Operational Paper

A troubleshooting manual for handling operational problems in water pipe networks

V. K. Kanakoudis

ABSTRACT

The paper presents some of the most common operational problems in water pipe networks, studied in the water distribution system of Athens, the capital of Greece. The study, which took place from 1995 to 2000, concerning individual pipes of a network with a total length of 7,000 km, was based on the leakage and pipe break records kept by Athens Water Utility. The main outcome was an easy-to-use troubleshooting manual for handling operational problems in water pipe networks. This troubleshooting manual, as a product of applied research, is a knowledge base that can form the basis of an expert decision support system for detecting, identifying, studying and solving the problems that occur in a water distribution system.

Key words | empirical study, operational and structural failures, pipe network, troubleshooting manual

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INTRODUCTION

The main goal of managing a water delivery system under normal operating conditions is to satisfy the existing water demands with the minimum operating cost. The probable system failures along with their various impacts, resulting from the kind and size of each failure, established the need for further studying these failure incidents. This study attempts to analyse some of the most common operational problems met in water delivery networks. This analysis is based on theoretical study and field experience gained from studying the water distribution network of Athens, the capital of Greece. The first step is to underline the symptoms of the problems, aiming at their safe and prompt identification. The next step is to describe the actual causes of the problems. Finally the necessary restoration actions for the permanent or short-term solution of each problem are presented. The study, which took place in Athens from 1995 to 2000, concerning 7,000 km of water pipes, was based on the leakage and pipe break records kept by Athens Water Utility, known as EYDAP, and constant feedback from the results of the applied leak detection techniques (Kanakoudis 1998).

ATHENS WATER DISTRIBUTION SYSTEM

The water delivery network of Athens satisfies the daily needs (approximately 1,000,000 m^3 as a mean annual value) of its effective population (approximately 4,000,000 people) who live and/or work in the greater metropolitan area of Athens, resulting in a daily per capita consumption of 280 litres (Figure 1). Initially the water supply system (510 km long) carries water from the Attica water resources (rivers: Evinos and Mornos, lakes: Yliki and Marathon) to the four water treatment plants located just outside the city limits. From there, the delivery system, through mains (diameters >400 mm of 1,250 km total length) and 'delivery' pipes (diameters <400 mm, of

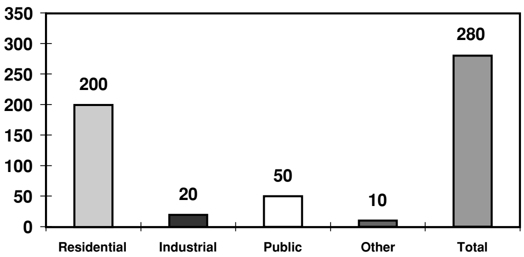

Figure 1 | Daily per capita water consumption in litres.

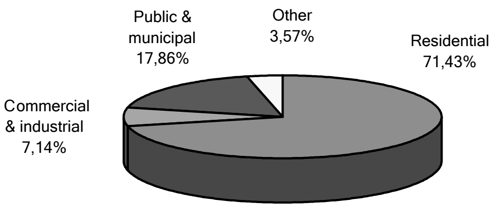

Figure 2 | Water consumption in Athens.

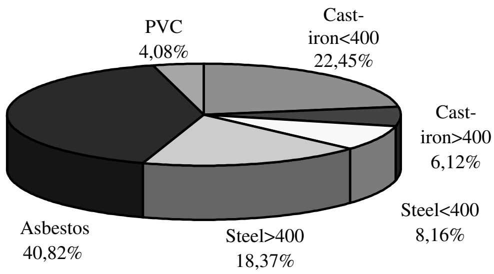

Figure 3 | Pipe material in Athens.

5,750 km total length), services 1,600,000 customers' connections (98.75% of them refer to domestic and 1.25% of them refer to industrial uses) (Figure 2). The water distribution system is divided into the sections of Athens (2,150 km), Piraeus (1,950 km) and Heraklion (2,600 km). The pipe materials are cast iron, steel, asbestos and PVC (Figure 3). The delivery pipes are of all kinds of materials and the mains are made of cast iron and steel. The cast iron pipes are not lined in contrast to steel mains. From the leakage and pipe break records that EYDAP has kept since 1989, it has been derived that the non-revenue water (water losses plus unbilled authorized consumption) is almost 35% of the total water volume exiting the water treatment plants. From this volume, 1% is the legal emergency use for fire fighting, park watering, road and sewerage cleaning. Water theft is only 1% as a result of a supervisory control and data acquisition system (SCADA) system that monitors the network. Finally, leaks, breaks and metering errors are responsible for the loss of 15%, 3% and 15%, respectively, of the water supplying the system (Figures 4 and 5) (Kanakoudis 1998, 1999, 2002*a*, 2002*b*). Due to the obvious significance of leaks a specific department of EYDAP is responsible for keeping continuous leakage records. These records include data gathered from customers' complaints reports and data collected by experienced personnel through leak detection techniques using portable sonic devices. From the complete leak data record it is apparent that 43.3% of the leakage occurs in pipe bodies, 24.1% in the customers' connections and the rest (32.6%) in other system devices such as valves, joints and gates (Figure 6). Figures 7 and 8 demonstrate the allocation of leaks and breaks according to pipe material (Kanakoudis 1998).

THE MAIN PROBLEMS IN ATHENS WATER DELIVERY NETWORK

The major operational problems in the case study of the Athens distribution system are water losses, structural and carrying capacity failures and, finally, poor quality of the water supplied (Table 1).

Water losses

The water losses in a pipe network can be distinguished into real and apparent losses. The former include the volumes that enter the system but are not used legally or properly due to leaks, breaks and illegal connections. In contrast, the latter include unauthorized non-metered water use and a justified error during the metering process of the actual consumption. The total water losses (real plus apparent losses) are very difficult to track down because the extent of metering errors and the volumes used to satisfy public and fire fighting needs (unbilled authorized consumption) cannot be accurately measured.

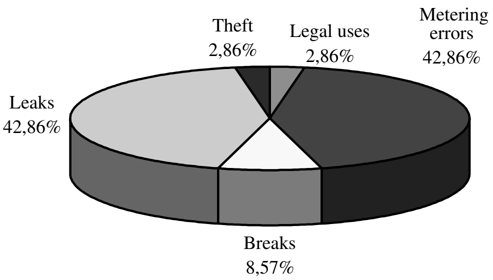

Figure 4 | Non-revenue water in Athens water network.

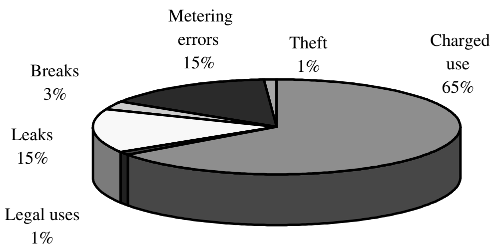

Figure 5 | Water balance in Athens system.

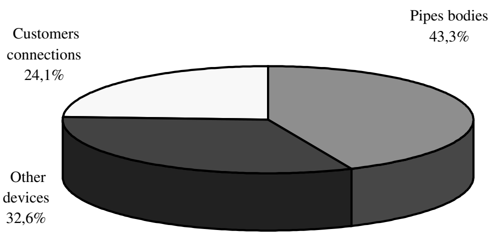

Figure 6 | Allocation of leaks to the system devices.

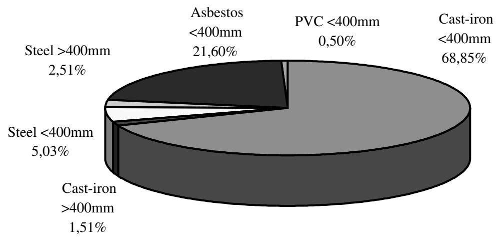

Figure 7 | Leaks allocation according to pipe material.

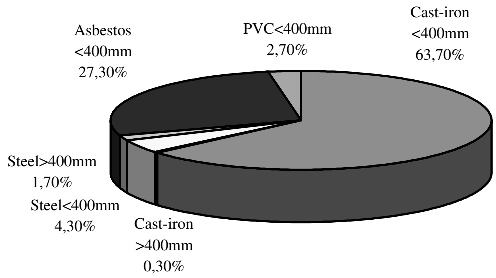

Figure 8 | Breaks allocation according to pipe material.

The field experience from managing water networks revealed that these losses could be as much as 40% of the total water volume entering the system, although the accepted levels barely reach 10% (Male *et al.* 1985). Water losses indices (easy to calculate) and water losses signs (derived from network surveillance and customers' complaints) provide a reliable way to detect and identify the problem. Some of the most widely used water losses indices are presented below.

Per capita water use index

Per capita water use index is defined as the water volume supplied daily by the water treatment plants, divided by the equivalent population served by the water utility. The value of this index follows the increase of industrial use and mean residents' income. When the index has values greater than 200 litres (Male *et al.* 1985), then water use metering and/or leakage problems probably occur.

Unaccounted-for-water index (UW)

UW is the most important index representing the network level-of-service (LOS). It estimates the deficit between the water supplied by the water treatment plants and the metered consumption. The UW includes legal public use, fire fighting use, water losses due to leaks and breaks, unauthorized consumption and metering inaccuracies. The index becomes more significant as the percentage of metered consumption increases. The UW can reach or even exceed the level of 50% in old or uncontrolled networks. A pipe network with UW less than 15% is supposed to be in good condition. If the value of UW is greater than 30% then the network needs immediate inspection. Existing directives from the United States Environment Protection Agency (USEPA) suggest that measures must be taken in order to keep the value of UW

Table 1 | Identification, analysis and solution of the problems in a water pipe network

Identification of problems		Main causes of the problems		Restoration actions	
(a)	(b)	(a)	(b)	(a)	(b)
WL	**Water losses**	**C**	**Corrosion of metallic pipes**	**SS**	**Structural strengthening**
WL1	Pipe corrosion holes	C1	Aggressive-corrosive water	SS1	Additional boosters & pressure reducing valves
WL2	Leaks in pipe joints and connections	C2	Bimetallic connections	SS2	Increase of tanks' storage capacity
WL3	High percentage of night consumption	C3	Direct contact with electricity source	SS3	Additional cut-off valves
WL4	High per capita non-industrial consumption	C4	Aggressive-corrosive neighbouring environment	SS4	Cathodic protection
WL5	High value of unaccounted-for-water index	C5	Unlined pipes	SS5	Network cleaning
WL6	Low per capita domestic consumption			SS6	Avoid bimetallic connections
WL7	High values of water losses indices	**LCC**	**Low carrying capacity**	SS7	Avoid direct contact with electricity source
WL8	Poor leak detection results	LCC1	Insufficient size of pipes	SS8	Improved pipe installation practices
WL9	Poor results of the water metering system	LCC2	Inadequate capacity of pumping system	SS9	Increase pumping capacity
WL10	Deficit in the water balance of the network	LCC3	Insufficient pressure reducing valves	SS10	Installation of release valves
WL11	Signs of surficial water	LCC4	Improper valve maintenance and control	SS11	Adoption of in-system chlorination
		LCC5	Debris in pipes	SS12	Check and repair of joints
SF	**Structural failures**	LCC6	Insufficient storage capacity of the tanks	SS13	Pipe cleaning and lining
SF1	Breaks at bimetallic connections/joints	LCC7	Scale and tubercle build-up	SS14	Looped network operation
SF2	Breaks below the level of the groundwater table			SS15	Installation of proper metering network
SF3	Breaks in clay soil bedding/backfill	**LB**	**Leaks and breaks**	SS16	Construction of alternative supply paths/mains
SF4	Breaks in high alkalinity soils	LB1	Poor joint material	SS17	Implementation of pipe insertion
SF5	Frequent circumferential breaks	LB2	Direct contact with other structures	SS18	Pipe replacement with corrosion-free material
SF6	Often accidental pipe breaks/crushes	LB3	Poor load bearing capacity pipes	SS19	Surge control
SF7	Frequent longitudinal breaks	LB4	Poor pipe material		

Table 1 | Continued

Identification of problems		Main causes of the problems		Restoration actions	
SF8	Increased pipe break rates in winter	LB5	Insufficient bedding depth	**OM**	**Operation & maintenance**
SF9	Increased pipe break rates			OM1	Change of valves settings
SF10	Pressure peaks	**WQD**	**Water quality degradation**	OM2	Regular pipe flushing
SF11	Signs of surficial water	WQD1	Intrusion of substances	OM3	Repair of leaks
		WQD2	Disturbed water characteristics	OM4	Calibration of water use metering network
CCF	**Carrying capacity failures**			OM5	Check of water use metering network
CCF1	Cloudy water	**M**	**Miscellaneous**	OM6	pH adjustment of water
CCF2	Corrosion of lining used items	M1	Insufficient surge control	OM7	Proper checking of valves operation
CCF3	Failure in supplying pressure under peak demands	M2	Illegal connections	OM8	Improvement of water treatment techniques
CCF4	Poor performance of the pumping system	M3	Incomplete water consumption metering		
CCF5	Decreased Hazen–Williams (C) coefficient	M4	Inaccurate water consumption metering	**DA**	**Data acquisition**
CCF6	Poor hydrant test results	M5	Insufficient number of cut-off valves	DA1	Hydraulic simulation of the system
CCF7	Pumping system capacity exhaustion	M6	Insufficient number of air-release valves	DA2	Implementation of leak detection techniques
CCF8	Scale or tubercles in pipe			DA3	System mapping using GIS
CCF9	Very high velocities			DA4	Keeping full data records (normal/abnormal)
CCF10	Wide storage tank fluctuations			DA5	Systematic control of billing records
				DA6	Intrusion control in high-risk points
PWQ	**Poor water quality**				
PWQ1	Customers' complaints of dirty water				
PWQ2	High asbestos levels				
PWQ3	High lead levels				
PWQ4	Poor Langelier index (LI)				
PWQ5	Customers' complaints of red water				

to below 5% (AWWA 1996). An increase in UW might be a symptom of illegal connections to the network, water theft, inadequate or false metering and leaks. The calculation of the per capita residential water use index and the non-industrial-commercial per capita residential water use index is a reliable way to check whether high values of UW result from water use metering errors or extended leakage.

Per capita residential water use index

Per capita residential water use index expresses the metered residential daily water use divided by the equivalent population of residents being served. As its value drops (<100 litres), the probability of the occurrence of extended water use metering errors increases.

Non-industrial-commercial per capita residential water use index

This index expresses the water entering the system, apart from the industrial-commercial daily use, divided by the equivalent population being served. As its value grows (>200 litres), the possibility of extended leakage occurring increases.

Minimum night-time ratio index

This is defined as the minimum hour water use (usually during night) divided by the mean daily hour water use. It is used to check whether water is being lost due to leaks and, furthermore, to locate them. The value of the index should be practically zero. Values greater than 30–40% strongly indicate that significant water losses occur due to leaks.

Apart from the above-mentioned indices, several indications of water losses can be observed in a water network, such as surfacing water and spatial clustering of consumer complaints. Surfacing water, wet spots on the ground, unexpected green patches and complaints of low water pressure, cloudy and coloured water indicate possible pipe leaks or breaks.

Structural failures

The physical integrity of a distribution system refers to the ability of the system to withstand either external or internal stress and is reflected in the number and type of pipe breaks. To measure the rate of the system's weakness, the break rate value is used. The brake rate value equals the number of breaks per unit length of the system divided by the number of years that the system has been in service, or by the number of years for which break data is available. The type of a pipe break helps to determine its causes. In Athens, the first three of the following types of break are the most common: (a) circumferential, (b) longitudinal, (c) pinhole, (d) tap and joint blowout, (e) cracked bell, and (f) crushed pipe. The circumferential breaks usually result from failure of the pipe as a beam (pipe diameter <250 mm). The break covers the perimeter of the pipe and results from improper bedding during construction, excessive external loads, poor pipe material, uniform corrosion and soil erosion caused by leakage or high groundwater table. The longitudinal break covers the pipe's length. Larger pipes (>300 mm) usually experience such breaks from crushing caused by exterior loads or excessive internal pressure due to operating conditions, surge or frost. The pinhole break starts as a small hole in the pipe walls, due to internal or external corrosion, and as it grows the pipe finally breaks. The remaining types of pipe break are mainly caused by poor pipe bedding conditions or poor joint material.

The characteristics of the backfill soil can also be blamed for pipe breaks (e.g. as clay retains moisture it can cause external corrosion problems). Breaks due to corrosion also result from direct contact of the pipe with an electricity source or bimetallic connections due to substances in the bedding soil. The state of the pipe walls (signs of internal or external corrosion, visible as pitting and/or encrustation) before installation reveals the structural condition of the pipe. Pipe break rates are also affected by other parameters such as weather conditions and contact with other structures. For example, the minimum temperatures recorded during winter can, in conjunction with the type of bedding soil, result in frost of either the water into the pipe or of the water retained by the backfill soil. This increases the internal and external stress resulting in sudden pipe breaks. Finally, the existence of other constructions or public networks next to the pipe is a crucial parameter as the soil propagates the external loads and vibrations coming from them.

Carrying capacity failures

Carrying capacity failures, due to inadequate pipe size or scale–tubercle build-up and encrustation in the pipe walls, may prevent the network from fulfilling its mission, that is, to constantly satisfy water needs. Water pressure reduction and inability of the water storage tanks to be refilled during peak or emergency demands are signs of poor system carrying capacity. In the tanks, small or large water level fluctuations reveal that they have been over- or under-sized. Other crucial parameters are how sensitive the pipe material is towards corrosion and the aggressive-corrosive character of the supplied water. The latter can be estimated through the calculation of several indices such as the Langelier index (saturation index representing the concentration of carbon dioxide in the water). By studying these parameters, the variation with time of the pipe's internal characteristics, such as the Hazen-Williams factor, due to corrosion, can be estimated (Ormsbee & Wood 1986; Walski 1986; Sharp & Walski 1988). Cloudy water in the house taps indicates concentration of air bubbles in the high parts of the network because of the lack of air-releasing valves, blocking the water flow. Finally, the frequency, intensity and extent of customers' complaints indicate the significance of the problem.

Poor water quality

The quality of the water supplied by the water treatment plants and through the pipe network reaching the house taps determines the way that the operating state of the pipe network affects and is affected by the physical and chemical characteristics of the supplied water. Most of the characteristics of the supplied water (taste, odour, colour, alkalinity, pH, lead concentration) result from: (a) the water resource, (b) the state of the pipe walls, and (c) the chemicals used in the water treatment plants without using the necessary after-treatment neutralizers. Customers' complaints of red or dirty water also indicate poor quality of the delivered water. Red water indicates high levels of iron concentration caused by the deterioration of the pipe walls or originating from the water resource. Dirty water indicates a recent pipe break, flushing of remaining substances caused by low flow velocities or pollutant intrusion from pipe holes near pumps or boosters.

THE MAIN CAUSES OF THE PROBLEMS IN ATHENS WATER PIPE NETWORK

Usually, the operational problems of a water network are easily detected, but it is very difficult to identify their causes. To achieve a sustainable solution for each problem, its actual causes must be faced. Unfortunately, time restrictions and lack of know-how and experience among the water utility managers force them to face any problem by applying temporary measures that postpone and displace it to another part of the network. The following paragraphs present and analyse the several categories of the causes of the operational problems in Athens's water distribution system. This was an extremely difficult task because the problem's symptom–cause relationship is not a direct link. It is possible for one problem to have several causes and one cause to result in more than one problem. Also, a parameter could be the cause of one problem and at the same time result from the impact of other parameters. Specifically, the causes of the problems are distinguished into internal and external causes as far as the network is concerned. Additionally, the causes can be categorized into five major groups: (a) corrosion, (b) low carrying capacity, (c) leaks and breaks, (d) water quality degradation, and (e) miscellaneous (Table 1).

Corrosion of metallic pipes and other metallic devices

Corrosion of metallic pipes and other metallic devices could be either the cause of other operational problems or the operational problem itself. Corrosion is the cause of high breakage rates, high leakage, low pressure and can contribute to poor water quality. Corrosion is distinguished into internal or external forms. In the former, the characteristics of the water supplied are important. In the latter, the environment surrounding the pipe is responsible for the deterioration of the network. The main corrosion factors are water quality (aggressive water), corrosive backfill soil, bimetallic connections, stray direct current and lack of pipe lining.

Low carrying capacity

Insufficient pressure causes extended system problems. It can result from operating failures, lack of necessary control devices, inadequate pipes, insufficient water storage tanks, inadequate capacity of the pumping systems and unpropitious characteristics of the transferred water. Analytically, insufficient storage of water tanks causes wide water level fluctuations during peak demand resulting in poor system carrying capacity. Inadequate pumping capacity could be blamed for inadequate pressure, caused by great hydraulic head losses due to undersized pipes. Significant problems also result from substantial hydraulic head losses because of improper operation of control or pressure reducing valves through improper maintenance. Air bubbles gathered in the higher parts of the network, due to the lack of the necessary air releasing valves, cause water blockage. Finally, scale, turbulence and encrustation of pipe walls due to either a high concentration of floating or dissolved substances in the water or high subsidence rates, could also restrain or even block the water flow.

Leaks and breaks

Leaks, apart from pipe bodies, mainly occur in pipe joints and customer connections. They are difficult to detect, as they are not visible, and cause various problems such as water quality degradation and external corrosion, in other parts of the system. The main cause of weakened pipe walls is internal or external corrosion creating pinholes or openings from which the water leaks. The gradual deterioration of the joints materials that are being decayed (easy to break) under normal internal pressure, surge or external loads is another cause of leakage. Additionally, internal pressure becomes extremely significant when the pressure reducing valves are inadequate or even absent, causing the gradual loosening of the joint materials.

Breaks often cause great social reactions, as they are visible failures with extended impacts. Breaks can be distinguished into those that come as a gradual result of a leak and those that occur without any previous sign of an existing leak. Breaks differ significantly from leaks, as they are greater pipe ‘cracks’, occur mainly on a pipe body, cause more damage, result in greater water loss rates and their repairs take longer and cost more. A break can be immediately detected and repaired in contrast to a leak, which can escape notice for a long time causing greater water losses. A break can be caused by external load or internal pressure strength excess (under normal operating conditions, hydraulic surge or frost), a simple failure due to strength reduction resulting from ageing pipe material or pipe bedding failures, internal or external corrosion, direct contact with other constructions and, finally, seismic activity.

Water quality degradation

The quality of the water flowing through a pipeline can deteriorate because of: (a) the intrusion of pollutants through pipe holes under particular circumstances (low or even negative pressure areas) and (b) leaching (e.g. lead or asbestos) from pipe walls due to the aggressive-corrosive character of the water (e.g. low pH). Low velocities and stagnation, poor initial quality and insufficient disinfectant residual are also some of the main reasons that usually contribute to bacterial re-growth and failure in meeting the water quality standards.

Miscellaneous

There are also several causes of problems in the Athens water distribution system that do not fit into the previous categories. A failed meter or water theft through illegal connections result in loss of revenues, inability to control water use, encouragement of water waste and therefore failure of any implemented urban water use

Table 2 | Symptoms: main and possible failure causes

Symptom of the failure	Main cause of the failure	Possible cause of the failure
Water losses		
WL1	C2	C4
WL2	LB1,M1	
WL3	LB1	C1,C2,C3,C4,C5,M1,M2
WL4		C1,C2,C3,C4,C5,LB1,M1,M2,M3,M4
WL5		C1,C2,C3,C4,C5,LB1,M1,M2,M3,M4
WL6	M4	M2
WL7		C1,C2,C3,C4,C5,LB1,M2,M3,M4
WL8		C1,C2,C3,C4,C5,LB1
WL9	M4	LCC7
WL10		C1,C2,C3,C4,C5,LB1,M2,M3,M4
WL11		C1,C2,C3,C4,C5,LB2,LB3,LB4,M1
Structural failures		
SF1	C2	C4
SF2	C4	LB4
SF3	C4	LB4
SF4	C4	LB4
SF5	LB2,LB3,LB4,LB5	C4
SF6	LB2,LB3,LB4,LB5	
SF7		C4,LB4,M1
SF8	LB5	C4,LB3,LB4
SF9		C1,C2,C3,C4,C5,LB2,LB3,LB4,M3
SF10	M1	
SF11	LB1,LB2,LB3,LB4,LB5,M1	C1,C2,C3,C4,C5
Carrying capacity failures		
CCF1	M6	
CCF2	C1	

Table 2 | *Continued*

Symptom of the failure	Main cause of the failure	Possible cause of the failure
Carrying capacity failures *continued*		
CCF3	LCC1,LCC2,LCC4,LCC5,LCC6,LCC7	C1,C5,LCC3
CCF4	LCC2	LCC1,LCC3,LCC4,LCC5,LCC6,LCC7
CCF5	C1,C5,LCC7	
CCF6	LCC1,LCC2,LCC4,LCC5,LCC6	C1,C5,LCC3
CCF7	LCC2	LCC1,LCC3,LCC4,LCC5,LCC6,LCC7
CCF8	C1,C5,LCC7	
CCF9	LCC1	
CCF10	LCC6	LCC1,LCC3,LCC4,LCC5,LCC6,LCC7
Poor water quality		
PWQ1	C1	WQD1,WQD2,M6
PWQ2	WQD2	
PWQ3	WQD2	
PWQ4	C1	
PWQ5	C1,C5	WQD2

conservation programme. Finally, inadequate, insufficient or inoperable network devices such as valves cause significant operational and management problems in a pipe network.

RESTORATION ACTIONS FOR THE PROBLEMS IN ATHENS'S WATER NETWORK

The restoration actions taken to solve the problems occurring in Athens's water network can be distinguished into: (a) simple- or multiple-goal actions depending on whether they are facing one or more than one problem, respectively, and (b) main or emergency actions, that directly eliminate the cause of the problem or just postpone its impacts offering temporary alternatives by facing the impacts and not the causes, respectively. The restoration actions can be categorized into three major groups (topics): (a) actions that improve the structural strength (physical characteristics) of the network, (b) actions that optimize its operating and maintenance practices, and (c) actions that optimize data acquisition practices (Table 1).

Improvement of the structural strength (physical characteristics) of the network

The successful implementation of these measures presupposes: (a) accurate knowledge of where water is being used, by repairing the failed meters and eliminating any water theft; (b) the installation of cut-off and air-release valves; and (c) surge control using special devices (e.g. surge tanks, relaxation valves). One of the most common restoration actions is pipe cleaning (e.g. flushing, scraping) used to remove scale and tubercles from the pipe walls. To prevent recurrence of the same problem, in-system chlorination and looped network operation are suggested. Looping improves water quality, as the slow flowing water in dead ends tends to stagnate thus allowing sedimentation or leaching of metals from pipe walls. To face corrosion, several preventive or therapeutic actions are suggested, such as:

- pipe replacement with pipes of corrosion-free material;
- pipelining practices using slow-hardening cement-mortar membrane;
- internal pipe coating with a slightly smaller (slip lining) diameter pipe;
- external pipe coating with a slightly larger (pipe insertion) diameter pipe (a machine called a 'mole' is used to break apart the original pipe);
- cathodic protection of the pipe (galvanic or impressed current);
- avoidance or elimination of any bimetallic connection or electricity source;
- repair of joints and pipe connections;
- external support for the pipe walls.

There are also several ways to increase the network's carrying capacity, such as:

- building new water tanks or increasing the storage capacity of the existing ones;
- increasing the pumping capacity with additional units;
- installation of booster pumps;
- installation of isolation, air release and pressure reducing valves;
- construction of alternative parallel mains;
- looping, which also increases the system reliability.

Improvement of the network operation and maintenance practices

The first step to achieve this goal is to improve the trenching, pipe construction and pipe installation practices. To upgrade the operation of the system, the following actions are necessary:

- frost prevention in dead ends by avoiding low flow velocities (looping reduces the potential for freezing since the water is more likely to be moving);
- pH adjustment and corrosion prevention by adding special chemicals (reduction of internal corrosion reduces the leakage/breakage rates and improves water quality, decreasing the rate at which metals or other chemicals are leached from the pipe walls);
- modified operation of the pumps to achieve optimum efficiency;
- modified operation of the pressure valves to form self-supporting and controlled network pressure zones.

To improve the network's maintenance, the following actions are necessary: (a) regular internal pipe flushing, which improves the quality of the water by removing any settled material (eliminates the symptom, not the underlying problem), and (b) experienced repair groups to check and assure the proper operation of cut-off valves, to detect pipe leaks, to check and repair the water meters and finally to detect any unauthorized water use or water theft.

Data acquisition practices

The required data acquisition practices aim at gaining full knowledge of the operational and physical characteristics of the network, which is the necessary presupposition for designing, scheduling and implementing the most appropriate measures to successfully face the network's problems. First of all, the formulation of a hydraulic simulation model for the pipe network, equipped with a supervisory

Table 3 | Failure causes: restoration actions

Failure cause	Main action	Emergency action
Corrosion		
C1	OM6,OM8	SS13,SS14,SS17,SS18,OM2,DA4
C2	SS6,SS18	SS4,DA3,DA4
C3	SS7	SS18,DA3
C4	SS4	SS18,DA2,DA3,DA4
C5	SS13,SS17,SS18	SS4
Low carrying capacity		
LCC1	SS14,SS16,SS17	SS1,SS2,SS5,SS13,DA1
LCC2	SS1,SS9	SS2,DA1
LCC3	SS1	DA1,DA3
LCC4	OM1,OM7	DA4
LCC5	SS5,SS8,SS17,SS18	OM2,DA1
LCC6	SS2	SS9,DA1
LCC7	SS5,OM6,OM8	SS14,SS16,SS17,SS18
Leaks and breaks		
LB1	SS12,SS18	SS13,OM3,DA2,DA3,DA4
LB2	SS8	
LB3	SS8,SS17,SS18	DA3,DA4
LB4	SS17,SS18	SS13,DA2,DA3,DA4
LB5	SS8,SS18	DA4
Water quality degradation		
WQD1	DA6	SS18
WQD2	SS11,OM8	SS13,SS14,SS18,OM2,OM6,DA3,DA4
Miscellaneous		
M1	SS8,SS19	
M2		SS15,OM5,DA5
M3	SS15	OM4,DA3,DA4
M4	OM5	OM4,DA4,DA5
M5	SS3	DA1,DA3
M6	SS10	

Table 4 | The importance of each problem cause with regard to the 37 problem symptoms

	C1	C2	C3	C4	C5	LCC1	LCC2	LCC3	LCC4	LCC5	LCC6	LCC7	LB1	LB2	LB3	LB4	LB5	WQD1	WQD2	M1	M2	M3	M4	M5	M6
Main cause	**6**	2	0	**3**	3	3	4	0	2	2	3	3	3	3	3	3	4	0	2	3	0	0	2	0	1
Possible cause	**11**	9	9	**14**	11	3	0	5	3	3	3	4	5	2	3	7	0	1	2	5	6	5	4	0	1

Table 5 | The importance of each category of causes in the 37 cases of problem symptoms

	Main cause	% of total main causes	Possible cause	% of total possible causes	Total main or possible cause	% of total main/possible causes	Main cause only once	% of cases where is the main cause only once	Possible cause only once	% of cases where is the possible cause only once	Main or possible cause only once	% of cases where is the main/possible cause only once
C	14	25.5	54	46.6	68	39.8	11	**29.7**	16	**43.2**	25	**67.6**
LCC	17	30.9	21	18.1	38	22.2	8	**21.6**	6	**16.2**	9	**24.3**
LB	16	29.1	17	14.7	33	19.3	6	**16.2**	12	**32.4**	17	**45.9**
WQD	2	3.6	3	2.6	5	2.9	2	**5.4**	2	**5.4**	4	**10.8**
M	6	10.9	21	18.1	27	15.8	6	**16.2**	10	**27.0**	14	**37.8**

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Table 6 | The importance of each restoration action in the 25 cases of problem causes

	SS1	SS2	SS3	SS4	SS5	SS6	SS7	SS8	SS9	SS10	SS11	SS12	SS13	SS14	SS15	SS16	SS17	SS18	SS19	OM1	OM2	OM3	OM4	OM5	OM6	OM7	OM8	DA1	DA2	DA3
Main action	2	1	1	1	2	1	1	5	1	1	1	1	1	1	1	1	5	**7**	1	1	0	0	0	1	2	1	3	0	0	0
Emergency action	1	2	0	2	1	0	0	0	1	0	0	0	5	3	1	1	2	**6**	0	0	3	1	2	1	1	0	0	6	3	10

Table 7 | The importance of each category of the restoration actions in the 25 cases of problem causes

	Main action	% of total main actions	Emergency action	% of total emergency actions	Total main or emergency action	% of total main or emergency actions	Main action only once	% of cases where is the main action only once	Emergency action only once	% of cases where is the emergency action only once	Main or emergency action only once	% of cases where is the main/emergency action only once
SS	35	79.6	25	38.5	60	55.1	20	**80**	14	**56**	23	**92**
OM	8	18.2	8	12.3	16	14.7	5	**20**	7	**28**	9	**36**
DA	1	2.3	32	49.2	33	30.3	1	**4**	19	**76**	20	**80**

control and data acquisition system (SCADA–telemetry and telecontrol) is absolutely necessary in order to provide the most reliable data. Detailed network mapping is also extremely valuable. At the same time highly experienced work groups are needed for accurate leak detection and constant maintenance of data records including information on the network's operation, break events, repairs, maintenance and the related costs. Finally the systematic control of billing records helps to detect metering errors due to false meters.

THE TROUBLESHOOTING MANUAL

In the previous paragraphs the operational problems of the Athens water distribution system, their causes and the suggested restoration actions have been analysed. Based on this analysis a troubleshooting manual for detecting, identifying and solving the most common operational problems met in a water distribution system can be developed (Tables 1, 2, 3). This troubleshooting manual, as a product of applied research, is a knowledge base that can form the basis of an expert decision support system.

Analytically, Table 1 includes all the necessary details concerning the identification, analysis and solution of any distribution system problem. Columns 1a and 1b list the various symptoms of the problems met in a water distribution system (e.g. water loss, structural failure, carrying capacity failure, poor water quality). So, if a symptom is detected, then using Table 1 the problem can be identified. Columns 2a and 2b list the causes of the problems (e.g. corrosion, low carrying capacity, leaks/breaks, water quality degradation, miscellaneous). Finally, columns 3a and 3b list the restoration actions suggested for solving each problem (e.g. structural strengthening, operation and maintenance, data acquisition).

The symptoms detected for each problem can reveal its main and possible causes using Table 2. This table is designed to assist in linking symptoms with causes. The table lists various symptoms in the left-hand column and causes (main or possible) in the two columns on the right. The table is not intended to provide a definitive analysis but rather to provide assistance and guidance to the decision-maker who is familiar with his or her own system. In some cases, the problem's symptom–cause relationship is not a direct link, as one symptom may call for more analysis to determine more definite symptoms.

Finally, for each failure cause, certain restoration actions are suggested. Table 3 relates actions that can be taken and the degree to which that action will eliminate (main actions) or alleviate the cause (emergency actions). The causes are listed in the left-hand column and actions in the other two columns.

Results of using the troubleshooting manual in Athens

In Athens, EYDAP uses this troubleshooting manual along with a simulation hydraulic model and a SCADA system, under either abnormal operating conditions, to detect, identify and solve operational problems, or normal operating conditions, to determine the time and place that any preventive maintenance action must take place (Kanakoudis & Tolikas 1999). The application of the troubleshooting manual decreased the network's resilience time (time between a failure occurrence and an emergency action taken) by about 25% and resulted in annual cost savings of 4 billion drachmas (€11.7 million) (Kanakoudis *et al.* 2000; Kanakoudis & Tolikas 2000, 2001).

Tables 4 and 5 show the importance of each problem cause with regard to the 37 problem symptoms recorded in the Athens water system. The basic outcome, as expected, is that corrosion-based causes are mainly or possibly responsible for 67.6% (29.7% as a main and 43.2% as a possible cause) of the water problems. Analytically, aggressive-corrosive water and an aggressive-corrosive neighbouring environment are the most common causes of water problems.

Tables 6 and 7 show the importance of each restoration action for the 25 problem causes recorded in the Athens water system. The basic outcome, as expected, is that actions aiming at the structural strengthening of the network can be long-term or short-term (emergency) solutions for 92% (80% as a long-term and 56% as a short-term solution) of the water problem causes. Analytically, pipe replacement with corrosion-free material and keeping full data records (normal/abnormal) are the most commonly implemented restoration measures.

CONCLUSIONS

The field experience gained by trying to understand and face the operational problems met in the Athens water distribution system was extremely valuable. The basic outcome was that corrosion-based causes are mainly or possibly responsible for most of the water problems. Also, actions that improve the physical integrity of the system can be long-term or short-term solutions for most of the water problems.

The ultimate goal achieved was to develop a trouble-shooting manual, as a product of applied research. This manual is a friendly tool for the decision-maker who runs the system from the control room. Using this manual the decision-maker has the ability, through successive approximations and exclusions of alternative solutions, to minimize the network's resilience time during abnormal operating conditions. Actually, the manual's emphasis is on decision-making and it provides guidance in determining the most beneficial remedy provided that the cause or causes of problems are detected. The guidelines are not meant to be dictates, but rather clues to be used in focusing on problems and their best solutions. Each water distribution system is unique and must be approached on an individual basis.

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