J Water SRT — Aqua Vol. 48, No. 3, pp. 106–114, 1999

Water quality and the replacement and repair of drinking water infrastructure: the Washington, DC case study

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ABSTRACT: A major challenge for society in the 21st century will be replacement, design and optimal management of urban infrastructure. It is estimated that the current world wide demand for infrastructure investment is approximately three trillion US dollars annually. Many developing countries are experiencing rapid growth, and developed countries are facing the need to replace old and obsolete infrastructure to meet existing and future requirements.

Sustaining and expanding infrastructure has traditionally been viewed as related to the need for maintaining economic stability or for providing the basis for sustaining economic growth. However, infrastructure also has a major role in enhancing environmental quality and protecting public health. There is a need to reassess some of our assumptions concerning the way infrastructure is designed, built, utilised, maintained and renewed if we are to satisfy both the economic needs of communities while fulfilling environmental and public health objectives.

Problems associated with ageing drinking water systems in the USA and their difficulty in complying with the increasingly stringent requirements of the Safe Drinking Water Act provide an excellent example of this difficulty.

Starting in September 1993 and lasting through to July 1996, the Washington, DC water supply system experienced a series of microbial violations under the Total Coliform Rule, which is part of the US Safe Drinking Water Act. The US Environmental Protection Agency assigned a team of Agency experts to work with the Washington, DC system to assess the problem and to make recommendations to bring it into compliance. The team suggested 26 major changes, including a US$200m capital investment programme, the development of a hydraulic and water quality model for the system, and a systematic flushing and valve turning programme. In addition, the DC government established a semi-autonomous water utility to operate the system. No new problems were experienced after the programme was initiated.

INTRODUCTION

A major challenge for society in the 21st century will be the replacement, design and optimal management of the urban infrastructure. It is estimated that the current world-wide demand for infrastructure investment is approximately three trillion US dollars annually [1]. Many developing countries are experiencing rapid growth, and developed countries are facing the need to replace old and obsolete infrastructure to meet existing and future requirements.

Sustaining and expanding the infrastructure has traditionally been viewed as related to the need for maintaining economic stability or for providing the basis for sustaining economic growth. However, infrastructure also has a major role in enhancing environmental quality and protecting public health. There is a need to reassess some of our assumptions concerning the way infrastructure is designed, built, utilised, maintained and renewed if we are to satisfy both the economic needs of communities while fulfilling environmental and public health objectives.

Problems associated with ageing drinking water systems in the USA and their difficulty in complying with the increasingly stringent requirements of the Safe Drinking Water Act provide an excellent example of this difficulty. This paper will present a case study that documents the dramatic impact that the regulations promulgated under the Safe Drinking Water Act have had on drinking water infrastructure decisions in Washington, DC.

ENVIRONMENTAL INFRASTRUCTURE NEEDS IN THE UNITED STATES

In 1988, the National Council on Public Works Improvement issued a report on the status of the infrastructure in the USA

[2]. The commission examined the following eight areas: highways, mass transit, aviation, water resources, water supply, wastewater, solid waste and hazardous waste. Based on the Council's findings it was estimated that the USA would have to invest over US$100bn each year in new and existing public works in order to satisfy its anticipated needs.

A 1990 report by the Congressional Office of Technology Assessment (OTA) in the areas of wastewater, drinking water and municipal solid waste evaluated the impacts of infrastructure needs in these areas for local communities. The OTA found that a community's environmental infrastructure needs are varied and interrelated [2]. Virtually all communities may have the same generic needs, such as providing safe drinking water, protecting receiving waters and providing for the environmentally acceptable disposal of solid waste. However, the solutions to these problems can vary greatly with community size. For example, small communities generally lack the financial and personnel resources to provide the same level of support as compared to larger communities. Therefore, they tend to use lower-cost and less-complex technologies.

A recent survey conducted by the US Environmental Protection Agency (US EPA) found that community water systems in the USA face significant infrastructure needs in order to protect public health and to assure the availability of safe drinking water. The Drinking Water Infrastructure Needs Survey conducted by the US EPA estimated that community water systems nation-wide have an immediate need of US$12.1bn in infrastructure investment, primarily to protect against microbiological contaminants that pose an acute health risk. The survey also found that over US$130bn is needed to maintain and replace existing drinking water systems [3].

STATUS OF DRINKING WATER SYSTEMS IN THE UNITED STATES

In the USA an estimated 16 trillion gallons (61 trillion L) of water is produced annually by 60 000 community water utilities to serve the needs of 223 million people [4]. This water is supplied by an estimated 880 000 miles (1420 000 km) of distribution system piping from water sources to residential, commercial and industrial properties (not including the service lines connecting the water main to the structure). The replacement value of this piping is estimated to be US$348bn. It is also estimated that 26% of this piping is unlined cast iron pipe and is judged to be in fair condition, at best, from a structural or hydraulic standpoint. However, much of the pipe has been installed since World War II, is less than 30 years old, and is judged by the utility operators to be in good condition. Unfortunately, some water utilities have a predominance of ageing infrastructure in a poor condition, especially in the older inner cities, whereas suburbs tend to have newer piping in better condition.

It is estimated that 13 200 miles (21 200 km) of new pipe are installed annually in the USA, with an estimated annual cost of US$2.8bn. The predominant types of new pipe are cement lined ductile iron (47.7%), polyvinyl chloride (38.7%) and concrete pressure (12.5%).

An estimated 4400 miles (7080 km) of pipe are being replaced annually at an estimated cost of US$174.2m. If we assume that there are 880 000 miles (1420 000 km) of installed pipe in the USA, then utilities would replace any given pipe only once every 200 years.

Distribution systems are traditionally designed to ensure hydraulic reliability, which includes adequate water quantity and pressure for fire flow, as well as to meet domestic and industrial demand. In order to meet these goals, large amounts of storage are usually incorporated into system design, resulting in long residence times, which in turn may contribute to water quality deterioration. Drinking water distribution systems are generally required to meet the stand-by or ready-to-serve requirements for fire fighting as well as domestic, industrial and other normal water use [5]. The National Board of Fire Underwriters governs the fire fighting capacity of distribution systems. In order to satisfy the need for adequate capacity and pressure, most distribution systems incorporate standpipes, elevated tanks and storage reservoirs. Frequently distribution systems are 'zoned' due to a desire to maintain relatively constant pressures in the system, or because of the way in which the system has expanded. The effect of designing a system to maintain adequate fire flow and reliability can result in long transit times between the treatment plant and the consumer. However, long travel times and low velocities may be detrimental to the requirements of drinking water standards. Long residence times lead to maximal formation of disinfection by-products, loss of disinfectant residuals and promote the formation of biofilm. A factor that is infrequently considered, and that may influence water quality in a distribution system, is the effect of mixing of water from different sources. Water distribution systems frequently draw water from multiple sources, such as a combination of wells, and/or surface sources. The mixing of waters from different sources which takes place within a distribution system is a function of complex system hydraulics [6–8].

DISTRIBUTION SYSTEMS AND WATER QUALITY

Most of the regulations established under the Safe Drinking Water Act and its Amendments (SDWAA) have been promulgated with little understanding of the effect that the distribution system can have on water quality. However, the SDWAA has been interpreted as meaning that some Maximum Contaminant Levels (MCLs) will be met at the consumer's tap, which in turn, has forced the inclusion of the entire distribution system when considering compliance with a number of the SDWAA MCLs rules and regulations.

SDWAA regulations, emphasising system monitoring include the Surface Water Treatment Rule (SWTR), the Total

Coliform Rule (TCR), the Lead and Copper Rule and the Trihalomethane Regulation. Both the SWTR and the TCR specify treatment and monitoring requirements that must be met by all public water suppliers.

The SWTR requires that a detectable disinfectant residual be maintained at representative locations in the distribution system to provide protection from microbial contamination. The TCR regulates coliform bacteria which are used as 'indicator' organisms to indicate whether or not system contamination is occurring. Monitoring for compliance with the Lead and Copper Rule is based entirely on samples taken at the consumer's tap. The current standard for trihalomethanes (THMs) is 0.1 mg/L for systems serving more than 10 000 people, but the anticipated Disinfectant and Disinfection By-Products (D-DBP) rule may impose the current (or a reduced) THM level on all systems. This regulation also requires monitoring and compliance at selected monitoring points in the distribution system. Some of these regulations may, however, provide contradictory guidance. For example, the SWTR and TCR recommend the use of chlorine to minimise the risk from microbiological contamination. However, chlorine or other disinfectants interact with natural organic matter in treated water to form disinfection by-products. Raising the pH of treated water will assist in controlling corrosion, but will also increase the formation of trihalomethanes. It is, however, an accepted practice in the USA to attempt to maintain detectable disinfectant residuals in all parts of the distribution system.

An example of the water quality problems associated with failures in distribution is provided by a recent study aimed at determining the movement of a waterborne contaminant found in the Cabool, Missouri distribution system. Cabool has a groundwater source and did not disinfect. During the period 15 December 1989 to 20 January 1990, residents and visitors to Cabool (population 2090) experienced 240 cases of diarrhoea and six deaths. The organism *Escherichia coli*, serotype O157:H7, associated with the faeces of healthy dairy cattle, was isolated in many of the stool samples of ill people. An investigation performed by the Centers for Disease Control (CDC), with assistance from the US EPA's Water Supply and Water Resources Division, formerly the Drinking Water Research Division, concluded that the illness was caused by waterborne contaminants that entered the distribution system through a series of line breaks and meter replacements that occurred during unusually cold weather. This conclusion was based on statistical studies performed by the CDC and corroborated by water quality modelling performed by the EPA [8,9].

In March 1991 the Water Supply and Water Resources Division of the US EPA was requested by the Peruvian Ministry of Health to send a team of water supply experts to Peru to assist in evaluating the waterborne disease potential associated with a major cholera outbreak [10]. The team provided technical support to the CDC field epidemiology staff which had been in Peru for some time. The investigative team concluded that one of the major factors in this outbreak was the marginal condition of the distribution systems in the areas visited. It was noted that water leaving a treatment plant would have adequate disinfectant residuals which would then disappear within the distribution system. Water systems experienced intermittent operation, fluctuating pressure, frequent pipe breaks, high water losses, and had unplanned cross-connections. Little repair and maintenance was practised in the utilities visited. It was the opinion of the investigative team that many of the waterborne disease outbreak problems associated with cholera were related to improperly operated and poorly maintained distribution systems [11].

In early December of 1993, a waterborne disease outbreak was identified in Gideon, Missouri (USA). Gideon also has a groundwater source and did not disinfect. Initially, 6–9 cases of diarrhoea were identified at a local nursing home. By 8 January 1994, 31 cases with laboratory confirmed salmonellosis had been identified. Seven nursing home residents who had exhibited diarrhoeal illness died, four of whom were culture confirmed. It was estimated that $\approx$44% of the 1104 residents, or almost 600 people, were affected with diarrhoea between 11 November and 27 December 1993. A system evaluation was conducted in which a computer model (EPANET) was used to develop scenarios, to explain possible contaminant transport in the Gideon system. It was concluded, based on this analysis, that the outbreak resulted from the contamination of a municipal water storage tank by birds [12].

Increasingly, drinking water systems in the USA will be faced with compliance problems associated with monitoring requirements under the Safe Drinking Water Act. Ageing infrastructure, inadequate maintenance and repair practices and the need to maintain disinfection residuals is posing, and will continue to pose, a major challenge for US drinking water utilities.

The Washington, DC case study, which illustrates this point, will be discussed in the following sections.

WASHINGTON DC CASE STUDY

The water supply system for Washington, DC consists of both a water supply or treatment system and a distribution system. Water supply in the District of Columbia area is provided by the Washington Aqueduct (WA), which is a Division of the US Army Corps of Engineers—Baltimore District, and which supplies water for approximately 1 million residents in the Metropolitan Washington Area. Construction of the WA was begun in 1852 by the Corps of Engineers. When the system went into operation in 1859, the WA was placed under the control and supervision of the Chief of Engineers. Prior to that time, DC obtained its water supply from local springs and wells. Today the WA serves DC, Arlington County, Virginia, the City of Falls Church, Virginia and approximately 50 square miles of Fairfax County, Virginia, via the City of Falls Church. Water distribution in these areas is the responsibility of the local governments [13]. The District of Columbia consumes approximately 76% of the water treated by the WA.

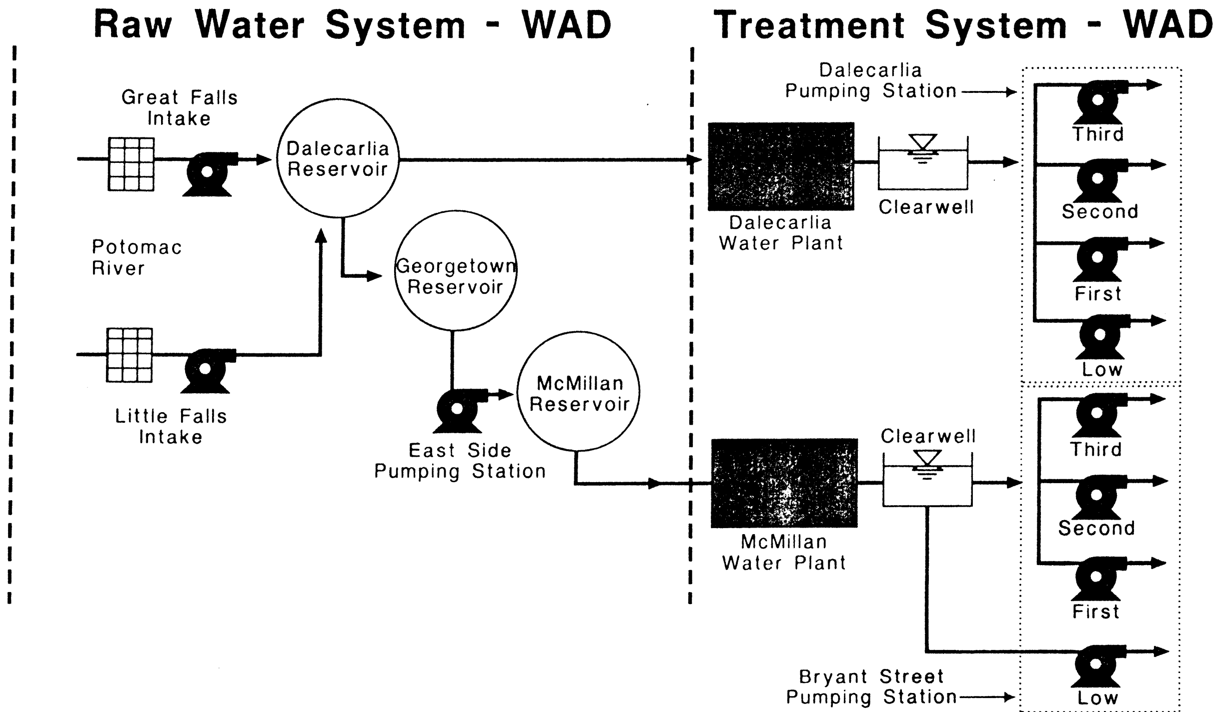

Fig. 1 District of Columbia water system—major facilities (source: Camp Dresser & McKee memorandum, 11 March 1996).

The WA operates and maintains two water treatment facilities which supply finished water to storage reservoirs located at different elevations throughout the DC area (Fig. 1). On an average day, 180 million gallons per day ($681 \times 10^3\,m^3$/day) is supplied to WA customers and on peak days, approximately 240 million gallons per day ($908 \times 10^3\,m^3$/day) is delivered to the DC area.

The DC water system is divided into eight service areas (Fig. 2). Pressure in each of these areas is maintained within a range of 35–100 pounds per square inch (psi) (246.1×10^2–$703.1 \times 10^2\,kg/m^2$) from the upper to lower elevations within each area.

The DC system consists of 6.8 million feet (2.07 million meters) of water mains ranging in size from 4 inches (10 cm) to 78 inches (200 cm) in diameter. The system has 5.7 million feet (1.7 million meters) of cast iron pipe. Transmission mains from the Dalecarlia Pumping Station to the First, Second and Third High reservoirs are owned and operated by the WA. The types of pipe used include cast and ductile iron and reinforced and pre-stressed concrete and steel. Cement lining was adopted in 1932 for some trunk mains, and in 1942 it was adopted as a standard for all sizes of main.

The service areas are generally interconnected through closed valves at all boundary intersections, permitting flexibility in supply from higher to lower services in emergencies. The system contains approximately 36 000 valves and 8500 fire hydrants.

In September 1993, based on monitoring requirements under the TCR, the DC system violated the MCL for total coliform, when the number of positive samples exceed 5% of all samples taken. Exceeding the 5% limit is considered to be a routine violation of the TCR. On 22 September, a total coliform-positive sample was detected in one of many samples taken on 21 September from the DC water distribution system. A retest taken on 23 September was positive for faecal coliform, and on 23 September a recheck of the site and also sites upstream and downstream of the site indicated a total coliform-positive sample from a downstream sample site. This testing sequence resulted in an acute MCL violation of the TCR. A retest of all three sites on 24 September was negative. Chlorine residuals at all locations were in compliance with the requirements of the Surface Water Treatment Rule.

On 29 September 1993, EPA Region III issued an Emergency Administrative Order to the District of Columbia. In the Order, Region III indicated that faecal and total coliforms were present in the DC public water supply. A 'boil water notice' was issued for the area immediately adjacent to the Woodson Junior High School in the North-east DC area, where the acute violation occurred. By 2 October, samples from the original acute violation site tested negative for four consecutive days and the boil water notice was lifted.

On 5 October 1993, Region III issued a preliminary Notice of Findings indicating that both plants serving DC were supplying water with higher than usual total coliform-positive samples

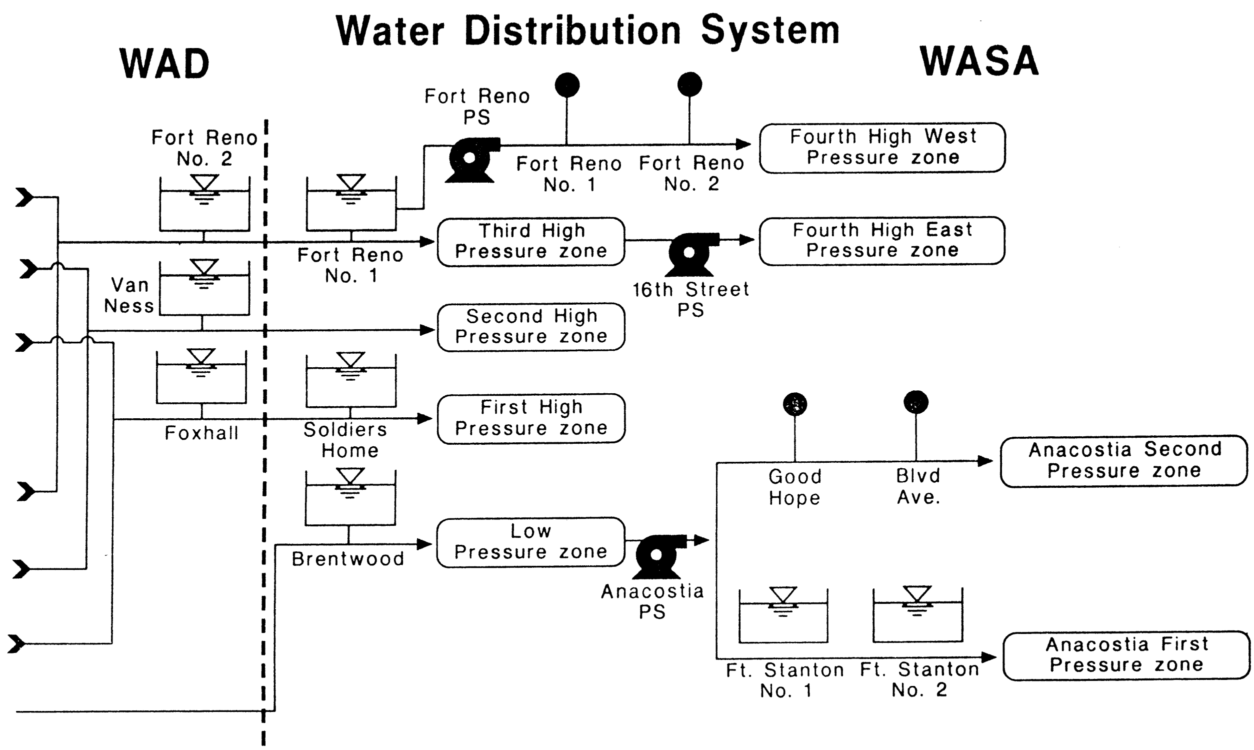

Fig. 2 District of Columbia water system—major facilities (source: Camp Dresser & McKee memorandum, 11 March 1996).

and that the plants would have been in violation of the TCR rule if the rule were applicable to them.

On 7 December 1993 a violation of the turbidity MCL at the Dalecarlia WTP, which, combined with prior microbiological events, resulted in the entire WA service area being placed under a precautionary boil water advisory. After four days, the boil water order was lifted. A study of the WA was completed in April 1994 which recommended improvements to the treatment plants. This study was one of the requirements of the administrative order issued to the Corps of Engineers by EPA Region III in March 1994.

In June 1995 the percentage of samples from the system that were found to be coliform-positive began to increase. On 15 June 1995, samples that had been taken from three sites in north-west Washington on 12 June were found to be faecal coliform positive. As required by the TCR, repeat samples were taken and analysed using two approved methods. The Colilert test provides results within 24 h. All of the repeat samples were negative using this test. The second test, a membrane filter technique, may require a total of 72 h for results. This test found that the resample for faecal coliform positive was negative, meaning that the original faecal coliform sample could not be ‘confirmed’. However, a resample for the third site taken at a fire house was total coliform positive and the sample was confirmed as faecal coliform positive. Thus, the District of Columbia incurred an acute violation of the TCR on 19 June 1995. Because the acute violation resulted from only one confirmed total coliform positive sample, Region III advised DC that the issue of a boil water notice which the Department of Public Works (DPW) was preparing, would not be necessary, but Region III did order a series of immediate actions, including raising the chlorine residual from 2.6 to 3.0 mg/L in the finished water leaving the treatment plants. The District of Columbia was also required to modify its flushing programme and had to flush until the water was clear. Additionally, they were required to issue a public notice of this acute violation. This series of occurrences is depicted in Fig. 3, and the monthly percentage of positive total coliform samples between 1993 and 1995 are shown in Fig. 4. The coliform positive values appear to be correlated with temperature.

In the autumn of 1995, the DC system incurred one routine and one acute monthly TCR MCL violation. In addition, a sanitary survey of the District’s water storage and distribution system conducted earlier in 1995 found numerous operational and maintenance deficiencies in the system and contained 185 recommendations for improvement. In response to these events, EPA Region III issued a preliminary administrative order in November 1995 which directed DC to develop short and long-term plans to correct the deficiencies. EPA Region III then began negotiating a final consent order with DC to finalise the plans for remediation and upgrading of the water storage

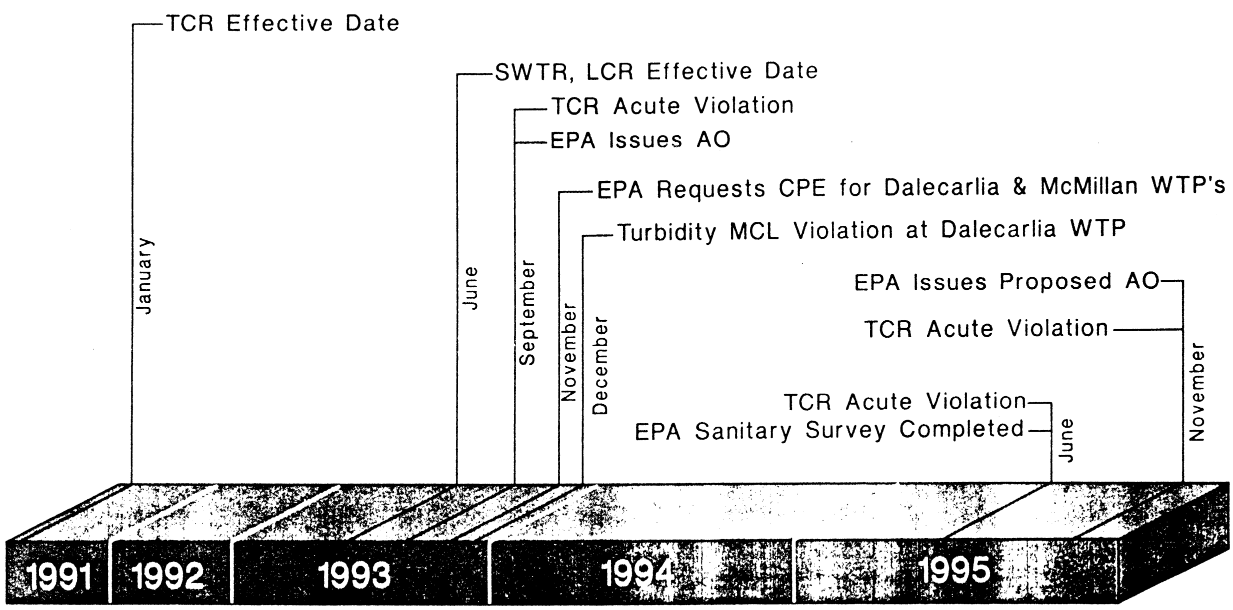

Fig. 3 Recent water quality problems/milestones in the District of Columbia (source: Camp Dresser & McKee memorandum, 11 March 1996).

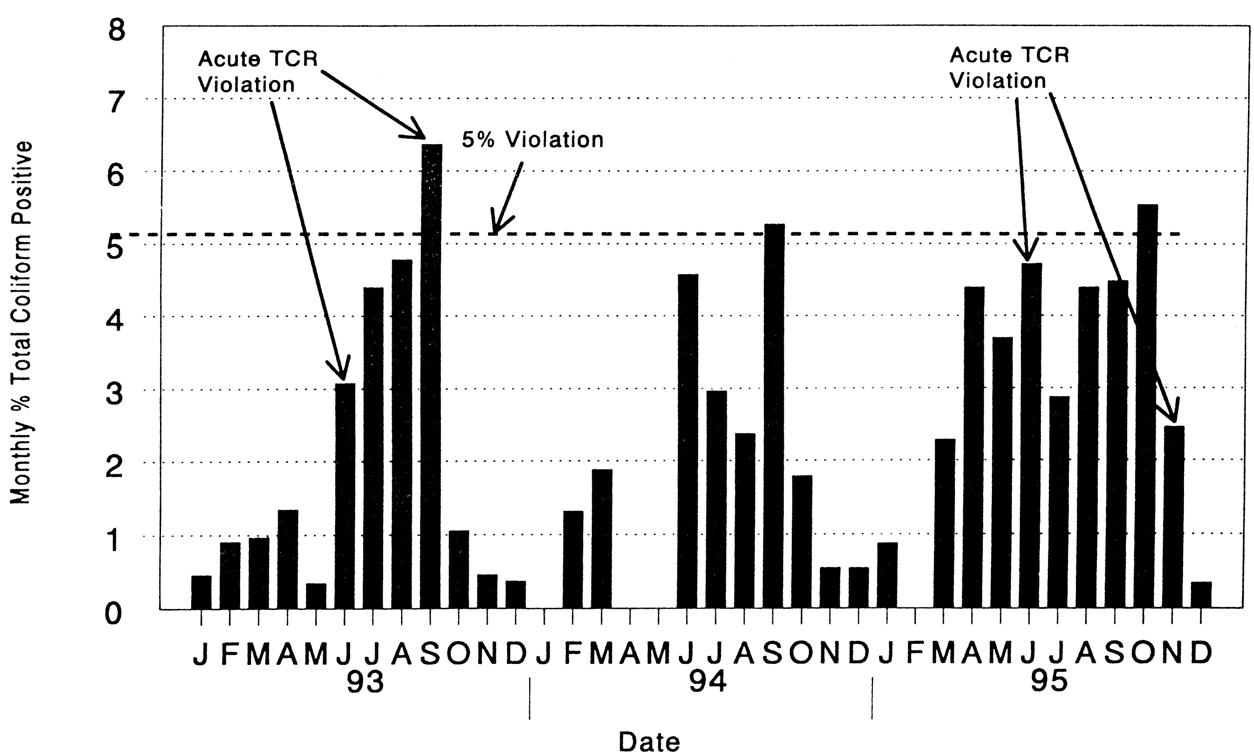

Fig. 4 Monthly recent total coliforms in the DC distribution systems (1993–95) (source: Camp Dresser & McKee memorandum, 11 March 1996).

and distribution system. Negotiations were interrupted twice during government furloughs during late 1995 and early 1996. In April 1996, the EPA conducted a public meeting in the District to provide a forum for interested parties to express their concerns about the District's water system. The EPA also conducted a public hearing in the District in April 1996 which concerned the provisions of the consent order.

Before the order was finalised, DC incurred a routine monthly TCR MCL violation in June 1996. When DC issued the required public notice of this violation on 3 July 1996, the city's public health director issued a boil water advisory because of his concern that certain susceptible populations might be adversely affected by consuming the city's water. This advisory caused great confusion in the city, as it was preparing for a large influx of visitors for the 4 July (independence day) holiday. When it was determined that the EPA had not recommended the boil water advisory and that there was no indication of any specific pathogen problem in the city's water supply, the boil water advisory was rescinded.

In the wake of this incident, discussions between EPA Headquarters and Region III staffs resulted in a memorandum from EPA Administrator Carol Browner to Region III Administrator Michael McCabe, dated 10 July 1996. This memorandum listed the actions that Administrator Browner and Regional Administrator McCabe agreed to take, in response to the problems with the DC drinking water system. The action items included:

- Deployment of a team of federal drinking water experts on site to assist with and oversee District Improvements to the tap water system.
- Create a special new EPA drinking water 'hot line' for District residents.
- Launch independent testing by EPA of District tap water in locations throughout the city.
- Immediately convene a special meeting among EPA, Army Corps and District officials to explain the EPA action plan and to improve cooperation, coordination and communication in implementing changes to the city's drinking water system.
- Order the District to immediately develop and implement plans to evaluate, overhaul and pay for long-term major improvements as quickly as possible.

In July and August of 1996, the DC system violated the MCL for total coliform each month. EPA Region III formed a 'District of Columbia Drinking Water Team' in July of 1996 to address the problems which the District was experiencing at that time in its drinking water distribution system. In addition to Region III staff, the team was composed of EPA personnel from Region I, Cincinnati and EPA Headquarters. On 12 July, the DC and the US EPA, acting through Region III, entered into an Administrative Order and Consent Agreement based on violations applicable to the District's water storage and distribution system.

During July and August 1996, the team assembled each week at EPA Headquarters and worked closely with the staffs of the Washington Aqueduct Division of the US Army Corps of Engineers and the District of Columbia Water and Sewer Authority (DC WASA). The team identified 26 action items that they believed would serve to improve the drinking water treatment and distribution system in the district. Many of these items were already under development by the Aqueduct and/or the District and have required a substantial commitment of time and financial resources in their implementation. These items are presented in Table 1.

The team recognised that there was no short-term solution to the problem. This was demonstrated by the fact that DC exceeded the TCR MCL during July and August 1996. Region III issued notices of violations (NOVs) to DC for these two TCR MCL violations. On 30 September 1996, a follow-up report to the earlier Sanitary Survey was completed. It found that 23 of the 185 recommendations from the earlier report had been completed and 129 others were either under contract, were to be under contract, were planned or under consideration.

The Safe Drinking Water Act Amendments of 1996 allow the Aqueduct's customers (DC WASA, Arlington County, and the City of Falls Church) to create or identify a nonfederal public or private entity to receive title to and operate the Washington Aqueduct. The Amendments also created the framework for transferring the Aqueduct to the control of this entity. A semi-autonomous DC WASA now operates the drinking water distribution system in the District. DC WASA controls all revenues generated by the sale of water which prevents diversion of these revenues for other municipal uses, as had happened in the past. As of this writing, the WA has not been combined with DC WASA or absorbed by any other public or private entity.

The DC drinking water system has not incurred any violation of the drinking water regulations since the last TCR violation in August 1996. There was no recurrence of the microbiological problems during the summer of 1997. Of the many actions taken to reduce this problem, three seem to have had a significant effect. First, all of the drinking water storage tanks and reservoirs operated by the Aqueduct and DC WASA had been cleaned, inspected and disinfected. Second, Aqueduct staff closely tracked the rise in source water temperature during Spring 1997 and adjusted residual chlorine levels accordingly. In the past it appeared that microbiological activity increased substantially as source water temperatures increased. The Aqueduct used chlorine application to limit the increase in microbial activity. Third, DC WASA initiated a comprehensive flushing and valve-turning programme in March 1997 which continued through to November 1997. The entire system was flushed, which resulted in significantly lower coliform and trihalomethane levels. The flushing programme also eliminated some service area pressure problems by identifying inoperative or incorrectly closed valves in the distribution system.

Table 1 Summary of drinking water activities in the district of Columbia

Number	Action item	Current status
1	Continue and improve flushing programme	Extensive flushing programme is underway
2	Institute valve turning programme	Valve turning programme is underway
3	Establish cross-connection control programme	A plan for CCC has been developed
4	Rehabilitation of distribution system	Cleaning and lining programme has begun and WASA is proposing to spend $10 million per year for 20 years to complete
5	Establish sampling stations for microbiological testing	Sampling stations have been installed
6	24-hour remote monitoring sites for chlorine, pressure, temperature, and pH	One site has been selected and has been operational. Two more are planned
7	Review pipe maintenance and disinfection programme	EPA contractor has prepared and presented a course to WASA personnel
8	Evaluation to determine correlation between temperature and total coliform detection	Effort is underway
9	Expand hydraulic model to include piping less than 16 inches in diameter and low flow areas	Effort is underway
10	Flow limiting devices for fire hydrant used for summer recreation	Item has not been addressed
11	Correct deficiencies noted in sanitary survey for reservoir system	All reservoirs have cleaned, inspected, and disinfected. The first rehabilitation project has started.
12	Repair cracks and holes in reservoirs and related structures	Effort is underway
13	Prior to cleaning of tanks, conduct sampling to determine if reservoir contributes to water quality problems	Has been conducted
14	Expand hydraulic model to include water quality	Effort is underway
15	Expand water quality model to determine if reservoirs have a true turnover	Effort is underway
16	Continue aggressive treatment of drinking water	Effort is underway
17	Dredge Dalecarlia reservoir	Effort is underway
18	Initiate sampling for microbial nutrients in the distribution system	Effort is completed
19	Continue to implement recommendations of 1994 CPE and Modernisation Plan	Effort is underway
20	Have WA's Supervisory Control and Data Acquisition System interface with monitoring in the distribution system	This is planned to be included in the final development of the distribution model
21	Develop a plan for the periodic inspection, cleaning, and maintenance of reservoirs	This effort is underway and a plan has been developed so that each reservoir is cleaned and inspected at five year intervals
22	Investigate the use of continuous solids removal devices in sedimentation basins	Effort is suspended pending negotiations concerning WASA's NPDES permit
23	Investigate the use of alternate disinfectants to prevent growth of biofilms	Effort is underway
24	Establish public education and outreach programme	Effort is underway
25	Corrosion control of distribution system	Effort is underway
26	Develop a master plan for distribution	Effort is underway

SUMMARY AND CONCLUSIONS

Traditional sanitary engineering has concentrated on achieving drinking water standards in water leaving the treatment plant. With the advent of the Safe Drinking Water Act of 1974, drinking water standards were interpreted as being required to be met at the consumers tap. Consequently, some of the first regulations promulgated under the SDWA, including the Surface Water Treatment Rule and the Total Coliform Rule, dealt with distribution system problems.

Conservative design philosophies, an ageing water supply infrastructure, and increasingly stringent drinking water standards are resulting in concerns over the viability of drinking water systems in the US. Questions have been raised over the structural integrity of drinking water systems in the USA, as well as their ability to maintain water quality from the treatment plant to the consumer.

It should not be surprising that when water quality in drinking water distribution systems is carefully examined, an increasing number of problems is found. Part of this increased frequency of reporting is due to the use of increasingly sensitive chemical and microbiological monitoring methods and the ageing infrastructure. The combination of increasing attention to distribution system problems and the ageing infrastructure and negligence of maintenance and repair is causing an increasing awareness of drinking water problems in the USA.

The situation that has occurred in the Washington, DC system is an illustration of this point. It was after the promulgation of the TCR that the distribution system problems in Washington, DC began to come to light. Clearly, the SDWA and its regulations are the basis for the major transformation that has taken place in the Washington DC water system. Changes have occurred in operating and maintenance policies and procedures, and a water quality monitoring programme and a flushing programme has been established. Major investment is being made in replacing parts of the distribution system and a semi-autonomous water authority has been created.

The lessons learned in the DC Case Study will have ramifications for all major urban water supplies in the USA.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance of Ms Jean Lillie, Mr Steven Waltrip and Ms Jean Scruggs in preparing this manuscript.

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