Change of bacterial water quality in drinking water distribution systems working with or without low chlorine residual

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Abstract Investigations into distribution systems (DS) working without or with low disinfectant residuals showed that the main process for the bacteria change in such systems is the release of bacteria from the biofilm, whereas the growth of bacteria in the water can be neglected. Important for the quality are short-term increases of bacteria release connected to an increase of bacteria growth on the inner pipe surface as a result of changes in the concentration of biodegradable organic matter (BOM) in the water. A model to describe the bacterial water quality change was developed on the basis of investigations. In contrast to other models, a consideration of the formation of BOM as a result of NOM oxidation by disinfectant residuals as well as the decreasing effect of inactivation of released bacteria by the decreasing disinfectant residual concentration, were necessary.

Keywords Bacterial water quality; distribution system; model

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Introduction

In past years, different models were developed and tested under practical conditions (Camper *et al*., 1994; Servais *et al*., 1995a, 1995b; Dukan *et al*., 1996; Laurent *et al*., 1997; Mary-Dile *et al*., 2000) to describe the change in water quality in distribution systems (DS). In general, the models are used to describe the quality change in systems where water with higher concentrations of biodegradable organic matter (BAM) and/or higher disinfectant residuals is being distributed.

In Germany, drinking water usually is distributed without or only with low disinfectant residuals. One prerequisite for this practice is good water treatment which guarantees drinking water with a low BOM content and low turbidity. There is no information about the process of the bacterial water quality change in such systems. Therefore, a research program was carried out. The objectives of the investigations were:

- evaluating the bacterial water quality in a long distance DS;
- estimating the main processes which determine the increase of the bacteria concentration in such a system;
- examining the influence of low chlorine and chlorine dioxide concentrations and the change in the water quality on the bacterial growth;
- developing a model to describe the change of the bacterial water quality in a DS working without or with low chlorine residual.

Methods

Distribution system

The investigations were carried out on the long distance DS of the Fernwasserversorgung Elbaue Ostharz GmbH (FWV) which is located in the center of the eastern part of Germany. Figure 1 shows the scheme of the DS. A treated bank filtrate of the river Elbe (Waterworks

Torgau-Ost) and a reservoir water treated by floc filtration (Waterworks Wienrode) were fed into the system. Both waters were disinfected by using low doses of chlorine and chlorine dioxide.

The diameter of the pipes varies between 600 and 1200 mm. The so-called Südring consists of two parallel pipes. One pipe is lined with cement, the other one with bitumen. The maximal flow distance of the system is approximately 100 km, the maximal residence time is up to 145 hours.

Table 1 gives an overview of the water quality after treatment. The quality of the bank filtrate is more or less constant over the year, whereas the reservoir water quality changes. The changes, e.g. of the temperature and the content of BOM, are of special relevance.

Sampling strategy

In order to study the change in water quality, sampling points were selected in five pipes (see Figure 1). Sampling campaigns were performed monthly during a period of two years. The biofilm formation potential was estimated by using biofilm measuring tubes which were installed in the waterworks as well as in the middle and at the end of the pipes. Each biofilm line consisted of 10 PVC tubes (diameter 2 cm, length 8 cm), which could be exchanged. The flow velocity in the biofilm lines was about 0.27 m/s. Monthly, one tube was changed and the biomass was estimated. To obtain information about the biofilm in the real pipes, every opening of the pipes connected to constructions was used for biofilm sampling.

Measured parameters

The following parameters were measured in the water: temperature, free chlorine, total

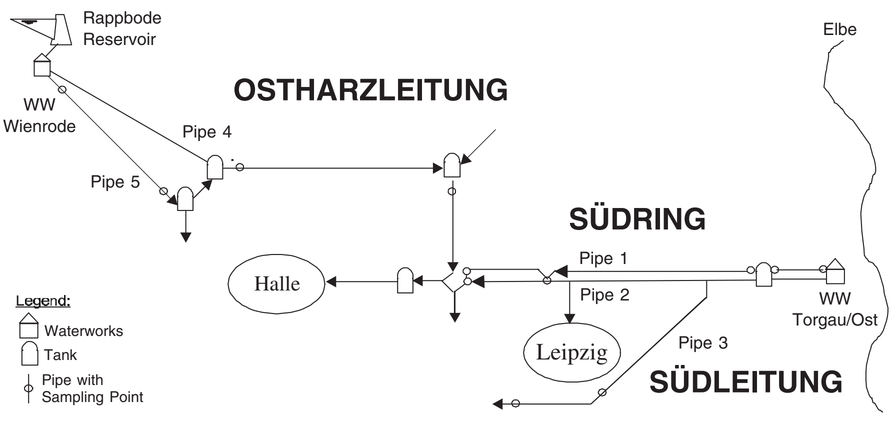

Figure 1 Scheme of the FWV Elbaue-Ostharz long distance DS

Table 1 Water quality after treatment before disinfection

Parameter		Waterworks Torgau Ost (bank filtrate) median	Waterworks Wienrode (reservoir water) median	min.	max.
Temperature	(°C)	9.8	5.5	2.8	8.2
DOC	(mg/l)	1.75	1.5	1.2	2.1
BDOC	(mg/l)	0.2	0.12	0.07	0.16
AC	(μg/l)	111	111	60.9	191.3
TDC	(cells/ml)	3.4×10^4	5.6×10^4	2.6×10^4	1.4×10^5
CFU at 20°C	(cells/ml)	0.4	0.2	0	4.5

residual chlorine, chlorine dioxide, DOC, assimilable carbon (AC) calculated from the regrowth factor which was estimated by the Werner (1985) method, total direct counts (TDC) after staining with DAPI and examination on epifluorescence, the number of colony-forming units at 20°C and 36°C (CFU), according to the German Drinking Water Guidelines.

For the characterization of the biofilm in the real pipes it was removed by scraping. The biofilm in the biofilm tubes was detached by shaking with a physiological sodium chloride suspension and small glass beads (diameter 1–2 mm). For characterization, TDC and CFU were estimated.

Results and discussion

Change of the water quality in the DS part fed with treated bank filtrate

Figure 2 shows the change of different water quality parameters in the *Südring* (pipes 1 and 2) and the *Südleitung* (pipe 3) which were fed with treated bank filtrate. The data are mean values over the entire sampling period.

As a result of depletion the concentration of free chlorine and chlorine dioxide decreased. After 24 hours no free chlorine, and after 70 hours no chlorine dioxide, were detectable. However, at every measuring point low concentrations of total residual chlorine could be found. There were no differences in the results of the different pipes. Because of the large diameter of the pipes, the depletion on the inner pipe surfaces did not influence the total depletion of the disinfectants.

In the first part of the DS, where free chlorine and/or chlorine dioxide were detectable, the concentration of BOM (measured as AC) increased whereas the TDC decreases and the CFU did not change. The formation of BOM is the result of an oxidation of natural organic matter (NOM) by chlorine and chlorine dioxide, whereas the impact of the disinfectants allows only a low biodegradation of these substances in the biofilm. As shown by Petzoldt *et al.* (1995) the effect of the BOM formation by chlorine depends on the chlorine/DOC

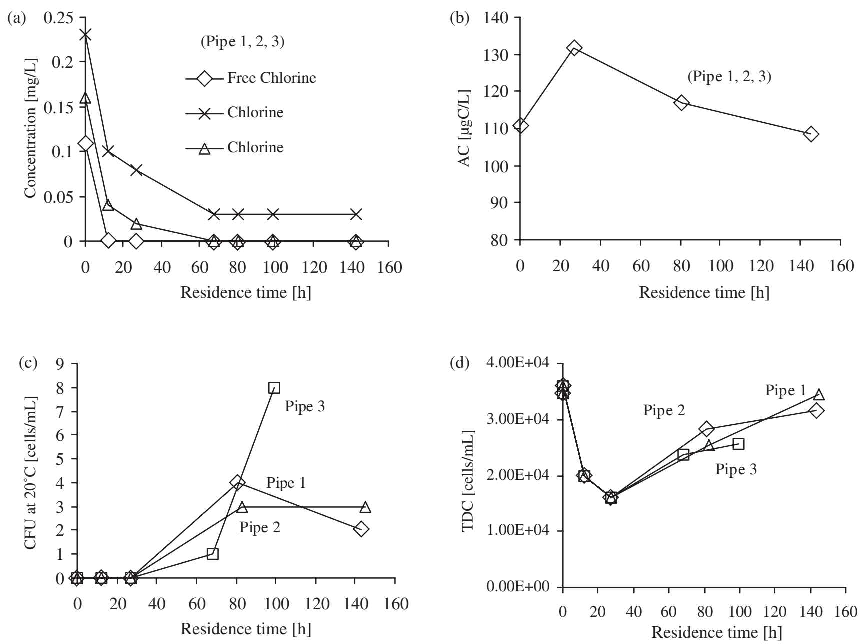

Figure 2 Change of the water quality in the different pipes of the Südring and the Südleitung: (a) concentration; (b) AC; (c) CFU and 20°C; and (d) TDC

relation as well as on the BOM concentration of the water. The higher the concentration of BOM is, the lower the formation of further biodegradable substances will be. It seems that at higher BOM concentrations the oxidation agents react faster than they do with the NOM.

In the area of the DS, where no free chlorine or chlorine dioxide was detectable, the concentration of AC decreased and the TDC, as well as the CFU, increased. The increase of the TDC and the CFU was different from pipe to pipe. However, if there was a high increase of the TDC the increase of the CFU was lower and reversed. Because of the same flow velocity in the pipes the differences might have been caused by the different inline material. Higher TDC were found in the pipe which was lined with bitumen, whereas higher numbers of CFU were found in the pipes lined with cement. Table 2 gives an overview of the results of biofilm investigations which were carried out in connection with constructions.

The differences of the biofilms were the same as they had been in the water. In further laboratory tests it could be shown that the higher total bacteria density on bitumen is caused by the release of BOM. On the other hand, the alkalinity on the surface of the cement influences the population of the microorganism in the biofilm.

These results, as well as the results of different laboratory and stagnation tests (Wricke and Petzoldt, 1999), showed that the release of bacteria from the surface, and last but not least, out of the biofilm, is the main process for the increase of bacteria in such a DS, whereas the growth of bacteria in the water can be neglected. If the water only has a low regrowth potential, this means the biodegradation of organic substances mainly takes place in the biofilm.

In connection with the decrease of BOM in the water, the biofilm formation potential decreased, too. Figure 3 shows the results of the tests carried out with the biofilm lines. The TDC and the CFU were lower in the biofilm in the waterworks before disinfection than in the biofilm lines installed in the DS.

Change of the water quality in the DS part fed with treated reservoir water

Looking at the mean values, the water quality change in the *Ostharzleitung* (pipes 4 and 5), which was fed with the reservoir water, showed the same development as the water in the other pipes. Taking the measurements into consideration over the period of one year, there were different conditions, especially in the change of the bacterial quality of the water.

Figure 4 gives an overview of the development of CFU in the water of two parallel pipes with different flow velocities and the results of the CFU determination in the biofilm estimated in the three biofilm lines. Whereas there were only very low CFU in pipe 5 having a

Table 2 Results of biofilm investigations in pipe 1 and pipe 2 of the Südleitung (mean values)

		Pipe 1 lined with bitumen	Pipe 2 lined with cement
TDC	(cells/cm^2)	2.16×10^6	2.38×10^5
CFU at 20°C	(cells/cm^2)	870	1465

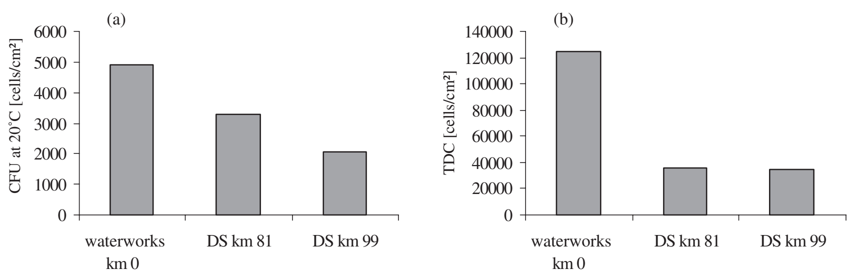

Figure 3 (a) CFU and (b) CFU at 20°C in the biofilm measuring tubes in the DS fed with treated bank filtrate

high velocity (approximately 1 m/s), there was an increase of the CFU in pipe 4 and in the biofilm in spring and in autumn. Of special interest was the fact that the CFU in the water increased when the CFU in the biofilm increased too, whereas in June and July, when the CFU in the biofilm varied from 500–6,500 CFU/cm^2, the CFU in the water were low. Also in the phase of decreasing CFU in the biofilm there was no increase of CFU in the water.

These results show that there is no direct correlation between the CFU in the biofilm and the CFU in the water. However, a change of the BOM concentration may cause a relevant increase of bacteria in the water in connection with an increasing growth of bacteria on the inner surfaces of the pipes. If the bacteria mainly grow in the biofilm, the bacteria release does not increase. However, if the biofilm is not well developed, as it may partially be the case in pipes where the flow velocity is low or where the biofilm was disturbed by changing concentrations of disinfectant residuals, bacteria may grow outside of the biofilm, especially outside of the extracellular substances (EPS). This leads to an increase of the release of bacteria in the water. On the other hand, the bacterial growth on the surface results in a stabilization of the biofilm and, therefore, in a decreased release of bacteria in the water.

Water quality model for a DS working with or without low disinfectant residual

A model for DS working with or without low disinfectant residuals was developed on the basis of the investigations. Figure 5 gives an overview of the main processes influencing the change of the bacterial water quality in such systems. In contrast to other quality models, a consideration of the BOM formation as result of NOM oxidation by disinfectant residuals was necessary. On the other hand, the growth of bacteria in the water could be neglected, as described before. The main process for the increase of bacteria in the water in these systems is the release of bacteria out of the biofilm. The amount of bacteria increase mainly depends on the condition and the volume of the biofilm which is being influenced

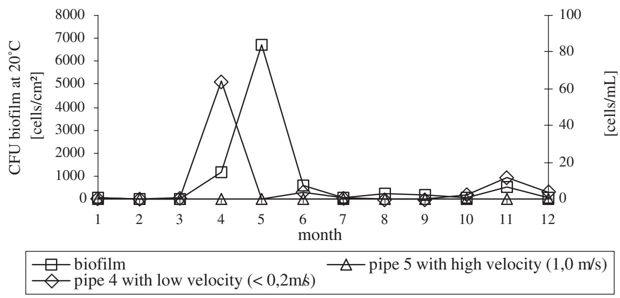

Figure 4 Change of the CFU number in the biofilm and in the water of two pipes with different velocities

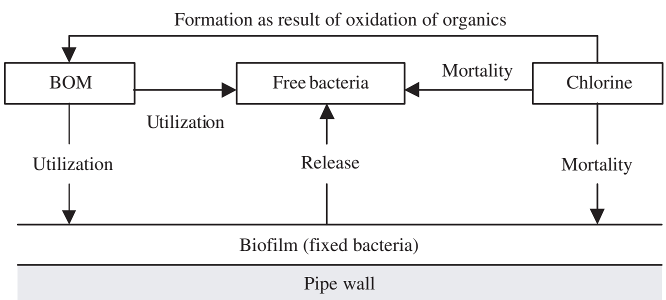

Figure 5 Major processes of bacterial quality change in a distribution system with low BOM and chlorine concentrations

by the concentration of biodegradable substances of the fed water, the hydraulic conditions in the DS, the pipe material, and the residual disinfectant concentration.

One factor influencing the increase of the bacteria in the DS is the disinfectant residual concentration in the water. The inactivation rate of the bacteria released by the biofilm in the water depends on the disinfectant residual concentration in the water. Figure 6 shows the theoretical increase of CFU in distribution systems working with or without low chlorine residual concentrations.

In drinking water systems without chlorine, the input of bacteria leads to a gradual increase of CFU with increasing flow distance. However, the distribution system with low chlorine residual may be divided into three different zones. In the first zone, the chlorine inactivates the bacteria immediately. The release of bacteria from the biofilm does not result in an increase of the CFU in the water. In the second zone the time, which is necessary for the inactivation, increases by decreasing chlorine concentration. This causes a slow increase of the CFU. In the third zone, the conditions are the same as in the system working without chlorine.

In a first step the model was used as a calculation program. In order to check the relevance of the model assumptions, the model was used to describe the bacterial water quality change in the *Südring* of the FWS DS. Figure 7 shows good agreement of the calculation, using the model compared to the results of the measuring program. Further tests in different systems are necessary.

Conclusion

The investigations carried out in a long distance DS to obtain information about the microbiological and chemical processes in a system showed that there was only a low increase of

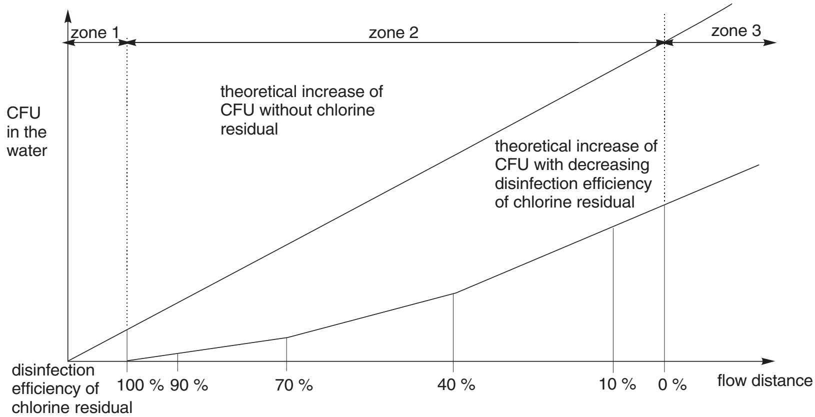

Figure 6 Theoretical increase of the CFU with flow distance

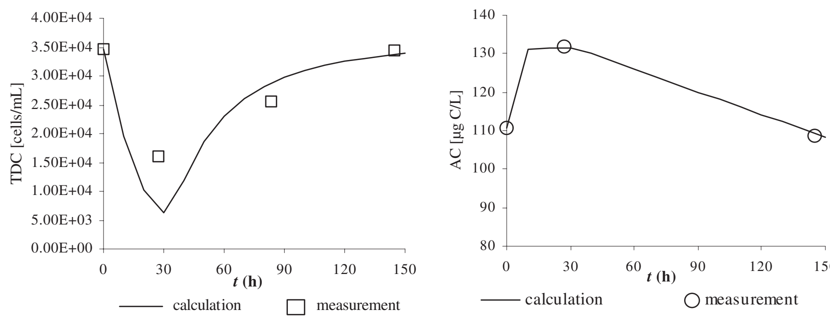

Figure 7 Calculation of the TDC and AC development depending on the flow time in the Elbaue-Ostharz DS

TDC and CFU in these systems working with low disinfectant residuals, although the flow time and the flow distance were relatively long. Higher numbers of CFU only were detected for a short time in one pipe of the part of the DS fed by treated reservoir water.

The main processes influencing the bacterial water quality change in systems fed with water with a low BOM and working without or with low disinfectant residuals are:

- the formation of biodegradable organic substances as a result of the oxidation of NOM by the disinfectants;
- the release of bacteria from the biofilm, whereas the growth of bacteria in water does not play an important role;
- the inactivation of released bacteria by the disinfectant residual with decreasing effect by decreasing the residual concentration.

A high CFU concentration over a short period of time could be connected to an increase of bacteria growth on the pipe surface. One cause for an increase in bacterial growth is an increase in the BOM concentration in the water as a result of changes of the water quality, for example, in a reservoir or when starting chemical disinfection in a system which had been working without disinfection up to this time. The highest risk of an increase in bacteria release exists in pipes where the biofilm is not well developed, like in pipes with a low flow and in areas with changing disinfectant concentrations.

As a result of the investigations, a model was developed allowing a description of the bacterial water quality change in systems fed with a low BOM containing water, working with or without low disinfectant residuals. Further investigations are also necessary to obtain information about the process of short time increases of bacteria release as a basis for modeling this process.

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