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Concrete Pipe News is designed to provide a communication forum for the concrete pipe industry to facilitate the exchange of information regarding product use and applications, industry technology and trends among members of the American Concrete Pipe Association, contractors, engineers, vendors, suppliers and other interested parties.

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Precast Concrete Products Are Adaptable To Just About Any Application

Not only do precast concrete drainage products endure for generations; they can be adapted to meet just about any challenge facing designers and specifiers - from providing drainage solutions under busy roadways to servicing mixed use developments. The research and anecdotal evidence is in, and it is strong in its support of precast concrete drainage products as the construction industry's material of choice.

In this issue of *Concrete Pipe News*, we honor a family committed to the quality and use of precast concrete drainage products over three generations. The reflections of Charles (C.W.) Wilson on the growth of the industry since his father and grandfather first introduced reinforced concrete pipe at a town meeting in Iowa, 95 years ago, attest to the longevity of the product.

Many designers and contractors clearly understand the value of engineering large projects with precast concrete. But, there is also another area where these products often are overlooked, and alternative products used, without careful reflection upon long-term benefits and cost efficiencies. These are the small repair and improvement projects and infill development projects. This issue of *Concrete Pipe News* features three projects where local challenges were quickly solved with precast concrete drainage products.

In October 1999, a heavily traveled section of Delaware Route 4 was closed after a corrugated metal culvert collapsed. The repair was made with precast reinforced concrete pipe, a product that should have been used when the culvert was first constructed, 14 years ago.

In Athens, Tennessee, the headwall of an old concrete culvert collapsed into the drainage channel causing damage to the shoulder of the local road and possibly obstructing storm water flow. The repairs were made using precast concrete box sections that were modified on-site by the City's own forces. Work was done quickly with considerable savings in time and money.

A developer in a growing Ontario town also saved time and money by servicing its high profile infill development project with a variety of precast concrete products for storm sewers and storm water quality and quantity facilities. It is a case study that demonstrates the versatility of our members' products.

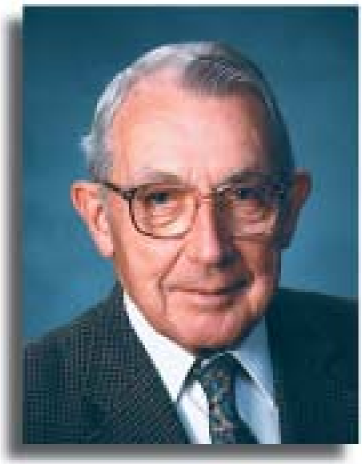
For the past 30 years, interest has grown steadily in the performance of old drainage systems and the need for high quality installations of new systems in light of costs associated with inflow and infiltration (I/I), and the growing need to conserve fresh water resources. Rehabilitation of old sewer systems with modern precast concrete pipe has taken on new significance in our industry. Governments throughout North America are beginning to come to terms with the high cost of maintaining buried infrastructure, and are acting to build asset management plans into their tax base. In this issue, we highlight the problem of I/I and present an option for tackling the issue of asset management.

Sharon deMonsabert, Chee Ong and Paul Thornton have developed a model for analyzing costs and benefits of reducing the amount of I/I through selected rehabilitation methods. Their paper, "An Integer Program for Optimizing Sanitary Sewer Rehabilitation Over a Planning Horizon" is reprinted with permission from the Water Environment Federation.

The concrete pipe industry is moving quickly to introduce new product applications in this new era. This issue serves to remind the reader that our members' products are designed with long service lives to contribute to a legacy of healthy buried infrastructure. Future generations will benefit from decisions taken today to use precast concrete products on projects, regardless of size.

Industry Spotlight

Charles (C.W.) Wilson



America's concrete pipe industry is most fortunate to have a colleague whose family can rightfully claim three generations of concrete pipe producers. Wilson Concrete Company, headquartered in Red Oak, Iowa is truly one of the pioneers of the precast concrete pipe industry. And, it is well documented that the grandfather and father of Charles (C.W.) Wilson introduced reinforced concrete culvert pipe to America.

In October 1905, 17-year-old Charles Franklin Wilson, accompanied by his father Charles Harrison Wilson, delivered a sample of culvert pipe to the courthouse in Mills County, Iowa to demonstrate the versatility of concrete. The 48-inch long pipe had a 3-inch wall and a diameter of 30 inches. Unique to the pipe were the steel bands encased in the walls, running both ways. Circular rings of reinforcement were placed into the forms as the dry mix was tamped by hand. The resulting product was America's first reinforced concrete pipe.

C.H. Wilson had established Red Oak Bridge and Iron Works in 1904 (to become Wilson Concrete Company) after working as superintendent of county bridge work in Montgomery County for 15 years. Today, Wilson Concrete is led by the founder's grandson, Charles W. Wilson. The company has 700 employees and 11 plants in four states.

We asked Mr. Wilson a few questions about his rich heritage and outlook for concrete pipe technology. This is what he had to say.

Q: *Did your grandfather ever tell you how he learned about reinforced concrete pipe?*

Wilson: My grandfather passed away when I was one-year old, but my dad told me where the idea came from. He said that in early spring, work crews would go to construction sites and put in the timber forms for box culverts. However, spring floods would occur sometimes, and wash out the forms. This led my grandfather and father to develop precast reinforced concrete pipe in place of the poured-in-place culverts.

Q: *Wilson Concrete has been an innovator of design, considering reinforced concrete pipe and post-tensioned, prestressed designs for beams. Can you share with us other firsts that the company has enjoyed over almost a century of family business?*

Wilson: In the thirties and forties, dad had a plant in Nebraska for irrigation pipe. After the plant closed, I started one in 1949 in Grand Island, Nebraska to continue producing irrigation pipe. Joints were a problem because there is a slight pressure in the pipe systems, and joint leakage was an issue. After considerable research, we found a good process from Australia called the "Rocla system". We developed and patented an improvement in the joint, and we still have the patent. In 1951, we went into prestressed concrete, and in 1958 into architectural concrete products, both of which we still produce today.

Q: *You have heard first hand, and seen the steady progression of concrete pipe technology over 100 years. In your opinion what has been the single greatest technological change since reinforcement was introduced?*

Wilson: There were two significant technological changes: good economical joints and production techniques. I remember wet casting pipe under a stiff leg derrick.

Q: *What technology do you see ahead for the next generation of concrete pipe producers?*

Wilson: This is hard to foresee, but I am sure that there will be continuous improvement to automated production techniques from the mixers and reinforcing processes right through to the kiln. Today, we have very good pipe.

In closing the interview, Mr. Wilson commented that he still has one of the early pipes made by his grandfather and father.

CMP Failure Creates Sinkhole

Busy Delaware Thoroughfare Reopened with Precast Concrete Pipe

By Bob Perrone and Dwayne Greene
CSR Hydro Conduit, Middletown, Delaware
302-378-8920

The failure of a 66-inch diameter corrugated metal pipe (CMP) culvert under a busy stretch of Delaware's Route 4 serves to remind taxpayers not to sacrifice quality for low cost bids. The failure not only cost taxpayers additional funds for repairs, but also created a major inconvenience for commuters on this busy thoroughfare.

On October 28, 1999, state road crews closed a quarter mile section of Route 4 where the culvert collapsed and the pavement failed after a 25-feet deep and 3-feet wide sinkhole opened in the middle of the road. The closure was made after state officials determined that the road might collapse under the weight of about 25,000 cars and trucks that travel it daily.

The CMP was supposed to have a 25-year service life, according to Delaware Department of Transportation (DELDOT). The original roadway was only two lanes with no median or sidewalks. It was expanded to include two additional traffic lanes, a large median, and sidewalks. Covered by 25 feet of backfill, and comprised of 16 gage uncoated metal, the CMP culvert lasted 14 years - just over half the time it was expected to last. Upon inspection of the culvert, it was clearly apparent that the invert of the pipe was deteriorated and missing in most areas. In addition, backfill had entered the line through displaced joints.

The contractor worked quickly to replace the failed CMP with precast concrete pipe.

The state decided to replace the 240-feet long CMP culvert with 66-inch diameter reinforced concrete pipe because it is recognized as being more durable. CSR Hydro Conduit, Middletown, Del., a member of the American Concrete Pipe Association, was

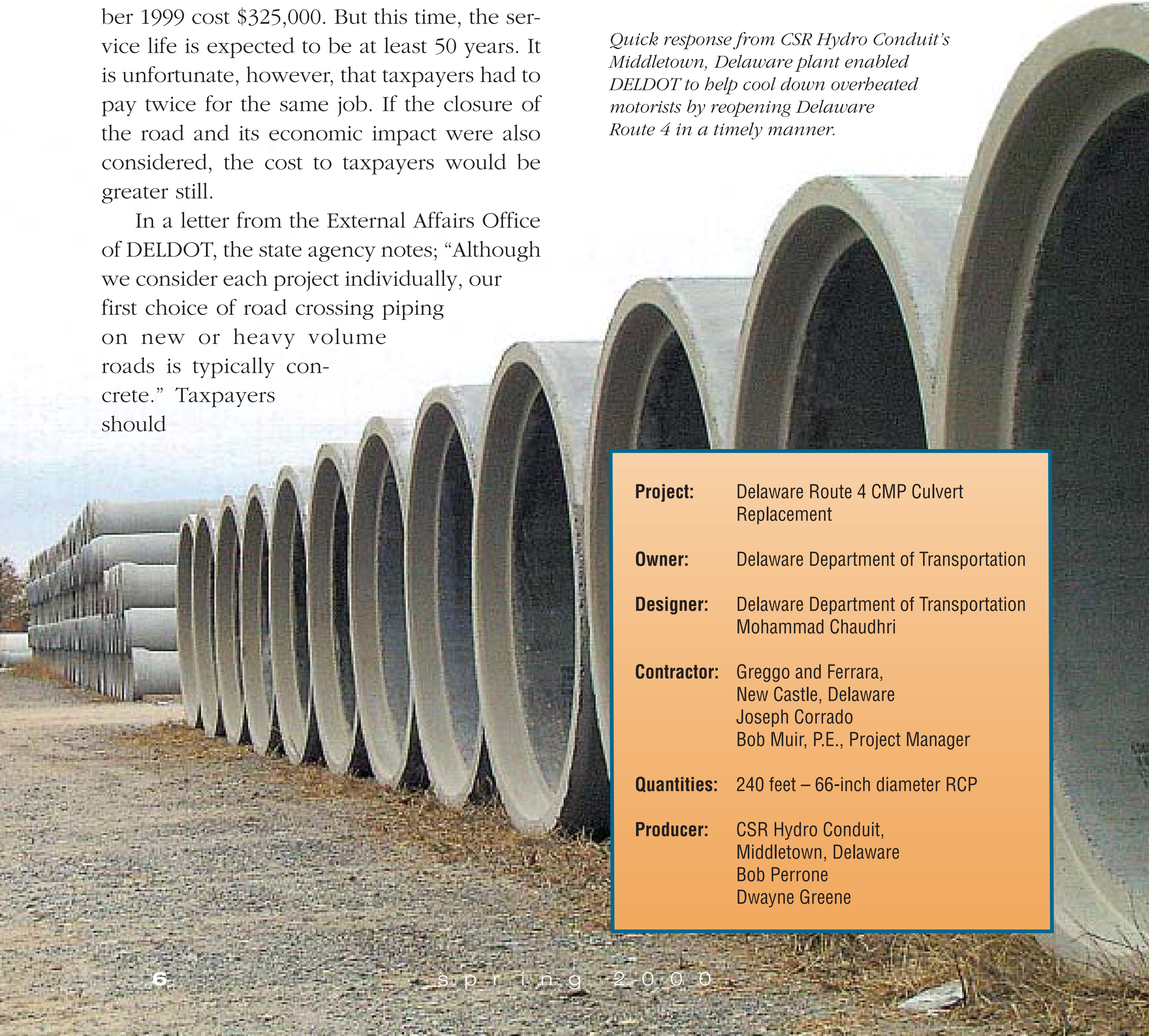
contacted by DELDOT to supply the concrete pipe under a very tight timetable. Pipe delivery was made within 5 days of the order and quickly installed to get the traffic moving again.

A proper LCA of the alternatives, including concrete, would have addressed the cost of the replacement. If reinforced concrete pipe had been used instead of CMP, the additional cost would have been a mere $12,000 more than the original CMP installation. Replacement of the culvert with concrete pipe in November 1999 cost $325,000. But this time, the service life is expected to be at least 50 years. It is unfortunate, however, that taxpayers had to pay twice for the same job. If the closure of the road and its economic impact were also considered, the cost to taxpayers would be greater still.

In a letter from the External Affairs Office of DELDOT, the state agency notes; "Although we consider each project individually, our first choice of road crossing piping on new or heavy volume roads is typically concrete." Taxpayers should feel confident that the reinforced concrete pipe now beneath Delaware Route 4 will not let them down, and will give them the value they expect in their buried infrastructure. ❍

Authors' Note:

CSR Hydro Conduit wishes to thank the contractor, Greggo and Ferrara of New Castle, Delaware and project manager Bob Muir, P.E. for allowing frequent access to the job site during the project.



Quick response from CSR Hydro Conduit's Middletown, Delaware plant enabled DELDOT to help cool down overheated motorists by reopening Delaware Route 4 in a timely manner.

Project:	Delaware Route 4 CMP Culvert Replacement
Owner:	Delaware Department of Transportation
Designer:	Delaware Department of Transportation Mohammad Chaudhri
Contractor:	Greggo and Ferrara, New Castle, Delaware Joseph Corrado Bob Muir, P.E., Project Manager
Quantities:	240 feet – 66-inch diameter RCP
Producer:	CSR Hydro Conduit, Middletown, Delaware Bob Perrone Dwayne Greene

Repairs with RCP Mean Smooth Roads and Drainage Flow for City of Athens

By Calvin Clifton, P.E., Director of Public Works, City of Athens, Tenn.
Larry N. Taylor, P.E., Sales Engineer,
Sherman-Dixie Concrete Industries, Inc., Knoxville, Tenn.
423-546-0870

A joint effort between the City of Athens (Tennessee) Public Works Department and Sherman-Dixie Concrete Industries, Knoxville, Tenn., led to a quick, structurally sound solution that saved the city thousands of dollars.

In the first week of July 1999, a large "L-shaped" concrete headwall on Thompson Street was discovered severely damaged, and near failure. In only a few days, the headwall collapsed into the open drainage channel. The failure undermined the edge of the pavement, obstructed the drainage channel, and closed a lane of traffic. Emergency repairs were required to restore the capacity of the drainage channel, and to maintain two-way traffic on Thompson Street.

The City of Athens Public Works staff determined that the existing four-by-four-foot box culvert needed to be extended to improve drainage flow and roadside safety. Several circumstances made this, otherwise simple repair, quite difficult.

The angle of the existing box culvert, and the open ditch that it drains, would require the new box culvert to be cut on an angle to match the existing culvert. The new culvert

▲ *Collapsed headwall damages road and drainage channel.*

◀ *Old cast-in-place structure being prepared for new box section.*

◀ *New precast box section cut on site to fit existing structure and accommodate storm sewer pipe.*

▼ *Precast concrete box sections form new culvert extension.*

would have to be core-drilled, or cut to accommodate the connection of an existing storm water line.

Corrective action called for the extension of the existing box culvert by approximately 22 linear feet. In addition, the repair would require a customized installation of a manhole structure to accommodate an existing 24-inch reinforced concrete pipe that serves as a storm drainage line from a side street.

Athens Street Superintendent Harvel Henry, Street Construction Foreman Mike Walden, and Public Works Director Calvin Clifton worked closely with Larry Taylor, Sales Engineer with Sherman-Dixie Concrete Industries, throughout the process of making the necessary repairs and improvements. This included working through site-specific requirements and issues to ensure that the proper flow would be accommodated for many years.

The four-by-four-foot precast concrete box culvert, and other drainage products manufactured and supplied by Sherman-Dixie, were shipped to the project on July 20. The box culvert was cut on site to match the angle necessary to accomplish the installation. The top of the box culvert also was cut in the field to accommodate the lateral storm water pipe connection.

The Athens Public Works Department staff completed the entire project in approximately one week at a cost of less than $6,500. The price included materials, equipment rental, and overtime labor. It was completed on July 27 — just 14 days after the headwall collapsed.

Although the repair and improvements were small, this project demostrates the versatility of precast concrete products and the value of solid relationships between producers and the communities they serve.

The project was brought to a successful conclusion because there was continuous coordination between Athens Public Works staff and the supplier throughout the process. A team approach allowed application of certain "value engineering" solutions to expedite the repairs while improving the overall level of service, appearance, and safety of the existing drainage structure. The Public Works Department was able to work with the supplier to use precast drainage structures that were modified in the field to meet the specific requirements of the project. This made for a speedy, structurally sound solution using the City's own forces to complete the project and save money. The application of precast concrete products is limited only by the imagination.

Reprinted in part with permission from Tennessee Public Works magazine.

The precast concrete box culvert extension is field modified, installed and backfilled in just 14 days.

Project:	Culvert Repair and Improvement
Owner:	City of Athens, Tennessee
Designer:	City of Athens Public Works Department Calvin Clifton, P.E., Public Works Director Harvel Henry, Street Superintendent Mike Walden, Street Construction Foreman
Quantities:	22 feet – (4-feet x 4-feet) precast concrete box sections
Producer:	Sherman-Dixie Concrete Industries, Inc. Knoxville, Tennessee Larry N. Taylor, P.E., Sales Engineer

Round and Elliptical Pipe Used in High Profile Development

By Roy P. Hylkema, P.Eng., Mgr., Land Development, KMK Consultants Limited, Brampton, Ontario and Eugenio Favaro, Certified Technician, Centennial Concrete Pipe & Products, Inc. Cambridge, Ontario
519-622-7574

Round and elliptical concrete pipe service a highly visible mixed-use development in the Georgetown area of the Town of Halton Hills, Ontario, Canada. High quality precast concrete products are used for the unique storm water quality and quantity management system that channels flow from the site to a cold water fishery. Concrete products supplied to the site meet stringent provincial and national standards, as well as certification through the Plant Prequalification Program of the Ontario concrete pipe industry. The contractor, Drexler Construction Limited, prefers the use of concrete in sizes 450 mm (18-inch) diameter and larger because of installation considerations.

Bradley Gardens is a 22-ha (54-acre) site located on lands that were once the home of the world-renowned Dominion Seed operation. The site was the last major agricultural enterprise near the center of Georgetown, and is remembered for the fields of flowers harvested for bulbs and seeds. The planning process for the development of the site covered many years and involved numerous public hearings. It concluded with the approval of a mixed use development by Parallax Development Corporation that included medium and high density residential, major retail, commercial, a school and parkland areas.

Servicing of the site presented interesting challenges for the consulting engineer, KMK Consultants Limited of Brampton, Ontario. The topography of the site slopes gently to the southwest with an average grade of 1.5% to 2%. Underlying soils were not well drained in many locations, making it difficult to meet a requirement of development set by Credit Valley Conservation for storm water infiltration. The water supply of the Georgetown area is generated by deep wells, and it is important to include soil recharge techniques in any new development. Techniques for soil recharge included specially designed catch basins and swales at the rear of townhouse blocks, and the ponds.

Existing storm sewers and sanitary sewers adjacent to the site were at elevations that determined the grade of the buried pipe needed to drain the site. In some locations, the installations were restricted to shallow bury. Circular concrete pipe was used to withstand loads from collector roads, and elliptical pipe at the outlet to the pond. Elliptical pipe carries the flow that discharges into an on-site storm water management pond located adjacent to the major intersection of Maple Avenue and Guelph Street (Highway 7).

The storm water management plan for the site had to address quality and quantity issues for post-development flows for one in five and 100-year storms via overland flow routes. The pond includes 3,063 m^3 (4,006 cu. yd.) of permanent pool storage below the elevation of 251.52 m (825.19 feet) and 985 m^3 (1,288 cu. yd.) above the 251.52-meter elevation. Discharges from the pond are controlled by a single control structure with two orifice plates outletting to the receiving sewer. An emergency 15.2-meter wide (49.87-feet) overflow weir is also in place, in case of blockage of either of the outlets.

The mixed-use Bradley Gardens development used a wide variety of precast concrete drainage products, including round pipe, elliptical pipe, manholes, catch basins and valve chambers.

Centennial Concrete Pipe & Products, Inc., a member of the American Concrete Pipe Association, was contracted by Drexler Construction Limited to supply all precast concrete products. Centennial Concrete is a leading precast concrete pipe producer in Ontario with plants in Windsor, Cambridge and Ottawa.

Round concrete pipe used for the storm water management system ranged from 450 mm (18-inches) to 1200 mm (48-inches) in diameter. The 20.9 meters (73 feet) of elliptical pipe was 1090 mm x 1725 mm (43-inches x 68-inches) in diameter. The elliptical pipe used for the storm outfall to the storm water management pond was connected to the round concrete pipe with a 2400 mm x 1800 mm (96-inch x 72-inch) control box manhole. The consulting engineer had originally considered a long run of elliptical pipe over a distance of approximately 468 meters (1594 feet), but decided to use a heavier class of round concrete pipe with additional cover to accommodate an access road into the site.

A sewage pump station was built on-site in the event that the downstream sanitary sewers being constructed by the Region of Halton were not commissioned by the time the new construction on the site was occupied and generating waste water flows. The pump station was constructed using precast concrete manhole components. The pump station may never be commissioned if the downstream sewers are constructed on schedule.

The need for soil recharge resulted in specially designed catch basins used to collect storm water at the rear of the residential units. Storm water is channeled into a swale and then into catch basins where it enters the infiltration chamber consisting of 250 mm (10-inch) diameter perforated pipe wrapped in a geotextile sock and enveloped in clear stone. These chambers are located at the base of the catch basins and installed parallel to the base. A second outlet pipe is located above the infiltration chamber on the proper slope to connect with the storm water collection system. These pipes collect storm water flow in heavy rainfall events. Storm water generated by light rainfall is held in the catch basins and directed into the infiltration chamber where the water is returned to the soil. The storm water management pond has also been designed to retain runoff so that it can infiltrate into soil.

Servicing of the Bradley Gardens development made efficient use of precast concrete products. There were immediate savings to the developer in the cost of materials and time. Construction using precast concrete products was able to continue beyond December into January 2000 despite winter weather conditions. The site is now ready for the 2000 construction season.

Project: Bradley Gardens Development
Owner: Parallax Development Corporation,
Toronto, Ontario
Designer: KMK Consultants Limited,
Brampton, Ontario
Roy P. Hylkema, P.Eng.,
Manager, Land Development
Bill Butler, P.Eng.,Project Manager
Contractor: Drexler Construction Limited,
Rockwood, Ontario
Jerome Drexler, Project Manager
Quantities:
Round Concrete Pipe
1,047 meters (3,438 feet)
65-D to 100-D Class (Class III and IV)
Horizonal Elliptical Concrete Pipe
20.9 meters (73 feet)
1090 mm x 1725 mm
(43-inches x 68-inches rise and span)
Manholes
17 sanitary
1-2400 mm diameter Pump Station
(96-inch diameter)
21 storm
1-2400 mm x 1800 mm Box Control
(96-inchs x 72-inches)
9 Rear-Lot Catch Basin
Catch Basins
23 Single Street
2 Double Street
13 Rear-Lot
3 Ditch Inlet
Valve Chambers
4-1800 mm Chambers
(72-inches x 72-inches)
3-2400 mm x 1800 mm Chambers
(96-inches x 72-inches)
Producer: Centennial Concrete Pipe & Products Inc.,
Cambridge, Ontario
Eugenio Favaro, C. Tech.

An Integer Program for Optimizing Sanitary Sewer Rehabilitation Over a Planning Horizon

"An Integer Program for Optimizing Sanitary Sewer Rehabilitation Over a Planning Horizon" by Sharon deMonsabert, Chee Ong, and Paul Thorton from Water Environment Research (Volume 71, No. 7, 1999, pages 1292-1297) Copyright (c) Water Environment Federation. Reprinted with permission.

ABSTRACT: Inflow and infiltration (I/I) associated with sanitary sewer pipeline and manhole defects have been known to cause unnecessary treatment expenditures. It is estimated that 10% or more of treated wastewater sources can be attributed to extraneous I/I. This paper documents an optimization model that analyzed costs and benefits of reducing amounts of I/I through selected rehabilitation methods recommended following a closed-circuit TV inspection over a 20-year planning horizon. An integer program was formulated using the General Algebraic Modeling System to optimize the sewer rehabilitation schedule and present value costs of repairs and I/I treatment. Results of a detailed analysis and the optimal rehabilitation schedule for a subshed of the Little Huntington Creek sewer system in Fairfax County, Virginia, are presented.

KEYWORDS: infiltration, inflow, collection system, modeling, integer programming, optimization, sewer rehabilitation, closed-circuit television inspection, sewer system evaluation survey (SSES).

Introduction

Inflow and infiltration (I/I) can contribute a significant amount of flow to a sanitary sewer collection system and create excess flow for treatment. It is estimated that average I/I contributes 3 to 5% of peak hourly or 10% of treated average daily domestic flow (Metcalf and Eddy, 1991). Similarly, there are reported cases where I/I can amount to 4900 L/cap-d (1300 gpd/cap) which represents a significant increase over the average dry weather flow of 270 L/cap-d (70 gpd/cap) (WEF and ASCE, 1982). Depending on severity of the I/I and associated repair and treatment costs, proper and timely I/I reduction can cause significant savings. This is especially true when the cost-benefit comparison is made over a defined life cycle of a system.

Inflow, by definition, is extraneous flow that enters through roof leaders, cellar and areaway drains, foundation drains, cleanouts, sump pumps, manhole covers, combined sewers, and illegal cross-connections. It is typically associated with rainfall events and brief in duration. It decreases available hydraulic capacity of the conveyance sewer and increases pumping costs and the potential for sewer overflows. Additionally, it increases the potential for pipe deterioration and collapse. Infiltration is defined as extraneous flow that enters a system through defective pipes, pipe joints, missing pipe segments, root intrusion, damaged lateral connections, or manhole walls. It is typically associated with high groundwater tables but can also be influenced by rainfall events. Durations of infiltration events are typically longer than inflow durations. Infiltration is typically greater during the winter season and at the end of the rainy season.

A comprehensive sewer system evaluation survey (SSES) entails flow data collection and analysis accompanied by a physical inspection of the sewer system. This evaluation is performed on a selected sewer basin to determine the excessiveness of I/I. The SSES provides an assessment of pipe and manhole conditions and recommends corrective actions for areas where I/I is deemed excessive. An SSES is performed to examine the specific location flow rate and associated rehabilitation cost of I/I sources. It is a systematic means of confirming the presence, location, and severity of I/I. It uses TV inspection, smoke testing, manhole inspection, flow monitoring, and other simulation methods to identify sources of I/I and appropriate corrective actions such as line-manhole grouting, point repair, and pipe-manhole rehabilitation or replacement.

The SSES will identify I/I areas of concern. However, additional analysis is needed to determine optimal allocation of financial resources to develop a prioritized repair strategy. A Benders decomposition model was developed by deMonsabert and Thornton (1997) to select the optimal solution within budgetary constraints.

Objectives

The optimization approach developed by deMonsabert and Thornton (1997) was limited to a current-year repair budget cycle. The main objective of this research is to provide an approach that makes repair decisions over a defined planning period. The model will determine not only the best repair strategy for a given budget, but also the recommended year in which the repair should be performed. Utility engineers must consider future needs and plan for the necessary funding required to complete these improvements in a manner that minimizes present value costs of I/I treatment and repair. The model presented in this paper will address the degradation of sewer systems and accent the consequences of delayed sewer repair. A case study for a subshed of the Little Huntington Creek sewer system in Fairfax County, Virginia, demonstrates the results of the developed model.

Integer Programming

Linear optimization problems that are based on purely integer variables are referred to as integer programming models. A special form of integer programming in which the decision variables are restricted to values of either 0 or 1 is known as a binary program. The generic form of a binary linear program is as follows:

$$\min \sum_{j=1}^{n} c_j x_j \qquad \text{where } j = 1,2,....,n$$

$$\sum_{j=1}^{n} a_{ij} x_j \, \mathrm{GE} \, b_i, \qquad \text{where } i = 1,2,....,m$$

$$x_j \in 0,1$$

Where

x_j = decision variable,
c_j = coefficient of the decision variable in the objective function,
b_i = boundary on a particular feature of the stated problem and is usually referred to as a resource to be allocated, and
a_{ij} = parameter that defines the contribution of each decision variable to the constraint.

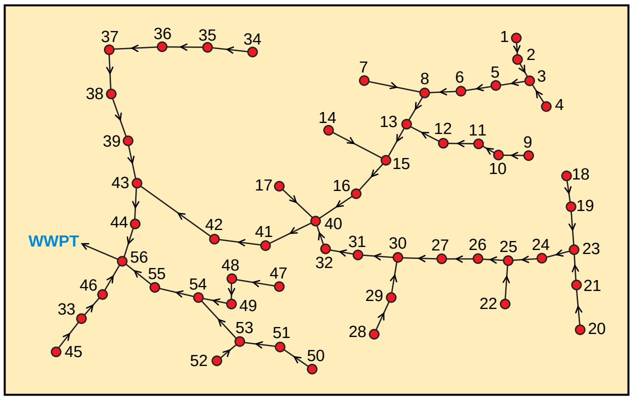
Binary problems cause large “holes” in the feasible region that require an ordered search technique (e.g., branch and bound. What does branch and bound mean? The practical importance of this integer programming method is apparent because many problems require discrete solutions with definite, not contiguous values or numbers. For all practical purposes, problems of linear programming with integer solutions are of an even greater importance than the classic problems of linear programming (Kaufmann and Henry-Labordere 1977). For example, in the sanitary sewer maintenance problem, a binary program can be developed from which to base decisions on whether to perform a repair of a deteriorated pipe, to use a particular repair strategy, or to make a repair at a particular time.

Case Study

The Line Maintenance Division (LMD) of Fairfax County, Virginia, is responsible for operation and maintenance of the county's sewer system. This sewer network system consists of approximately 4760 km (2960 mi) of collection sewer system, 72 km (45 mi) of pressure force main, 62 pumping stations, 234 grinder lift stations, 61 permanent flow meters, and 30 temporary meters. It serves an area of approximately 100 km^2 (40 sq mi) with a population of 850,000 and includes part of Arlington County and the City of Falls Church. The focus of this study is a subarea located within the Little Huntington Creek sewer basin, located in southeastern Fairfax County. The average age of the pipe in this area is 40 years. All of the pipes in the study area are concrete pipes ranging in diameter from 200 to 300 mm (8 to 12 in.). The total length of the system is 3459.8 m (11 351 ft). Figure 1 shows the schematic diagram of the pipes and connecting manholes for the study area.

Fairfax County's LMD performs approximately 190 km (120 mi) of TV inspection each year in addition to routine visual inspections of pipeline and sewer mains that are performed every 2 years. Because of the higher operating expense and limited resources, TV inspection is typically performed in areas where a closer observation of the sewer main is warranted. Such instances include deteriorated sewer main investigations, I/I source identification, and inspection of new sewer mains before acceptance. The TV inspection results reveal pertinent information related to conditions of the sewer mains, defects, and I/I sources. Figure 2 shows an example of a TV inspection photograph for an approximately 80 L/min (20 gpm) leak.

Figure 1: Subbasin of Little Hunting Creek



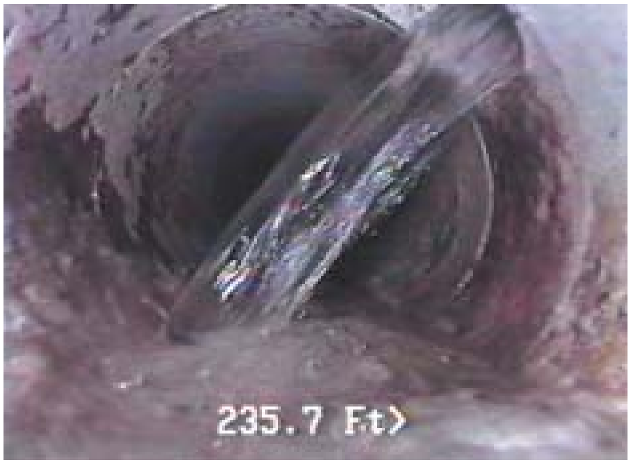


Figure 2: Television inspection photography for an approximately 80L/Min Leak

Table 1 summarizes the 1992 visual observations and TV inspection results for the study area (Fairfax County, 1992). With the exception of line segments P33, P40 and P45, television inspection data were collected. Some defects typically observed by TV operators are as follows: longitudinal-circular cracks; offset joints; root intrusion; calcium deposits; and leaky pipe joints, service connections, and manholes. Occasionally, broken pipe segments and sagged or collapsed pipe that require immediate attention are observed. In addition to describing the condition of the sewer main and manhole, TV operators also include the estimated observed I/I data coming into the system through pipes and manholes. Once the TV inspection tape is brought in from the field, it is further reviewed by the TV operator's supervisor and rehabilitation staff who in turn recommend appropriate repair options. Some typically recommended repair options are line-manhole grout, point repairs, and pipe-manhole rehabilitations. Most TV inspection work (80%) was performed during the dry weather period because of scheduling. Therefore, it is reasonable to assume that any observed I/I will get worse during the wet weather period.

Sewer System Optimization Model

The objective of this research was to introduce the maintenance planning horizon into the decision strategy for optimal sewer repair. The model was developed to select the repair strategy that yielded the minimum present value-cost solution over a 20-year planning period with maintenance at 5-year intervals. The present value cost represents costs associated with repair and wastewater treatment for excess I/I. Present values were calculated by applying the single-payment, present-worth factor to treatment and repair costs for the specific time frame and a 7% rate of return according to recognized engineering economic practices (Grant et al., 1976). The objective of the program was to select the optimal repair strategy (including time and option) to minimize total cost subject to budget constraints. The model assumes the severity of each defect will increase with respect to time if not repaired, which will result in increased I/I and therefore increased treatment costs. The model predicts defects in future years based on the historic rate of pipe and manhole failure that was calculated for this study area. The binary programming model developed to optimize the sewer system maintenance program is as follows:

Table 1. Summary of Sewer System Data, Television Inspection Observations and I/I Defects

Pipe/ HM No.	Pipe Length ft.	Pipe Dia. in.	Est. Pipe I/I gpm	Est. MH I/I, gpm	TV Inspection Observations	Recommended Option
1	170	8	1.5		Longitudinal crack	Point repair
2	163	8	1.5		Circular crack	Line grout
3	163	8	1.5		Longitudinal crack	Point repair
4	360	8	1.5		Offset joint	Line grout
5	194	8	1.5		Offset joint, roots & broken pipe	Line grout & point repair
9	347	8	0.5		SC leak & roots	Point repair & line grout
11	78	8	0.5		Calcium deposit	Line grout
13	166	10	0.5		Leaking joint	Line grout
14	341	8	0.5		SC leak	Point repair
15	263	10	0.5		Leaking joint	Line grout
16	171	10		0.5	Leaking MH wall	MH grout
17	200	8	1.5		Leaking joint	Line grout
20	316	8	1.5		Severe offset joint & broken pipe	Point repair
21	301	8	1.5		Offset joint	Line grout
26	98	8	0.5		Leaking joint	Line grout
27	141	8	0.5	1	SC leak & MH wall leak	Point repair & MH grout
32	129	8			Calcium deposit	Line grout
34	243	8			Calcium deposit	Line grout
35	142	8	1.5		SC leak & calcium deposit	Line grout
36	108	8	1.5		Longitudinal crack & calcium deposit	Point repair & line grout
37	399	8	1.5		Calcium deposit & roots	Line grout
38	369	8			Roots	Line grout
41	155	12		20	MH wall leak	MH grout
42	369	12	7	3	Offset joint & leaky MH	Line & MH grout
44	219	12	1.5		Circular crack & calcium deposit	Line grout
46	231	8	1.5		Calcium deposit	Line grout
50	94	8	1.5		Offset joint & roots	Line grout
51	168	8	1.5		Roots	Line grout
53	338	8	1.5	1.5	Broken pipe, calciumdeposit & circularcrack	Point repair & line grout
54	237	8	0.5	2	Leaking joint & MH	Line grout & MH grout
55	220	8	1	3	Longitudinal crack, leaking joint & MH	Cast in place and grout
56	367	12	5	1	Multiple defects	Cast in place
Total	**11245**		**41**	**32**		

Note: The following Pipes/MHs do not have any observed defects (6-8, 10, 12, 18-19, 22-25, 28-31, 33, 39-40, 43, 45, 47-49, 52).

$$\min \sum_{t} \mathrm{TCost}(t) * \sum_{s} F_{s,t} + \sum_{s,d,r,t} \mathrm{RCost}(s,d,r,t) * y_{s,d,r,t}$$

$$F_{s,t} + \mathrm{Repairs}(s,d,r,t) * y_{s,d,r,t} = \sum_{d} \mathrm{Defects}(s,d,t)$$

$$(\mathrm{Defects}(s,d,t) - \sum_{r} \mathrm{Repairs}(s,d,r,t) * y_{s,d,r,t})$$

$$* \mathrm{Age}(s,d,t) = \mathrm{Defect}(s,d,t{+}1)$$

$$\sum_{s,d,r} \mathrm{RCost}(s,d,r,t) * y_{s,d,r,t} \le \mathrm{Buget}(t)$$

$$\sum_{r} y_{s,d,r,t} \le 1$$

$$F_{s,t} \ge 0, y_{s,d,r,t} \in \{0,1\}$$

Where
s = superset of all manholes and pipes,
$p(s)$ = set of pipes,
$h(s)$ = set of manholes,
r = set of repair strategies,
d = set of defects,
t = time periods to model,
Defects(s,d,t) = I/I flow for defects in s at time period t,
Repairs(s,d,r,t) = I/I flow reduction for defect d when s is repaired by r in time t,
Age(s,d,t) = defect increase factor due to aging,
Rcost(s,d,r,t) = repair cost to fix d in s using r in time t,
TCost(t) = treatment cost in time t,
Budget(t) = repair budget in time t,
$F(s,t)$ = flow to treat in segment s during time t, and
$y(s,d,r,t)$ = decision variable to repair defect d in s with method r during t.

This integer programming model was formulated using the General Algebraic Modeling System (GAMS) Release 2.25 (Brooke 1992) to optimize the sewer rehabilitation schedule.

Assumptions Used in the Model Formulation

Assumptions included in the model development are summarized as follows. (Most of the I/I values [80%] estimated by the TV inspection crew were determined during dry weather periods.) The first assumption is that there are inherent variations in the estimated flow observed by the TV operator. For example, a 5.7 L/min (1.5 gpm) leak observed by one operator may be interpreted as 4 L/min (1 gpm) by another operator. Observed defects are reasonable despite the subjective means by which they were collected.

Second, some I/I values were estimated from TV inspection data for cases in which the TV operator did not record I/I. Therefore, an average estimated I/I value of 5.7 L/min was assigned to line segments where line grout was recommended and no I/I value was assigned in the inspection report. This figure was based on the average observed I/I for the 13 line segments in the study area. Similarly, an estimated I/I through manhole leak of 15 L/min (4 gpm) is assigned to manholes that require grouting. This value is derived based on the average observed I/I for the eight manholes in the study area. Third, the estimated defect rate for pipes was calculated as a 3.75% increase in I/I per year. This value

Table 2. Unit Cost Data

Item	Unit Cost
Insituform 8" 10" 12"	 $59/lf $62/lf $64/lf
Point repair (dig up)	$2,000/ea
Line grouting	$1.60/lf
Manhole grouting	$310/ea
Wastewater treatment	$2.60/1,000 gal

Table 3. Repair Budget vs. Net Present Worth of Total Repair and I/I Treatment Costs

Repair Budget ($)	Net Present Worth of Total Repair and I/I Treatment Costs ($)
0	2,047,230
1,000	1,206,489
2,000	883,390
5,000	553,536
7,500	457,488
10,000	416,419
15,000	342,509
20,000	322,494
25,000	318,990
30,000	289,606
40,000	272,048
50,000	252,271

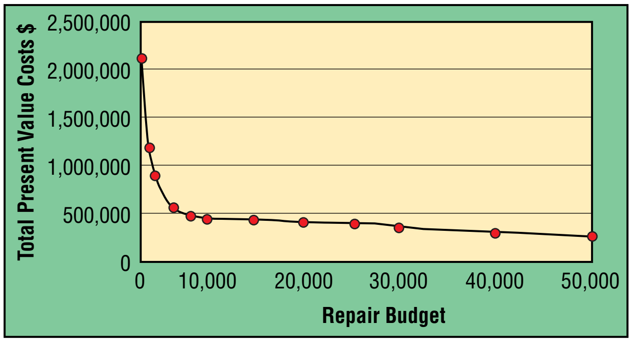
represented an average for defective pipes in the study area. Similarly, the manhole defect rate was calculated in a similar fashion as a 10.0% increase in I/I per year. Also, it was assumed that the effectiveness of I/I reduction with line grout or manhole grout is 80%. The cast-in-place pipe effectiveness is estimated to be 80%.

Last, a Monte Carlo approximation was used to determine expected failures in 5, 10, 15, and 20 years based on the probability of failure. The random probability of occurrence based on an analysis of historic data for the study area is as follows: (1) Frequency of I/I through pipe leak = 0.7 out of 56 line segments in any given year. (2) Frequency of I/I through manhole leak = 8 out of 56 manholes in 40 years or 1 every 5 years. (3) Frequency of point repair = 1 every 5 years. The unit cost data used in the analysis are shown in Table 2 (Fairfax County, 1996).

Case Study Results

The model was run for a variety of budget options. The detailed results for a planning budget of $0 to $50,000 for each planning budget period (5 years) are summarized in Table 3. Based on the results of the model (Figure 3), a repair budget greater than $50,000 does not reduce the net present worth of total repair and I/I treatment costs. Any additional repair budget spent in excess of $50,000 will not yield a lower net present worth of total costs. This type of information can be useful from the budget planning perspective. If this sewer subshed (1/1500 of the total system) is representative of the Fairfax County collection system, an estimated $75 million budget would be needed for each of the 5 years in the planning horizon. Use of the integer program will allow proper prioritization and timely appropriation of adequate funding to minimize costs associated with necessary system improvements.

Figure 3: Total Cost for Given Repair Budget



The shape of the curve shown in Figure 3 also reflects the relative gains associated with the increase in repair budget. Significant reductions in total cost are realized as the 5-year budget increases from $0 to $7,500. The reduction in repair and I/I treatment is $212 for every $1 budgeted. However, the reduction in repair and I/I treatment is only $4.8 for every $1 budgeted for a budget increase from $7,500 to $50,000. This represents a significant decrease in return on budget investment in this range. A similar observation was noted by deMonsabert and Thornton (1997) for a simple 1-year optimization. Results suggest that this phenomenon is not exclusively related to the short-term planning scenario but is also characteristic of the optimal long-range planning period.

Recommended Rehabilitation Schedule

In addition to optimal budget, the model also predicts optimal repair schedule subject to stated budget constraint. Samples of optimal pipe and manhole repair schedules for a $7,500, 5-year planning budget are shown as Tables 4 and 5. Note that many of the pipe and manhole repairs are repeated. This is because of the assumed 80% repair efficiency for both manhole and pipe repair options. Similarly, the rate of deterioration is assumed to be 3.75% for pipes and 10% for manholes on an annual basis. A comparison of the two tables shows that manholes are repaired in multiple years in 11 out of 12 cases (92%) compared with pipes, which are scheduled for repair in multiple years in 13 out of 36 cases (36%). This may be in part a result of the higher rate of deterioration associated with manhole defects, which would contribute to increased I/I and associated treatment costs.

Summary and Conclusions

The integer programming approach can be used as an effective planning method to optimize and prioritize a sewer rehabilitation schedule. The model can be modified to evaluate different budget constraints at a variety of time intervals, as necessary. The model can also be used to evaluate the effects on the budget and schedule for changes in estimated pipe and manhole deterioration rates and repair efficiencies. Many factors could affect the rate and extent of sewer deterioration. Modifications may be required subject to changing field conditions. For this reason, the

Table 4. Recommended Pipe Rehabilitation Schedule for a $7,500 Budget

Pipe No:	Defect Observed or Predicted	Optimum Repairs To Be Performed At Year					Net Present Worth Of Repair Costs, $	Net Present Worth of I/I Reduction's Savings, $
		0	5	10	15	20		
P1	Y	X		X			$ 410	$ 26,361
P2	Y	X	X	X			$ 542	$ 27,463
P3	Y	X	X				$ 447	$ 27,375
P4	Y	X					$ 576	$ 24,383
P5	Y				X		$ 837	$ 4,530
P7	Y		X				$ 455	$ 14,629
P8	Y				X		$ 218	$ 3,108
P10	Y	X	X	X	X		$ 40	$ 8,703
P11	Y	X					$ 158	$ 8,209
P12	Y					X	$ 84	$ 342
P13	Y	X					$ 266	$ 8,053
P15	Y		X				$ 300	$ 5,315
P16	Y	X	X	X		X	$ 210	$ 7,857
P17	Y	X		X			$ 483	$ 26,289
P19	Y					X	$ 101	$ 325
P20	Y				X		$ 909	$ 7,784
P21	Y	X		X		X	$ 852	$ 25,948
P25	Y	X		X		X	$ 232	$ 7,835
P26	Y	X					$ 198	$ 8,169
P28	Y					X	$ 24	$ 402
P30	Y		X	X			$ 303	$ 16,690
P32	Y				X	X	$ 128	$ 3,300
P33	Y			X			$ 1,017	$ 8,533
P34	Y			X		X	$ 299	$ 7,769
P35	Y	X		X			$ 343	$ 26,429
P36	Y		X				$ 1,550	$ 15,296
P37	Y	X					$ 638	$ 24,321
P40	Y					X	$ 63	$ 363
P42	Y	X	X				$ 1,011	$ 128,828
P44	Y	X	X				$ 528	$ 26,243
P46	Y	X	X				$ 730	$ 27,121
P48	Y		X	X			$ 167	$ 16,827
P50	Y	X	X				$ 258	$ 27,565
P51	Y	X		X			$ 406	$ 26,366
P53	Y					X	$ 657	$ 170
P54	Y		X				$ 271	$ 5,345
Total							**$15,711**	**$604,246**

Note: The following pipes do not require any repair over the 20-year planning horizon (6, 9, 14, 18, 22-24, 27, 29, 31, 38,39, 41, 43, 45, 47, 49, 52, 55,56)

Table 5. Recommended Manhole Rehabilitation Schedule for a $7,500 Planning Budget

Pipe No:	Defect Observed or Predicted	Optimum Repairs To Be Performed At Year					Net Present Worth Of Repair Costs, $	Net Present Worth of I/I Reduction=s Savings, $
		0	5	10	15	20		
H8	Y			X	X	X	$ 350	$ 35,373
H16	Y		X	X			$ 379	$ 12,972
H20	Y		X	X	X		$ 492	$ 80,951
H25	Y					X	$ 80	$ 1,198
H27	Y	X		X			$ 468	$ 33,140
H41	Y	X	X	X	X		$ 802	$ 695,395
H42	Y	X	X		X		$ 612	$ 102,572
H48	Y				X	X	$ 193	$ 11,756
H53	Y	X	X				$ 532	$ 50,996
H54	Y	X		X	X		$ 549	$ 66,752
H55	Y	X	X		X		$ 645	$ 103,128
H56	Y	X		X			$ 469	$ 33,139
Total							**$5,571**	**$1,227,372**

Note: The following MHs do not require rehabilitation over the 20-year planning horizon (1- 7, 9-15, 17-19, 21-24, 26, 28-40, 43-47, 49-52)

integer program model is intended for use as a supplemental planning tool. It is, nevertheless, a powerful and flexible planning tool that can be effectively used to provide a significant savings to the collection system rehabilitation program.

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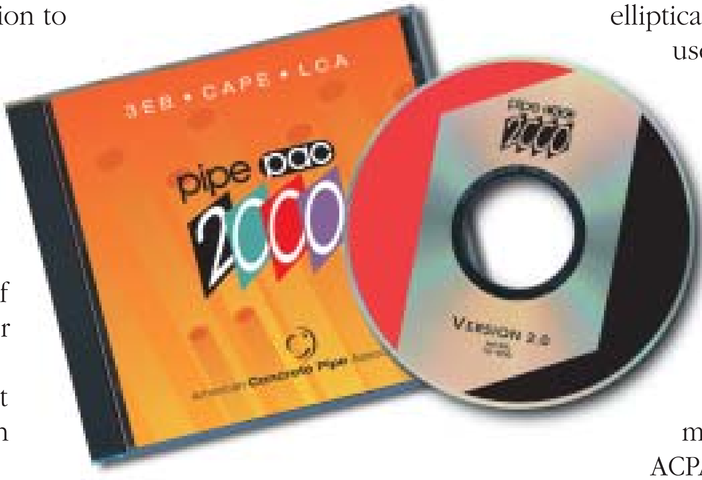

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