An integrated approach to assess the causes of water quality failures in the distribution system of Caen

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Abstract Understanding the reasons for water quality failures in drinking water distribution systems has become a priority for network managers. The proposed approach provides a unique tool for assessing the consequences of water supply changes and the consequences of distribution system operation and maintenance on the quality of distributed water. Its main benefit is to help the water producer understand the origins of local water quality problems, and consequently to eliminate them from their distribution system.
Keywords Coliforms; contamination; databases; drinking water distribution systems; GIS; water quality

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Introduction

The use of indicator organisms, such as coliforms, as a way of controlling the possible presence of pathogens in drinking water has been of paramount importance in the approach to assessing water quality in distribution systems. Even if raw water is correctly treated to eliminate microorganisms, there remains a risk that post-contamination will occur in the distribution system (DS) as a result of intrusion during pipe bursts or transient negative pressure events (Kirmeyer *et al*., 2001). Moreover, it is difficult to precisely identify the location of these intrusion events since the contamination may be diluted and transported downstream where regrowth and/or favourable conditions will make it detectable. Such conditions are, for example:

- a high water temperature (Colbourne *et al*., 1991);
- a long water residence time (LeChevallier *et al*., 1987; Gauthier *et al*., 2000);
- a low disinfectant level (Mathieu *et al*., 1992; LeChevallier *et al*., 1996);
- the presence of pipe corrosion (LeChevallier *et al*., 1987; Clement *et al*., 1998);
- sediment accumulation in pipes (Oliver and Harbour, 1995; Gauthier *et al*., 1999).

Consequently, only a few studies have been able to determine the origins of DS contamination (Geldreich *et al*., 1992; Clark *et al*., 1996; McMath and Casey, 2000). Moreover, attempts to predict coliform occurrence have met with only limited success (Volk and Joret, 1994; LeChevallier *et al*., 1996; Gale *et al*., 1997). This may be explained by the fact that such models mainly considered water quality data and did not look at local phenomena such as DS hydraulics and operating procedures. The aim of the current research project, therefore, is to define and test a new integrated approach to explaining water quality failures in DS – and especially coliform occurrences – by taking into account not only water quality data, but also all kinds of events related to the operation and maintenance and accidents in the DS.

The so-called "integrated approach" can be divided into three parts: (i) construction of the integrated approach, which includes the collection of different types of data, formatting of the data and geocoding; (ii) building of a hydraulic model of the area under study; and (iii) visualisation and exploration of databases (by means of database queries) in order to identify the possible relationships between the parameters studied and water quality problems.

This integrated approach was developed and tested at five utilities to evaluate its applicability to different types of DS (configuration and management) and its ability to identify the causes of quality failures for various types of water quality and network configurations. These utilities are located in France (Caen), the UK (Egham) and Canada [Montreal and Laval (Quebec), Moncton (New-Brunswick)].

In this paper, we present the methodology of the proposed "integrated approach" and its application to one section of the DS of the City of Caen (Normandy, France). The approach was applied with a view to better understanding the causes of variation in the quality of distributed water (evaluated through routine and dedicated sampling programmes, and through consumer complaints).

The selected DS area (called ZB) has the following characteristics: an average water demand of about 7,100 m^3/day, a pipe diameter range of 40–600 mm, and a total pipe length of about 80 km. The area is especially interesting because it is supplied from two types of water: a chlorinated groundwater (CGW) during the night (about 20% of the daily flow) and a fully treated surface water (TSW) from the Orne River during the day, using chlorine dioxide as the DS disinfectant. For this specific project, five sampling stations were set up in this part of the network in order to enrich water quality monitoring databases (Figure 1).

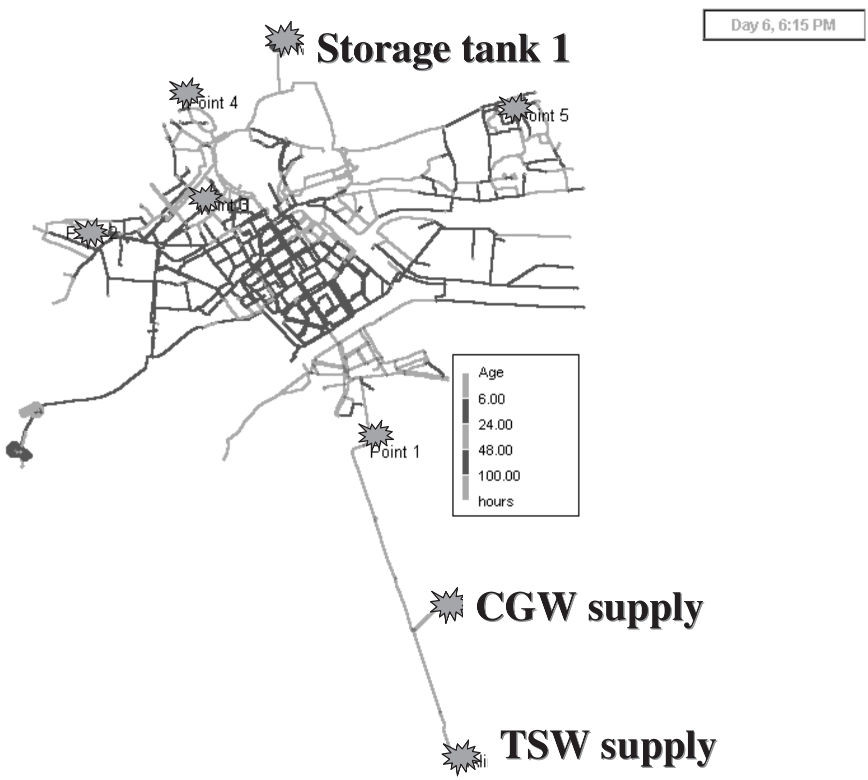

Figure 1 Hydraulic model of the zone under study and location of the DS supply, storage and sampling points

Regrowth of heterotrophic bacteria has been observed on some occasions in this part of the DS.

Building the integrated approach

The first step of the integrated approach consists of data collection. This step is totally dependent on data availability in the utility under consideration with respect to the following domains:

- water quality at the treatment plant and in the distribution system (chemical, physical and microbiological characteristics, as well as consumer complaints);
- structural data related to DS components (diameter, length, age, material, configuration, etc.) – most of these data are usually provided by the hydraulic model;
- events in the DS such as pipe breaks and leak repairs, pipe flushing, maintenance work, etc.

Table 1 details the available data collected from the City of Caen for the 1997–2000 period. These data were initially dispersed, maintained by the water quality control laboratory, the technical staff (design and planning) and the operational staff.

Microsoft Excel was the software chosen for storing all the databases because it is both widely available and flexible; data transfer from the different types of information management systems in utility departments to an Excel file format is usually quite an easy task. Once all the data have been collected, minor formatting operations must usually be performed in order to obtain a standard database format. The easiest way to handle and visualise all these different types of data is through a GIS-type system, since DS events and operational and water quality data are usually spatially located with reference to a civic

Table 1 Data collected within the framework of the integrated approach (ZB area of the Caen DS)

Parameter	Description
Water quality	
Temperature, pH, free/total Cl_2, ClO_2, turbidity, conductivity, HPC 22°C and 36°C, total and thermo-tolerant coliforms	Weekly monitoring at the two points of entry into the zone (CGW and TSW), weekly monitoring at the storage tank, monthly monitoring at 4 DS points and weekly monitoring at 5 DS points[a]
Consumer complaints	For water quality (taste and odour, colour, aspect)
Structural data	
Pipe characteristics	Diameter, length, material, age
Hydrants	Type, diameter, location
Storage tanks	Volume, location
Vents/air drainage	Type, location
Valves	Type, diameter, location
Operational data	
Type of water supply	Log file for all changes in water supply for the zone (different types of groundwater and a treated surface water may be used)
Intervention type	
Maintenance (pipe breaks, leak repairs, hydrants)	Location, date of beginning and end of work
New pipes	Location, date of beginning and end of work
Pipe rehabilitation and replacement	Location, date of beginning and end of work
Water interruption notices	For repair/replacement
High-flow hydrant testing	For compliance with fire-fighting usage
Low-flow dead-end flushing	Automatic or manual flushing of dead-ends to restore chlorine levels
Cleaning of storage tanks	Log file for the yearly cleaning of each storage tank compartment

[a] This weekly monitoring at 5 DS locations was performed specifically for this study in order to better evaluate the spatial variations of water quality in the DS

address, a street intersection or even an item ID (a hydrant or a valve number). A geocoding step (i.e. allocation of *x* and *y* coordinates) must therefore be performed in order to visualise the various data elements. The ESRI Arc Explorer software was selected for data visualisation because it is simple, and it is also free (http://www.esri.com/software/arcexplorer).

The hydraulic links among all the types of data listed in Table 1 are provided by the hydraulic simulation model which permits consideration of the transport of a contaminant from an upstream to a downstream location. The zone of the Caen DS under study was modelled using Epanet software (http://www.epa.gov/ordntrnt/ORD/NRMRL/wswrd/epanet.html) by deriving input data from a previously calibrated model developed under Synergee (Stoner Associates Inc.). The model includes 950 pipe sections (Figure 1), and simulation results such as flows, pressures and residence times have been included in the database. Extended period simulation was used to allow for stable results, and only minimum, maximum and average values of each computed parameter were integrated in the database.

Visualisation and exploration of databases to identify the origin of water quality failures

Once the data have been validated and geocoded, and when the hydraulic model is available, the available information may be explored and visualised using an interactive data analyser (Besner *et al.*, 2001b).

This non-commercial interactive analyser (Figure 2) is the central element of the integrated approach. The tool is used for database management and for the conversion of Excel files into geographical files for GIS visualisation (ESRI shapefile format .SHP). However, its main function is to execute multi-criterion queries (spatial/temporal/specific features) throughout databases with respect to specific water quality failures. Sources of water quality problems become easier to identify and links between quality failures and potential contamination origins may be established (Besner *et al.*, 2000, 2001a). For example, if a positive coliform sample were detected on 30 July 1999 at the sampling station “26 rue de l’Oratoire”, it would be possible to search all the available databases for interventions such as pipe breaks or repairs, hydrant testing, etc. that may have occurred in the vicinity during the previous days or weeks.

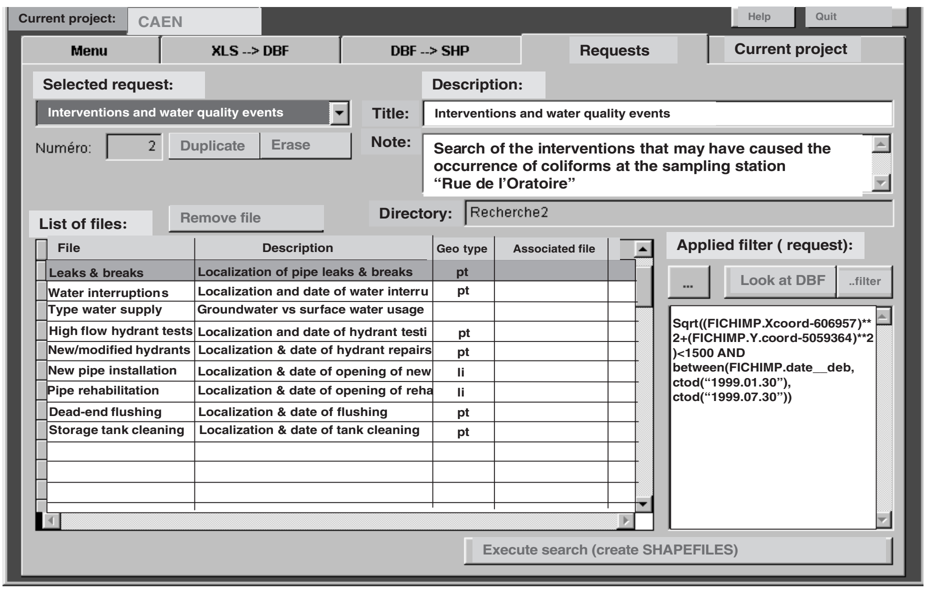

Figure 2 Interactive analyser for database treatment and queries related to distribution systems

A database study, using the interactive analyser, was performed in order to explain some of the water quality variations experienced within the Caen DS. A sudden water quality variation in the ZB area was looked at first, and the search conducted for the possible origins of positive coliform samples measured at three of the five sampling points on 30 October 2000, is illustrated in the second case study. The main purpose of these examples is to demonstrate that network modifications can sometimes be identified solely through the study of water quality parameters, whereas in other situations, such as in the second case studied, the use of other parameters – such as operations and maintenance data – is of prime importance in identifying the origin of a water quality failure.

Case study 1: general water quality variation in the area under study

An abnormal water quality variation occurred in the ZB area at the beginning of September 2000. Important changes in water temperature, conductivity and HPC 36 (incubation period of 68 hours at 36°C) were noted on or about 11 September at the five sampling stations located in the area (Figure 3). However, the measured values showed no unusual trend in the other water quality parameters (turbidity, free and total chlorine and coliforms). As the ZB area may be supplied with both surface water and groundwater, it could be hypothesised that such a variation originates from a time-limited modification in the type of water used to supply the area. In particular, the higher conductivity and marked decay of water temperature directly pointed towards an increased proportion of groundwater in the supply to the zone.

This hypothesis was verified, since an examination of the operational data (Table 1) revealed that a change in the type of water supplying the zone occurred on 8–9 September 2000. Chlorinated groundwater characterised by a lower temperature and higher conductivity was used to supply the area full-time (100% instead of the 20% under normal conditions) following maintenance work close to the mixing point between the TSW and CGW supplies. Besides, the query to the intervention databases described in Table 1 are performed with the interactive analyser, led to the identification of two interventions confirming the origin of the observed water quality: (a) on 7 September, a by-pass was installed close to the mixing point and led to the supply of the zone with CGW; and (b) the cleaning of the CGW storage tank located just upstream of the zone took place on 6

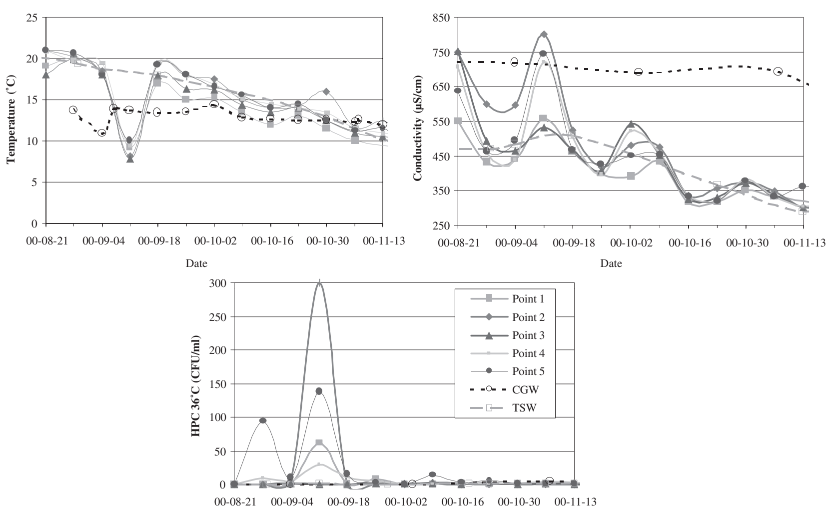

Figure 3 Weekly monitoring of the water quality parameters at the five sampling points from August–November 2000

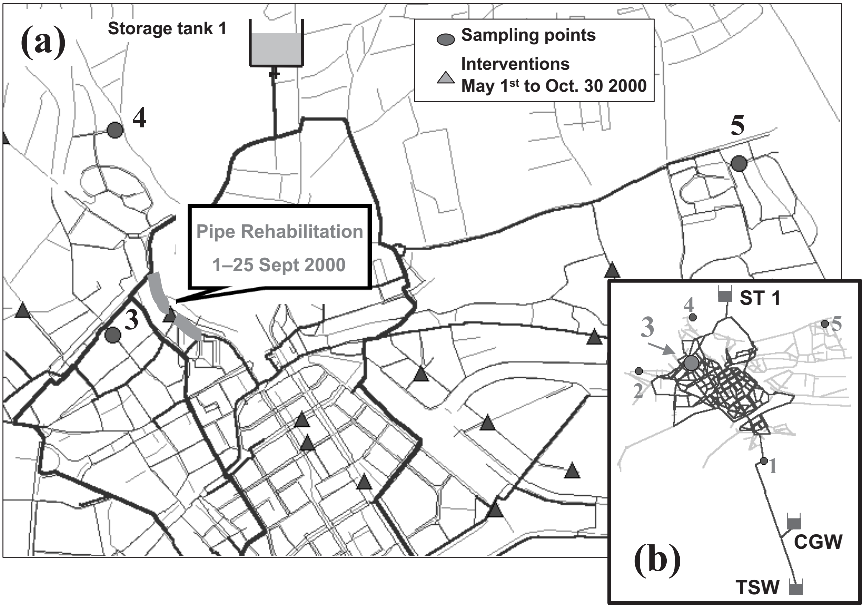

Figure 4 (a) Results of a time/space query for interventions around sampling points 3, 4, 5 where positive coliform samples were collected on 30 October 30 2000. (b) All possible upstream hydraulic paths supplying sampling point #3 (derived from Epanet results)

September. The latter could be responsible for the higher HPC 36 observed in most sampling locations during the following week along the DS. Consequently, in this case, the interactive analyser was mainly used to confirm and detail what was suspected from the water quality analysis.

Case study 2: simultaneous coliform occurrence in three different locations

On 30 October 2000, positive total coliform samples were collected at sampling station 3 (1 CFU/100 ml), 4 (2 CFU/100 ml) and 5 (1 CFU/100 ml), all located in the northern part of the ZB network area (Figures 1 and 4). These three sampling stations were characterised by very low free chlorine concentrations (<0.02 mg/L) and by water temperatures around 11.5°C (Figure 3). According to the sampling staff, the possible origin of such positive samples was the contamination of sampling taps, since they are outdoors for these specific points. Nevertheless, the analysis of water quality parameters at storage tank 1, performed by a different laboratory, also showed a positive coliform sample (1 CFU/mL) on the same day. Further examination of other water quality parameters measured at these points (turbidity, pH, HPC 22°C and 37°C and conductivity) showed no unusual trend in the measured values. Consequently, as no major water quality variations took place, other factors needed to be considered in order to explain the coliform occurrence measured in the network.

From the results of the Epanet model, and using a function of the interactive analyser allowing the identification of all the possible upstream paths for a specific DS location, it was established that these three sampling points were under the influence of both the TSW (during the day) and CGW (during the night) supplies, as well as that of storage tank 1 (Figure 4b). Consequently, these points may sometimes be supplied with water coming from the tank, where water residence times may reach values up to 5 days.

Using the interactive analyser, a search was made of the various databases in order to find the possible origins of the total coliform occurrences on 30 October. The following interventions were considered:

- pipe leaks and breaks;
- pipe rehabilitation and replacements;
- hydrant repairs;
- storage tank cleaning,

The search for DS interventions was carried out using a time frame of 6 months prior to the occurrence of coliforms (from 1 May to 30 October 2000). As shown in Figure 4(a), 13 DS interventions were recorded in the area under study during the period considered. Important work was performed throughout the entire month of September, in the area of sampling point 3, where a 160 mm cast-iron pipe was replaced with a PEHD pipe, and the subsequent supply pipe transfers, resulting in successive pipe openings and closures. Such maintenance work may have caused a degradation of the microbiological quality of the water due to the penetration of microorganisms into the DS following inadequate cleaning or disinfection of the new pipe materials, or from transitory low pressure events allowing the introduction of exogenous material into the DS. Moreover, re-suspension of contaminated sediments in some pipe sections due to the modified hydraulics in place in the area at the time the work was being carried out is also a possible explanation for the observed contamination. The fact that the work was being performed alongside one of the two 400 mm pipes supplying storage tank 1 could explain why only three (of the five) sampling points, which are supplied from this tank on a part-time basis, tested positive. For such a complex situation, a combination of the examination of water quality, operation and maintenance, and hydraulic data reveal the absolute necessity of attempting to identify the possible origin(s) of the contamination.

Conclusion

The proposed integrated approach underlines the importance of taking into account not only the parameters relating to water quality, but also hydraulic features and the structural, operational and intervention data relating to the network under study, in order to obtain a better understanding of water quality failures in DS. Understanding the origin of these failures is the first step in controlling water quality, and the integration of all data using simple tools also allows a better DS management for the sake of water quality (Pena, 1995; Boulos *et al.*, 1997).

The two case studies presented in this paper illustrate the application of the so-called "integrated approach" to a section of the Caen drinking water distribution system. The feasibility of this integrated approach relies on updated and geocoded data relating to all types of events having a potential impact on drinking water quality. As more results are obtained, the approach will be gradually improved so that it can play a key role in the maintenance of good water quality at the consumer's tap. As water utilities improve their data capture (using GPS, etc.) and approach optimal management of their databases, the integrated approach will be a great help in managing drinking water distribution systems.

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