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Original Research

Feasibility of Bacterial Technology for Treating a Polluted Urban Streams from the Perspective of Numerical Modelling

Doddi Yudianto*, Yue-Bo Xie

State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering,
Hohai University, Nanjing, China

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Abstract

With the recent use of bacterial technology for the restoration of a polluted urban stream in China, this paper will show the general feasibility of such biological treatment from the perspective of numerical modelling. Based on the results, a low concentration of BOD_5 can be achieved in shorter distance for higher bacterial concentration applied. Generally greater flow of domestic wastewater will be proportionally balanced by higher bacterial growth. Under limited DO concentration, higher bacterial concentration would also create a breaking point on the declining distribution of BOD_5. The combination of oxygenation and artificial mixing of bacteria would result in lower concentrations of BOD_5 at the downstream.

Keywords: biological treatment, bacterial technology, polluted urban streams, numerical modelling, MATLAB

Introduction

The presence of oxygen dissolved in water is of fundamental importance to the life and health of any surface water. Dissolved oxygen (DO) is essential to allow aerobic microorganisms to stabilize the biodegradable material present and, in addition, the level of dissolved oxygen will often have an effect on the toxicity to fish and other aquatic life of extraneous materials dissolved in the water. In general, the dissolved oxygen in surface water is mainly obtained from the atmosphere in which air is a mixture of about 20.9% oxygen and approaching 80.0% nitrogen [1]. Up to a certain level, the dissolved oxygen is also produced by photosynthesis [2-8]. Due to its low solubility, unfortunately, even under optimum conditions, it is rare to find more than 8.00-10.00 mgL^{-1} of oxygen in surface water. Moreover, this concentration is not steady but varies inversely with salinity, directly with pressure and inversely with temperature.

Streams have always been the recipient of the wastes of human activities. Be it domestic sources, industrial or agricultural effluents or mining process waters, the massive increase of industrial productions accompanied by high growth of large urban populations has led to severe water pollution problems for over the last two centuries. Such a situation was found to be even worse in many of the lesser developed countries and some of the megalopolises with unbridled population growth and uncontrolled industrial development [9].

In order to avoid the depletion or complete removal of dissolved oxygen in surface waters, some water pollution regulations have been proposed by the authorized environmental agencies. These regulations are basically implemented to either control or eliminate the addition of readily biodegradable organic, slowly biodegradable or non-biodegradable substances, and other toxic materials to sur-

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*e-mail: doddi_yd@yahoo.com

face waters. A simple concept of loading capacity including total maximum daily load (TMDL) and waste assimilative capacity (WAC) was also then introduced as part of the management planning efforts [3, 10].

Leaving aside the various issues above, it is obvious that the process of stream self purification, as stated by Streeter and Phelps, is inseparably associated with the concept of pollution in the form of readily biodegradable organics. During this stabilization process, dissolved oxygen in a stream is removed by the aerobic microorganisms involved, and it is the heterotrophic bacteria that are responsible for decomposing most of the organic materials [1, 8, 11-12]. Due to various interactive biochemical and biodegradation processes, the level of dissolved oxygen will continue decreasing.

In general, there are some possible options that have been proposed for stream/river restoration. These techniques mainly include enhancing the re-aeration using a series of weir [5-6, 13-15], shifting effluent discharge locations [16], pumping air into the water body using a local oxygenator [8, 13] and introducing a constructed wetland [17-21]. Although it is obvious that the employment of a local aerator or oxygenator is much more expensive than weirs, both alternatives were identified as able to maintain the dissolved oxygen above 4.00 mgL^{-1} as required for fish survival. On the other hand, based on the study of water quality in Thane creek, the results show that the option of shifting the location of discharge does not yield any appreciable improvement in water quality. Wetlands, among those alternatives, were found to be the most effective way to treat the polluted stream/river. According to some research, wetlands and its modifications are able to remove the nutrients above 70% and cost much less in construction, operation and maintenance than conventional wastewater treatment plants [22].

Although the biological treatment has been widely used in many countries for the treatment of both industrial and domestic wastewater, it is still a challenging method to treat seriously contaminated surface water through the self-purification process [23]. In China, such technology (i.e. bacterial application) has been implemented recently for treating a polluted lake [24] and the influent of a wastewater treatment plant [25]. It is also good to know that the practical application of this technology was found to be successful in speeding up the recovery process of some streams in Shenzhen City, China. The final concentrations of BOD and COD after treatment were informally reported to be less than 5.00 mg L^{-1} and 20.00 mg L^{-1}, respectively. Although the use of bacteria is so far still limited for streams polluted by domestic wastewater, it might somehow be identified as an innovative method for solving the surface water pollution problems. In fact, this technology can be very useful where there is limited space, i.e. urban area for the installation of treatment facilities or even constructed wetlands. Referring to this issue and as some field data are still in the process of collection from a pilot project in Wuxi City, this study is aimed at providing general feasibility of the bacterial technology to treat a polluted stream from the perspective of numerical modelling. As MATLAB has been proved to be highly accurate and widely implemented in many fields of water quality modelling [15, 26-30], it has been selected to be used for the model development in this study.

Methodology

In order to understand the relationships between bacterial growth, substrate removal and DO concentration in the stream, the Monod kinetic equations are employed in the numerical model developed in this study. Two basic reactor models – continually stirred tank reactor (CSTR) and plug flow reactor (PFR) – are also briefly presented here to explain how a stream as a real representation of PFR has clear advantages compared to a CSTR model in the process of biodegradation. Furthermore, due to various influences of hydraulic properties the role of a dispersion term in transport model becomes crucial [31, 32]. Therefore this mixing parameter will also be included in the PFR model simulations.

Both steady state and dynamic simulations applied in the paper are basically done by MATLAB using mathematical function of *pdepe*. As a dynamic plug flow system with dispersion, the system of partial differential equations (PDEs) is solved by taking into account both advection and dispersion fluxes. Here, the influences of these fluxes are evaluated in relation to substrate removal and bacterial concentration. Due to the low concentrations of oxygen usually found in polluted urban streams, in further simulations the DO concentration is considered as a limited parameter to bacterial growth. To simplify the case, this paper will only consider a readily biodegradable substrate that is measured as 5 days of biochemical oxygen demand (BOD_5), and it is also assumed that all degradation processes involved occur at 20ºC.

Reactor Analysis

In general, two widely used methods for formulating mass transport in one dimensional surface water are CSTR and PFR. If CSTR is usually referred to an ideal completely mixed system that can be illustrated using a lake, PFR is employed to represent a stream/river in which it is assumed that no longitudinal mixing occurs between adjacent fluid elements. Each element of fluid for this type of reactor is basically analogous to a completely mixed batch reactor. Thus, in a PFR, the variation in concentration of a substrate in both space and time is of interest.

From some previous works of Lawrence and McCarty [33] followed by Benefield and Randall [34], it was obvious that PFR has greater efficiency compared to CSTR. Moreover, as noted by Weber [35], the CSTR would also require a larger volume than PFR to produce identical effluent concentrations. Since both reactors represent the extremes of mixing, these situations can very rarely be observed in practice. Some evidence from the previous work of Grieves et al. [36] showed that ideal PFR situations do not actually exist but for a plug flow tank with a certain intermediate mixing. Generally, the complete systems of PDEs for continuous load to CSTR and PFR with dispersion using the Monod kinetic equations are given as follows:

CSTR

$$\frac{dS}{dt} = \frac{Q}{V}\left(S_0 - S\right) - \frac{\mu_{\max H}}{Y^o{}_{X/S}}\frac{S}{K_s + S}X \tag{1}$$

$$\frac{dX}{dt} = \frac{Q}{V}\left(X_0 - X\right) + \mu_{\max H}\frac{S}{K_s + S}X - k_{dH}X^n \tag{2}$$

PFR with dispersion

$$\frac{dS}{dt} = -u_x\frac{dS}{dx} + E_x\frac{d^2S}{dx^2} - \frac{\mu_{\max H}}{Y^o{}_{X/S}}\frac{S}{K_s + S}X \tag{3}$$

$$\frac{dX}{dt} = -u_x\frac{dX}{dx} + E_x\frac{d^2X}{dx^2} + \mu_{\max H}\frac{S}{K_S + S}X - k_{dH}X^n \tag{4}$$

...where:

S : substrate concentration, measured as BOD_5 (ML^{-3});

X : bacterial concentration (ML^{-3});

Q : volumetric flowrate into the reactor (L^3T^{-1});

V : volume of the reactor (L^3);

μ_{maxH} : maximum specific growth rate (T^{-1});

$Y^o{}_{X/S}$: true yield coefficient;

K_S : saturation coefficient (ML^{-3});

u_x : average flow velocity (LT^{-1});

E_x : dispersion coefficient (L^2T^{-1});

k_{dH} : bacterial decay coefficient (T^{-1});

n : order of decay reaction, assumed equals to 1 for a linear term.

By considering a medium level of BOD_5 at 20ºC equal to 200.00 mg L^{-1} [34, 37] and similar properties of activated sludge model as given by Lawrence and McCarty [33], the following Fig. 1 shows that PFR with dispersion approaching complete mixing will result in a low concentration of substrate in about 0.15 d. Although this situation is a similar form of ideal plug flow, it reveals the possibility of an effective treatment process in polluted streams using the biological treatment, i.e. bacterial technology.

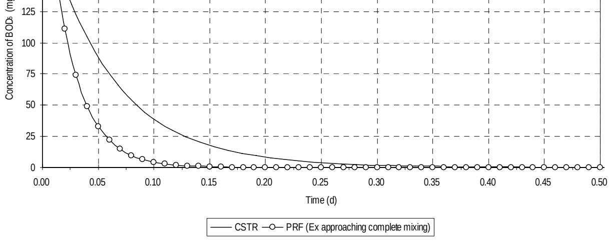

Fig. 1. Comparison of CSTR with PFR with dispersion; μ_{maxH}= 16.70 d^{-1}, K_S = 100.00 mgL^{-1}, $Y_{X/S}$ = 0.60, k_{dH} = 0.05 d^{-1}.

Parameters Involved in BOD Removal Using Bacterial Technology

Started by the introduction of Fickian analogies as an initial concept of diffusion, there has been a long history of the use of quantitative techniques to assess the impacts of pollutants on DO concentration in streams. Only after the establishment of a classical equation self-purification of a stream by Streeter and Phelps in 1925, however, was a significant achievement truly identified [6, 37, 38]. According to Streeter and Phelps, the DO concentration in a stream will continue decreasing with downstream distance due to degradation of soluble organic BOD. The simplest manifestation of these equations is usually applied for a stream reach characterized by a plug flow system with constant hydrology and hydraulic geometry under steady state conditions. The DO sag curve will become more complex when the stream is influenced by longitudinal dispersion as a result of various changes of bed slope, irregularity of stream bed and bank, sequences of pools and riffles, bed roughness, and turbulent eddies. The complete equations of Streeter and Phelps for a natural stream are given as follows.

$$\frac{dL}{dt} = -u_x\frac{dL}{dx} + E_x\frac{d^2L}{dx^2} - k_dL \tag{5}$$

$$\frac{dC}{dt} = -u_x\frac{dC}{dx} + E_x\frac{d^2C}{dx^2} - k_dL + k_a\left(C_s - C\right) \tag{6}$$

...where:

L : ultimate BOD concentration (ML^{-3});

C_s : saturated dissolved oxygen (ML^{-3});

k_d : first-order deoxygenation rate constant (T^{-1});

k_a : first-order reaeration rate constant (T^{-1}).

Adopting the basic concept of stream self purification and activated sludge process, the kinetic model based on Monod equations will be used in this paper to relate the balances of bacteria and substrate in the process of biodegradation in a polluted stream. Although there was evidence that the removal of BOD was an enzymic process carried out by bacterial enzymes and could occur in the absence of viable bacteria [39], here it is assumed that this enzyme involvement can be temporarily ignored to simplify the case. In further simulations, as sufficient dissolved oxygen is required for bacterial growth while its availability in a polluted stream is always limited, the developed models will later on include the oxygen limitation.

Moreover, as the movement of stream flow is also influenced by a certain level of mixing, the longitudinal dispersive mixing parameter will be taken into account. Since both advection and dispersion processes in streams are governed by the presence of velocity gradients, the involvement of a hydraulic model to derive longitudinal flow velocities, without excuse, becomes very important. In this paper, the bacteria are assumed to migrate with flow; that is why the advection and dispersion terms should always be included in the equation of bacterial rate.

Literally, there are some available equations that can be used to technically predict the longitudinal mixing in a stream such as McQuivey and Keefer (1974), Fischer (1975), Jain (1974), Liu (1977), Seo and Cheong (1998), and Deng et al. (2001) [32]. Although most of these equations have been widely applied in many research works, Wallis and Manson (2005) showed that such equations result in a wide range of values for the same hydraulic characteristics of flow [32]. The one mos often cited, a predictive equation developed by Seo and Cheong, is then chosen in this paper and defined as follows:

$$E_x = 5.915\left[\frac{u_x}{u_*}\right]^{1.428}\left[\frac{W}{H}\right]^{0.62} Hu_* \tag{7}$$

$$u_x = \frac{1}{n}\left(\frac{A}{P}\right)^{2/3} S^{1/2} \tag{8}$$

...where:

W : width of water surface (L);
H : average water depth (L);
u_* : shear/friction velocity (LT^{-1});
A : wet area of channel cross-section (L^2);
P : wet perimeter (L);
S : channel bed slope;
n : roughness coef of Manning.

Development of Numerical Model

Some of the most common problems in applied sciences and engineering are usually formulated in the form of either ODEs or PDEs. Since occasionally the exact solutions in closed form of such problems do not exist in many cases, this makes numerical solutions of special interest. Water quality and environmental modelling problem is no exception, and has been explored and solved up to an extraordinary level of understanding using various numerical methods to find such an approximate solution, as there are tolerance parameters that mostly ensure accuracy.

Generally, there is a vast amount of literature on numerical solutions for such differential problems. Some of the well known methods used in solving these problems are finite differences, finite volume and finite elements. Aside from these classical approaches, there are other important numerical schemes that have also been widely employed in many mathematical computing programs, i.e. MATLAB.

In this study, the numerical solutions for the above dynamic system are performed using the *pdepe* function of MATLAB. The necessity of introducing this method is because it offers more possibilities and flexibilities for both beginners and experts to evaluate or even invent a model, since there have been numerous mathematical functions developed inside MATLAB. Refs. [26-28], in this case, have recently shown some great advanced applications of MATLAB in the field of water quality modelling.

Besides, it can be applied for a broader aspect of numerical solution of ODEs, in MATLAB, the PDEs with various forms of additional terms can also be easily included and solved as a system [40]. The *pdepe* function basically applied for initial-boundary value problems consists of systems of parabolic and elliptic PDEs in one space variable and time. In this scheme, the initial conditions are allowed to be space-dependent and boundary conditions to be time-dependent. In solving a system of PDEs, the *pdepe* function is generally written in the form of:

$$c\left(x,t,u,\frac{\partial u}{\partial x}\right)\frac{\partial u}{\partial t} = x^{-m}\frac{\partial u}{\partial x}\left(x^m f\left(x,t,u,\frac{\partial u}{\partial x}\right)\right) + s\left(x,t,u,\frac{\partial u}{\partial x}\right) \tag{9}$$

Using *pdepe* MATLAB, various boundary conditions can also be flexibly formulated either as Dirichlet, Neumann or even Cauchy/Robin. Here, as the downstream boundary of the model is theoretically equal to zero for positive infinity, the Neumann condition is considered for all algorithms.

Model Applications

The developed numerical models are applied to a straight and uniform rectangular channel for in-bank flow case where the hydraulic dimensions used are: channel width B_1=5.00 m, bed slope S_0=0.00001, and Manning coefficient n=0.020. The flow rate applied for all model simulations is 0.50 m^3s^{-1}. In addition, to understand the further impact of bacteria on BOD removal, the concentration of bacteria used in the simulations also will be varied. Detail scenarios and data used in this paper are briefly described below and presented in Table 1.

Assuming that the concentration of BOD_5 in the river follows the standard values as given in the Environmental Quality Standard of the People's Republic of China for Surface Water (GB 3838-2002) under category III, which is applied for drinking water and normal fishing [41], the model is simulated using the typical BOD_5 values of domestic wastewater as given by Metcalf and Eddy [37] and also the bacteria characteristics as presented in Wiesmann et al. [42]. To provide basic information before further simulations, various loading of BOD_5 and bacterial concentration injected into the polluted urban stream will be first presented without expecting oxygen limitation.

As previously mentioned, the growth of bacteria is not only limited by substrate but also oxygen, under this second scenario, these conditions will be evaluated and the dissolved oxygen sag curve, as a result, is presented here. By considering the limitations of substrate and oxygen, the general equations used are given as follows:

$$\frac{dS}{dt} = -u_x\frac{dS}{dx} + E_x\frac{d^2S}{dx^2} - \frac{\mu_{\max H}}{Y^o{}_{X/S}}\frac{S}{K_S+S}\left(\frac{C}{K_{O_2}+C}\right)X \tag{10}$$

$$\frac{dX}{dt} = -u_x\frac{dX}{dx} + E_x\frac{d^2X}{dx^2} + \mu_{\max H}\frac{S}{K_S+S}\left(\frac{C}{K_{O_2}+C}\right)X - k_{dH}X^n \tag{11}$$

$$\frac{dC}{dt} = -u_x\frac{dC}{dx} + E_x\frac{d^2C}{dx^2} + k_a(C_s - C) - \mu_{\max H}\frac{1-Y^o{}_{X/S}}{Y^o{}_{X/S}}\frac{S}{K_S+S}\left(\frac{C}{K_{O_2}+C}\right)X \tag{12}$$

Table 1. The values of model parameters for different scenarios.

Model Parameters	Scenario 1	Scenario 2
Stream flow rate, Q_r (m^3s^{-1})	0.50	0.50
Stream flow velocity, u_x (ms^{-1})	Eq (8)	Eq (8)
Dispersion coef, E_x (m^2s^{-1})	Eq (7)	Eq (7)
Domestic wastewater flow rate, Q_w (m^3s^{-1})	(0.10, 0.20, 0.30) Q_r	0.10 Q_r
Bacterial concentration, X_0 (mgL^{-1})	25.00, 50.00, 75.00	25.00, 50.00
Natural stream BOD_5, L_r (mgL^{-1})	5.00	5.00
Domestic wastewater BOD_5, L_w (mgL^{-1})	200.00	200.00
Max specific growth, μ_{maxH} (d^{-1})	16.70	16.70
True yield coefficient, $Y^{o}_{x/s}$	0.60	0.60
Saturation coef., K_S (mgL^{-1})	100.00	100.00
Bacterial decay coefficient, k_{dH} (d^{-1})	0.05	0.05
Order of decay reaction, n	1.00	1.00
Stream DO, C_r ($mg\ L^{-1}$)	-	5.00
Domestic wastewater DO, C_w (mgL^{-1})	-	max 2.00
Saturated stream DO, C_s (mgL^{-1})	-	5.00
Reaeration rate, k_a (d^{-1})	-	Eq (13)
Oxygen limitation coef, K_{O_2} (mgL^{-1})	-	0.20

If (10) is compared to the previous classical equations of dissolved oxygen sag presented by Streeter and Phelps for the natural stream self purification, it can be noticed that the deoxygenation rate constant (k_d) is a function of many biodegradation parameters. Much data are required to balance these analogues, so it is assumed that the deoxygenation rate will be included as part of (10).

The other important parameter, also given in the above equations, is the reaeration rate constant. Since O'Connor and Dobbins developed the first model equation for calculating the reaeration rate constant (k_a) in streams in 1958, there has been quite a bit of research done in this field by the likes of Churchill et al. (1962), Owens et al. (1964), Tsivoglou and Neal 1976, USGS - Melching and Flores (1999), and Thackston and Dawson (2001), etc. [3]. Most of those developed formulas, pertaining to different stream flow velocity (at 20ºC), are usually empirical power function relationships of the form:

$$k_a = \frac{c u_x^m}{H^n} \qquad (13)$$

All empirical constants of c, m and n are basically dependent on the physical and hydraulic conditions of the channel. For the reaeration formula proposed by O'Connor and Dobbins the values of those constants are $c = 3.93$, $m = 0.50$, and $n = 1.50$.

Results and Discussion

Scenario 1

Based on simulations of the plug flow model with dispersion, it can be seen clearly from Fig. 2 that the addition of bacteria into a stream will enhance the biodegradation process. A very low concentration of BOD_5 can be achieved in a shorter distance for greater concentrations of bacteria. From the same Fig. 2 and supported by detail results presented in Table 2, the influence of dispersive mixing itself can in fact be clearly observed as the minimum values of BOD_5 are plotted a little bit downstream from the turn points where the bacterial concentrations start to decline.

As it is also necessary to identify the impact of different loading of domestic wastewater, as shown in Fig. 3, a greater flow of domestic wastewater will be proportionally balanced by higher bacterial growth. Although there is an increase of bacterial concentration employed by the stream but the lowest concentrations of BOD_5 are closely located at 4.2 km. For a constant bacterial concentration of 50.00 mgL^{-1}, Fig. 4 shows that after travelling time of about 0.10 day, the BOD_5 concentration will start to reach 5.00 mgL^{-1} at distance further than 2.00 km. Furthermore, in order to maintain a lower BOD_5 concentration downstream, the artificial mixing of bacteria may be helpful. As described in

Table 2. Concentrations of BOD_5 and bacteria.

Distance (km)	Xo = 25 mgL^{-1}		Xo = 50 mgL^{-1}		Xo = 75 mgL^{-1}	
	BOD_5	X	BOD_5	X	BOD_5	X
3.2	1.643	37.257	0.188	62.795	0.025	87.578
3.4	1.344	37.497	0.135	62.931	0.016	87.731
3.6	1.108	37.549	0.097	62.802	0.010	87.521
3.8	0.938	37.195	0.072	62.041	0.007	86.429
4.0	0.838	36.201	0.056	60.259	0.005	83.902
4.2	0.814	34.396	0.050	57.168	0.003	79.533
4.4	0.876	31.730	0.058	52.692	0.001	73.220
4.6	1.036	28.302	0.095	47.004	0.003	65.217

Fig. 5, there is only a very slight change of BOD_5 distribution at the upstream area but quite significant at the downstream.

Scenario 2

As presented in the following Fig. 6, it can be noticed that for greater concentrations of bacteria applied to the stream, the bacterial growth will obviously be limited. A breaking point will differentiate the declining distribution of BOD_5. As the logarithmic phase of bacterial growth seems to end, the biodegradation of BOD_5 will run much slower. Considering this significant role of oxygen, sufficient supply of oxygen during the injection of bacteria into the stream will retrieve the decomposing ability of bacteria. A clear illustration about that is presented in Fig. 7 as oxygen concentration of 2.00 mgL^{-1}is added at the beginning of the process.

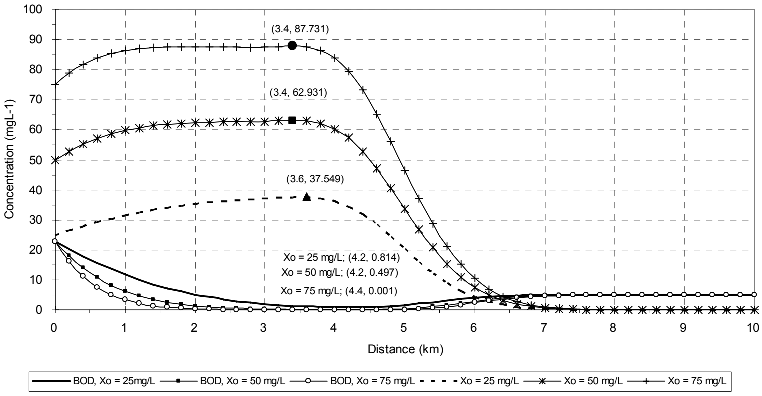

Fig. 2. Concentrations of BOD_5 as results of various loading of bacterial concentration.

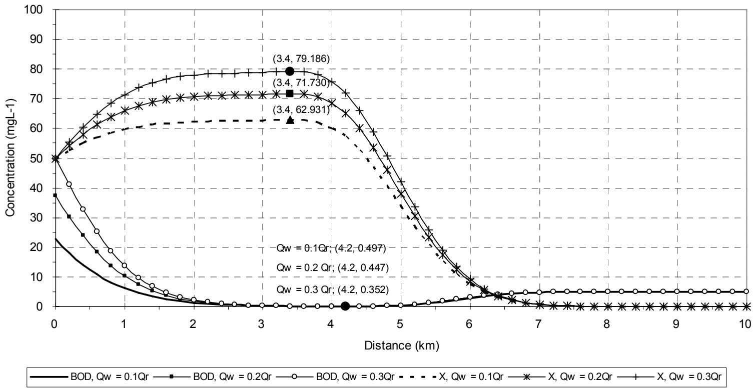

Fig. 3. Concentrations of BOD_5 as results of various loading of domestic wastewater flow.

Furthermore, when the advantage of artificial mixing of bacteria is also included in the model, the results show that the declining distribution of BOD_5 will remain steady for upstream reach but gain lower concentration of BOD_5 downstream.

Conclusions

By adopting the concept of stream self purification and activated sludge model, there are some important issues that can be pointed out to identify the feasibility of that related technology. Based on the results obtained, it is shown that greater bacterial concentrations applied to the stream will decrease the required distance for BOD_5 in reaching very low concentrations. A higher bacterial growth also will be performed when there is greater loading of domestic wastewater flow to the stream. Moreover, as a result of dispersive mixing in flow transport phenomena, the locations of minimum concentration of BOD_5 will be located a little bit downstream from the turn points where the bacterial concentrations start to decline.

When oxygen is also considered a limitation factor for bacterial growth, higher bacterial concentration applied to the stream will create a breaking point on the declining

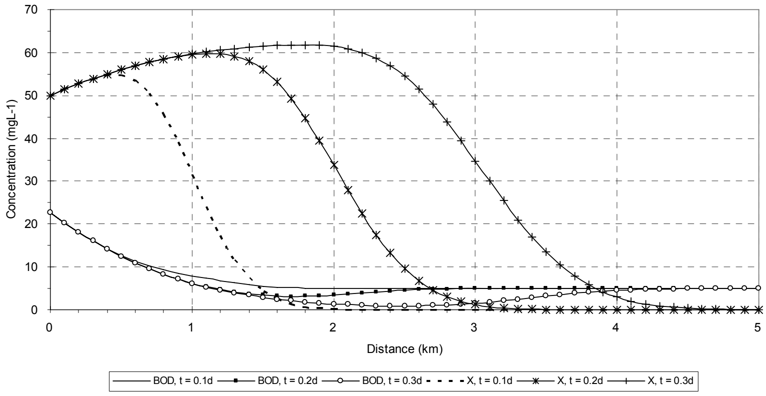

Fig. 4. Concentrations of BOD_5 and bacteria for various duration times of bacteria addition.

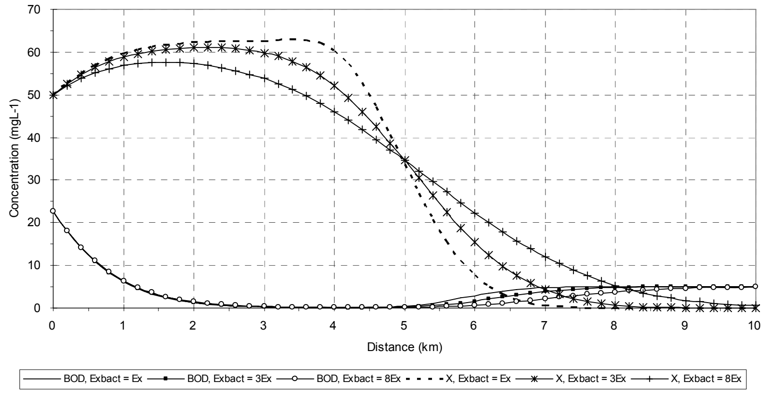

Fig. 5. Concentrations of BOD_5 for various dispersive mixing coefficients applied to the bacteria.

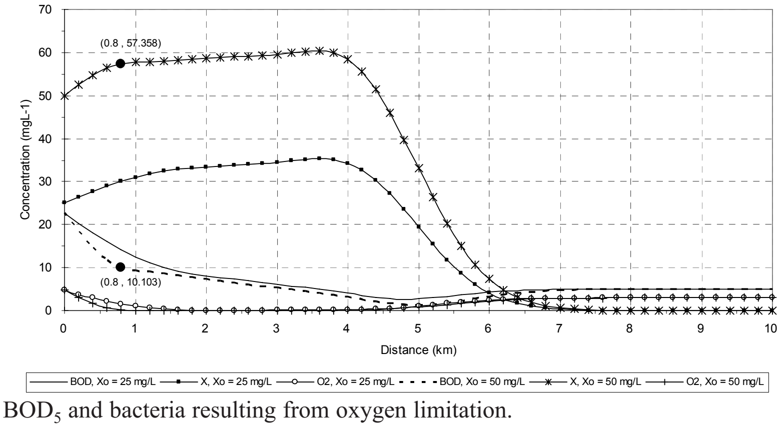

Fig. 6. Concentrations of BOD_5 and bacteria resulting from oxygen limitation.

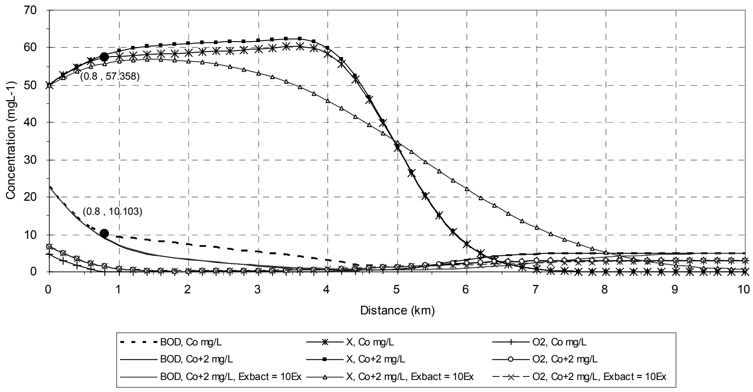

Fig. 7. Impact of oxygenation and artificial mixing of bacteria on BOD_5 concentrations.

distribution of BOD_5. Sufficient supply of oxygen at the beginning of the process is found to be able to retrieve the ability of bacteria in decomposing the organic matters. The combination of this oxygenation and artificial mixing of bacteria will result in lower concentrations of BOD_5 downstream.

Soon after the completion of data collection, further studies are planned to include other elements of natural biodegradation such as pH, temperature, nitrification, denitrification, COD and phosphorus degradation, decomposition of bacteria, impact of toxic pollutants on the bacteria, involvement of sediment, etc. It is also hoped that in further works this research can be tailored to simulate the actual process as close as possible in order to provide new information for the practice of pollution control.

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