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Modelling bacterial biomass in a non-chlorinated drinking water distribution system

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Abstract

Water quality can deteriorate as it travels through a drinking water distribution system (DWDS). The DWDS offers reaction surfaces and contact time and, thus, acts as a bioreactor where biofilms develop that influence biomass dynamics. Under normal operational conditions the biofilm is in a steady state and the exchange of biomass between the biofilm and the bulk water phase is in equilibrium. When this equilibrium is disturbed, e.g. by a hydraulic incident, there is a potential of release of biomass from the biofilm leading to higher concentrations of biomass in the drinking water. This could lead to a discolouration event and may have an impact on microbial water quality. The main issue for a water company is to know where in the network the risk of these disturbances of the equilibrium is the largest and what control measures can be taken. The goal of our research is to combine and improve water quality models and a hydraulic network model to determine high and low risk locations in the DWDS with respect to bacterial biomass. As a first result a conceptual model, with parameter values based on internationally published laboratory and in situ measurements in the DWDS, has been developed.

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Keywords: drinking water distribution; water quality modelling; bacterial growth; risk based modelling

1. Introduction

1.1 Problem definition

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In the Netherlands, the distributed drinking water does not rely on residual disinfectants. To control and minimize growth of micro-organisms, the drinking water is produced with low concentrations of degradable substances (i.e. assimilable organic carbon (AOC)). Some dynamics of increase and decrease of micro-organisms in the water (biomass) during residence in the DWDS is to be expected [1]. Micro-organisms can multiply and accumulate in the water phase but also on the interface between the water phase and surfaces (particulate material and the pipe wall) in the DWDS, leading to the development of biofilms.

Under normal operational circumstances in the DWDS the biofilm is in equilibrium with its environment and there is little net exchange of biomass between water and biofilm. In case of a disturbance of the equilibrium there is a risk of biomass detachment which may result in discolouration, increased biological active particulate material and/or detachment of biofilm related opportunistic pathogens such as *Legionella pneumophila*.

The goal of our research is to identify areas of high risk of potential release of biomass and to evaluate mitigation strategies. Risk is defined as the combination of probability of a disturbance and its effect. We are aiming at determining the typical circumstances in which, and where in the distribution network, increases in total microbial biomass in the drinking water may occur, and also how much increase is considered a large effect.

1.2 A modelling approach

There are three basic alternative approaches to obtain knowledge on the growth of biomass in a given DWDS, namely based on measurements, expert knowledge (operational expertise, literature, scientists), or models. All approaches have their own merits and most is learned from combining information from all three. The pros and cons regarding these three different approaches are: 1) Measurements provide information of the reality, allow validation and are therefore of great value. However, they have the drawback of restricted availability, a limited number of locations and circumstances that can be studied, and have limited elucidative capacity. 2) Expert knowledge based on the combination of theory and observations has an advantage when it is not available from any other source, provides an integral view, and can be used for validation. However, it is difficult to translate this knowledge to specific/different DWDS. Also, there is the risk of bias towards specific situations due to generalization of assumptions and missing insights. In addition, operational expertise is not fool proof as it tends to overly focus on some areas and ignore others. 3) Models allow an integral approach to processes, extrapolation to locations without data, predictive capacity, and therefore sensitivity analyses and evaluation of management strategies. They also provide information on additionally required data or identify knowledge gaps. The most important drawback of models is that the quality of models depends on the quality of data and understanding of the complex physical, chemical and biological processes. Therefore a combination of measurements and theoretical modelling will add to expert knowledge for future optimization of drinking water quality.

1.3 Existing models

Available models from the literature are either statistical models e.g. [2], based on regression analyses, or deterministic models, based on a theoretical approach (e.g. RIGA [3], ZHANG [4], SANCHO [5], and PICCOBIO [6]). Both types of models have pros and cons, resulting from the different approaches that are used. Where statistical models are based on observations, deterministic models use understanding of physics, chemistry and biology. Most of the existing models are not yet applied in non-chlorinated conditions. Most available models have the drawback that they are very complex and often contain (too) many interdependent parameters, making it difficult to validate [3]. Even if good predictions are obtained it is hard to tell why and if this will be the same under different conditions, making these models less suited for sensitivity analyses or water management. Other drawbacks are that calculating times can be substantial and not all existing models are translated to a water quality model in a DWDS. Although existing models have drawbacks from a perspective of risk identification, they serve as a valuable starting point.

1.4 Our approach towards a practical model

Biological activity in a DWDS is very complex [7]. It is not our goal to create a comprehensive model. Instead, the modelling approach as used in this study is mostly focussed on modelling the risk of disturbances, and only taking into account the dominant microbiological processes, therefore simplifying the model and reducing the number of required parameters. Most existing models that are used to model bacterial growth use a detailed description of the fundamental processes and the specific microbiology from which growth in the DWDS can be explained. An important advantage of our approach is that a resulting model is not too complex and is therefore easily applicable in water management, and can be tested on a real DWDS. Furthermore, by including interactive validation with field observations using well defined parameters describing the actual (micro)biological and physical/chemical water quality conditions in a specific DWDS, the model can be designed for local optimization of this DWDS.

Unlike most existing models we aim to describe risks in a non-chlorinated DWDS. The presence of residual chlorine is not compatible with the specific biological conditions in the network without residual disinfectants. We apply a different microbial approach where (micro)biological conditions are more stressed and variable and therefore more difficult to describe.

This paper provides the outcome of a literature study aiming at exploring and evaluating existing models and the development of a conceptual numerical model based on a risk-based approach. More specifically, we present an inventory of the relevant processes and parameters that make up a conceptual model, and can then lead to the development of a numerical model, based on microbial- and hydraulic water quality theory and models in the DWDS. In the derivation of the conceptual model both biotic and abiotic factors are considered which are discussed in more detail in section 2.1. Section 2.3 and 2.4 describe how to model the probability and effect of hydraulic disturbances.

2. Conceptual model

2.1 Description of concepts and parameters

The first step in biofilm development is the formation of a conditioning film, consisting of a thin layer of organic molecules and ions that adhere to the surface of the pipe wall due to either physical or chemical processes. The next step is the adhesion of micro-organisms to the conditioning film, mainly due to electrostatic interactions and Van-der Waals-forces. The bacteria first need to adapt to their new environment in a so-called lag phase in which no growth takes place. Subsequently, the attached bacteria start growing and produce extracellular polymeric substances (EPS) which improves their bonding with the surface initiating the production of a biofilm [8].Then the biofilm can start to grow, based on the (amount of) substrate that is available [9].

The biofilm formation process (Fig.1) starts with a short exponential growth phase, followed by a linear phase in which the substrate supply is diffusion limited resulting in a reduced growth rate. The last stage is the stationary (or maintenance) phase in which growth and decay are in balance. Fluctuation in substrate supply, growth and starvation of bacteria combined with hydraulic disturbances may lead to biomass detachment [8].

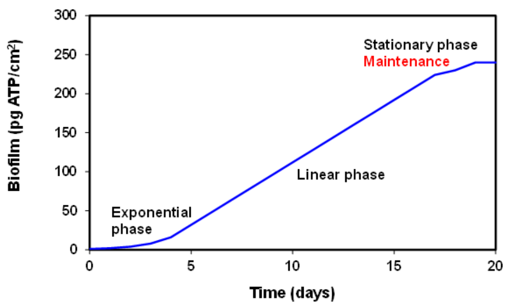

Fig. 1. Growth phases of a random biofilm on a solid phase (Note that values are depending on a specific situation [10] and are thus arbitrary).

Figure 2 shows a schematic presentation of a single pipe with length L (in m), diameter D (in m), x_1 a location at the start of the pipe and x_2 a location at the end of the pipe. Indicated are the microbial biomass in the bulk fluid B_{BF} (in ng ATP ml^{-1}) and the substrate concentration in the bulk fluid S_{BF} (in mg AOC or total organic carbon (TOC) l^{-1}).

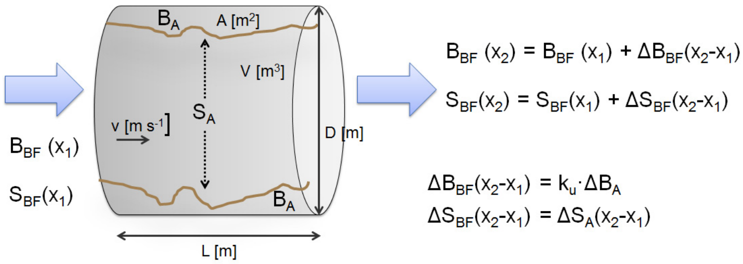

Fig. 2. Schematic presentation of biomass- and substrate flux in a single pipe. *B* is biomass, *S* is substrate, the subscript *BF* indicates bulk fluid, the subscript *A* indicates attached to the wall or biofilm, and k_U is the detachment rate.

Additionally the fluxes that give rise to changes in B_{BF} and S_{BF} over the length of the pipe are shown: the flux of biomass from the microbial biomass attached to the wall and sediment (B_A) to the bulk fluid (BF), described by the product of the detachment rate k_U and the change in attached biomass (ΔB_A), and the substrate flux, the substrate uptake of the attached biofilm, S_A, (in (mg substrate-C)/ (mg biomass-C·day)), which equals the specific rate of utilization of the energy source, defined by [11] as:

$$q = \frac{\mu}{Y_G} + M_S \ , \tag{1}$$

where μ is the growth rate in number of cells per day, $M_S = \mu_m \cdot Y^{-1}$ is the specific substrate uptake for maintenance, with μ_m the specific maintenance rate, and Y the yield, which is the amount of biomass (in g biomass-C) that can be produced per g of substrate-C, and Y_G is the maximum growth yield.

The specific substrate uptake for maintenance is determined by substrate concentration and composition with respect to biodegradability and energy content related to Y, the growth kinetics of the micro-organism (substrate affinity) and temperature [12].

Taking into account the pipe characteristics as in Fig.2, where v is the flow velocity (in m s^{-1}) of the BF in the pipe, the substrate flux in the biofilm of a single pipe can be defined as:

$$\Delta S_A = M_S \cdot \frac{A}{V} \cdot B_A \cdot \frac{L}{v} \ , \tag{2}$$

where the ratio L/v equals the retention time (in s).

Results of first calculations with equation (2) and some available values of the specific maintenance rate μ_m from literature revealed that the substrate uptake (decrease of substrate concentration) to maintain the biofilm over a km length of pipe at nominal water flow conditions (0.1 m.s^{-1}) in a DWDS is in the order of micrograms of an easily biodegradable compound such as acetate. This corresponds with literature observations where biofouling (biomass accumulation and pressure drop increase) of spiral-wound membranes operated under similar flow conditions (0.1 m.s^{-1}) occurs at a low AOC concentration of 1 µg acetate-C· l^{-1} [13,14]. Also recent measurements in DWDS showed that AOC concentrations hardly decrease during distribution. Furthermore, predicted biomass concentrations on the pipe wall with equation (2) are in the same order of magnitude as observed under field conditions.

Regarding biotic factors, for the development of an integral numerical model, the above mentioned equations with correlated parameters (Table 1) will be applied.

Table 1. Important biotic parameters for the biomass modelling in a DWDS.

Parameter	Description	Unit	Reference
B	Bacterial biomass (ATP, mg C)	$g \cdot cm^{-3}$	[15,16,17]
$\mu_{g,\,m}$	Growth (g), or maintenance (m) rate	number of cells $\cdot (h,d)^{-1}$	[11]
$Y_{r,max}$	Yield (real (r) or maximal (max))	mg/mg	[11,12]
M_S	Maintenance: Specific maintenance rate	mg S_A-$C$$\cdot$(mg B_A-$C$$\cdot$d)$^{-1}$	[11]
BFR	Growth: Biofilm formation rate	pg ATP$\cdot cm^{-2} \cdot d^{-1}$	[10]
AOC	Substrate, biodegradable compounds	$\mu g\ C \cdot l^{-1}$	[10]
k_u	Detachment rate	$(h,d)^{-1}$	

Abiotic factors include temperature, hydraulics, and pipe characteristics such as length, diameter and pipe material and roughness. An important process in a DWDS is the exchange of biomass between the BF and the biofilm, the so-called biomass flux ΔB_{BF}, which is defined as the product of the attached biomass B_A and the detachment rate $k_{U.}$ The detachment rate is a function of temperature T (K), τ (N m^{-2}), flow volume Q (m^3 s^{-1}), pressure p (kPa), pipe wall roughness ε (mm), and the Reynolds number Re (dimensionless). Shear stress is an important abiotic parameter in the context of growth in the DWDS: most of the biomass release in bulk water is due to shearing events, which are determined by wall shear stress τ_w (Prediction of Discolouration in Distribution Systems (PODDS) model [18,19] / VCDM model [20]). The amount of τ_w is affected by the flow condition in a pipe. Wall shear stress is defined as:

$$\tau_W = D\frac{\Delta p}{8L} \ , \tag{3}$$

where Δp is the pressure drop caused by friction (expressed in Pa) as defined by the Darcy-Weisbach equation:

$$\Delta p = f\,\frac{\rho L v^2}{2D} \ , \tag{4}$$

where f is the Darcy-friction coefficient (dimensionless), and ρ the density of the fluid (in kg m^{-3}). The friction coefficient f depends on the pipe dimensions and conditions (e.g. roughness, diameter), and the flow velocity, i.e. it is a function of Re and ε. The friction coefficient can be derived from the so-called Moody diagram [21].

Following from what is discussed in this section regarding the hydraulics of a pipe or DWDS, Table 2 gives an overview of important abiotic input parameters, including a range. Hydraulic modelling software (e.g. EPANET [22]) calculates flow velocity, contact time, shear stresses, and Re. The velocity profile is very much influenced by whether flow is laminar or turbulent, with turbulence causing much higher velocity gradients near the wall, resulting in relatively high values for τ_w. Turbulent flow occurs for velocities of 0.04 m s^{-1} and higher, depending on the pipe diameter, and therefore most flows in the DWDS are turbulent. However, laminar conditions occur as velocities vary over the day e.g. due to different water demands during day and night.

Table 2. Important hydraulic input parameters for the biomass modelling in a DWDS.

Parameter	Description	Range	Reference
D	Diameter of pipe	50–1500 mm	GIS
k	Pipe roughness, depends on pipe materials	0.05– 5 mm	From theory and model validation
L	Pipe length	1 m– km	GIS
Demand	in $m^3 h^{-1}$		Drinking water companies
Turb	Turbidity, indicator for sediment volume	0 – 100 NTU	Measurements

2.2 Model boundary conditions and assumptions

We consider the measurable biomass concentration as the main model parameter. This enables an interactive process of modelling and validation. Total active bacterial biomass in biofilm and water is measured as adenosine triphosphate (ATP) (in g cm^{-3}), which has been proved to be a usable measure for the amount of active biomass in drinking water and biofilms in non-chlorinated drinking water [15,16,23].

We assume a microbial equilibrium, and therefore only regard the biofilm maintenance phase, and not a growth model from scratch with transition towards the equilibrium biomass conditions (exponential and linear phase in Fig. 1). Hydraulic events as disturbances of the equilibrium are considered to affect biomass concentrations and can be modelled. Seasonal temperature and water quality variations are an intrinsic part of the model, but may also be part of short periodical disturbances. It is assumed that under normal daily operating conditions, the microbial biomass in the network is stable and shows low variation, only on a larger time scale the biomass will show slow adaptations (seasonal fluctuation).

When considering the biotic factors this leads to the following simplifications: there is no time-dependence, there is a constant flow with constant flux of substrate and biomass, the biomass is in its maintenance state (section 2.1), and only bacterial active biomass (ATP), both attached and in the water phase, is modelled. Regarding the abiotic factors we assume that maintenance is not affected by the pipe material but is affected by shear stress τ, and contact time. EPANET is used to extract related information.

First operational conditions are defined, consisting of an undisturbed pipe or DWDS. In a next step disturbance conditions are added. These consist of hydraulic disturbances: bursts, disconnecting/reconnecting parts of the network, large change in demand, change in operational conditions, long contact times followed by restored demand (e.g. holidays), and flushing events.

2.3 Probability of hydraulic disturbances

The probability of a hydraulic disturbance is not equal over the entire DWDS:

- The probability of a pipe break depends on pipe diameter, pipe material and year of installation. It may also depend on the environment: stresses from ground movement, traffic, etc. The Dutch pipe failure registration database USTORE [24] provides input for this pipe specific failure probability.
- A large change in demand can occur from the use of hydrants in case of a fire or from high coinciding residential demands e.g. during the interim of the finals of the world cup of football. The probability of such events is difficult to assess. Instead a sensitivity analysis will be performed. The amount of flow increase depends on the capacity of a hydrant (depending on the pressure) and the number of homes that are connected. These follow from the hydraulic network model. A change in demand from normal to low demand during holidays and vice versa can be treated in the same way.

- Closing a valve in the system may lead to a change in contact times, a change in flow direction, a change in flow velocity, a change in water quality (as the path towards a pipe may be very different). These effects, again can be determined with a hydraulic network model. The probability of closing a valve can be estimated from the number of planned and unplanned work that is done on networks. After the work is finished some of these valves may unintentionally be left closed. This means that the setting of valves is not only of interest with respect to the hydraulic disturbance, but also for the determination of the biofilm equilibrium under “normal” operations. An inventory of one of the Dutch water companies of the status (open or closed) of a statistically significant amount of valves showed that ca. 0.7% of the valves are not set to the expected position [25]. A Monte Carlo approach of closing valves in the hydraulic network model will help identify the effect of valve settings.

2.4 Effects of hydraulic disturbances

The hydraulic effect of hydraulic disturbances (increase in flow velocity and shear stress) depends on the local pressure and the pipe diameters surrounding the location of interest. This can be simulated with a hydraulic network model. The effects of hydraulic disturbances are modelled by first determining the shear stresses resulting from a disturbance using EPANET and subsequently using PODDS or VCDM to calculate the resulting erosion (causing discolouration) of the biofilm, described by the conceptual model for maintenance (section 2.1).

The effect of a hydraulic disturbance is determined by the disturbance of the microbial equilibrium, and thus is determined by the maintenance conditions of the biofilm. As the maintenance of a biofilm depends on pipe length and diameter, and on substrate availability, and thus on the distance (in traveling time) between a certain pipe and the water treatment works, the biofilm varies over the DWDS. As a consequence the same is valid for disturbances. Additionally, the effect of a disturbance is also determined by the size of the disturbance.

3. Summary and outlook

We have developed a conceptual model combining microbiological and hydraulic equations that is applicable for risk-analysis of biofilm detachment in a non-chlorinated DWDS. The model can easily be extended for modelling more complex situations. This is facilitated by the carefully chosen (focussing on the aim of the model) limited amount of parameters used in the model, making it possible to separately track different processes and rank their importance.

The numerical model is currently under construction, and for the parameters mentioned in Table 1 and 2 values are being collected from the literature. Separate laboratory experiments on biomass dynamics and hydraulics in a model distribution will produce additional parameters for the model. This process and further model testing will identify knowledge gaps. The model will first be applied on the level of a single pipe and then be extended to the entire DWDS. The consequences of moving from a single pipe to the whole DWDS are both spatial and temporal. Spatial changes include diameter transitions, temperature, pipe materials, velocities, and a different path/history of water. Temporal changes include temperature (seasonal variations and local hot or cold spots), and daily variations in velocity and flow direction, due to diurnal demand patterns.

As a starting point for the numerical model and to describe the hydraulics of the DWDS, EPANET will be used. To include the biotic factors a ‘biomass module’ will be created, which will be coupled to EPANET through EPANET MSX [26]. Next a sensitivity analysis of the combined model will be performed using a stochastic water demand model, SIMDEUM [27]. This sensitivity analysis will give an indication of how (much) the different parts of the model affect growth in the DWDS. Then, the abiotic parameters, the effect of hydraulics on biomass detachment, will be implemented using the VCDM or the PODDS model to model erosion of the particulate material and biofilm, which also is coupled to EPANET.

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