGill/FCM Report (1996), Water Infrastructure: Research for Policy and Program Development Report (Infrastructure Canada, 2004), the Technology Road Map (CSCE, 2004), etc., there is an urgent need to develop a precise inventory, along with the condition assessment of the existing infrastructure assets. This is the first step in addressing the infrastructure crisis, and possibly, the most costly. However, this is a milestone from which further benefits can be drawn, and without it, "correct" management of each type of infrastructure is not possible. The creation of such an inventory database can further serve as a starting point, where engineering and management are integrated to develop an effective intervention plan with reference to the best technical and technological solutions to be employed, along with a sound asset management plan.

The database should address the infrastructure by types, and the process should be implemented at municipal, provincial and federal levels. Attempts should be made to incorporate the latest technological advances in terms of equipment and techniques, tools and knowledge, to create the inventory. Of course, more related research will be useful to improve the inventory and condition assessment processes.

CHAPTER 4

SPECIFIC FEATURES OF WATER INFRASTRUCTURE

4.1. Water Supply Systems- Components Description

A water supply system is very complex and comprises all facilities and equipments needed in the process of production and distribution of potable water, from the intake to the user. The main parts of the system are the water treatment plant and the distribution system.

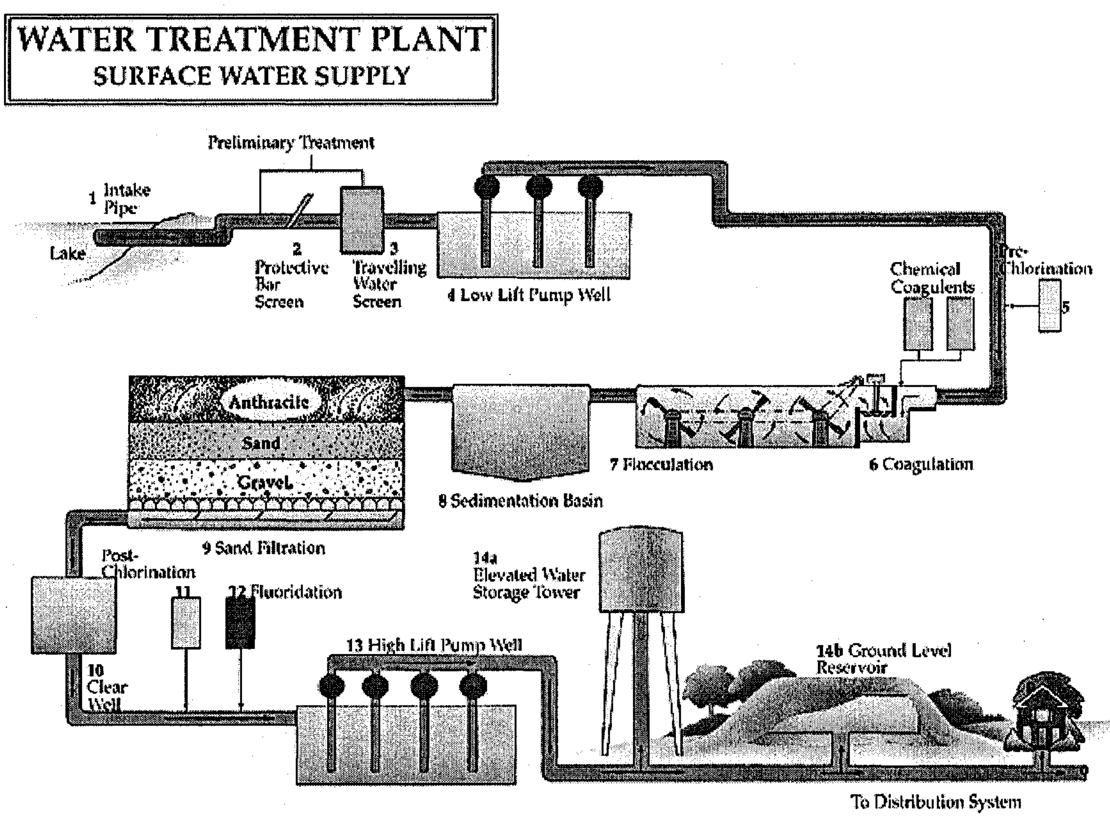


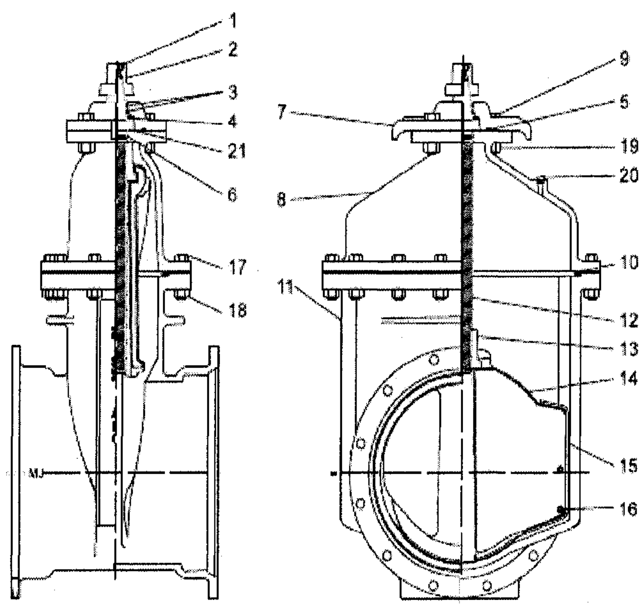
Figure 10. Surface Water Treatment Plant (Durham, 2006)

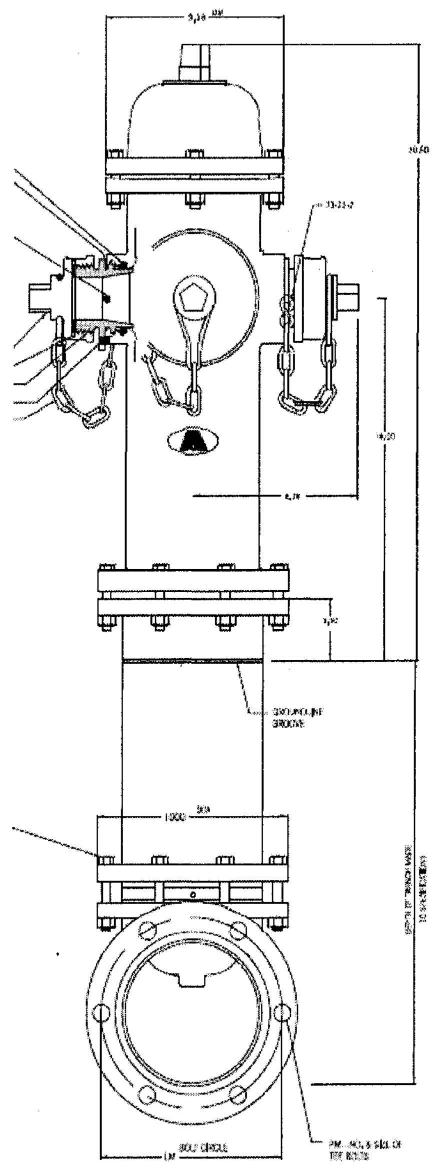
A schematic layout of a water treatment plant is shown in Figure 10. The **water intake** is the entry of water in the system. It may originate from lakes, rivers or, in the case of a sub-surface water supply system, from wells. The water follows the **screening** process, to remove suspensions, algae and other major impurities. After this preliminary treatment, water is pumped to the next process which involves **coagulation** and **flocculation**, by chemical reaction. Aluminum sulphate is commonly used as a coagulant agent which forms flocs and attaches to impurities in the water such as mud and bacteria. Water then reaches a **sedimentation basin**, where the flocs and impurities settle to the bottom; they are periodically removed and drained to the sewer system. The following step in the treatment process is **filtration**, which usually consists of a bed of sand at the top and gravel at the bottom and, in some cases, a supplementary anthracite layer. This step screens most of the remaining impurities in the water. **Disinfection** (deactivation of pathogenic microorganisms) is the last process, which usually uses chlorine as sterilizing agent, and at this point, water is ready to be delivered to the consumers. Of course, some other alternate disinfection mechanisms do exist, such as ozone or UV treatment; this method is most widely used in the treatment plants across North America. The treated water is stocked in large **reservoirs** and sometimes, especially in smaller communities, in **water towers** to ensure the necessary pressure in the system. In larger communities, **pumping stations** send the water from the reservoirs to the consumers and maintain adequate pressure in the **distribution system.**

The project focuses on the distribution network of a water supply system and a description of its constituent elements follows. The treatment plant remains a fundamental part of a water supply system.

The distribution system comprises the entire network of reservoirs, pumping stations, water mains and distribution piping to the consumers. It stretches from the water treatment plant to the consumer's watermeter (or to the limit of the consumer's property), with all of the related accessories such as valves and valve chambers, hydrants, pressure reduction facilities and air valves, fittings, gauges, etc. A common view of a gate valve and of a fire hydrant is presented in Figure 11. **Valves** are of many types i.e., gate, butterfly, check tapping and non-return valves; each type has its advantages and limitations, and therefore it is suitable for specific situations only. For instance, a gate valve is more practical than a butterfly valve for controlling the water flow of a sector.

Conversely, a butterfly valve is most economical (smaller dimension, simpler construction and lower price) when its intended use is to close or open a section in a system. Other special valves have been developed to feed the specific needs in water supply system applications, such as the tapping valves which are very effective for consumers branching, or the spherical valves, used in the HVAC systems and gas industry, but newly implemented in water systems with appreciable results.





Ref	Description	Material
1	Hex Hd Bolt	Steel, zinc plated
2	Operating Nut 2" Sq	Ductile Iron, ASTM A536
3	O-Ring	Rubber
4	Upper Thrust Washer	Delrin
5	Stuffing Box Gasket	Rubber O-Ring
6	O-Ring	Rubber
7	Stuffing Box	Ductile Iron, ASTM A536
8	Bonnet	Ductile Iron, ASTM A536
9	Hex Hd Bolt	Steel, zinc plated
10	Throat Flange Gasket	Rubber
11	Valve Body	Ductile Iron, ASTM A536
12	Stem	Bronze
13	Wedge Nut	Bronze
14	Resilient Wedge	Rubber
15	Wedge Cover	Acetal Copolymer
16	Wedge Cover Pin	Acetal Copolymer
17	Hex Hd Bolt	Steel, zinc plated
18	Hex Nut	Steel, zinc plated
19	Hex Nut	Steel, zinc plated
20	Pipe Plug	Brass
21	Lower Thrust Washer	Delrin

Figure 11. Typical Gate Valve and Fire Hydrant used in Water Works (www.acipco.com)

Valves are generally buried in the ground and can be operated from the surface through a vertical shaft protected by a PVC/steel trench adapter and a surface cast iron box, by the aid of a wrench. In some cases, i.e., nodes in the systems, the valves are located in chambers and can be operated by the working personnel, through handwheels, levers, wormgears, or by electrical actuators.

Generally, the valves are made of cast iron (ductile iron over the last decades) and are protected against the aggressive environment by coatings. The newly produced valves are internally provided with epoxy lining and externally with epoxy and/or bitumen coatings. However, steel valves are also utilized (e.g. spherical, with the sphere stopper in stainless steel), and recently, plastics, with a limited use for larger diameters (more than 200-250mm). The dimensions are internationally standardized to ensure trouble-free replacement.

Fire **hydrants** are another important feature of a water supply system. They are the exterior interface of the buried system and allow drawing water off the system in emergency situations, such as fires. The hydrants give the water supply system the second major role, which is that of a fire fighting network. Many municipalities have embarked for building water infrastructure from the necessity of a fire fighting system and consequently the system was conceived accordingly, i.e., providing rings in the network and valves at precise locations so that water will be always available, even in the case of a temporary breach in the system. The distance between hydrants and their repartition in a municipal water supply system is regulated by national or provincial fire codes, i.e., Quebec implemented the Provincial Fire Code, however, it is almost similar to the National Fire Code; all major municipalities adopted the National Fire Code (www.nationalcodes.ca, 2006).

The **pipes** form the prevailing part of a water supply system. The **mains** are the primary network and conduct water from the treatment plant to the reservoirs and pumping stations. These are usually of larger diameters, especially in larger municipalities, i.e. 400-1200mm, or even more, and operate at high pressure, i.e. 10 to 12bars (1.0-1.2MPa).

The common pipes used for the large diameters are the cast iron, the composite and the precast concrete cylinder pipe. The **secondary distribution** network is formed of smaller diameters pipes, i.e., 50-350mm, and the operation pressure is less than 6bars. In some cases, where the terrain presents highly differential levels, the operating pressure must be limited by pressure reduction devices, to protect the domestic appliances from surge pressures. The secondary pipes are made of a large variety of materials, from grey and ductile cast iron to steel, asbestos-cement, vitrified clay and plastics. The whole system (including the mains and the secondary network) is buried into the ground, at specific depths according to the geographic region, to prevent freezing of water in cold seasons.

4.2. Water Consumption per Capita- Canadian Cities Consumption Patterns, U.S. and European Means

The water use in a community is evaluated as the average daily consumption attributed to one person, i.e. liters/capita, gallons/capita. For a municipal consumption assessment, it is usually convenient to consider, besides the household usage of water, the commercial and industrial sector. Of course, the unaccounted water is also included, which incorporates the leaks in the distribution system, the water used for fire fighting or the water drawn off illegally (i.e. cooling systems in small commercial businesses). In Canada, the municipal water consumption per capita is between 620 and 700litres/ capita/day (Figure 12).

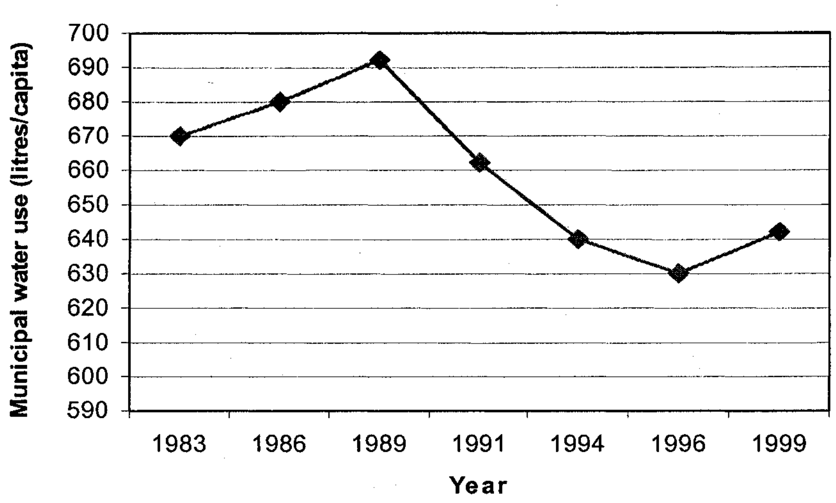


Figure 12. Canadian Municipal Water Use, in liters/capita (Environment Canada, 2001)

The information available from Environment Canada reveals a consumption pattern between 1983 and 1999 which is almost steady. A peak of 694liters/day was recorded in 1989 and a dip of 628liters/day in 1996, however, the variation is less than 10% and can be attributed to dryer warm seasons, population increase and enhanced economic activity. The residential consumption roughly accounts for more than 50% of the water use across the Canadian municipalities. Commercial sector accounts for about 20%, industrial for 17% and other consumptions (losses, fire fighting, etc.) represent the remaining 13% of the total potable water produced by municipalities. Without these related sectors, the residential water use is between 330-350litres/person/day, which is still very high compared with other OECD (Organisation for Economic Co-operation and Development) countries. According to Burke et al., (2001) Canadians used "327 litres per person per day in 1996, compared with 128, 130 and 149 litres per person per day in Germany, the Netherlands and the United Kingdom, respectively (OECD, 1999)".

The water use pattern is not constant all along the country, with some cities recording increased water consumption per capita, i.e., Montreal uses double the Canadian average. Water consumption in cities with a population of more than 100,000 inhabitants is compared in Figure 13, to relate to the Canadian average water consumption; cities from different provinces were included, along with a couple of municipalities in Quebec, for comparison with the City of Montreal.

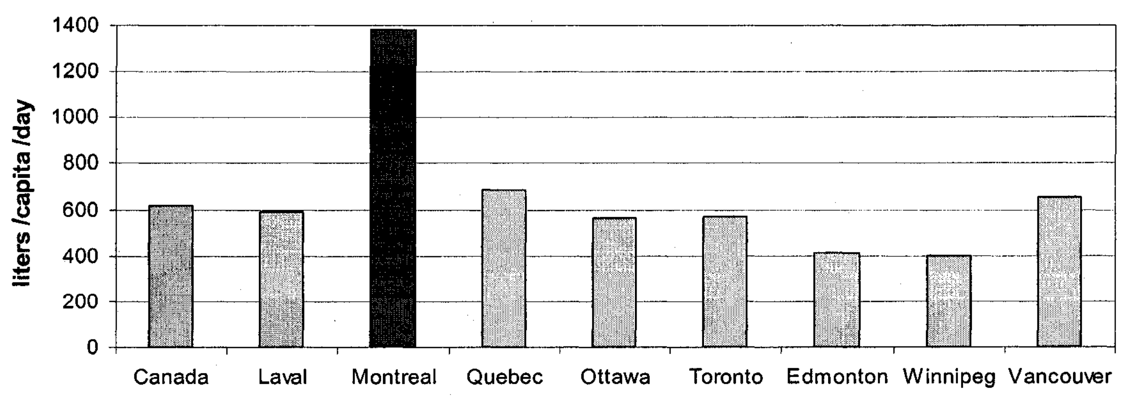


Figure 13. Water Consumption in Canada in l/capita/day, for Cities with 100,000 Inhabitants and More (SNC-Lavalin/ Dessau-Soprin, 2002, Environment Canada, 2004)

At the provincial level, New Brunswick, Newfoundland and Yukon Territories head, with 1314, 971 and 803liters/capita/day, respectively, followed by the Province of Quebec with 777liters/capita/day (Environment Canada, 2004). This increased consumption rate might be partly attributed to the low percentage of metered consumers, a fact that will be discussed later.

In the United States, the average water use is about 680litres/capita/day for domestic, public, commercial and industrial needs (Environmental Works, 2006). Some other estimates show a higher water consumption rate. According to Fetter (1994), the average domestic water consumption is between 200 and 300 liters per day, but when industrial and energy production usage is added, the consumption rate of fresh water might be as high as 5,000liters/capita/day. The World Bank (2000) estimated the U.S. domestic, industrial and agricultural water use to be 448 billion cubic meters, which gives more than 4000litres/capita daily water consumption, and 1460cubic meters per capita on an annual basis.

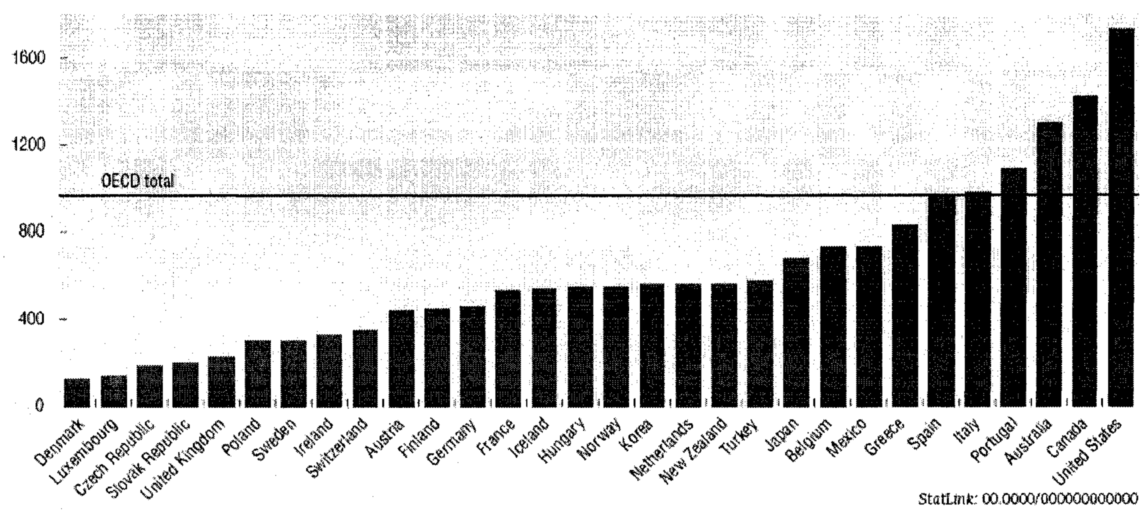


Figure 14. Water abstractions, cubic meters/capita (OECD, 2004)

On a larger scale, OECD (2004) has assessed the water abstractions per year in several countries (Figure 14). The evaluation is quite accurate since, in the U.S. case, the results seem to be similar to the ones available from the World Bank, 2000. Canada is the second major water consumer, after the United States, with about 3 times more than the mean consumption of the European countries.

4.3. The Cost of Water in Canada

In Canada, residential consumers pay the water supplied by the municipal utility on a volume-based rate, or on a flat-rate basis. The flat rate is commonly applied in the municipalities with un-metered households, and the rate is included in the municipal taxes. According to Burke et al. (2001), only 56% of households were metered in 1999, a steady percentage since 1996; consequently, 44% of the Canadian households paid flat rates, whereas the remaining consumers paid volume-based rates. A special volume-based rate was applied for 7% of the households, which accounts for a minimum charge corresponding to more than the normal volume of water used by a household, which had a similar effect to that of the flat-rate charge. Therefore, nearly 50% of households can be considered that had been charged on a flat-rate basis, with an average price of $22.40/month (1999), and an annual average increase of 3% from 1991 to 1999.

The volume-based rates account for the other half of Canadian households; this includes the constant unit charge (CUC), the declining block rates (DBR) and the increasing block rates (IBR). Increasing block rates are conservation oriented rates, whereas decreasing block rates are usually applicable to large consumers such as commercial and industrial users, a practice where regional economy which uses large volumes of water is encouraged. At the national level, the price of water on a volume-based rate is about $1/cubic metre (Burke et al., 2001). In the commercial and industrial sector, the water price manifests the same trend and can be considered to be about the same, i.e., $1/ cubic metre. However, this rate is highly dependent on the region, with low rates in Quebec and higher rates in the Prairies. The water price reflects both the cost of local water production and the level of governmental subsidies.

The City of Montreal has one of the highest levels of water consumption, around 1100 l/person/day, or even more (1380 l/person/day) according to some experts (Siblin, 1999). This peak amongst Canadian cities might partially result from the lower price of the production of water. In Figure 15, Montreal is compared with other Canadian municipalities from the same province and from other Canadian provinces. The picture shows that Montreal has the lowest price the consumers pay for the water.

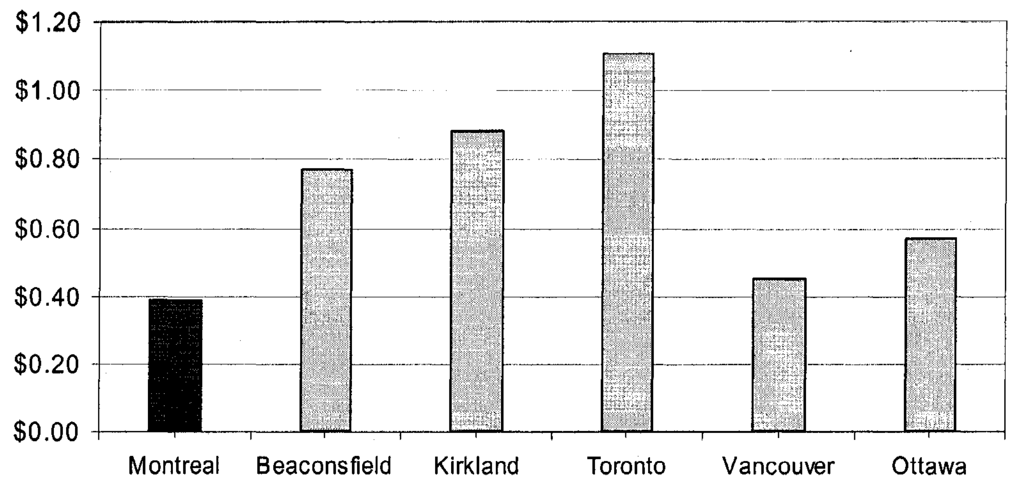
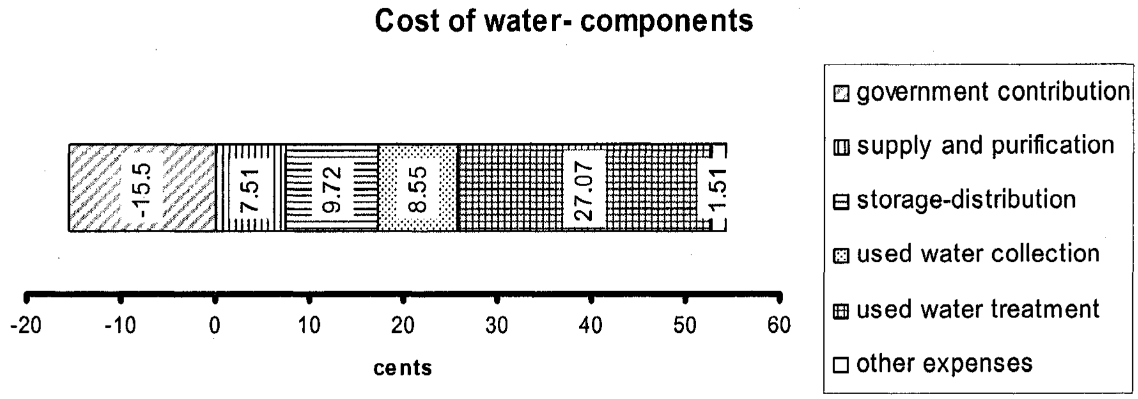


Figure 15. Water Prices in Different Canadian Municipalities, $\$/m^3$ (PWC, 2003)

To have a better approach to the costs of production, distribution and used water collection and treatment, the example of the City of Montreal is considered further. The components of the cost of water in Montreal are presented in Figure 16. They include production, storage and supply of potable water, and the used water collection and treatment, with the cost implied by each operation. The final cost of a cubic metre of water rises to 54.36 cents. However, consumers pay less than 40cents/cubic metre (Figure 15) and therefore, the remaining gap is subsidized and in this case, Montreal receives a subsidy from the provincial government. By subtracting the governmental subsidy, the final price of Montreal water is **38.86 cents/m^3**. With an annual consumption of 725 million water cm, the entire cost of production, distribution and water treatment is about **$282 million/year.**



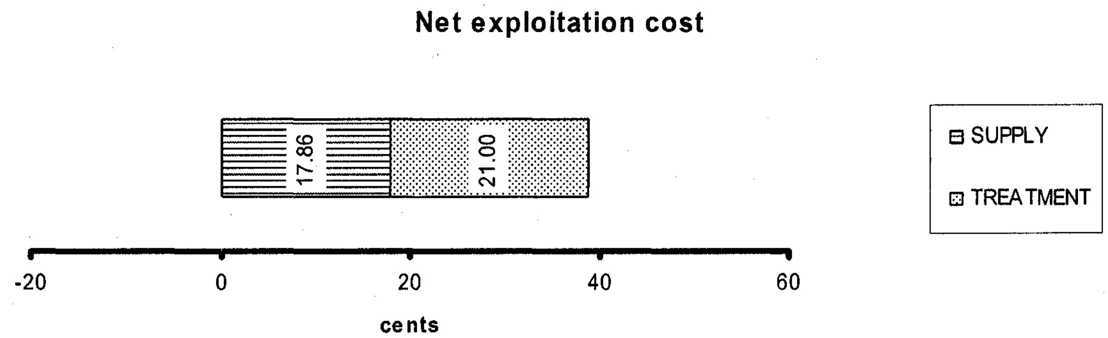


Figure 16. Price of water in Montreal- components (PWC, 2003)

Montreal has the cheapest water in Canada. In comparison with other major cities across the world, Montreal seems to be the leader in low price water. According to Burke (2001), European cities charge much higher prices per cubic metre of water (late 1990, US dollars), i.e., Vienna (AUT) $1.48/cm, Brussels (BL) $ 1.51/cm, Copenhagen (DK) $ 1.68/cm, Lyon (FR) $ 1.45/cm, Berlin (GE) $ 1.94/cm, etc.

4.4. Pricing of Water and Other Alternatives of Financing

It is common across Canada that pricing of water is not kept at the level of service provided. This has resulted in increased rates of water consumption, as is the case with Montreal, and has led to the notion that Canadian water is cheap and that Canada has unlimited fresh water resources. However, this has been proved to be a incorrect since the depletion of the natural resources is not a sustainable solution, especially in a developed country such as Canada. Under-pricing leads to higher consumption, therefore higher demand and increases the volume of used water.

Some alternatives of water infrastructure financing are explained in the following, with consideration of the full cost pricing, the public-private partnerships and the development charges, bonds and funds.

Full cost pricing is based on the principle that consumers who benefit from the service pay for it. It eliminates or reduces subsidization, and these savings can be used in water rehabilitation for instance. This model has been applied successfully around the world and generally leads to service auto-financing. Even if the water price is slightly increased, it leads to a high quality of level services. It is important that the switching from the old pricing system to the full cost pricing be done gradually and not necessarily entirely because of the impact on the consumers and the response manifested by the population.

Public-Private Partnerships have gained increasing popularity and sometimes may be a good solution in financing public infrastructure. PPP may be regarded as a fusion between public and private sector which presents some advantages. It is generally accepted that the management of private sector is more efficient, and the incorporation of the private sector may result in better fund management within a utility, reduced project completion times, mitigation of government financial risk and availability of private knowledge and expertise. Even if the private sector is implicated in building and/or operating a utility, the government (public sector) continues to be the regulating body, and the public participation is not lost, therefore this partnership does not represent a privatization.

Development charges are sometimes used instead of increasing taxes, when a new infrastructure is built. The charges come from the population that will benefit from the new infrastructure. **Special district** is another form of financing infrastructure and it results from fees collected from the future beneficiaries that will use the infrastructure (successfully used in U.S.). **Funds** can also be obtained when a percentage of tax revenue is used to finance a specific area (special taxes such as a gasoline tax). Another alternative to consider is the issuance of **bonds** by a municipality to finance a new infrastructure project.

4.5. Water Metering Issue in Canada

As discussed previously, 44% of the Canadian households were not metered in 1999. Moreover, part of the metered consumers were not encouraged to conserve water, being charged for more than an average household consumption, which in many cases was not reflecting the reality, causing increased consumption. Roughly, 50% of Canadians were not provided with tools and incentives to reduce water consumption, being charged on a flat rate basis. Burke et al. (2001) showed that the water consumption was 70% higher when consumers were charged on a flat monthly rate, compared with the households which paid volume-based rates. He also noted that the largest water consumption was recorded in Yukon and Newfoundland, with a mean of about 600 l/capita/day, followed by British Columbia, New Brunswick and Quebec with 400- 450 l/capita/day and the lowest consumption rates were observed in Prince Eduard Island and Northwest Territories, around 200 l/capita/day and less, in 1999.

Figure 17 shows the trend of water metering between 1991 and 1999 across the provinces of Canada. It also shows the average monthly flat rates charged to the consumers in each province. The first conclusion that can be drawn is that most of the provinces with lower flat rates are big water wasters, i.e., Newfoundland, Quebec, followed closely by British Columbia and New Brunswick (with the exception of Nova Scotia). Moreover, the consumers of these provinces are metered in a very low percentage leading to a decreased population interest in water conservation. One can also observe that in an 8-year period (1991 to 1999) many provinces have shown no improvement in the metering process, maintaining the non-metered consumers at a steady level.

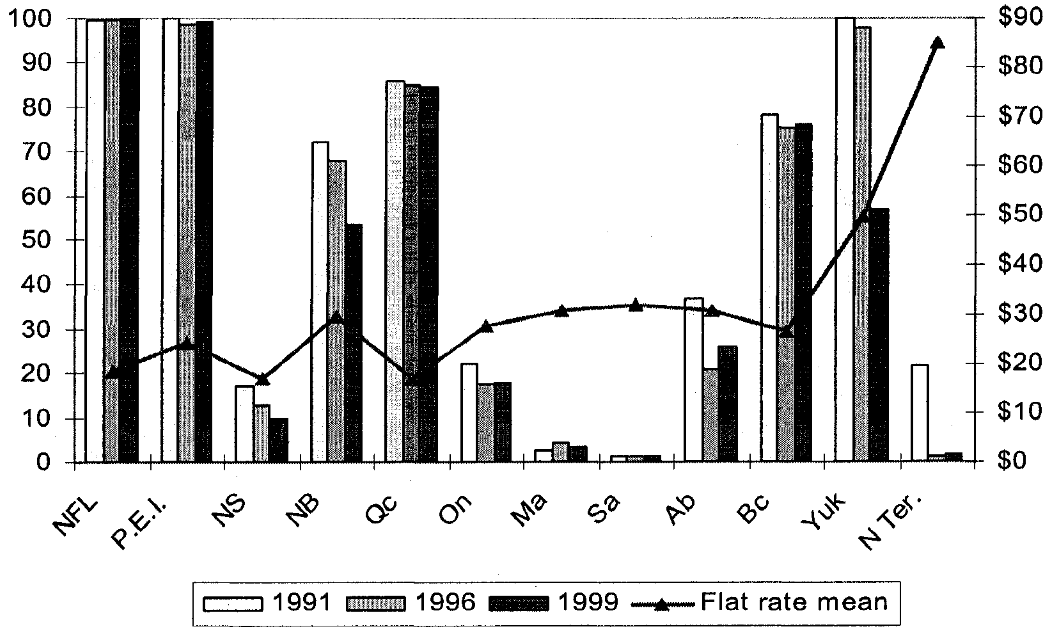


Figure 17. Percentage of unmetered population and the monthly water flat rate for the Canadian Provinces (based on data from Burke, 2001)

4.6. Demand Side and Public Input

Understanding the demand side of water is of major importance. Demand management focuses on reducing water flows, by an accurate appraisal of water needs. A key tool in demand management is the metering of water, which implies reduced consumption, thus a reduced water demand. Metering will also result in public education regarding water and will create incentives to conserve water, with the consumers determined to repair any brakages or leakages, water recycling and conservation. To assess consumer need, water audits have become somewhat common and are offered by several municipalities. This brings the contribution of each consumer to a water efficiency program by encouraging water reduction measures. These measures will not affect the human comfort, but will provide an efficient strategy of water consumption. According to Environment Canada (1997), reducing the water demand includes system optimization, i.e., refurbishing or retrofitting of household appliances using water, recycling systems, i.e., reusing of wastewater, alternative water sources, i.e. lawn watering with non-potable water if available, metering, and, most important, user habit change.

Technological, educational and economic measures have also been developed during the last few years (Environment Canada, 2001), with the aim of encouraging water conservation. A lot of water-saving devices are now available, which can be easily implemented in the daily household and business use, and educational materials concerning the efficient water use and the sharing of knowledge amongst people are available to the public. These were developed mainly by Environment Canada and Canadian Water and Wastewater Association and are available mostly via the Internet. Finally, the economic measures come from the federal government funding through Infrastructure Canada (6-year $2.6 billion plan announced in 2000), along with municipal and provincial fund, which will primarily focus on green municipal infrastructure projects, including water and wastewater supply systems improvements.

Public input is therefore very important because it can tremendously improve water conservation, resulting in an increased efficiency in water supply and service quality. However, public education and orientation towards sustainable green principles might be a very difficult task especially in the municipalities with low percentage of metered households. Besides the education and sensitizing of population to the water supply concerns, the accommodation with a new billing system, i.e. volume-based, might be regarded with scepticism and might take some time to be implemented, even if it is more realistic whilst it accounts for the real volume of water consumed. The public should be convinced that having the water consumption metered, can result in significant advantages.

Some other benefits of metering, besides lowering water consumption, will be mitigation of water theft, increasing hydraulic efficiency of the system and reducing the used water volume- which will have a beneficial environmental impact. Meantime, the need to build larger water infrastructure is reduced.

CHAPTER 5

DEVELOPMENT OF BURIED UTILITIES INVENTORY

5.1. The Methodology

The proposed methodology is aimed at establishing a framework for developing a detailed inventory of the underground infrastructure along with its condition assessment. The inventory will be based on in-situ measurements to establish the location and condition of specific underground services, using non-destructive techniques, i.e., ground penetrating radar (GPR), remote field eddy current (RFEC) methods, which will be discussed later. The inventory will commence with archiving the existing documents and data in digital or paper-based format.

The basic steps to be followed during this process involve the detection of underground infrastructure, development of a GIS (Geographic Information System), the in-situ condition assessment and the data management of (historical and current) engineering information. Eventually, the analysis of data can be performed which will help in developing an accurate state-of-the-art of the "out-of-sight" infrastructure. These methodology steps are described in the following.

Detection and location of underground infrastructure can be performed presently without altering the environment, by employing non-destructive techniques, e.g., the ground penetrating radar (GPR). Recent advances in technology permit a precise location of underground obstacles, objects, etc, in this case the water and sewer pipes, regardless of the materials used. The new generation of the GPRs is now capable of locating utilities in congested areas, and provides information about utility's depth and position. Both metallic and non-metallic pipes can be located and the information is displayed on the screen while the device is moved along. Usually, GPR devices are placed on wheel carts to allow a rapid and qualitative scan of the underground facilities. Images are recorded on the internal memory and can be easily transferred to a computer through the device's interface. Situations arise when antennas with different frequencies are needed to determine the different properties of the subsurface area. A 100-500 MHz (or even 800 MHz for high sensitivity) antenna is typically used to detect underground water and sewer pipes. If an increased frequency antenna is used, e.g., 1-1.4 GHz, the device is able to detect voids in the ground which is useful information regarding the bedding and compaction condition of the earth surrounding the pipes. This information is useful in the complex condition assessment process. The archived data for the location and graphics images for each infrastructure detected can be finally imported into a GIS database.

A GIS, called the Platform from here on, will be used to **develop a map** of the buried utilities. One notes that this approach can also be used to archive other types of infrastructure, such as electrical or telephone lines. Further, above-ground infrastructure can be digitized on the same map, however, this is not the object of this project.

In-situ **condition assessment** can be also performed using non-destructive techniques. Since unearthing underground pipes is costly and time-consuming, which only permits assessment of the pipe exterior wall and which has a direct impact on the environment, it is preferably to omit it. Consequently, non-destructive testing techniques are the key solution in the process of underground infrastructure condition evaluation. A few suitable techniques have been developed, however, they are not commercially available. These methods will be discussed later.

At this point, water supply and sewer systems will be treated separately, since they require different assessment methodologies, i.e., water supply is a closed system operating under pressure and its condition assessment cannot be performed using a stationary camera (CCTV), as in the case of sewers, which usually are gravitational systems and are accessible for inspections through the manholes. Remote field eddy current (RFEC), ultrasonic inspection or impact echo/spectral analysis of surface waves will be employed as methods to assess the condition of the water supply system. Because of application limitations and high costs, the focus will be on the RFEC, based on the electromagnetic field method- for water systems. It should be emphasized that these methods will be used where critical sectors are first detected by preliminary simpler methods, such as the leakage detection, or in sectors with aggressive microclimates. Even if these methods are costly and require advanced assistance in application, they appear to provide valuable data about the underground infrastructure facilities. Since the technologies are quite new, and in some cases still under development, it is anticipated that further technological advances will enable the use of GIS- created database. Sewers will be inspected using stationary or mobile cameras (CCTV), and, in specific situations using the laser scanning, tracer method, etc.

Data management of engineering information will use the Platform developed by a partner in the project, called from here on Software P., Inc., software which is capable of processing data in different formats such as CAD, World, etc. It also enables to link the data to the GIS-based map initially developed, and allows information retrieval at any location on the map. The Platform will be used to archive existing old documents as well as the data reflecting the latest assessments of the infrastructure condition.

At this point, diagnosis of a system can be performed by analyzing both historical and in-situ data collected by visual inspection, direct measurements, or non-destructive testing. This will help to create a database which will finally facilitate the assessment of the system condition. Eventually, information for a specific part of the infrastructure at a given location can be updated continuously. This can help with arriving at the most technically efficient and economic solutions. Subsequently, priorities can be identified and an intervention plan can be developed.

5.2. Example of Cities Embarked for a Digitized Infrastructure Inventory. Pros and Cons for Different Archiving Frameworks

Some attempts to digitize the infrastructure assets in municipal areas were made across North America during last decade. Many municipalities have already modeled some of their infrastructure assets in CAD format and have created a considerable database, which can be used for management and forecasting purposes. The GIS- based framework was also applied throughout several municipalities to archive information dealing with different types of infrastructure and seemed to be efficient. For instance, the City of Tucson uses a GIS framework since several years to assess its infrastructure (City of Tucson, 2006). They have reported reduced costs and improved efficiency in many sectors, e.g., the fire department was helped with the precise localization of fire hydrants, leading to an increased efficiency of the service. Some important improvements have been noted in transportation, police, planning and water management, as a result of the GIS developed maps for specific sectors, but a lot of work is still to be done.

However, this database requires all documents to be converted into the GIS format. This process is time-consuming and expensive, therefore its effectiveness should be questioned. Moreover, newer digitized documents available for the recently constructed or renovated infrastructure are available in CAD format, which have already consumed human resources, and their conversion into GIS files is not economically sustainable. On the softer side, an underground utility might be represented with simple lines and do not contain information about its characteristics, such as geometrical dimensions, material, age, repair records, state of health, etc.

On the other hand, it is appreciable that attempts have been made by some cities to initiate the infrastructure inventory process, which is so valuable for a municipality. The created database could be upgraded and improved in the future, with the development of new technologies and technical advances.

5.3. Available Tools. Recent Developments. Model Accommodation to Future Technology Advances

The presently available tools in building infrastructure databases - the GIS or CAD-based systems - have proved their efficiency in municipal infrastructure-related applications and satisfactory results have been achieved. The development of more capable technologies to perform more accurate and powerful databases envisages a much promising future in the municipal infrastructure sector, which will primarily lead to better management and consequently to the improvement of the state of health of the infrastructure facilities and the services delivered.

As previously discussed, the Platform developed by Software P., Inc., counterbalances the drawbacks of the GIS databases with applications to municipal infrastructure inventories. Its capability to archive files in different formats to finally make them available on a GIS map might be the key solution in infrastructure management.

This Platform is also applicable in cases where attempts to develop infrastructure databases have been already made; this will allow future development of the databases, by plugging in valuable available resources but which could not be initially integrated in the databases. Eventually, an archiving framework, with specific features for each type of infrastructure can be developed and standardized, and implemented at the municipal, provincial and federal levels. The standardization will allow performing spatial queries and information retrieval at the national level and therefore the condition assessment could be easily performed over a periodic schedule, with a high level of accuracy.

The implementation of a National Policy with the standardization of the infrastructure inventory and the assessment methodology at local, provincial and federal levels will facilitate future research in database archiving technologies, since the development of a single methodology is needed. Their applicability will have to respond to the same need, which is not the present case in which each municipality or operating institution uses different approaches for inventory development and management purposes.

5.4. Cost versus Long Term Benefits

The implementation of the inventory and the condition assessment processes will initially involve some costs. However, once the methodology has been established, its application will become simpler and less expensive. The return on such an investment will have a long-term beneficial impact on Canada's infrastructure. Once the database is developed, the assets could be managed more efficiently and will lead to considerably improved decisions in terms of infrastructure investments, namely when, where and how to rehabilitate the existing deteriorated facilities. This will ensure that efficient investments are made on sectors needing immediate attention, with the constrained funding available. The future use of the methodology will result in large budgetary savings which could be invested in new infrastructure projects or in specific rehabilitation projects to ensure a healthy infrastructure for all Canadians.

CHAPTER 6

DETECTION OF BURIED SERVICES

6.1. Old Methods and New Technologies

Underground service detection in congested municipal areas has always been a challenge for the city engineers. Presently, even if plans are available from the city, they do not reflect the real underground layout of the different services such as water, sewers, gas, etc. This is mainly due to the poor design or nonexistent policy for infrastructure data archiving and database upgrading over the years. It is very likely that this aspect was not addressed with due consideration from the inception of underground utilities across Canada and currently, this trend has not changed much.

The old methods for detection the buried services are somewhat empirical and usually rely on the knowledge and memory of the elders who might have been confronted with their construction, operation, and repair and rehabilitation. In many cases, they retire and the information is lost. This knowledge, combined with in-situ reference points such as older pavement cuts, location of fire hydrants, buried valves, and inspection of the valves chambers through the manholes, can give an approximate estimate of the pipes layout. However, this might be imprecise and provides only guidance regarding the age, material, geometrical characteristics, etc. of the buried system.

In comparison with the earlier methods of approximate detection of the buried utilities, the GPR has proven its usefulness in underground detection, with a considerably high level of accuracy due to the recent technology developments. However, any information which can be available from other sources, i.e., drawings, visual location of hydrants and valves on the site, etc., might be useful in a utility location project, and might considerably reduce the investigation time. For instance, a review of the existing drawings can provide a quick idea of what is expected to be found underground; inspection of an underground valve chamber or of a pumping station which is close to the studied area might give accurate information on the pipe burial depth, diameter and material. Consequently, the GPR can be used much more efficiently if the general arrangement of the studied utility is obtained in a preliminary manner, therefore, an in-depth radar inspection may confirm the initial assumptions. However, if these data are not available, the GPR is able to scan large areas to determine the location of the underground utilities. In many instances, GPR is used to locate any other obstructions to clear the path in an area where a new service is to be installed, prior to unearthing or drilling (in the case of a trenchless installation).

6.2. The Ground Penetrating Radar (GPR) - Principle and Applications

The interest in developing a technology in the mining industry in Sweden for prospecting ore body dates back to 1930's (MALÅ GeoScience, 2005), when research for geophysical instruments was initiated. However, the GPR became commercially available only in the 1970's and was developed for mapping geological structures. Soon, the application of the GPR to other fields of interest was investigated, fostering the related research. Currently, there are more than 300 patents around the world, related to the GPR technology (g-p-r.com, 2006) with some major advances in mining, i.e., borehole investigations, archaeology, civil engineering, e.g., concrete investigation of concrete systems, and utility detection, and other fields.

The GPR uses electromagnetic waves which identify structures and objects hidden underground. The waves emitted by the source have a frequency within a range of 25-1600MHz, according to the dimension and depth of the object to be determined, i.e., to the type of application. The higher frequencies are not able to penetrate to higher depths, but they have the advantage of detecting smaller objects, i.e., a service connection or an electric line. Conversely, the lower frequencies penetrate deeper but they are not suitable for determining smaller objects. The spectrum of low frequencies is generally suitable for archaeological purposes. Table 7 presents guidance for the resolution and penetration depths, for different frequencies of the antennas used in the detection process.

Antenna Frequency Range (MHz)	Resolution (m)	In Soil (m)	In Rock (m)
25	1.000	25.0	40.0
50	0.500	20.0	30.0
100	0.250	12.0	20.0
250	0.100	6.0	12.0
500	0.050	3.5	5.0
800	0.030	1.5	3.0
1200	0.020	1.0	1.9
1600	0.015	0.7	1.5

Table 7. GPR Antenna Range, Resolution and Penetrating Depth (MALÅ GeoScience, 2005)

For utility detection, the method uses a device which usually consists of a radar source, an antenna, and a carrying cart to facilitate movement on the site. The source emits electromagnetic fields (200-500MHz) and the antenna picks the fields reflected through the ground on the pipe wall. The amplitude of the reflected signal is registered along with the time between the transmission and reception. The location of different infrastructure facilities is possible due to the differences of signals reflected by different materials with different dielectric constants.

The method is suitable for all materials but it has limitations because highly conductive soils and metallic structures in the proximity may influence the results. However, it provides enough information and the location of utilities can be determined quite accurately. The measurements are relatively easy to make, and the data can even be interpreted in the field when the device is capable of performing real-time transversal sections. It also permits rapid data acquisition, thereby saving valuable time in the field. The subsurface image is displayed directly in digital form. Images can be stored on a digital video logger (DVL), or on a laptop connected to the device. Figure 18 presents a typical image of a scanned subsurface.

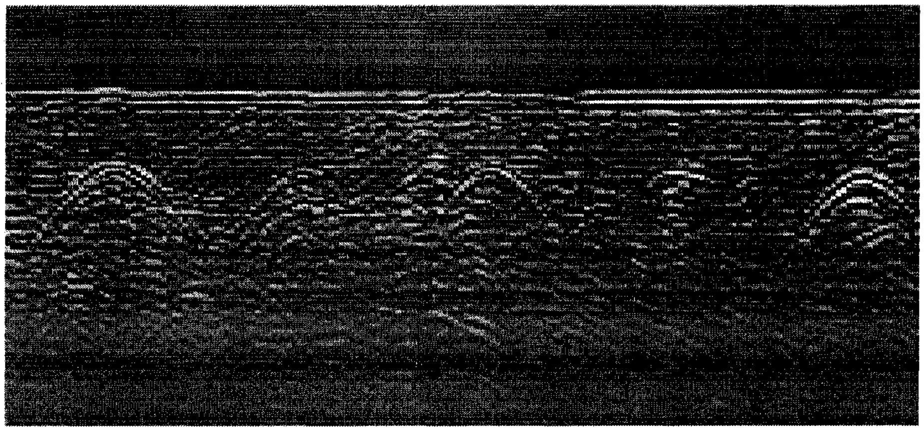


Figure 18. Typical view of an underground scan: Scale traces
(Sensors and Software, 2005)

The data include the depth at which the pipes are located along with the horizontal distances between the underground utilities. The peak of the hyperbola in Figure 18 designates the location of the pipe, in both horizontal and vertical directions.

6.3. Adaptability of GPR to Different Underground Infrastructure and Other Applications

Besides locating metallic and non-metallic pipes, the GPR can detect other buried services in a municipality, such as electrical lines, telephone networks, gas pipelines, heating distribution networks and other underground services. The location of different buried services in a congested area requires considerable attention and experience in data interpretation and a corresponding knowledge of the underground infrastructure. The high resolution of the GPR along with the instrument facility to record and store data on the site, permits creation of subsurface maps of the surveyed area quite easily, with reasonable accuracy.

The method is also suitable to test the condition of the ground surrounding the pipe, by determining the voids and the weak regions. To yield accurate results, higher frequencies

(1400MHz) need to be used, which are much higher compared with the previous applications, when buried objects were to be detected, e.g., the pipes. Therefore, the method is a valuable tool in determining the possible critical sectors, for example, where the compaction was not adequately performed, which causes internal stresses in the pipe wall, sometimes leading to breakage if the material used is brittle, e.g., cast iron, asbestos-cement, etc. Also, any minor leaks which cannot be detected through simple acoustic methods may create cavities in the ground surrounding the pipe, causing a non-linear distribution of stresses around the pipe wall. The phenomena may result in a sudden breach of the buried pipe. These discontinuities in the soil mass can be detected by the GPR. However, the GPR is limited in soil surveys with very low resistivity, i.e., less than 50 Ohm.m, as is the case of the moisture dependent light clays (MALÅ GeoScience, 2005).

6.4. Results

In conjunction with the software used to display the data, GPR scanning allows to reproduce three- dimensional (3-D) visualization, which, in some instances, provides a clear view of the scanned area. The cross sections and the longitudinal sections are used to map the underground services on the scanned area, with clear assessment of the burial depth and distances between the different services. The data acquired on the site can be easily managed and finally linked to a GIS map. Different underground utilities can be plotted on separate maps if the study focuses on a single service, e.g., water supply infrastructure. However, having the same GIS-reference map, different maps can be overlapped, to finally create a total picture of the subsurface.

In addition, other underground obstacles or soil irregularities can be mapped; these data are very useful in developing degradation models in a specific area for a specific type of infrastructure, or in forecasting the appearance of disruptions in the system, e.g., a water main breach if the surrounding soil presents irregularities, giving indices that a sudden break might occur.

CHAPTER 7

CONDITION ASSESSMENT OF UNDERGROUND INFRASTRUCTURE

7.1. Methods and Approach

The process of condition assessment of underground services, based on realistic measures and not solely on statistical data, is quite complex and involves several techniques and technologies, along with the experience and knowledge of several buried systems, i.e., water supply systems, sewage systems, and the degradation mechanisms that might occur in the underground environment. This follows the location process, which was discussed earlier.

Despite the fact that the water supply and sewage systems have common features (similar environment, similar distribution grid), their condition evaluation must be performed separately. In general, their causes of deterioration are quite different. Water pipes undergo diverse types of deterioration which lead mainly to loss of pipe structural capacity, especially due to corrosion, i.e., the case of metallic (grey cast iron, ductile cast iron and steel) and PCCP (precast concrete cylinder pipes) pipes and/or soil movement during freezing and thawing cycles, e.g., the case of brittle pipe materials such as asbestos-cement, vitrified clay and grey cast iron pipes. In some instances, chemical attack can affect the integrity of the water distribution infrastructure and occasionally operation or testing accidents may occur when the pressure exceeds the designed network capacity. The sewers experience different modes of deterioration which are basically due to external mechanical action, e.g., penetration of roots, water infiltration/exfiltration through inefficient mortar joints and manhole walls, along with the chemical and biological attacks which can result from the exterior or interior pipe environment. In the following, the water supply systems and sewer systems are discussed separately and steps to assess their condition are suggested, including the testing methods to be employed, incorporation of the available data from older documents and drawings, and other relevant features which can provide information about the infrastructure state, performance and its environmental exposure (microclimate and macroclimate).

7.2. Water Supply Systems

As discussed earlier, the water supply systems across Canada have a similar pattern in terms of age, materials used, and often workmanship and installation techniques, and environmental exposure. Some minor differences might exist from one municipality to another, however, the condition of a water supply system can be assessed by employing the same procedure which is described in the following, with minor adjustments. About 50% of the total length of the Canadian municipal water pipes is grey cast iron, followed by ductile cast iron, asbestos-cement, polyvinylchloride and precast concrete cylindrical pipes. The most problematic part is the high rate of breaks related to grey cast iron and ductile cast iron pipes and consequently, the emphasis should be on their condition assessment since they account for the majority of the water pipes in Canada. However, a correct approach must account for the different types of the pipes in the system along with their modes of degradation, and consequently, this will be included in the analysis.

7.2.1. Time-Saving Methods

Irrespective of the pipe type in the water system to be assessed, the preliminary steps in the evaluation process are similar. These first steps allow for a rough estimation of the system condition by employing simple techniques such as leak detection, water audits, hydrant water discharge inspection, or pressure tests.

Once the location of the water supply pipes has been determined, the state of fire hydrants and valves must be evaluated. For instance, the detection and replacement of a defective valve (e.g., with the gate blocked or damaged) can solve the problem of local ineffectiveness of the system. Similarly, a hydrant inspection and flushing can provide information on the network in its vicinity (e.g., a rusty water discharge shows a stagnant water sector or low water flow in the system, which can be due to advanced tuberculation in the water pipes and/or other causes because of which the sector may be obstructed). Water analysis at the hydrant discharge is important to assess the water quality, however, an analysis of corrosion products removed from the inner walls of the system during flushing can provide significant information on the pipe degradation. This method is not recommended during the cold season.

Another rough appraisal on a specific segment of the network can be obtained from pressure tests through which low capacity sectors can be identified (i.e. pipes with a high rate of tuberculation). One should note that pressure tests are not used on specific sectors with historic high breakage rates to avoid the occurrence of bursting due to high pressures. This method helps in determining the critical sectors in the distribution network where further investigation is required.

The preliminary inspections may refer to specific points in the system, but do not necessary reflect the state of the entire system. For a broader assessment, leak detection and consumption analysis can be very useful. Water audits or sonic detection of leaks are simple but effective, low-cost and time-saving methods. They are capable of evaluating leaks in the system and, in the case of acoustic leak detection, they help with the location of the leaking sectors. Complementary, non-acoustic technologies such as radar, tracer gas and infrared imaging can also be used, if further investigations are needed.

Water audits are usually performed on district metered areas (DMA) and require a continuous monitoring of the minimum night flows, which comprises the night flow delivered to the consumers along with the losses in the system and in the consumer's household network. This continuous monitoring assists in the evaluation of leakages with appreciable accuracy, in some cases detecting even a small breach (Halcrow Water Services, 2006). The effectiveness of water audits is well known, however, few water companies utilize it. An appreciable initiative was launched by the Halifax Regional Water Commission in 1999, for a water leakage reduction strategy implementation of the water supply system. The approach, developed by the International Water Association, was mainly based on DMA monitoring, supported by a supervisory control and data acquisition (SCADA) system. The consumption trends were continuously evaluated such that a leakage could be immediately detected. Along with a permanent pressure monitoring and control throughout the system, and rapid interventions for repairs, backed up by a good asset management, the Halifax Water Commission has considerably reduced the leakage in the water supply system by 2004, with about 27,000 cubic meters of water a day, corresponding to an annual saving of $500,000 (HRWC, 2006).

Sonic leak- detection equipment is normally used in determining and locating the leaks in a water distribution system. The methodology is based on the sound identification made by the water escaping a pipe, which is captured by geophones/ hydrophones, placed directly on the ground or in contact with the hydrants and/or valves. Usually, the small leaks are easier to locate because they are noisier than the larger ones. However, the existence of a small leak in the system is not easily identifiable unless a leak detection is conducted, compared with a larger breach which leads to a sudden release of a large volume of water, and which can be detected quickly, especially when water reaches the ground surface. Large breaks do not usually account for large water losses in the system since they are easily detected and repaired, compared with smaller leaks which can not be noticed and which can accumulate large volume of lost water over time (Zacharia, 2006). Leak noise correlators are also employed to pinpoint a leak; the principle is based on signal listening and interpretation at two different points, i.e., at two hydrants which makes it possible to locate a leak precisely. Most of the newer correlators are provided with noise filters and signal amplification, leading to more accurate results.

7.2.2. Critical Sectors and Assessment Techniques to be Employed

Assessment of the structural degradation of pipes is the most time-consuming part of a system evaluation. To ease the assessment process of a water system, only the critical sectors, determined through the foregoing simple techniques are to be considered for further evaluation. It is assumed that parts of the water supply system which provide good results through simple testing, correlated with the document-based or other data, if available, are in an acceptable condition. However, if any indices point out a higher breakage- rate, this will be considered a critical sector. This screening process requires a large amount of time that must be dedicated for advanced testing and therefore it cannot be performed on the whole system since it would not be justifiable economically. The methods used for an insightful analysis of critical sectors in a water supply system are based on magnetic field theory (remote field eddy current, magnetic flux leakage),or on ultrasonic or surface waves analysis (ultrasonic inspection and impact echo test). However, the latter are more suitable for analysis of large diameter pipes, such as precast concrete cylindrical pipe mains or large clay/concrete/ brick sewer lines and require that the pipes are empty when conducting the tests (Makar, 1999). The testing methods are still under development and are not commercially available presently.

For a detailed evaluation of the critical zones of metallic pipes, e.g., cast iron and steel, where condition of the pipe wall and loss in its thickness is suspected, the magnetic field methods such as the remote field eddy current and the magnetic flux leakage are employed. These techniques are able to detect material changes in thicknesses, i.e. wall pipe pitting corrosion, but their effectiveness has not been largely tested. However, the remote field eddy current method shows promise, with good response in tests performed on pipes having diameters up to 150 to 200mm.

7.2.3. Remote Field Eddy Current and Magnetic Flux Leakage. Application and Limitations

The two methods basically use the same principle of detection, the electric field/ magnetic flux alteration when passing through irregular surfaces (e.g., differences in wall thickness) and are suitable to assess the condition of metallic pipes (e.g. GCI, DCI and steel pipes).

A schematic arrangement of the elements comprised in the **Remote Field Eddy Current** technique is presented in Figure 19. A field effect is induced by a probe (hydroscope) inserted into the pipe. The exciter coil generates an alternative current magnetic field, which basically follows two different paths; the direct path is inside the pipe, in the direction of the pipe axis and the indirect path travels from the exciter coil through the pipe wall and returns to the receiver coil, via the pipe wall.

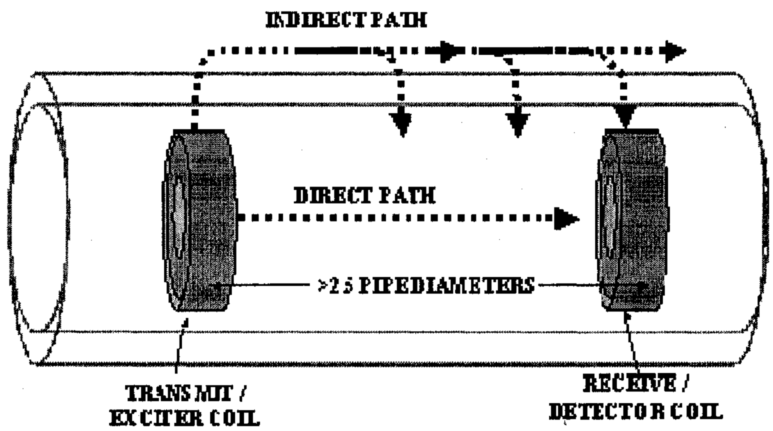


Figure 19. Remote Field Eddy Current Technique (Csiro, 2006)

The pick-up coil, which is also inside the pipe, is placed at a point which is at least 2-2.5 pipe diameters away from the emitter, where the field transmitted through the indirect path is stronger than the internal field (Csiro, 2006). The field emitted along the direct path is rapidly attenuated by the pipe wall and causes the waves traveling in the outer pipe to be picked-up faster by the receiver coil. The field is sensitive to the material thickness changes, i.e., the pipe wall, and therefore the method is able to detect the thickness reduction, holes, and cracks with a high level of accuracy, for both internal and external pipe deficiencies. The different phenomena which led to the pipe deterioration can be consequently detected, i.e., pitting corrosion, longitudinal cracking, etc. These data help to assess the actual state of the utility besides providing valuable information to further assist the validation of deterioration models in a specific area.

Remote field eddy current technique is not influenced by the potential tuberculation in the metallic pipes, i.e., grey cast iron pipes, or by the presence of non-metallic linings, i.e., the newer ductile cast iron pipes with cement-mortar lining (Makar et al., 1999). This gives the methodology a major advantage, making it appropriate for assessment of any metallic pipes allowing the hydroscope to pass through. However, the technology is applicable for smaller pipe diameters up to 200mm, therefore its use is generally limited to secondary distribution in a water supply system. The technique is promising and future research is needed to improve and develop it for larger pipe sizes to suit the needs of a municipality.

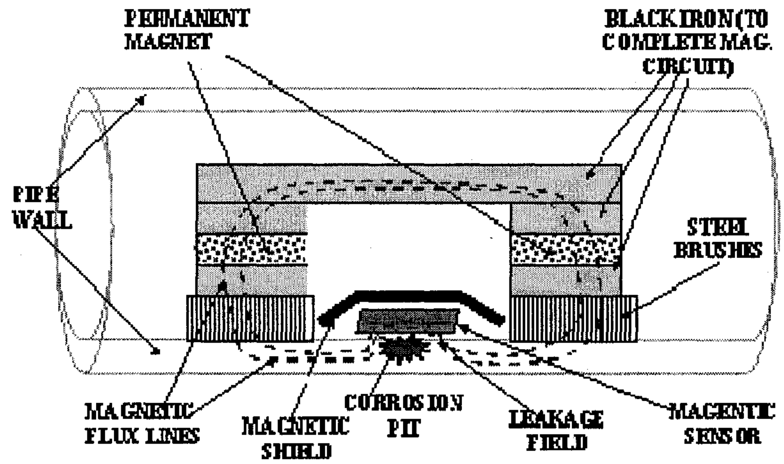


Figure 20. Magnetic Flux Leakage Technique (Csiro, 2006)

Magnetic flux leakage method can be also used for the same purpose. A couple of strong magnets, interconnected by steel plates at the upper side and by steel brushes at the lower side, provide a firm contact with the inner wall pipe, and are used to magnetize the sector of the pipe being studied (Figure 20). The magnetic flux induced is altered if a decrease in wall thickness is noted, i.e., in the presence of corrosion pits, and the surplus of the magnetic field which cannot be driven through the decreased wall thickness is captured by a magnetic sensor. This indicates the location where the wall pipe integrity has been affected.

Computer programs are now capable of assessing the changes in dimensions with an impressive level of accuracy of about 90%. However, compared to the Remote Field Eddy Current, this technique has multiple shortcomings, which may not make it sustainable for future development. The method is only suitable for metallic pipes since it is based on its magnetic properties to enable the formation of a magnetic field, therefore the pipe lining and the internal scaling will compromise the ability of the pipe to close the induced magnetic field circuit. The pipe must be thoroughly clean, and tuberculation removal is normally required, which leads to increased costs in performing the test. Furthermore, the weight of the magnets and steel plates needs to be higher than the weight of the pipe, which imposes dimensional limitations of the equipment and hence cannot be developed for smaller diameters. Finally, the strong magnetic forces between the equipment and the pipe wall do not allow the hydroscope to be propelled by the water pressure in the water distribution system (Csiro, 2006).

Some other methods such as ultrasonic inspection or impact echo/spectral analysis of surface waves are also available. **Ultrasonic inspection** is more suitable for concrete and ceramic pipes, and is based on the sound reflection induced by a high frequency beam when there is a change in the density of the material. This can determine material deterioration, e.g., concrete delamination, however, some possible cracks in the pipe wall might not be determined, if their orientation coincides with that of the ultrasonic waves (Makar, 1999). **Impact echo and spectral analysis of surface waves** employ similar techniques, and analyse the sound waves produced by a falling weight, which are captured by geophones mounted against the pipe wall. The wave analysis can provide information of the general state of the pipe, but it may not be able to locate specific defects (Makar, et al., 1999).

For PCC pipes, acoustic monitoring has been proven to be a valuable tool. This method is able to detect wire breaks in an operating pipeline using hydrophones for the monitoring of a given sector. The sound of broken wires is transmitted by hydrophones and the location of breakage can be evaluated. Despite the information available on the PCCP mains, acoustic monitoring is time-consuming and expensive. It is applicable to all types of prestressed pipes which are usually of large diameters and are used as water mains.

7.2.4. Analysis of Documents Relating History of Infrastructure

The analysis of information provided by the existing documents and records (repair and intervention records, frequency of repairs, etc, if available) is important. It permits a quick assessment of a specific underground facility in terms of age, type and frequency of deficiencies related to malfunctioning, etc., and sometimes it reveals the possible causes of previous failures. Hence, a preliminary analysis can be conducted to generate the information for pipes operating in an aggressive environment, which break periodically. In cases where the pipe approaches or has already reached its service life, or, if the sector is prone to frequent high pressure occurrences due to operating conditions, etc., the traces can lead to the identification of the critical sectors, where adoption of further testing techniques is considered.

The results obtained through in-situ methods, i.e., the GPR, sonic detection, etc. can be expected to detect defects in the system, which are already documented. However, the analysis cannot singularly rely on records which sometimes do not exist, or are even poor regarding the available information. Their use confirms the location of the critical sectors and the probable causes of deterioration of the pipe segment.

7.2.5. Assessment Process

The data gathered through the above techniques are computerized and interpreted. A thorough hydraulic capacity analysis and fire protection analysis can be conducted. Highlights of the analysis will be the identification of the priorities and an updated database. Further analyses can be performed, including the impact of non-realization of the imminent priorities. Correlation of structural degradation and soil corrosivity data related to the operating conditions of the water mains and historical records of breakages, if available, can be very helpful in validation of the pipe deterioration models. Therefore, an evaluation of the remaining service life of the system can be implemented and integrated in the newly created database for further reference. The techniques to assess the system condition were discussed earlier. Table 8 shows the steps which need to be followed in the assessment process.

No.	Steps
1	Confirmation of location of pipes using GPR
2	Map development- CAD/GIS
3	Fire hydrant and valve condition assessment
4	Sonic detection leak and/or water audits
5	Use of non-acoustic techniques, if required, for leak detection
6	Pressure tests -low capacity sector identification
7	Water inspection at hydrant discharge
8	Analysis of historical data for breakages and repairs
9	Identification of structurally critical sectors
10	Remote field eddy current test for critical sectors
11	Further investigation if needed- ultrasonic inspection, magnetic flux
12	Soil aggressiveness zone detection- if any
13	Soil instability zone detection- using high frequency GPR
14	Soil sampling and laboratory sample analysis
15	Interpretation of results
16	Identification of priorities
17	Integration of historical data analysis
18	Validation of degradation models
19	Estimation of remaining service life
20	Priority plan development
21	Cost estimation
22	Impact of non-realization

Table 8. Checklist for assessment of a water supply system

7.3. Sewer Systems

To visualize the composition of the sewer systems of Canadian municipalities, the City of Montreal is again used as a reference, a case which may be generalized to the national scene, since the systems were constructed generally using the same materials during roughly the same time periods. The differences in materials employed may be insignificant from one municipality to another.

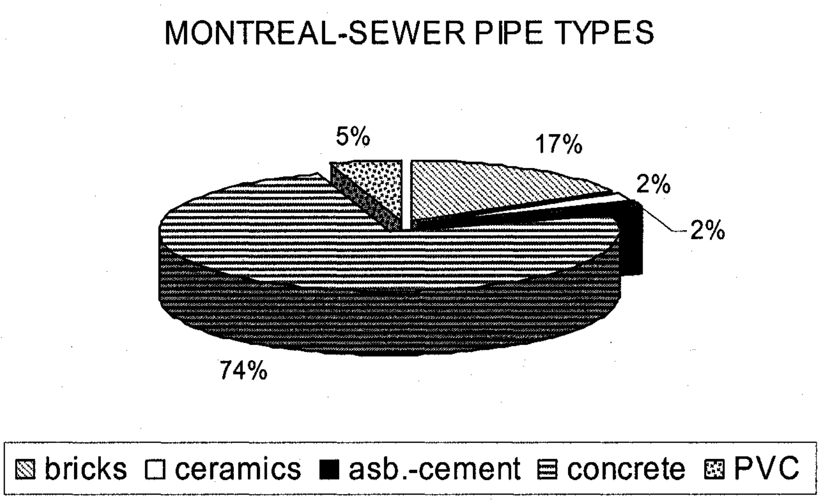


Figure 21. Materials used for the sewer systems in Montreal (SNC-Lavalin/ Dessau-Soprin, 2002)

Figure 21 shows the composition of Montreal's sewer system. One notes that the largest length of the sewers is made of concrete and account for 75% of the total stock, followed by brick sewer lines, PVC, asbestos-cement and ceramic pipes. The age of sewers, as discussed in Chapter 1 (Figure 2), can be considered to be less than 60 years old for the majority of the pipes, with only 25% of the sewers having ages between 60 and 100 years. Of course, some older pipes may exist in older municipalities and are still in service, however, they account for a very small percentage. According to Gaudreault et al. (2006), the different tiers of government focussed their investments on roads which in some cases resulted in some sewers rehabilitation, improving their status. For the year 2003, the ages of provincial and federal sewer systems were estimated to be 24.1 and

23.2 years, respectively. The age of municipal sewers was only 15.8 years old in 2003, as a result of increased municipal investments in the late 1990s, which have "rejuvenated" the system. This seems to contradict the theory of ageing infrastructure in Canada and does not accommodate the age pattern of municipal sewers on a national scale. With an average predicted service life of 115 years, i.e., concrete 114years, asbestos cement 138years, PVC 75years and vitrified clay 136years (Vanier, 2005), it leads to the conclusion that the municipalities across Canada have a brand new sewer system, which is surely not the case. Even the problems encountered with the sewers are of smaller extent compared with the water supply infrastructure, e.g., as mentioned previously, only 6% of the sewers in the Province of Quebec experience overflowing or infiltration problems (La Gestion de l'eau au Québec, 1999), they should be addressed with the same due consideration whilst they have a negative impact on the environment and on the population they serve.

7.3.1. Preliminary Inspection

The sewers across Canada are generally combined sewers, and in few instances separated, as wastewater and storm water sewers. Even if initially this idea was considered economically viable because of employing less material and work, over the long range, combined sewers put a significant pressure on the wastewater treatment plants, which finally have to treat the rain water, originally clean. This resulted in over-designed treatment plants to respond to higher water flows during storms and consequently, in an increased expenditure for wastewater treatment.

Regardless of the type of sewer, their condition assessment must follow the same steps, with the same testing methodologies employed. As in the case of fire hydrants (and sometimes valves) for the water supply system, the manholes constitute the "interface" between the buried utility and the exterior, being the singular points where the network can be accessed to gather information. Moreover, the inspection is simpler than of the water supply systems, since the sewers are generally gravitational systems and can be easily accessed without altering or disturbing the service they provide. Therefore, the structural inspection of the sewer system should start with a detailed visual inspection at the manholes. Some simple facts can be easily noted, such as the pipe diameter, material used, etc., and a preliminary estimate of its flow capacity, especially if the inspection is performed immediately after a rainfall, in the case of storm or combined sewers. Meantime, the condition of the manhole wall may help in assessing the age of sewer and provide indices of possible sewer overflow or infiltration problems through the manhole joints. Also, anaerobic biological activity can possibly be detected.

At the pipe level, a preliminary inspection can be performed using a zoom camera (**Stationary CCTV**) which will give partial information about the condition of the sewer lines (roots and infiltration, mortar and joint tightness). The video camera is introduced through the manhole, and it is capable of zooming in, giving accurate observations up to about 35m beyond the manhole. The method can investigate all type of pipes. Note that infiltration is simple to be observed when the water table is high, as is the case after a rainfall.

This method permits a quick assessment of the sewer condition and allows for creation of a preliminary database, which will help to determine the critical sectors with low capacity. Even if the results are not quite precise regarding the defects in the system, they still provide enough information about the low capacity sectors where further examination must be performed. Some advanced methodologies to investigate the critical sectors are the mobile CCTV, the laser scanning and the ultrasonic inspection, explained in the following section.

7.3.2. Review of Available Techniques

The closed circuit TV (**CCTV**) method is the most popular and convenient method to detect surface cracks, infiltration/exfiltration problems, significant erosion or pipe deformation. The simplest technique, described in the previous paragraph, uses a stationary CCTV, allowing for a quick evaluation. For a more in-depth analysis of the inner state of the sewer, the **mobile CCTV** is convenient to be used. The technique is based on information collection and defect identification using a remote mobile camera, which is pulled through the pipe. The operator monitors the process from the ground surface and identifies precisely the sectors which require repairs or replacements. The images can be videotaped and used for further analysis or reference. The process can be also assisted by a computer, allowing the information recording in a digital format, which can be correlated with a GIS-based subsurface map and eventually included in the inventory of the infrastructure studied. This methodology can be easily employed in pipes with even small diameters, i.e., 200mm, regardless the material type of the pipe. For most of the current CCTVs, an image perpendicular to the pipe wall is not possible, unless a remote device is installed on the pipe crawler, to enable the camera orientation in the desired direction.

Ultrasonic inspection, impact echo/ spectral analysis of surface waves are other techniques that can be employed in sewers conditions assessment. These methods and their application were discussed previously, in the water supply systems section. However, they seem to be currently more expensive than the CCTV technique and are not proved to be more accurate in detecting possible defects; moreover, they may require pipe cleaning to yield correct results (Makar, 1999).

Laser scanning is a valuable tool in assessing the pipe geometrical characteristics. This technique is able to detect the deformations of pipes due to overloading or advanced deterioration. In some instances, deformation of the pipe walls cannot be observed by common techniques (even by CCTV), especially when dealing with small deflections, therefore a laser scan is effective in these situations. However, only deflections above the water line in the sewer can be observed; a detailed inspection requires the pipes to be emptied prior to analysis.

Complementary tests may be also used, depending on the type of information required, e.g., smoke test, tracer method. These techniques are used to retrieve basic information from the system, such as infiltration and branch connectivity to the sewer main. In the smoke test, non-toxic smoke is sent into the pipe sector, blocked at the ends;

consequently, if any deficiencies in the pipe wall do exist, the smoke will escape through them, enabling location of infiltration spots in non-saturated grounds. The tracer method uses a coloured liquid or powder to check if branches are properly connected to the sewer main.

7.3.3. Historical Documents

As in the case of water supply systems, the available data is helpful in a primary assessment of the system condition. It delineates the critical sectors where failures had occurred in the past, and where aggressive zones or accidental loadings may occur to finally cause failure. Eventually, the age of the buried infrastructure as well as the geometrical characteristics (shape, diameters) and the type of materials used can be obtained from the "old" documents. The sectors where repairs were conducted regularly can rapidly identify possible critical sectors along with the locations where further investigation might be required. However, the paper-based evidences must be backed up by real in-situ measurements to precisely locate the critical sectors.

The information from the paper-related documents, if available, should be used in conjunction with the complementary tests performed in-situ (CCTV, laser scan, and other tests). The condition assessment of a given sector should not rely solely on the analysis of the existing documents since the information may be incomplete, and occasionally obsolete.

7.3.4. Assessment Process

The assessment process is similar to the water supply system, with the difference that different testing methods are employed. Data gathered from both paper- based document and in-situ measurements and tests can help in creation of a database of the analysed sewer system, based on "real" data. If referenced to a GIS-based map, the database will allow performing spatial searches, with classification of defects and deterioration range of the infrastructure studied.

The inventory and the updated database will enable validation of a hydraulic model for the sewer lines and will allow identification of the priorities. As in the case of the water network, the impact on the nearby infrastructure can be assessed in cases where the priorities have not been considered, e.g., soil contamination, water system contamination, impact on other underground utilities and environment.

The steps to be followed in the assessment of sewer systems are presented in Table 9.

No.	Steps
1	Location of pipes using GPR
2	Map development- CAD/GIS
3	Analysis of manholes -structural and tightness against leakage
4	Zoom camera - for preliminary inspection of sewers through manholes
5	Preliminary database creation with delineation of suspected critical sectors
6	Interpretation of the preliminary results
7	Identification of low capacity sectors
8	Analysis of historical data (plans, drawings, repairs, etc.)
9	Identification of structurally critical sectors
10	CCTV Test for further investigation of critical sectors/ Laser scanning
11	Smoke test and tracer method, if required
12	Soil aggressivity and instability detection using high frequency GPR
13	Soil sampling and laboratory analysis
14	Identification of priorities
15	Validation of degradation models
16	Estimation of remaining service life
17	Priority plan development
18	Cost estimation
19	Impact of non-realization

Table 9. Checklist for assessment of a sewer system

CHAPTER 8

DETERIORATION MODELS- WATER AND SEWER PIPES

8.1. Causes of Deterioration

Underground water pipes can fail in different modes of failure and are due to several typical factors, such as improper installation, accidental loads (internal and external), and material degradation. In many instances, failure can be induced by a combination of factors, such as extreme loads and advanced pipe weakening due to material deterioration. While the first two issues can be easily controlled by quality control measures during installation, and pressure monitoring, and control during the operation of the facility, respectively, the latter is somewhat more complicated to observe, unless a routine inspection and maintenance plan is performed, which is not the case with most of the underground infrastructure, regrettably. Therefore, the deterioration mechanisms, that take place in the underground environment, will be emphasized in the following sections.

8.2. Installation Conditions. Applied Loads

Pipes are usually overdesigned, i.e., the wall thickness could resist more than 1.5 to 2 times or more than the expected pressure in the system, granting a safety margin. For instance, a high density polyethylene pipe designed for a pressure of 6bars may withstand 5 times the design pressure for a certain period of time, enabling the pipe to perform satisfactorily under possible surge pressures in the system. A cast iron pipe would have enough wall thickness to assure an adequate resistance to internal water pressure for a certain period of time, even if some deterioration occurs and might weaken the wall. However, these reserves taken into consideration during the design phase should not be used for other purposes, such as accounting for poor installation or increased external/internal loading, e.g., a cast iron pipe is not supposed to resist the loads caused by improper installation, or by other external loading, normally not considered in design. Therefore, proper pipe bedding is mandatory and should be carried out with the pipe installation; it must provide a uniform pipe support and should be permeable to allow water to escape by seeping into the soil, thereby causing no damage to the bedding and mitigating the risk of corrosion. The backfill is equally important, and it should be clean, and it must avoid uneven loading of the pipe. These issues are very important in reducing the breakage frequency (O'Day, et al., 1986).

Design standards require a pipe to be designed for the weight of the overburden soil and traffic, and internal working/surge pressure (Smith, et al., 2000). Surge pressure known as "water hammer" does not usually occur during normal operating conditions, but can develop as a result of shutting down a valve or by starting a pump, especially when the system is not protected with air release valves and expansion vessels.

Accidental conditions such as a car hitting a fire hydrant or a caterpillar hooking an underground pipe on a construction site may occur. These damages are visible and easy to locate, therefore repair can be conducted immediately after the accident. Also, an overloading created by heavy construction equipment may result in significant damage if the pipe is not designed to resist this type of loading.

Some loadings which cause no visible damage such as a powerful hammer driving piles into the ground may cause through repeated vibration significant destruction of a water service or sewer in the site neighbourhood on the long run, by initiating leakages at the sensitive points of the system such as joints, which can ultimately lead to pipe bursting. These unobserved injuries might also be created by earthquakes. However, if the earthquake is strong, bursting is instantaneous in many instances. In a case study of the water system damage (comprising of more than 80% ductile iron pipes) after the earthquake in Kobe, Japan, Smith, et al., (2000) highlighted that the predominant failure was the pullout of joints (in more than 40% of cases), followed by damage to the hydrants and valves (in 21% of cases) and broken pipes (16%). The study clearly showed what the most vulnerable points are in a ductile-cast iron-based water supply system in the case of an earthquake.

The buried elements of a water supply system can be subjected to large forces caused by expansive soils (clay) during wetting and drying cycles. This will cause soil movements along with increased loading on the pipe, with an axial/ beam loading pattern. Brittle materials such as grey cast iron, asbestos cement or vitrified clay are prone to failure under these conditions, but flexible pipes such as high density polyethylene are the best choice.

Since most of Canadian municipalities are confronted with harsh climate, water pipes can be severely affected by extreme temperatures. Besides the contraction induced in a buried system due to cold weather, water in the soil pores might freeze and expand, causing downward pressure on the pipe. For a metallic pipe, weakened by increased corrosion activity, this might cause it to fail. Rajani, et al., (1995), showed that axial stress modifies by about 20% for each 5` C change in temperature, resulting in circular water main breaks. During the same study, a peak of the breakage rate was observed during the coldest period. Again, for these conditions of operation, flexible and elastic plastics, e.g., medium and high density polyethylene pipes represent the most suitable choice.

8.3. Pipe Degradation

8.3.1. Metallic Pipes

Failure of metallic pipes is generally caused by corrosion, in many instances combined with instantaneous loading from increased external loading or from internal water pressure. In a study of 27 grey cast iron pipes failures from different municipalities in the region of Ottawa-Carleton and Toronto, Makar (1999) noted that a majority of the failures was associated with corrosion, and certain failures were produced by a multi-stage process. This combined phenomenon usually leads to pipe fractures which generally induce the most expensive pipe failures (Makar, 1999). For cast iron pipes, which constitute a majority of the Canadian water supply systems, typical failure modes were observed. For instance, small diameter cast iron pipes (<400mm) are prone to failures caused by circumferential cracking, blowout holes and bell splitting, whereas the larger diameter pipes (>400-500mm) fail through longitudinal cracking, bell shearing and spiral cracking (Makar et al., 2001).

Corrosion is a major cause of metallic pipe deterioration; it is an electrochemical reaction between the pipe and the environment - water internally and surrounding soil externally. In the process, electrons are transferred from the metal to an oxidizing agent (such as oxygen or hydrogen ions). The reaction takes place between different metals in the system (galvanic corrosion), or different areas of the same metal, e.g., pipe- fitting, or pipe-pipe interactions. The anode is formed where electrons are able to be released which are then accepted at the cathode for a reduction reaction. The process can be summarized as follows:

$$Fe \rightarrow Fe^{2+} + 2e^- \qquad (8.3.a)$$

The electrons must be accepted by a reduction reaction at the cathode for the anodic reaction to occur, which will result in the formation of hydroxyl ions:

$$O_2 + 4e^- + 2H_2O \rightarrow 4OH^- \qquad (8.3.b)$$

The iron ions and hydroxyl ions then combine and form iron hydroxide,

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2 \qquad (8.3.c)$$

which gets oxidized, finally forming rust products.

$$4Fe(OH)_2 + O_2 \rightarrow 2Fe_2O_3 \cdot H_2O + 2H_2O \qquad (8.3.d)$$

8.3.1.1. Internal Corrosion of Metallic Pipes

Internal corrosion leads to serious problems, such as decrease of load bearing capacity, reduced flow capacity, tuberculation, increased roughness and sometimes water contamination (Smith et al., 2000). Corrosion initiates at points where the pipe material is depassivated due to scratches, scaling, or alteration of the internal lining for the newly installed ductile iron pipes, if it was initially provided. While the pipe is always full of water, the internal pipe environment is apparently oxygen-free, and corrosion occurrence is minimized, however, water contains sufficient dissolved oxygen that can promote the production of hydroxyl ions at the cathode (equation 8.3.b). The iron hydroxide formed (equation 8.3.c) precipitates at the anode in a porous layer, which is further oxidized into ferric oxides (rust products), leading to the formation of the so-called tuberculation. According to Smith et al., (2000), this medium is ideal for the anaerobic bacteria to develop, which accelerates the rate of corrosion and deteriorates the water quality.

Parameter	**Effect**
Dissolved oxygen	Increases rate of corrosion
Temperature	Increases corrosion rate and stimulates biological activity
Low pH vs. high pH	Low pH- increases corrosion rate; High pH- tends to minimize corrosion, but favours zinc removal from brass (fittings) and damage copper pipe (used for connections)
Low/high water flow	High flow- increased turbulence thus increased erosion Low flow- favours pitting corrosion, crevice corrosion
Alkalinity	Forms a protective coating of scale; high alkalinity increases copper, zinc and lead corrosion
Calcium	Forms a protective coating of scale, but increased concentration causes high scaling, and tuberculation
Chlorine residual	Increases rate of corrosion; decreases biological activity
Chloride, sulfate, hydrogen sulfide, ammonia	Increases corrosion; ammonia determines copper pipe corrosion, chloride and sulfate may promote corrosion in galvanized steel
Magnesium	Inhibits calcite precipitation (from calcium carbonate)
Total dissolved solids	Increases water conductivity, therefore increases corrosion rate

Table 10. Effects of the Parameters influencing Internal Corrosion of Metallic Pipes (Adapted from Vik et al., 1996, and O'Day et al., 1986)

The conditions at the inner surface of pipe are different in each case, depending on the water quality, temperature and network inhomogeneity. Thus, the internal corrosion of metallic pipes is influenced by a number of physical, chemical and biological parameters such as the presence of dissolved oxygen, temperature, flow, alkalinity, chloride content, sulfate, hydrogen sulfide, ammonia, etc. The different effects of these parameters on the corrosion activity are presented in Table 10.

Graphitization involves selective leaching of iron, due to the differences in the galvanic acidity between two elements in an alloy (Smith et al., 2000). It is a slow process which takes place along a large area of the pipe and results in a uniform distribution of corrosion. This results in a porous metal surface with a matrix of residual graphite, corrosion products (hydroxides, iron oxides) and voids. Corrosion appears to be superficial with little loss in the material thickness, however, it results in significant strength reduction. Cast iron is sensitive to graphitization. Initial, laboratory and field studies (LaQue, 1995) led to establish that graphitization is present to the same extent in grey and ductile cast iron. However, recent research shows that grey cast iron is much more vulnerable, and in many cases it is the cause of failure, especially if combined with mechanical stress or hydraulic shock.

Crevice Corrosion is a phenomenon caused by the chemical environment in a small area of the pipe, i.e. damage of the internal lining, scale deposits or joint imperfections and is likely to occur in pipes with stagnant water (or a low velocity flow). The dissolved oxygen in the crevice has the tendency to deplete at a higher rate, as a result of internal corrosion of the pipe, giving the crevice an anodic character. As a result of the varying concentration of the dissolved oxygen, the electrons migrate from the crevice to areas with more oxygen (cathodic areas) due to the consequential drop of voltage, where they react with oxygen and form hydroxide ions. Eventually, hydroxides and other iron impurities migrate to the anode (the crevice) and deposit, forming a porous tubercule. The deposit of corrosion products will worsen the situation, by further obstructing the anode for oxygen, leading in some cases to an acidic- microenvironment formation in the anodic area. This may cause a significant local drop of the water pH, accelerating the corrosion from about 0.2mm/year to up to about 1-1.8mm/year (Corrosion-Doctors, 2006). Crevice corrosion causes a rapid weakening, or perforation of the pipe wall due to its increased rate of perpetuation.

Occurrence of **Pitting Corrosion** is based on the same principle of differential oxygenation, however, it starts at the pipe surface, with formation of small diameter pits. Occasionally, the cavities formed may be larger. Pitting corrosion is usually manifested on small areas with isolated pits, but it can also take place on larger areas, with multiple adjacent pits. In both instances, the amount of metal removed through this process is small, but the damage is relatively high because it causes a local weakening of the pipe wall resulting in failures eventually. Pits are difficult to detect due to their small dimensions; moreover, they are typically concealed by the corrosion products.

Pitting corrosion is common in cast iron pipes, however, it also causes significant deterioration in the ductile cast iron pipes. In an analysis of data collected on water main breaks in 21 Canadian municipalities, Rajani et al. (1995) showed that only 20% of the water main breaks in grey cast iron were associated with pitting corrosion, whereas in the case of ductile cast iron pipes, pitting led to failure in 76-78% of the cases. Ductile cast iron pipe can deteriorate at an alarming rate, if unprotected. According to De Rose et al. (1985), in a survey of 359 corrosion failures conducted in the UK, pitting corrosion rate of unprotected ductile iron pipes range from 0.5 to 1.5mm/year, with maximum values of up to 4mm/year.

Erosion Corrosion is most likely to occur in pipes with high flow (i.e. areas of reduced cross-section, sharp elbows) and it accelerates corrosion when the pipe was initially passivated (i.e., deposits of corrosion products, or mild scaling). The protective layer of passivation is damaged or entirely removed by the high water flow, leaving the inner wall unprotected and increasing the corrosion rate. Corrosion results in the formation of grooves, or rounded holes. Erosion can be significantly reduced from the design phase of a water supply system if appropriate measures are initially considered, i.e., assuring uniform flow in the distribution system, providing large bends instead of sharp elbows or providing erosion-resistant materials at the key points with expected erosion occurrence.

Biological Corrosion involves aerobic microbial growth on the inner pipe surface. The microbiological film consumes oxygen and causes a drop in the local dissolved oxygen, and it may also form a barrier inhibiting the oxygen migration. This local drop of dissolved oxygen promotes further corrosion. Also, the metabolic process of some microorganisms, e.g., which produces various sulphur species or phosphorous compounds, or the hydrogen peroxide, may accelerate the reactions that promote corrosion (ASM International, 2006).

8.3.1.2. External Corrosion of Metallic Pipes

External corrosion follows the same basic principles as the internal corrosion, the difference being the environment, which this time is the surrounding ground. The degradation process leads to the pipe bearing capacity alteration which eventually may result in pipe failure. External degradation of metallic pipes can be sometimes accompanied by other phenomena such as freezing and thawing cycles, pipe contraction during cold seasons, or accidental loading, which increase its probability of failure.

The parameters that influence external corrosion are the pipe material and the variations in its microstructure, homogeneity of the water network (pipes, fittings, valves, connectors, etc.), type of soil and its properties, humidity, and the presence of external electrical fields.

The **soil** has a decisive **influence** on the corrosion of the pipes. Its composition, moisture content, salt content and/or its acidic character, and even the contact with the pipe are some factors to be considered in a pipe-soil interaction analysis. The Ductile Iron Pipe Research Association (DIPRA) first introduced the 10-point soil evaluation procedure, which was further adopted by the American Water and Wastewater Association, and incorporated as an appendix in the Standard for Polyethylene Encasement for Ductile Iron Pipe Systems in 1993, revised recently in 2005 (ANSI/AWWA, 2005), This soil evaluation is usually applied in the case of grey cast iron and ductile cast iron pipes.

Table 11 describes the basic principle of the 10-points system. The soil is graded as a function of its properties which are its resistivity, pH, redox potential, quantity of sulfides and moisture content.

Soil Characteristics	Points
Resistivity (ohm-cm)	
<1500	10
1500-1800	8
1800-2100	5
2100-2500	2
2500-3000	1
>3000	0
pH	
0-2	5
2-4	3
4-6.5	0
6.5-7.5	0
7.5-8.5	0
>8.5	3
Redox potential (mV)	
Negative	5
0-50	4
50-100	3.5
>199	0
Sulfides	
Negative	0
Trace	2
Positive	3.5
Moisture	
Good drainage, generally dry	0
Fair drainage, generally moist	1
Poor drainage, continuously wet	2

Table 11. Soil test evaluation (ANSI/AWWA, 2005)

If the total number of accumulated points is more than 10, corrosion is most likely to occur in the pipe embedded in the soil.

The soil classification in Table 11 shows that the main characteristic that drives the result of interpretation is the soil resistivity. Consequently, a quick soil evaluation which does not require much data can be withdrawn from Table 12, which is solely based on the soil resistivity (Hamilton, 1960).

Resistivity (Ohm-cm)	**Soil Corrosivity Description**
Below 500	Very corrosive
500 – 1,000	Corrosive
1,000 – 2,000	Moderately corrosive
2,000 – 10,000	Mildly corrosive
Above 10,000	Progressively less corrosive

Table 12. Soil Corrosivity Rating (Hamilton, 1960)

Soil corrosivity favours **external pitting corrosion** of metallic pipes. This type of degradation is manifested in all metallic pipes and is directly related to the soil resistivity. However, a low resistivity soil is likely to cause more attack on ductile cast iron. Data acquired by several surveys and studies in the U.S., Canada and Europe, are reflected in Figure 22, which gives the potential pitting rate of ductile iron pipes for different soil resistivities (Angelfire, 2006).

Figure 22 gives the maximum pitting rates observed in ductile iron pipes, but they have been observed to decrease with time. Pitting corrosion rates in ductile iron pipes were considerably higher compared to those of grey cast iron which were much older (Angelfire, 2006). The age issue may explain the discrepancy between the ductile and grey cast iron behavior, the latter being observed to be more resistant to this type of degradation. Meantime, the wall thickness of older grey cast iron pipes (which is around twice that of the ductile iron) might support the theory of being more resistant to pitting.

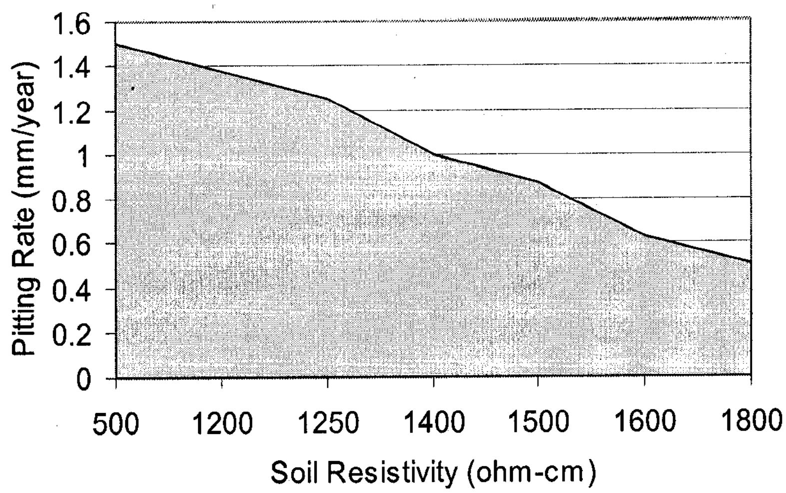


Figure 22. Maximum pitting rates (mm/year) for ductile iron pipes (Adapted from Angelfire, 2006)

Galvanic Corrosion is a phenomenon that appears when the water supply system is not homogeneous in terms of materials used, or when galvanic insulators between different pipe materials are not installed. In some instances, accelerated failures might occur as a result of the galvanic reaction of dissimilar metals, usually at the tapping saddle of metallic pipes with a copper household connection. A galvanic corrosion cell is formed, with the copper acting as a cathode and the iron pipe as the anode. Since the North American household connections are usually of copper, this type of degradation is often observed in water supply systems. Even the probability that this type of corrosion leads solely to failure is small, studies have reported that this contributes to metallic pipe failures in many cases. Stetler (1980) observed that 80% of 23 ductile cast iron pipes failures in Wisconsin were located at less than one meter from a copper element in the system, i.e. a copper service connection, or a brass valve.

In underground conditions, **Microbiological Corrosion** is likely to appear, be it aerobic (oxygen to promote the corrosion reaction is available in the soil) or anaerobic corrosion. In the latter case, corrosion is driven by anaerobic bacteria which may exist in the soil, i.e., sulfate reducing bacteria, which are capable of delivering oxygen from the existent sulfates and nitrides in the soil, or corrosion products. Evans (1948) indicated that corrosion under anaerobic condition may proceed at an alarming rate as much as 19 times faster than in sterile conditions. Ferguson et al., (1984) estimated that 50% of causes of metallic pipe failures were due to microbiological attack in a study conducted in Australia.

In urban areas, where electrified railways and trolley bus systems are present (direct current systems) or where high voltage current lines with ground return are installed, **Stray Current Corrosion** may occur in the metallic water pipelines. The water pipelines are ideal paths for earth-return currents, which provide higher conductivity than the earth "cables". Exceptions are the new ductile cast iron water pipelines, which are not good electrical conductors since the pipe segments are connected through rubber gaskets, providing an electrically discontinuity in the system. Stray current corrosion is mostly prevalent at the confluence where the current leaves the pipe and enters the ground and results in accelerating the corrosion by enhancing the potential of existing anodes and cathodes (Angelfire, 2006). Horton (1991) reported that Alternative Current Corrosion requires minimum currents densities, i.e., $1 mA/cm^2$ for corrosion to be initiated in underground metallic pipelines.

In addition, there are other factors that influence corrosion. Being given that pipes are usually installed above the water table, the exterior of pipes is subjected to wetting and drying cycles, which favour the corrosion process. Also, salt exposure that comes from the sea water intrusion in the soil in coastal regions, or from intrusion of deicing salts after thawing periods, can accelerate the rate of corrosion in buried pipes.

8.3.2. Concrete Pipes

To minimize the use of steel, engineers have introduced the pre-cast concrete cylinder pipes (PCCP) during the World War II. It is an efficient mode of benefiting from the high concrete compressive strength and the high steel tensile strength (Worthington, 2004). Besides, it is a low cost solution in producing large diameter pipes. However, despite the advantages these pipes seemed to offer, PCCP may degrade at an accelerated rate once the deterioration process is initiated. A common arrangement of the five different layers of a PCCP, i.e., cement-mortar, prestressing rings, concrete, steel cylinder and concrete, is presented in Figure 23.

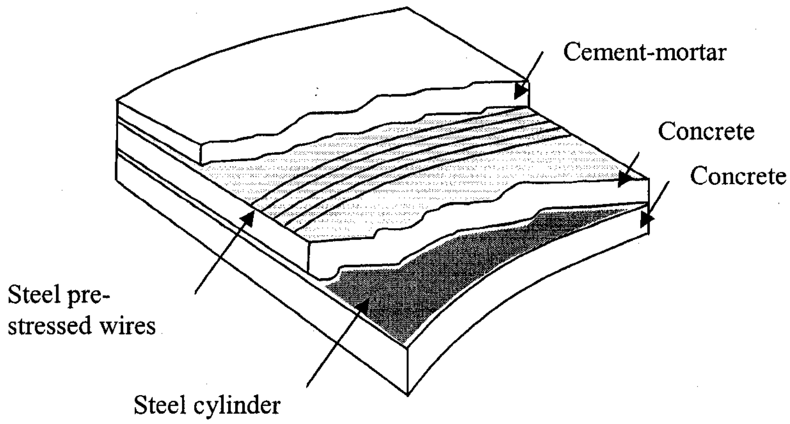


Figure 23. Pre-stressed Concrete Cylinder Pipe (PCCP)

8.3.2.1. Internal Degradation of Concrete Pipes

Deterioration of the inner surface of a concrete pipe leads to loss of the wall thickness, a decrease in the flow capacity, and an increase of calcium content in the water. As the concrete structure is porous and the pipe is subjected to varying quality of water, it is obvious that different chemical reactions can develop at the level of the pores which can lead to a decrease in the performance of the concrete pipe.

Leaching of Cement Compounds- Because of the different compounds contained in the pore water of the hydrated cement paste, and the transported drinking water, chemical reactions occur and these may result in damage to the concrete pipe. The pore water in the concrete structure which has not reacted in the process of manufacture (which is in a very small quantity) contains ions released by the hydration reaction of concrete (calcium, magnesium, hydroxyl). On the other hand, drinking water has a higher concentration of carbonates. Diffusion of carbonates in the concrete pore structure is therefore possible, along with the migration of the calcium ions contained in the water pores. Calcium carbonate formed tends to precipitate, which is possible if the quality of the drinking water promotes this process (low flow rate, carbonate concentration, pH, etc.). In this case, the calcium carbonate will tend to block the pores, hindering calcium from leaving the pores. Conversely, if the water does not allow formation of stable calcium carbonate, removal of calcium will continue and will result in the enlargement of the pores, and deterioration of the pipe walls.

Sulfate Attack- Contact with water with high concentration of sulfates, exposes the concrete pipe walls to sulfate attack. The phenomena involves the formation of ettringite, as a result of reaction between the calcium aluminates in the cement with the sulfate, which will expand upon imbibing water and lead to cracking and spalling of the concrete, therefore, the load bearing capacity will be significantly reduced, or even lost. The reaction may be avoided by using cement with lower tricalcium aluminate content (less than 5%) and by the use of a low permeability concrete.

Alkali-Aggregate Reaction- If the aggregates used in the manufacture of concrete pipes contain dolomite, feldspar, schist, the pipe will be vulnerable to alkali-aggregate reaction. Aggregates react with the alkalis from the alkali-silica gel and will cause concrete expansion due to the formation of low-density compounds in the presence of water. The process can result in concrete spalling and cracking. The water which is necessary for the reaction to take place may be the pore water, or the drinking water in the pipe.

Biological Attack can occur in sewer pipes in anaerobic conditions. The hydrogen sulphide which is formed in this environment is oxidized by the bacteria on the pipe walls and transformed to sulphuric acid, which attacks the concrete pipe. The chemical reaction of the acid with the calcium compounds in the concrete results in formation of calcium salts of the attacking acid (calcium sulphate), which leads to the destruction of the entire layer of the affected concrete.

8.3.2.2. External Degradation of Concrete Pipes

External degradation of concrete pipes occurs for the same reasons as in the case of metallic pipes, and consequently, as mentioned in the previous paragraphs, it is influenced by the presence and concentration of underground humidity (level of the water table), soil properties, and bedding configuration. In addition, aggressive soils, containing acids or high amounts of sulfates will lead to acid/ sulphate attacks, resulting in concrete delamination and corrosion of the prestressing strands in the case of the PCCP. Furthermore, wetting and drying conditions are also harmful as they contribute to the migration of chemical compounds from the soil into the concrete structure, by adsorption and diffusion. Freezing and thawing cycles may also be present in the case of low burial depths. In some cases, pipes may be subjected to chlorides, as a result of their infiltration into the ground, proceeding from the use of deicing salts on pavements used for traction in the cold seasons. The worst, combinations of these attacks can possibly develop and cause accelerated degradation.

Usually, concrete pipes are used for sewers. As previously discussed, they account for the majority of the sewage pipes across Canada and their state is generally acceptable, showing that the underground environment does not produce extended damage to concrete in most instances, as compared with the metallic pipes.

Prestressed concrete cylinder pipes are more prone to external degradation, because a local delamination can initiate and promote corrosion, leading to breaking of the prestressed reinforcement and finally the pipe bursting. Once the concrete in the surface of the pipe is damaged, irrespective of the mechanism; corrosion of prestressing reinforcement occurs and takes place at a high rate, because of stress corrosion. Hydrogen embrittlement is another cause leading to the destruction of the reinforcement, eventually causing failure of the pipe. When the prestressed rings break, the stress is transferred to the coating which separates from the core and promotes corrosion of the adjacent reinforcement. The core compression is released and the water pressure will cause internal concrete coating to crack; when the single layer in the pipe which can withstand this pressure - the steel cylinder - reaches its yield point, the cylinder expands and bursts. Moreover, as the PCCPs are employed for water mains, a breach can cause significant costs and health and social consequences to the population, such as service interruption or increased probability of water contamination.

A clear model of deterioration of PCCP has not yet been established. There is no evidence of how many broken wires will cause an imminent failure of the pipe (Makar et al., 2000). Moreover, in a NRC study of acoustic emission monitoring of a precast concrete cylinder pipe, Makar and Baldock (2000) reported that cracking of the outer mortar was observed where ten adjacent wires broke. It is, therefore, an indication that failure is about to occur, prior to the breakage of several wires; this makes failure prediction of a PCCP a difficult task.

Plastic and ceramic pipes do not undergo significant degradation, even in harsh environments. Their degradation is not discussed here, since they are basically not bio-degradable materials. Bonds (2000) stated that ductile iron is much resistant than polyethylene pipe, based on laboratory tests, however, these pipes were not observed during a long period of service, e.g., 40years. Further, Pimputkar et al. (1997) noted the possible formation of pinholes in the gas polyethylene pipes, as a result of partial electrical discharges at imperfections of the pipe wall. Together, degradation of plastics is still insignificant compared to other commonly employed materials in municipal water and sewage systems, such as cast iron or concrete. According to Rajani et al., 1995 (Figure 9), for several Canadian water supply distribution systems, the breakage rates of plastic pipes, such as PVC, was around 10 times lower than that of ductile cast iron and 40 times lower than that of grey cast iron.

8.4. Data Analysis and Modeling

Based on **in-situ measurements and analysis** of the available data regarding the frequency of intervention in a given area, one can formulate a trend for an underground facility. For example, if in a sector of a distribution network, breakage occurs periodically due to the same cause, say corrosion induced by chlorides, it is expected that the entire region could be subjected to the same attack in the future. Accordingly, a deterioration model can be established, which can be applied to the other sectors with similar causes of deterioration.

Validation of a deterioration model is primarily dictated by the buried pipe type and underground microclimate. Adjustments can be made when applying the model to a location with similar characteristics, to account for minor details such as workmanship, bedding conditions or exterior loading conditions, e.g., a pipe under the traffic lane vs. a pipe running in an open green space. At this point, the use of paper-based records or other types of archived data is helpful.

For a quick assessment of a given area, a generalization of a model can be employed. However, this evaluation will not be accurate and therefore it must be appropriately checked by employing at least the simple tests discussed previously. Otherwise, some important details can be omitted and the evaluation will not give sufficient results with respect to the priorities to be addressed in the future. Of course, a detailed analysis can be also performed with a more in-depth observation of the existing or imminent drawbacks in the system. In analyzing the data, consideration should be given to the most affected sectors. The priorities will relate to areas that had a large number of interventions in the past. Meanwhile, increased attention should be focused on breakages resulting from the advanced age of the underground facility. Data analysis will allow establishing a prioritization plan along with clear recommendations in terms of technical and economic solutions to be adopted. This would provide protection against the specific attack that causes deterioration, and provide in partial rehabilitation of the sector, or even replacement of the entire sector using materials which can resist similar deterioration.

8.5. Preventive Measures

Depending on the different possible causes of degradation in the field, appropriate techniques to avoid degradation of new-planned pipe installations or to minimize future deterioration of already installed systems can be implemented; this is based on good knowledge of the degradation phenomena involved and of the other conditions that may lead/led to the pipe deterioration, along with a detailed soil survey. As such, prevention of deterioration can be implemented by adopting suitable protection measures against specific attacks.

Since corrosion of grey and ductile cast iron is the main concern in the water supply systems, consideration should be given to methods capable of reducing its occurrence. Cathodic protection has been proven to be very effective in decreasing the rates of corrosion of buried metallic pipe systems. The principle is presented briefly in Figure 24.

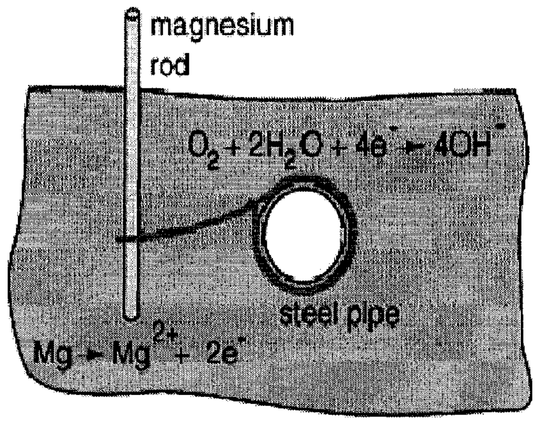


Figure 24. Cathodic Protection of Metallic Pipes (Hyperphysics, 2006)

A magnesium rod is installed in the ground, in the vicinity of the pipe to be cathodically protected. An electrical connection is provided between the rod and the buried pipe. Magnesium will serve as a sacrificial anode, due to its increased negative potential (-2.38V) compared to the iron (-0.41V) (Hyperphysics, 2006). The pipe will act as a cathode, and the conductive soil (where corrosion activity is likely present, i.e. resistivity below 2000 ohm-cm) will be the electrolyte of the voltaic cell formed, with a small current flowing through the electrical connection between the pipe and the magnesium rod. Eventually, the magnesium rod will be consumed preferentially instead of the pipe, and will require replacement. Hence, the entire process has to be continuously monitored, or inspected on a regular basis. Although the cost of such a protection method is high, it is much less expensive than unearthing the pipes for repair. Consequently, other direct and indirect costs can be avoided, such as the impact on the society and/or the environment in the case of service disruption or when the water main cannot be turned off.

To be applicable, cathodic protection requires some conditions to be fulfilled. The soil must be adequately conductive to act as the electrolyte of the galvanic cell, otherwise impressed current needs to be applied to assist the voltaic cell. Another very important aspect is the electrical continuity of the pipe circuit. The method is not suitable for the newly installed ductile iron pipes since they are connected using rubber gaskets, which interrupt the electrical continuity. In urban areas where stray current corrosion is imminent, the rubber gasket play an important role in corrosion protection, and therefore, the cathodic protection might be counterbalanced by the stray current corrosion. In such cases, the evaluation of cathodic protection effectiveness is imperative.

Soil Corrosivity	**Resistivity (ohm-cm)**	**Other Ground Conditions**	**Protection Recommended**
Non-aggressive	>2500 1500-2500	With or without water table Without water table	Metallic zinc plus bitumen paint
Aggressive	1500-2500 750-1500	Seasonal/Permanent water table Without water table	Standard coating (zinc plus bitumen) plus PE sleeve
Highly Aggressive	<750 <1500 <2500 <2500	Any natural soils Seasonal/Permanent water table Light chemical contamination Stray currents, proximity of cathodically protected pipelines pH<5 5<pH<6 and seasonal/ permanent water table	Standard coating plus tape wrap (25mm overlap)
	Any soil resistivity value	Soils with materials likely to cause mechanical damage (clinker, bricks, etc) Heavy chemical contamination Tidal water areas	Standard coating plus tape wrap (55% overlap)

Table 13. Recommendations of External Coatings for Ductile Iron Pipes (Adapted from Stanton, 1997)

Other protective measures which must be applied prior to pipe installation are the protection of the metallic exterior of the wall pipe with metallic zinc and bitumen paints or polyethylene sleeves. Stanton (1997) recommended different protection barriers according to the aggressiveness of the soil which will host the new ductile iron pipe. A summary of recommendations is presented in Table 13.

In some cases, soil decontamination may be a solution to eliminate the causes of exterior attacks on the pipes. Even if it implies high costs, it might be less costly than the replacement of the entire affected segment of the underground facility.

For the internal protection of metallic pipes, linings of cement mortar or epoxy are commonly used. A number of technological advances have been made recently in this area, and consequently the cost to implement this technique has decreased gradually. The internal lining, if not provided prior to installation in the manufacturing process, can be also implemented on an already buried pipe through different techniques such as sliplining (e.g., a new Polyethylene pipe inserted into the old metallic pipe), spray lining or spot repair (performed with the aid of robotics), cured in place pipe (liner impregnated with resin), etc. These trenchless methods can be employed for water or sewer pipes and are very advantageous, especially in crowded municipal areas because they require no excavation. In many cases, they are less costly compared to the traditional methods, especially where excavation to rehabilitate may cause severe direct and indirect costs to the society.

Some other measure to avoid underground water pipes deterioration can be the control of pressure in the system. This will also lead to leakage mitigation in a water supply system, since the leakage rate is dependent on the applied pressure; variation of pressure leads to fatigue effect at the sensible points of a distribution system, i.e., joints and fittings, finally causing leakage and bursting (Farley et al., 2003). Pressure can be controlled by using pumps with speed variation and valve modulation, which will stabilize the pressure disturbances in the system. However, this requires a consistent investment in the pumping stations of a water supply system.

Also, water chemistry control is a sustainable measure when water has low alkalinity, and implies the control of pH by using sodium carbonates, bicarbonates and hydroxides along with lime and carbon dioxide, and addition of corrosion inhibitors, i.e. ortho and polyphosphates, and/or silicates (Smith et al., 2000).

CHAPTER 9

DATA ARCHIVING- CREATION OF A DATABASE AND ITS BENEFITS

9.1. GIS and Data Management of Engineering Information

The capability of the Platform, the proposed framework to archive files in different formats, was discussed in Chapter 5. Whether the data related to an existing facility is paper-based or digital, in diverse formats (Word, CAD, GIS, etc.), the data need to be thoroughly analyzed when assessing the condition of a buried system, or a part of it. The process is time-consuming and requires important and qualified human resources to be accomplished; this multi-task involves searches of data, information superposition from different sources (paper-based and recently, digitized), and expertise to retrieve the essential from the available records. All these, along with the in-situ gathered information have to be put together to formulate the outcome of the analysis of the assessed infrastructure.

The task can become very easy if the above information is well managed on a computer, and linked to a digital map with a clear location of the infrastructure system(s) to be assessed. This will also grant that all documents which refer to the addressed infrastructure and which may contain important information are not omitted in the evaluation process. A framework for managing all of the information in different formats to allow their analysis has not yet been developed. Its absence has inhibited the knowledge development in terms of inventory and condition assessment of the infrastructure.

The proposed data management framework is based on a technology developed by a Partner in the project, a software company with applications in civil engineering, named earlier Software P., Inc., which allows management of information in different formats. Data available from the municipalities are especially paper- based documents with drawings, construction specifications, maps, etc., and recently, CAD drawings and GIS-based maps. These documents, which refer to a specific infrastructure, can be put together to develop, with no in-situ investigation, a preliminary state of the facility. A GIS-based map can then be developed by simple techniques discussed previously, which will allow relating the archived documents to the corresponding location.

The Platform is based on the concept of developing a 'database of databases' which is capable of spatial searches within its database. Consequently, an accurate inventory can be developed of all existing underground facilities for a given area. Also, the Platform allows for specific searches, e.g., revealing the inventory of fire hydrants or valves by types and diameters in a given neighbourhood; also, their condition can be similarly obtained, using specific search criteria. The main advantage is that such specific reports which usually require selection and sorting of data from an immense database can be obtained at a glance, and it becomes a valuable tool in the facility management, including the related decisions-making process.

9.2. Integration of Old Data in the New Database

Some attempts were made to convert paper-based documents, or already digitized drawings into the GIS-format, permitting the information to be easily managed and used for analysis. Some cities have already developed considerably large databases in GIS-format, for specific infrastructure facilities such as mass transit systems, or fire fighting networks for the local municipal fire stations. As discussed, the process requires the conversion of different available formats into GIS-based files to develop the final map. Significant improvements in the facility management and operation were recorded, however, the conversion process to develop specific infrastructure maps is time-consuming and expensive, and the investment to realize such a conversion might not be justified.

On the other hand, to optimize the conversion process economically, a selection of the available documentation can be employed, to reduce the quantity of data requiring GIS-conversion. However, some important information might be lost, unless specialized personnel are involved in the process, but again this adds to the final cost of the investment.

The technology developed by Software P., Inc. recognizes the different digital formats, therefore, no conversion is required. The existing paper-based documents can be easily transformed into the digital format, without too much endeavour and in a relative short time. There is considerable gain, compared to converting all the information so it can be used within a GIS database, since the archiving process is rapid and efficient.

9.3. Correlation of Data with the Corresponding Location

There are two sets of data which need to be linked precisely with the corresponding location of a water supply or sewer system, and they are the in-situ data and the raw data available from paper evidences or existing digitized documents. When the mapping of a buried infrastructure is performed, the GPR systems, provided with the corresponding software are able to save data as graphics images, which can be finally imported into GIS software. Graphic images can include cross-sectional views in any point of the scanned area. Moreover, these cross sections will help to establish maps for different services in the ground which operate in the same area, which is very important in case a repair is required.

Once the GIS map has been developed with the clear positioning of the underground services, the in-situ data, i.e., cross-sectional views and other graphics images can be archived and related to the corresponding location. The second type of data, comprising the available old documents in different formats, has to be now analysed to depict the position to which they refer. For example, a drawing involving a valve rehabilitation and/or network re-configuration in a node of the water supply system, performed at the intersection of two streets (location data available on the drawing) can be now precisely located on the map and archived with the archiving framework.

Finally, other in-situ measurements required for a more in-depth analysis of the critical sectors, performed with the non-destructive techniques described in Chapter 7, will be linked with the GIS map of the underground services. At this point, with all data archived and location-correlated, the assessment process can be conducted at any point of the infrastructure system, with consistent accuracy.

9.4. Intervention Plan Development

The main outcome of the inventory and the assessment process is the basis of the Intervention Plan development. When the state of a given infrastructure is accurately known, intervention schedules can be prepared, highlighting the priorities. In such a case, a rigorous and efficient plan can be achieved with a specific focus on the main problems that deal with a given infrastructure sector at a given location.

In a general context, the rating of the facility will suggest the kind of intervention required, ranging from simple maintenance operations to repair, rehabilitation or even replacement, and scheduling of the intervention and planning of the follow-up activity. Subsequently, technical solutions can be selected and a detailed cost of the operation can be evaluated. This enables the development of a rigorous plan over a period of few years along with the estimated financial needs over the period.

The intervention plan can be issued for separate underground infrastructure services, however, a more efficient approach should take into account all of the infrastructures in a given area which can be potentially affected by a possible intervention for repair, rehabilitation or replacement. As such, intervention plans can involve multiple stages referring to different infrastructure assets, i.e., a major need for a water pipe replacement can be used as an opportunity to repair the sewers in its vicinity, or to reconstruct the pavement on a street which is in a advanced state of deterioration. This requires a broader GIS-based inventory, adopted for different infrastructure assets such as roads, and sidewalks, water and sewers, electrical and gas lines, telephone lines, etc., but which can be easily implemented using the same framework, and having the same GIS map as reference. The inventory process can be implemented in each infrastructure sector, which will eventually help the municipal infrastructure practitioners to make the best decisions and to deal with the inadequate allocated budgets.

9.5. Decision Making Process Improvement under Budgetary Constraints

Once the priorities and the weak points in a system have been established, any related decisions can be made quite easily and efficiently. These decisions will be based on the intervention plan and hence the required investments will be fully justified with a definite level of certainty. A reconsideration of the decision making process will permit better investment of the available resources and will finally result in a better administration of the infrastructure assets and an improved fund management.

Due to the budgetary limitations, many municipalities in Canada intervene only in the case of an emergency to repair the deteriorated infrastructure. It is well known that the costs of such interventions are much higher than for the case of a planned repair activity, because in the former case, besides the basic cost of intervention, indirect costs resulting from an unexpected failure, e.g., a water breach, may accrue (flooding, service interruption, traffic problems, etc.). On the other hand, whilst the state of underground facilities is often unknown, it is obvious that an intervention plan cannot be developed. Also, in the case of a major rehabilitation, which may require a significant expenditure, one cannot be certain about the accuracy and the connotation of the decision, if no assessment of the infrastructure has been undertaken previously.

9.6. Towards Better Asset Management

The incorporation in the current practices of an intervention plan based on the inventory and condition assessment of different infrastructure assets will lead to significant changes in the management and administration of the infrastructure assets, resulting in an improved decision making process and an improved coordination of the available financial resources.

During the last decade, some attempts to address the present infrastructure management were made in few Canadian municipalities. It is obvious that the infrastructure issue started to draw the attention of politicians and officials, industries, education centres and even the population at large, and the awareness of the subject has increased significantly. In this light, the City of Edmonton can be cited as an example, which adopted a new approach through the Infrastructure Strategy program in 1998. The new management tools (Edmonton's Infrastructure Strategy, 2006) refer to a clear ranking of the infrastructure assets corresponding to their existing condition, a risk assessment method to deal with risk under financial constraints, and a life cycle cost of the facility to allow for long-term planning. The **ranking system** took into consideration three different parameters, i.e., the physical condition, the demand/capacity and the functionality of different types of assets, which were assessed through a preliminary inventory. Grades from A (very good) to F (very poor) were allotted for the various infrastructure categories, which finally led to a classification of the infrastructure assets with the following results: 13% of the assets were in a poor/very poor physical condition, 17% were below demand/ capacity and 7% had a poor functionality. With these numbers, a clear financial need for the most affected sectors could be evaluated and the basis of a prioritization plan could be constructed. In addition, the **life cycle costing** process to assess the return on investment and to incorporate the operation, maintenance and rehabilitation costs over the entire life of the asset was adopted. Finally, a **risk assessment methodology** was implemented to observe the possible service life of the infrastructure under different funding scenarios. The tools helped the City of Edmonton to develop its own Priority Plan, and to focus the investmants to address the most stringent drawbacks of the infrastructure systems.

In a more restrictive area, i.e., water and sewer infrastructure, the Affaires municipals et Regions du Quebec proposed a ranking system of the infrastructure which accounts for different characteristics of the underground water and sewer pipes, respectively. As specified in the Planning Guide for Water Supply and Sewage System Rehabilitation (Guide d'élaboration d'un plan pour le renouvellement des conduits d'eau potable et d'égout) (MAMR, 2005), the state of a water pipe sector, i.e., on a street in a municipality, can be ranked with regard to several parameters, as shown in Table 14:

Parameter- water supply systems	Points* (A)	Weight (B)
Frequency of repairs (breaks per 100km/year)	0-3	3-4
Losses (m^3/ day km)	0-3	2-3
Risk accrued in case of breakage	1-3	2-3
Functional deficiencies	0-3	1-2
Parameter- sewage systems	**Points* (A)**	**Weight (B)**
Functional deficiencies	0-3	3.5-4.5
Structural condition	0-3	3-4
Risk accrued in case of breakage	1-3	2-3

Table 14: Grading system for the state of water and sewer pipes (MAMR, 2005)
*0 points allotted for the worst case

The parameters taken into consideration for a water supply system (or part of it) ranking are the frequency of repairs per 100km of pipes per year (with 0 points allotted for the highest breakage rate and 3 points for the lowest breakage rate), the water losses (0 points for more than $20m^3$ water loss per kilometre per day and 3 points for less than $5m^3$ water loss per kilometre per day), the risk involved in the case of breakage (3 points for the lowest risk and 1 point for the highest) and the functional deficiencies (0 points for the highest level of deficiencies and 3 points for no functional deficiencies). The final grade will be assessed by summation of the products of cells (A) and (B), with values ranging from 2 to 30, and the lower values representing the most urgent needs of the system. This approach can be also regarded as a communication tool between the technical service of a utility and the management staff. The engineer should use his technical expertise to rank a given infrastructure asset whereas the manager will be able deal with the most urgent needs, on a basis of a prioritization scale. Accordingly, the sewage system can be ranked using the same procedure, and the parameter included in the ranking process are the functional deficiencies, the structural condition and the risk involved in the case of breakage.

Based on the grading system, the management staff will recommend the best financial planning, to deal with the repairs, rehabilitation, replacement, and further with operation and maintenance of a given infrastructure asset. This will also contribute to develop a database of the water supply and sewage infrastructure, which can be updated after each repair performed, rehabilitation, or replacement of the asset. Consequently, the data acquired can be readily analyzed at any time in the future, whilst the rehabilitated segment of a facility can be reassessed after the intervention. Moreover, based on the same upgrading of the database, a future check can be scheduled; this results in the initiation of a maintenance program.

In the future, unexpected situations (bursting of pipes, leaks, water contamination, etc) will diminish significantly, allowing more managerial, technical and financial resources to be coordinated towards a sustainable practice which deals with sustainable infrastructure maintenance. The inclusion of the maintenance concept in the routine management practices will lead to a closed-loop management process in which data will be periodically evaluated to help with decisions on the intervention plan; this will lead to upgrading of the state of the infrastructure through sustainable practices. The cyclic process is to be reinitiated after a well established period, according to the type of infrastructure, its importance and the existing state.

The need for incorporation of the 'sustainability concept' in the management practices may need time for implementation; however, it can be easily handled once the database reflecting the current state of the infrastructure is available. A wealth management plan should follow the principles of the World Council on Environment and Development, (1987), which defines sustainable development as that which "...meets the needs of the present without compromising the ability of future generations to meet their own needs".

CHAPTER 10

"SMALL-TOWN" MODEL: McGill Campus

10.1. Comparison with a Larger Municipality

To illustrate the applicability of the proposed methodology for development of infrastructure inventory and condition assessment, the first step is to undertake a preliminary study to relate it to a small community. For this purpose, the Downtown Campus of McGill University, in the heart of the City of Montreal is selected. The Area Studied in the proposed pilot project is the McGill Downtown Campus in Montreal, Quebec, within an area bounded by Sherbrooke Street, McTavish Street, University Street and Pine Avenue (Figure 25).

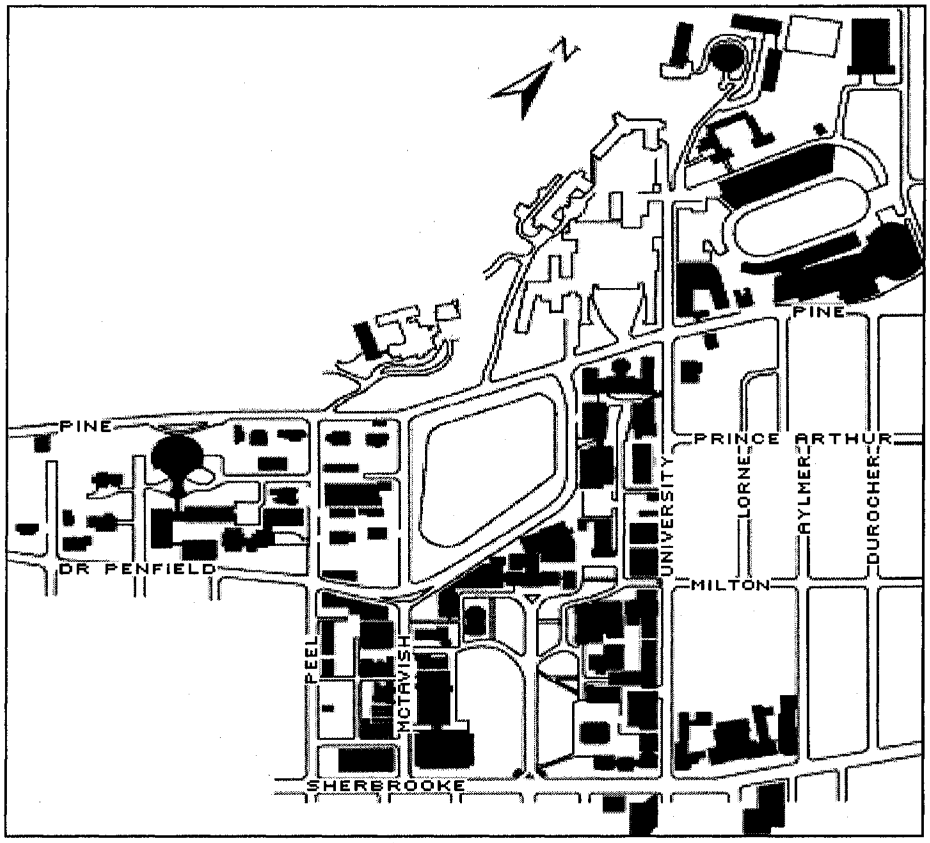


Figure 25. McGill Downtown Campus (McGill[2], 2006)

The Campus is basically a miniature city and it reflects an infrastructure pattern which is very similar to that in any Canadian community, with considerable underground infrastructure which was built during same period as for the City of Montreal. Therefore, the technologies used along the years, the pipe materials employed and even the workmanship are most likely to be similar to those used in the construction of the City's underground infrastructure. Accordingly, the environmental conditions of the buried utilities and the operational characteristics of the systems, e.g. water pressure, flow, etc., can be expected to be similar. Therefore, the process of inventory and condition assessment of the infrastructure which will be used in this case study would be similar to the ones used for larger cities, such as Montreal.

10.2. Available Information

The data available from McGill Facilities Management and Development Department, called from here on FMDD, provide considerable information about its infrastructure. Much of this data is on paper-based drawings, which provide infrastructure details starting in 1926. The gradual development of the campus can be observed during the period when major changes were implemented in the initial pattern of facilities. However, despite the campus enlargement, major infrastructure facilities have remained at their initial location, and although their condition may have deteriorated over the years, they are still in use. The real location of the water and sewer pipes is not clearly shown on the drawings, however, they include considerable information regarding the principal water lines crossing the campus and some water and sewer pipes surrounding the Campus area, on Sherbrooke, McTavish and University Streets and Pine Avenue, being component of partial rehabilitation plans, or developments on the Campus.

The main underground categories which will be addressed in this project are the water supply and sewer systems; however some specific services such as chilled water pipes, steam pipes or compressed air ducts are also present. They connect most of the campus buildings forming an internal network, but all of these services have been well organized with the Campus development and they were installed in underground tunnels, which are accessible for the maintenance and inspection personnel.

The particular underground layout and installation of these specific services in tunnels allowed for a better knowledge of their state, along with their location, therefore, for the through-tunnel services which were newly created and/or rehabilitated over the last decade, CAD drawings have been developed, showing an accurate portrait of these specific facilities. As previously noted, most buildings on the campus are connected by tunnels which helped to create an organized and interrelated underground network of services such as chilled water supply- used for air conditioning, steam supply and return-used for heating, and other specific services for some laboratories such as compressed air or technological drains for special equipments. These drawings refer to chilled water and steam networks and do not include the water supply system, or the sewers.

While the inventory and the condition assessment of these types of services are not the subject of this project, the available digitized and paper-based information related to these specific underground services can be easily included in the final portrait developed for the water supply and sewer systems, to complete a detailed map of the existing underground services at McGill, which can be further used for managerial and planning purposes.

10.3. Short History of Underground Facilities at McGill

In 1843, the Faculty of Arts was officially established (McGill, 2006). Even if there is no evidence of the water supply and sewer system construction at that time, it is most likely that these services have been installed on the campus since the mid 1850's, while the city had initiated the water supply system construction in 1801, which became a public-owned service by 1845. Moreover, a map of the City of Montreal of 1890 reveals that the most developed wards were in the Downtown, the Harbour and Lachine Canal, i.e., St. Anne, Centre Ward, St. Lawrence and St. Antoine Ward which comprised the McGill

Campus (McCord, 2006), therefore public water and sewer systems must have been developed initially in this areas.

The early plans available from the McGill FMDD, revealing an underground infrastructure at McGill Downtown Campus date from 1926 and 1932 which sketch some pipe arrangements and the layout of the underground. However, a clear location of water supply and sewer system is not available until 1978, when a plan of the underground water infrastructure was elaborated. The most recent drawings refer to the newer rehabilitated through-tunnel services, which were digitized in a CAD- format starting with the last 1990's. A general CAD-based map of the Campus was also developed, with the location of the roads, sidewalks and buildings throughout the Campus. Fortunately, the map can be used in the inventory and condition assessment process of the underground water supply and sewer infrastructure. The sewers are the most "relatively unknown" buried services since there is little information available related to them. However, the existence of some connections to the City sewer system is known, but the location of the main lines is a mystery.

In terms of materials used, based on the available documentation and on interviews with the Facility Department representatives, the water supply system was built with grey cast iron pipes and a few recent repairs and extensions were made with ductile cast iron, with the objective of maintaining the system homogeneity to prevent galvanic corrosion. The sewers are built mainly of concrete pipes. Some other materials were employed for the through- tunnel services, such as copper, steel and zinc coated steel pipes; their state is considered adequate since these systems were recently overhauled and the access for regular inspection is quite easy. The details of each specific underground service on the McGill Downtown Campus are discussed in the following.

10.4. Brief Portrait of Campus Services

The basic underground services on the McGill Downtown Campus are the water supply and the sewer systems. These services were built during the same period as those for the

City of Montreal and provide services within a well defined area. The Campus also features some specific services such as compressed air or chilled water networks which were installed later, to respond to the specific needs of the Campus. The underground tunnels were constructed for these specific services to ease the access for inspection, repair and replacement. Although these systems operate underground, their interaction with the environment is completely different from that of the water supply or the sewer systems. Moreover, they are not prevalent in the municipalities, and consequently, they will not be directly addressed in this study.

The situation for the gas network, telephone lines and electricity cables is similar since these services are provided by specialized agencies and they are not under the municipal jurisdiction. Moreover, two 24in. (600mm) diameter city water supply mains run through the campus area, from the 140,000 cubic meter City water reservoir- located on the northern side of the campus, to the filtration plant in Verdun. These pipes belong to the City and will not be studied in this project. Nevertheless, a short description will be provided for each underground service.

The project proposes to analyze two main categories of the underground infrastructure, i.e., the Water Supply System and Sewer System, whose assessment will be conducted separately because of the differences in the services provided and the dissimilar methods which are needed to evaluate their conditions.

10.5. Water Supply System

The Campus is connected to the city water supply system at several points, which are located on the streets bounding the Campus area, i.e., Sherbrooke, McTavish and University Streets. The Southern area is connected to the City on Sherbrooke Street, at two connection points with 100mm and 150mm (4 and 6 inches) diameter pipes. The same configuration was used for the Western boundary, on McTavish Street with 100mm and 150mm diameter (4in. and 6in. connections), whereas the Eastern Side of the Campus, because of the concentration of buildings on University Street, is supplied with water from the City through 6 taps, four of them having 100mm (4in.) and two of 150mm (6in.) in diameters. The Campus water system is supplied from the City from the city mains which are 200mm (8in.) and 1200mm (48in.) in diameter (Sherbrooke Street connection). Each connection is provided with a valve which enables to shut the water off, if required.

The water network created within the Campus resembles a city water supply network since it is provided with fire hydrants and service valves disposed in a ring-based pattern, so that the water for fire fighting can be available from any side of the Campus in the case of a temporary service disruption. The network has two primary purposes, i.e., it supplies water to the Campus buildings and meantime, it represents the fire fighting network which connects to the exterior fire hydrants. Moreover, it also serves secondary purposes, such as supplying water to the chilling units located in the different buildings, and bringing water to the sprinkler network in several locations. However, these technical installations only connect to the main Campus water supply system, and will be discussed separately in the project.

The several rings created in the distribution network, which mainly constitute provisions for an effective fire fighting system, permit more flexibility in the system used for unforeseen situations, and when water needs to be shut off in one sector due to a breach or a temporary repair. This allows the system to fulfill its intended purpose of supplying water, even if emergencies arise, since the affected zone can be isolated by closing the valves in the proximity.

To keep pace with the Campus development and re-arrangement, some portions in the water supply network were replaced and other routes were newly constructed progressively. Also, some routes in the water distribution system, which were not corresponding anymore to the new requirements implied by the Campus development (requiring increased flow, changed location and advanced deterioration), have been abandoned and newer pipes were installed. However, the basic network remained the same as it was initially conceived.

The water pipes in the Campus are generally grey cast iron. Ductile cast iron pipes were installed in the last 30 to 35 years and they were used mainly for repairs. There are only a few changes in the last decades in the original water supply system pattern provided in a paper-based drawing in 1978, and refer to some system improvements in the Eastern and Western sides of the Campus and some new connections for the chilled water systems. These upgrades of the system were performed with ductile cast iron pipes. The connections to the buildings are most likely of zinc coated steel pipes and for the newer ones, copper pipes. However, these elements are not part of the water supply system, they rather form the internal cold water distribution system within the buildings and will not be treated in this project.

The use of similar materials for repair and rehabilitation of the water supply system along the years has had the beneficial effect that the system has maintained its homogeneity. The pipes are grey cast iron and ductile cast iron, which is an advantage with respect to the galvanic corrosion phenomenon. As discussed, the replacements of parts or extensions of the system were performed using the same material, grey cast iron, or ductile cast iron after the 1970's, a fact which explains why breakages were mainly due to the soil movements, instead of the corrosion effects, as revealed by representatives of the FMDD of McGill. Therefore, the corrosion phenomenon may be of a smaller concern in the Campus water supply system.

The available documentation has permitted to primarily estimate the composition of the water supply system of the campus, in terms of pipe diameters and estimated pipe lengths. A summary of the geometrical properties of the pipes and their approximate lengths for each diameter are presented in Table 15. Pipes dimensions range between 50mm (2in.) and 200mm (8in.) in diameter, and their approximate total length is about 2300m. The mostly used pipe diameter of 100mm (4in.) accounts for more than 50% of the entire pipe length.

Fire hydrants are 150mm, or 100mm in nominal diameter and they are in good condition- a fact which was observed for the Montreal hydrants as well (SNC-Lavalin/ Dessau-Soprin, 2002). The valves used are flanged gate valves, with a majority of the valves situated inside the buildings, although, some buried valves do exist and they can be operated through a surface cast iron box, incorporated in the pavement or in the green area. Also, some valve chambers do exist for several valves, i.e., the City valve chamber at the Milton Gate.

No.	Diameter (mm)	Length (m)
1	50	30
2	75	120
3	100	1440
4	150	600
5	200	100
	Total approximate length	2290

Table 15. Approximate lengths of water supply pipes, McGill Downtown Campus

Interventions and repairs in the system have permitted partial assessment of the current state of the water distribution network which is considered to be in acceptable condition with some small exceptions (i.e. 200mm (8in.) and 150mm (6in.) diameter pipes which connect the City system on McTavish Street to University Street present a high risk of breakage, based on the past intervention records).

10.6. Sewage System

The Sewage System of the McGill Downtown Campus was created employing the same model as for the City of Montreal, of combined sewers, whose efficiency on the long run has been already discussed in Chapter 7. The system presents the extreme shortcoming of all campus utilities since its condition and even its location are not known. The used water is collected and conducted to the south side of the campus (Sherbrooke Street) because of the ground configuration which has the lowest levels on the southern side, following the slope of the terrain. Nevertheless, some connections to the city drain system also exist on McTavish Street where two sewage disposal lines run (diameter= 600mm, concrete pipe and 600x900mm brick sewer).

Two 600mm (24in.) diameter drains collect the wastewater from the buildings on the eastern and the western side of the campus. It is assumed that all the buildings are plugged into these two main pipes which are connected to the city network on Sherbrooke Street. A few 150mm (6in.) drains are installed in the Campus tunnels but these provide sewage for some equipment in laboratories and some chilling units. These drains are shown on several drawings available from the FMDD and were digitized during last decade, with the renovation of the underground through-tunnel services, but they do not constitute part of the Campus sewer system. However, they may indicate the existence of sewers mains in their proximity, to which they must be connected; this information can be useful in the sewer location process.

The buried sewage system was built of concrete pipes, and did not cause significant exploitation problems, e.g., overflowing, over the past few years. However, infiltration/exfiltration might be present in some older sewer lines on the campus. Their dimensions are expected to be in the range of 150mm (6in.) to 600mm (24in.), with the larger diameters employed for mains, as previously mentioned. Even if the data regarding the McGill sewers are hardly to be found on the available documents, their geometrical characteristics can be obtained by simple means, such as the inspection at the manholes on the Campus and at its boundaries, at the confluence with the City area. The total length of the sewer system is expected to be comparable with that of the water supply system since it serves the same buildings and therefore might follow the main routes of the water pipes. This can be roughly confirmed after the first round of inspection using the techniques discussed in Chapter 7, after the interpretation of the preliminary results.

10.7. Other Buried Facilities Specific to McGill Campus

The specific underground services of the Campus are not the subject of the project, however, a good knowledge and understanding of their location, condition and purpose is very important when developing the inventory of the main underground service network, i.e., water supply and sewer systems. Their known location will facilitate the positioning of the other buried services, when they can interfere with the GPR scanning process.

Another significant advantage is that the data regarding these secondary services can be uploaded on the GIS-based map very easily once it is created, since they are already available in a CAD digitized format. The final map will reflect the complete scan of the underground services on McGill Downtown Campus, which is a valuable tool for the McGill FMDD management purposes.

If a condition assessment of these systems were to be performed, it should be an easy task compared to that of water supply or sewage systems, since their routes follow the tunnels through the entire campus. No special equipments are needed for detection and assessment (except for the buried short sectors). Moreover, they can be inspected visually and even dismantled (at valve connections) during the non-operating period, enabling an easy maintenance and control of their state of health. Some small buried portions of these networks do also exist, where the site configuration did not permit building tunnels, but these routes are very short and usually end-up in the tunnels, allowing for a quick visual condition assessment.

These services appear to be in good condition since investments were made in their rehabilitation during the last decade. The networks differentiate from the water supply and sewage systems because they do not serve all buildings on the campus as some may have independent heating and chilling systems. Also, these services may be interrupted occasionally, i.e., heating during summer, or chilling during winter, hence, their use is intermittent and repairs can be done without affecting the routine activities on the Campus.

10.7.1. City Water Mains

City water mains are not part of the McGill underground infrastructure although some of them run through the campus. They are not the subject of this project; however, an estimate of the city water distribution network inventory is presented in the following. Large pipes with diameters ranging from 850mm to 1200mm are present on the main streets which define the area of the Campus, on McTavish, Sherbrooke, and Dr. Penfield streets, continuing on the north eastern side to Pine Ave. Also, some smaller diameter pipes on University Street provide water for the eastern boundary of the McGill Campus.

No.	Diameter (mm)	Length (m)
1	200	900
2	500	860
3	600	800
4	850	680
5	900	560
6	1050	160
7	1200	820
	Total approximate length	4780

Table 16. City water mains in the campus area and its boundaries

The use of large diameter pipes in the City water supply system is explained by the presence of a city water tank located on the north- western side of the campus which has a storage capacity of 140,000 cubic meters. Two 600mm (24in.) diameter pipes bring water from the Verdun filtration station to the municipal reservoir and run through the middle of the campus. The water mains are old, a fact confirmed by a major breach in the McGill Campus, a few years ago, and therefore they might cause problems in the future. The diameters and lengths of the city mains are as estimated in Table 16.

10.7.2. Steam Pipes

High pressure steam and steam condensate return are part of the McGill Downtown Campus facilities. They form a separate, individual system which connects all of the buildings through the underground tunnels of the Campus. The dimension of pipes varies from 50mm to 250mm (2 to 10in.), with the approximate lengths as shown in Table 17.

No.	Diameter (mm)	Length (m)
1	50	70
2	75	280
3	100	900
4	125	1020
5	150	400
6	200	1100
7	250	1080
	Total approximate length	4850

Table 17. Steam pipes diameters and lengths

The steam is supplied from the Campus Power House from where it branches out in 4 main directions, following the configuration of tunnels and buildings locations. The steam pipes are made of steel, assembled by flanges and threads. Their state is considered adequate since the entire network was overhauled in the last decade, a fact which can be easily checked visually, by inspecting the tunnels.

10.7.3. Chilled Water (supply and return)

Chilled water pipes basically follow the same route as the steam pipes, through the tunnels, and form a network between the buildings, although some buildings produce their own chilled water. Chilled water is supplied from the Power House and other three buildings of the Campus.

The network of supply and return of chilled water is made of steel pipes, connected by flanges or threads, depending on the cross section, i.e. small pipes are connected by threads and the larger pipes by flanges, and range from 100mm to350mm (4 to 14in.) in diameter, as shown in Table 18.

As in the case of the steam pipes, the chilled water network was recently renovated and therefore, it is considered to be in reasonable condition.

No.	Diameter (mm)	Length (m)
1	100	440
2	150	570
3	200	280
4	250	400
5	300	240
6	350	60
	Total approximate length	1990

Table 18. Chilled water pipes diameters and lengths

10.8. Paper Based and other Documents Related to the Existing Infrastructure

As discussed earlier, considerable information is available from the McGill FMDD, which comprises the different infrastructure assets and services on the Campus area. Old plans with specific details of facilities along with newer drawings have been already digitally archived, usually in TIF or DWG formats. This detail is very important since the digitally archiving process is time-consuming and consequently, important time-savings will be possible for this pilot project. However, a selection of all available documents is to be prepared prior to their direct correlation with the GIS-based map, to retrieve the most recent information about the Campus infrastructure.

Besides the engineering plans and drawings developed over the years, it is useful to include some other relevant aspects, such as the trend of water pipe failures or sewer overflows, the dates of interventions along with the repair blueprints, which can disclose data about the pipe material and age, technology used in performing the repair and its cost. Any other reports on the state of the services from other older inspections are helpful, if they are available.

The old practices of information archiving rely in many instances on the memory of the operation personnel, including engineers, technicians and foremen in charge of the service maintenance. Some very important details which cannot be found on the plans can be obtained verbally from persons involved in the operation and maintenance of the infrastructure during its life cycle, however, some of the elder employees with considerable knowledge of the facilities might have been retired and, in this case, the information is lost. Nevertheless, a questionnaire can be formulated and submitted to the present and/or still available retired employees for information collection.

Given the fact that the McGill Campus presents some advantages that are not likely to be encountered in many Canadian municipalities, i.e., the existence of a CAD map and a database of digitally archived documents, the analysis of the above information can initially lead to a preliminary assessment of the infrastructure. However, this is just the starting point and the real location and state-of-the-art of the underground infrastructure have to be confirmed by further tests, for each type of infrastructure. The methodology of location and condition assessment of the buried services should follow the steps described in Chapter 7.

10.9. State of Buried Services

A specific evaluation of the underground services at McGill has not yet been carried out and therefore the “existing” situation is not known. However, their state is considered reasonable, based on the fact that emergency situations raised by the water supply, or sewer systems have not occurred on a regular basis.

The probability of a water pipe failure in the Campus area is relatively small based on the recent records, however, some pipe sectors are considered to be at the end of their service life and they can be expected to fail. A pattern for the breakage rate of the water supply system at McGill cannot be established due to the poor repair record keeping, however, it seems to be smaller than the average breakage rate of the City of Montreal. This can be attributed to multiple factors such as differences in population served, different consumption patterns and dissimilar purposes of water use in comparison with the City.

The sewers are considered to be in an acceptable condition, based on their service supplied without the occurrence of observed major problems over the last decade.

However, this is much like a forecast since the sewer pipes were never inspected, and hence their location and condition are completely unknown. A precise location along with their condition assessment will allow a better knowledge of their state and the prediction of their service life, and will allow for a maintenance plan implementation through an effective management process.

The other underground services described succinctly in the previous paragraphs, which are mainly installed in the Campus tunnel network, have been renovated during last decade and are considered in a good condition. This state of health has been possible because of their installation in tunnels, allowing to regular inspection and maintenance by the operation and maintenance personnel, making them different from the main buried services of water supply and sewer systems.

10.10. Inventory and Condition Assessment of the Water Supply and Sewage Systems

The steps involved in the inventory development and condition assessment of the water supply and sewage systems were discussed previously in Chapter 7. These are suggested guidelines, and are not mandatory. The methodology can be improved and also adapted with regard to any particular situations which may occur when assessing an infrastructure system, to account for any potential specific aspects, e.g., water pipes operating in aggressive environmental conditions, or in a soil with high water table, or in a very low-breakage rate sector, etc.

As in the case of the McGill model, some steps can be shortened, i.e., a CAD- based map with the preliminary location of the underground facilities is already available and therefore the GPR location of water supply system - in some cases - will only confirm the already existing pipes layout. Water audits might not be needed if the system does not have a high breakage rate, however, some non-acoustic techniques for leak detection might be employed to determine any possible seeping in the system. Some specific tests considering non-destructive techniques can be arbitrary conducted, on short sections, in the zones considered most prone to deterioration. Conversely, some situations will require advanced investigation in specific area, i.e., if breaches are caused by soil movements, and therefore soil sampling and future soil analysis is required to determine the real cause of failure and to develop the deterioration models for the buried system to forecast the future deterioration response and service life.

Similarly, the sewer system state evaluation need not rigidly follow the steps suggested in Table 9. Some tests might not be necessary, or can be easily completed, based on the expected acceptable condition of the sewers at McGill. Therefore, a mobile CCTV inspection might not be justifiable, or even a laser scanning for geometrical disturbances assessment if the preliminary stationary CCTV test confirms the good state of health of the sewers. Moreover, additional tests which are more specific for municipalities such as smoke test or tracer method for detection of proper joints or secondary connections to the main sewer are not to be conducted. Poor bedding or filling conditions using high frequency Ground Penetrating Radar are again not to be checked mandatory only if sewer structural problems are detected with the CCTV, since such conditions should have conducted to failures in the early period of sewer operation.

10.11. Resources and Time Needed to Complete the Exercise

The pilot project proposes the development of an inventory and condition assessment of the water supply and sewer systems on the McGill Downtown Campus. The existent information regarding these services allows foreseeing the resources needed to complete the entire process. As discussed previously, some tests which require special equipments can be performed in lower extent, where major deficiencies are detected. However, the basic equipment for underground detection and information recording, i.e., a complete Ground Penetrating Radar testing module, including the corresponding software for data acquisition, is mandatory. The Remote Field Eddy Current Equipment is also needed, to perform sample tests in the most deteriorated sectors of the water pipes, along with a basic Close Circuit TV Camera system for sewer pipes assessment.

The GPR and CCTV testing equipments are available from different producers, and come with a complete supply (including all the necessary accessories), or by parts. McGill Department of Mining is in possession of a GPR equipment which can be used for this experiment. However, it will need adaptation for underground service detection, i.e., upgrading with a specific antenna, a carrying wheel cart, adequate display options and the complementary accessories for data archiving.

The Remote Field Eddy Current equipment is not commercially available and might be found with few specialized contractors across Canada. An advantage is that detailed tests which employ the Remote Field Eddy Current equipment are not to be performed only in few locations, as discussed previously. Finally, the archiving Platform is provided by the partner in the project. This information is available with Professor Saeed Mirza.

Besides the technical equipment, the time involving each phase of the project has been separately estimated for water supply and sewer systems. The needed human resources are presented in Table 19 and 20. The estimated time for the complete exercise was roughly assessed and no consideration was made with respect to situations when tests cannot be performed when the service cannot be interrupted or other impediments. The schedule accounts for the work of at least three individuals during the whole process. The tests which might require a disruption of the service are suggested to be performed during the summer period, when the activities in the Campus are considerably reduced.

No.	Steps	**Estimated time (working days)**
1	Confirmation of location of pipes using GPR	14
2	Map development- CAD/GIS	6
3	Fire hydrant and valve condition assessment	2
4	Sonic detection leak and/or water audits	4
5	Use of non-acoustic techniques, if required, for leak detection	4
6	Pressure tests -low capacity sector identification	5
7	Water inspection at hydrant discharge	2
8	Analysis of historical data for breakages and repairs	6
9	Identification of structurally critical sectors	4
10	Remote Field Eddy Current Test for critical sectors	10
11	Further investigation if needed- Ultrasonic Inspection, Magnetic	10
12	Soil aggressiveness zone detection- if any	2
13	Soil instability zone detection- using high frequency GPR	4
14	Soil sampling and laboratory sample analysis	4
15	Interpretation of results	10
16	Identification of priorities	7
17	Integration of historical data analysis	4
18	Validation of degradation models	14
19	Estimation of remaining service life	14
20	Final inventory and condition assessment database validation	15
21	Priority plan development	10
22	Cost estimation	10
23	Impact of non-realization	10

Table 19. Suggested time schedule to complete the inventory and condition assessment of the water supply system in the McGill Downtown Campus

No.	Steps	Estimated time (working days)
1	Location of pipes using GPR	14
2	Map development- CAD/GIS	5
3	Analysis of manholes -structural and tightness against leakage	3
4	Zoom camera - for preliminary inspection of sewers through manholes	4
5	Preliminary database creation; delineation of suspected critical sectors	4
6	Interpretation of the preliminary results	5
7	Identification of low capacity sectors	2
8	Analysis of historical data (plans, drawings, repairs, etc.)	2
9	Identification of structurally critical sectors	4
10	CCTV test for further investigation of critical sectors/ Laser scanning	10
11	Smoke test and tracer method, if required	2
12	Soil aggressivity and instability detection using high frequency GPR	2
13	Soil sampling and laboratory analysis	4
14	Identification of priorities	5
15	Validation of degradation models	12
16	Estimation of remaining service life	6
17	Final inventory and condition assessment database validation	15
18	Priority plan development	4
19	Cost estimation	10
20	Impact of non-realization	10

Table 20. Suggested time schedule to complete the inventory and condition assessment of the sewer system in the McGill Downtown Campus

CHAPTER 11

INVENTORY AND CONDITION ASSESSMENT AT A LARGER SCALE

11.1. McGill Campus Model

The water and sewer infrastructure on McGill Downtown Campus is proposed to be evaluated as a pilot project for the applicability of the described methodology for development of a computerized GIS-based inventory and condition assessment of the underground utilities in the municipalities across Canada. This framework involves some basic steps, such as the location of buried services and the map development, the delineation of the critical sectors and the assessment of the system condition by analysing the in-situ data obtained by inspections and tests, and the available paper-based and digitized information, along with further recommendations and the development of a priority plan.

The very first steps of the methodology involving the location and mapping process, along with the digital archiving of the available data are compulsory in the inventory process. The basic guidelines will be applied in most instances for assessing the underground system condition; the framework can be adapted and/or improved appropriately, to accommodate the possible differences from one municipality to another in terms of material used, age, and climatic and operating conditions. As mentioned previously, for the underground infrastructure at McGill some detailed tests, i.e., laser scanning for sewers or RFEC (remote field eddy current) for cast iron water pipes will be only applied on small sectors, since their condition is expected to be acceptable after the preliminary simple tests and consequently, the employment of these condition assessment methods on a large sample of pipes is not economically sustainable.

Some complementary testing methods such as the Magnetic Flux Leakage, Impact Echo and Spectral Analysis of Surface Waves and the Acoustic Monitoring Method for the Pre-cast Concrete Cylinder Pipes were highlighted in this project, to describe the applicable and available techniques on the market, which can help or better suit in the condition assessment process of any water and sewer system. As noted by Makar et al. (1999), most of these methodologies are still under development or are backed-up by long term experience in related fields, i.e., the gas industry, and their adaptation to water and sewer needs more research. However, with the up-to-date available technology, the condition assessment of a given water supply or sewer system can be conducted with reasonably accurate results.

Based on an evaluation of the test results, the framework for condition assessment can be improved and/or simplified. For example, the municipalities of the Montreal Island are most likely to have similar water and sewer infrastructure patterns, making the assessment process much easier once an underground service condition of a municipality is assessed. The experience gained through the first condition assessment of a given infrastructure system in a municipality will help to considerably reduce the necessary time needed for further inventories and investigation processes of the neighbour municipalities. Moreover, the trained personnel can develop similar inventories of similar infrastructure more rapidly leading to considerable time-savings and higher accuracy of the assessment process, and consequently to lower financial resources required.

The main advantage of developing and testing this methodology on the McGill Downtown Campus is its availability as a research site, where the process can be carried out without disturbing any activity and without raising any social and economic impediments which can affect the society (as it should have a street closure in the "real" life). Moreover, some tests which might require short disruption of the service delivery can be performed without affecting the service delivery, i.e., the McGill water system (as already discussed) was conceived in a ring arrangement, permitting the continuous Campus water supply even in emergency situations, caused by a possible breach, or, in our case, a pipe isolation for RFEC testing. However, if some tests should require the service shut-off and may affect the buildings occupants, these can be performed during the summer break, to minimize the effects on the various activities on Campus.

11.2. Municipalities in Canada

The implementation of a standardized methodology for the inventory and condition assessment of water supply and sewer infrastructure across the Canadian municipalities will allow retrieving the status of these specific municipal services at a national level. The outcome of such synthesis will result in tremendous advances in infrastructure management, involving precise budget investments and substantial improvements of the general state of the buried infrastructure systems throughout Canada, administrated with the same financial resources. Even if Canadian cities present a similar general pattern of water and sewer infrastructure in terms of age, materials and installation techniques employed, some differences would exist with a more detailed analysis. Some recommendations are suggested for the methodology standardization, to account for the major differences between the Canadian cities in terms of population, age, and climactic conditions.

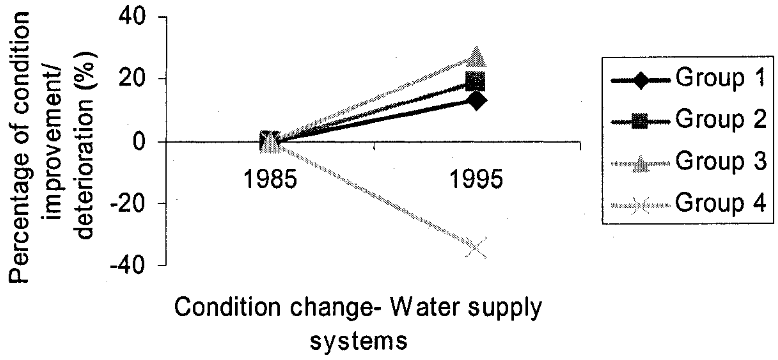
11.2.1. Population

The needs of water supply and sewer systems in the Canadian cities vary from one population group to another. The McGill/FCM report (1995) highlighted significant differences in terms of infrastructure quality and vintage, for diverse municipal population groups. In the survey of 589 municipalities, with 167 responses, four different population groups were established:

Group 1: Population below 10,000 inhabitants
Group 2: Population between 10,000 and 100,000 inhabitants
Group 1: Population between 100,000 and 400,000 inhabitants
Group 1: Population above 400,000 inhabitants

The survey roughly represented more than half of Canadian population (almost 16million people), which is significant and therefore the data obtained can be considered realistic.

The survey noted that the water supply and sewage system have not improved during the last 10 years, i.e., 1985-1995, with their status maintained steady at most. Figure 26 shows the condition change of water supply and sewer systems, for the four different selected groups of population.



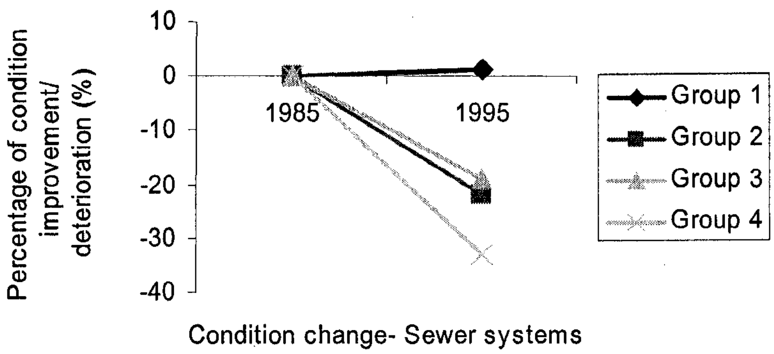


Figure 26. Canadian municipal water and sewer systems- change in condition from 1985 to 1995 (adapted from McGill/ FCM survey, 1995)

McGill/FCM (1995) noted that 41% of the water infrastructure of the municipalities analyzed in the survey was in an acceptable condition, whereas the rest of 59% needed repair, or it was in unacceptable condition. However, in a more in depth analysis, one notes significant differences of the underground infrastructure status within the population groups. For the small cities, the state of water supply systems has even improved during the ten year period, whereas the larger municipalities encountered a major decay of the water supply systems. Sewers show a broader trend of degradation during the same period for three larger population groups.

This figure clearly explains the dissimilarities referring to the same infrastructure, between different city sizes, which must be considered when implementing the methodology of inventory and condition assessment of underground infrastructure.

11.2.2. Age

An age pattern can be also established for the water and sewer infrastructure, regarding the population groups. Again, at the national level, the average age of water supply and sewer systems in 1995 was 37 and 42 years old, respectively. However, the small municipalities have newer services, with sewers averaging 29 years of service, compared with the large cities, with a mean of 46 years old sewers, in 1995 (Figure 27).

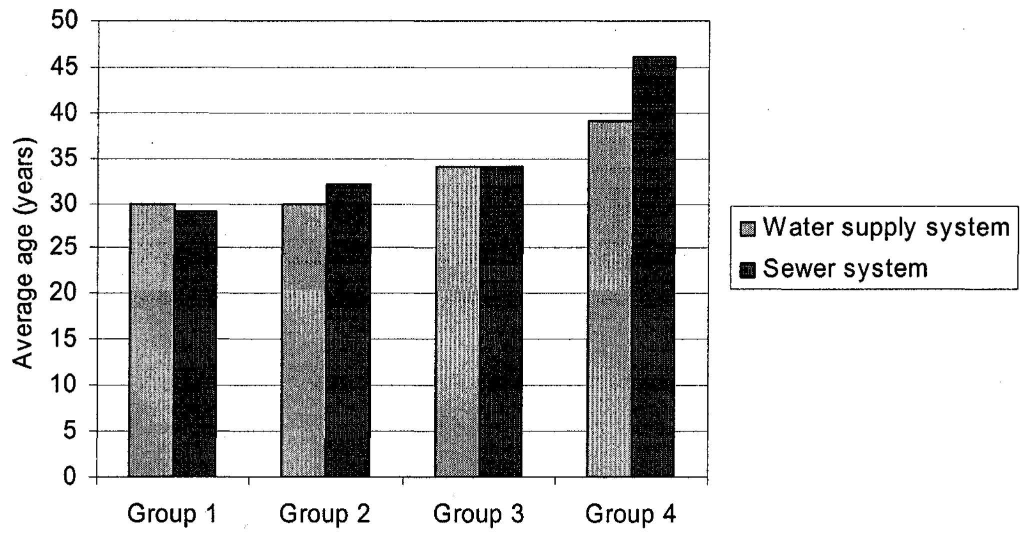


Figure 27. Age of water and sewer infrastructure for different population groups (Adapted from McGill/ FCM survey, 1995)

This arrangement in terms of age, with younger infrastructure in smaller cities can be explained by the baby-boom and urban sprawl phenomena recorded during 1960s and 1970s, which generated the necessity of building more infrastructure to keep pace with the population growth in the major cities suburb areas.

11.2.3. Climate

A very important concern in the life-cycle of the infrastructure assets is driven by the climatic conditions. More recent studies (Mirza, 2005b) have shown that the life of a structure is directly related to the environment, more specifically, to its macroclimate and microclimate. Even if the buried infrastructure is apparently protected from the harsh Canadian environment, its deterioration is frequently caused by freezing and thawing cycles (Rajani, et al., 1995), especially if the pipe is in an advanced state of degradation, e.g., corrosion. However, some regions in Canada do not encounter increased pressures on the infrastructure due to the cold climate, e.g., the Western Coast of British Columbia, and therefore a classification of Canadian municipalities by a climate prospective can be also useful in adapting a model for an infrastructure inventory and condition assessment.

As a conclusion, larger communities which also own the oldest infrastructure and which is exposed to harsher Canadian climate will need the most developed and detailed framework to analyse and assess the underground infrastructure condition, whereas smaller municipalities can benefit from a simpler methodology to cope with newer and less deteriorated infrastructure. For the smaller municipalities, the framework should probably focus more on the recommendations of preventive measures to avoid a premature deterioration since the infrastructure assets are newer and maintenance programs initiation would have a long term beneficial impact, which might be not applicable to older infrastructure which is in need of replacement because of deferred maintenance over a long time period.

11.3. Future Research

The necessity of establishing a framework for the inventory and condition assessment of the Canadian infrastructure has been a question of future research, highlighted in several recent reports, i.e., Mirza et al. (2003), CSCE (2003) in the Technology Road Map and Infrastructure Canada (2004), and discussed widely at recent conferences. Some methodologies have been established and rely on CAD or GIS-mapping, however, significant work needs to be performed to create an input database, i.e. for documents conversion into GIS format.

The proposed framework emphasizes the capabilities of the Platform mentioned previously for managing data in different formats, and consequently allowing for significant time-savings. The starting point is the application of the described methodology to a small town model, to observe and to address the shortcomings of the method, and to finally formulate the most efficient methodology for the inventory and condition assessment of underground facilities. Its adaptation to specific infrastructure patterns in different municipalities should be effective in the case of a larger scale infrastructure inventory since it will attract considerable time-savings and may lead to a standardization of the framework at a national level. This would help to easily obtain a real-time status of any Canadian facilities whilst the data can be retrieved within the same system of databases. Also, a similar methodology can be formulated to address other infrastructure categories, such as roads, bridges, transit systems or public cultural facilities, etc., irrespective of the jurisdiction- municipal, provincial or federal.

In terms of the methods used for underground infrastructure assessment, more research is needed in the area of non-destructive techniques, i.e., to develop a more accurate Remote Field Eddy Current technology for larger pipe diameters (for diameters larger than 6-8inches) or to perfect a more efficient and less expensive method for Pre-cast Concrete Cylinder Pipes monitoring and assessment, e.g., acoustic monitoring. Other non-destructive techniques, which were discussed earlier, and which are less developed for the water and sewer applications, can be tested further and improved. With the current

progress and advances in the plastics industry with applications in underground infrastructure systems, some methodologies should be also elaborated to deal with the problems related to the Polyethylene and Polyvinyl Chloride pipes, even if the breakage rate is significantly low compared with the classic metallic or concrete pipes which constitute the majority of water and sewer infrastructure.
At this moment, the available technologies for inventory and condition assessment of water supply and sewer systems should yield sufficiently accurate results. Some other technical advances which are expected in the future will enable developing more details of the status of the existing infrastructure. In this light, any future research should account for the technique or technology adaptability and compatibility with an existing assessment framework and database, to allow for easy updates and management of newer and existing data.

11.4. Summary and Conclusions

In summary, the project proposes to establish a framework for developing a detailed inventory of infrastructure at a municipality, along with its condition assessment. The data acquired will be stored in a GIS (Geographic Information System) database, which will enable the user, i.e., the public utility, to locate a specific infrastructure element on a digital map and to get information about its state of health and/or other available features related to that element, i.e., the state of the element at a given date, historical data, repair records, and any available drawings.

The underground infrastructure pattern of McGill Campus is generally similar in terms of overall services to that of the City of Montreal. Some other uncommon services are met in the Campus area, but they are summarily discussed and not included in the general framework of the inventory and condition assessment since they are not applicable to most of Canadian municipalities. The structure of Montreal's infrastructure was also compared to that of other Canadian municipalities, and based on the data available from other reports, a similarity was established in terms of infrastructure composition, age, technologies and workmanship employed along the years, along with the environmental and operational conditions (in most instances). Taking into account these similarities existing at the level of the Canadian underground infrastructure, the proposed methodology is quite easy to be implemented in other municipalities. Of course, some adjustments will have to be made for specific local conditions with varying macroclimate and microclimate to which utilities are subjected. The method may be also adapted for the study of smaller municipalities with newer infrastructure and/or with mild climate patterns. Also, the evaluation techniques may need to be altered when the pattern of a municipal infrastructure does not match the general one (e.g. the City of Regina, where majority of water pipes are of asbestos-cement). Eventually, the developed GIS-based map and the archiving Platform can be further used for other infrastructure inventories and condition assessment, such as highways, roads or pavements, electric or gas services, telephone lines, or other types of infrastructure.

As long as the methodology uses the same framework for managing the information, databases can be easily linked between several municipalities, thereby enabling a detailed view of the municipal infrastructure assets. Furthermore, the model could be adapted to address the provincial and federal share of the infrastructure. Eventually, an overall clear infrastructure assets inventory and assessment of infrastructure condition at municipal, provincial and national level can be obtained.

The final goal of the project is to strengthen the knowledge of the Canadian infrastructure and to disseminate the approach amongst communities, to contribute as a support tool for the policy and decision makers, to prioritize plans for infrastructure management which needs immediate attention and to better use the limited available financial, technical and other resources.

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