An Approach for Analysis of Natural Hazard Impacts on Activated Sludge Wastewater Treatment

P Zlateva[1] and N Dimitrova[2]

1 Institute of Robotics, Bulgarian Academy of Sciences, Sofia, Bulgaria
2 Institute of Mathematics and Informatics, BAS, Sofia, Bulgaria
E-mail: plamzlateva@abv.bg, nelid@bio.bas.bg

Abstract. The activated sludge process is a advansed biological wastewater treatment process for treating sewage or industrial wastewaters by using different aerobic types of microorganisms (biomass). In recent years, the activated sludge processes are shown to be significantly negative affected by the natural hazards (the climate factors) as extreme temperatures, intensive rainfall, etc. An approach for analysis of natural hazard (climate change) impacts on wastewater treatment process with activated sludge is proposed. The approach is based on qualitative analysis of the input-output static characteristics of the activated sludge process, involving uncertainties in the inflow parameters of the aerobic bioreactor. The process model is described by the system from two nonlinear ordinary equations with interval coefficients. The impact levels of one natural hazard on the activated sludge process are defined as a deviation between the nominal and the affected input-output characteristics. The negative effects are described by variation in given intervals of some process coefficients and are calculated as percentages (deviations) from the nominal process coefficients. This analysis of natural hazard impacts on activated sludge wastewater treatment process is necessary in order to operate such system stable and efficiently.

1. Introduction

The wastewater treatment generally involves the sequential carrying out of physical/chemical and biological treatment processes [1, 2]. In particular, the following wastewater treatment processes are caried out: preliminary treatment (physical) to remove large debris and grit, primary treatment (physical) to remove settleable suspended solids, secondary treatment (biological) to remove the remaining particulates and dissolved organic material, chemical precipitation to remove nutrients, tertiary filtration (physical) to remove remaining fine particulates, and chemical or ultraviolet light disinfection [3, 4, 5].

The activated sludge process is a advansed biological wastewater treatment process for treating sewage or industrial wastewaters by using different aerobic types of microorganisms (biomass) [6, 7]. This process can accomplish the oxidizing carbonaceous biological matter, oxidizing nitrogenous matter: mainly ammonium and nitrogen in biological matter, removing nutrients (nitrogen and phosphorus) [8, 9].

In recent years, many studies are established an increase in the negative impact of climate change on the biological wastewater treatment process [10, 11]. These problems due to the climate change are directly related to the natural hazards [3, 12]. The activated sludge processes are shown to be significantly affected by the natural hazards (the climate factors) such as extreme temperatures (positive and negative), intensive rainfall, prolonged periods of deviations from established average daily temperatures and rainfall [13, 14].

For example in [15] it is presented an investigation on climate change effects on a wastewater treatment system that receive sewage collected in a combined sewer system in Oslo, Norway, during winter operation. It is established an increasing number of days with temperatures below the critical daily air mean temperature in the area, despite the progressively warmer winter temperatures in the last decade. It is demonstrated that these impacts can deteriorate operation of the activated sludge processes through progressively increasing the relative frequencies of very high influent flow rate and of the very low influent sewage temperature. In [14] the effects of temperature variations on aerobic biological wastewater treatment are evaluated with respect to treatment efficiency, solids discharges, sludge physicochemical properties and microbiology.

The analysis of the theoretical results related to the waste water treatment is shown that mathematical models which adequately describe the potential negative impacts of climate factors on the activated sludge processes are still insufficient [6, 8, 9]. Therefore, the issue of developing innovative approaches to assess the risk related to the negative effects of natural hazards on effective wastewater treatment is very important.

The aim of this paper is proposed an approach for analysis of natural hazard impacts (climate change impacts) on wastewater treatment process with activated sludge. The approach is based on stability analysis of a nonlinear model with interval coefficients, describing the activated sludge process in aerobic bioreactor [16]. The impact levels of one natural hazard on the activated sludge process are defined as a deviation between the nominal and the affected input-output characteristics. The negative effects are described by variation in given intervals of some process coefficients and are calculated as percentages (deviations) from the nominal process coefficients. All computations and visualizations are performed in the computer algebra system *Maple*.

2. Problem statement
The activated sludge wastewater treatment process is generally carried out in a system, which main consists of an aeration tank with biomass (bioreactor) and a secondary settler. It is assumed that the hydraulic characteristics of aeration tank are those of a continuously stirred tank bioreactor with cell recycle. Ideal conditions are assumed to prevail in the settler [6, 9]. A schematic diagram of the activated sludge wastewater treatment process with bioreactor and settler is shown on Figure 1.

Because of the system specificity connected with use of the different microorganisms (biomass), the activated sludge processes are characterized with nonlinear dynamics and parameter uncertainty (parameters of the bioreactor).
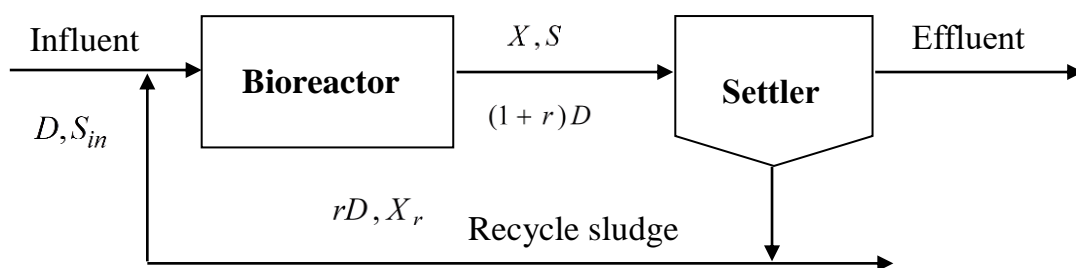

Figure 1. Schematic diagram of the activated sludge wastewater treatment process

The dynamical model of the the activated sludge process in the bioreactor is designed on based of the mass and energy balance equations. In this study, the model is described by the following two nonlinear ordinary differential equations [16]:

$$\frac{dx(t)}{dt} = \mu(s)x(t) + rD(t)x_r(t) - (1+r)D(t)x(t) \tag{1}$$

$$\frac{ds(t)}{dt} = -k\mu(s)x(t) + D(t)(s_{in} - s(t)) \tag{2}$$

where $x(t)$ is biomass concentration (activated sludge) [mg.l^{-1}]; $s(t)$ is substrate concentration (biochemical oxygen demand) [mg.l^{-1}]; D is dilution rate [h^{-1}]; s_{in} is influent substrate concentration [mg.l^{-1}]; x_r is recycle biomass concentration [mg.l^{-1}]; μ is specific growth rate [h^{-1}]; r is sludge recycle ratio; k is yield coefficient.

The specific growth rate $\mu(s)$ is presented by Monod law

$$\mu(s) = \frac{\mu_m \cdot s(t)}{k_s + s(t)},$$

where μ_m and k_s are kinetic process parameters.

It is assumed that the control input is $u = D(t) > 0$ and the output is $y = s(t)$ or $y = x(t)$.

Here is assumed that the main difficulty in controlling the activated sludge wastewater treatment processes comes from the variation of the process parameters and the influent waste load due to negative impacts of natural hazards. These variations induce process state changes that may lead to a reduction of the water treatment efficiency, unless the plant operation is continuously adjusted. Therefore, the steady state analyses should be performed to overcome this problem.

The activated sludge process steady state may critically depend on the process parameters and on the value of the influent waste load. Usually, practical investigations and computer simulations show that the process parameters s_{in}, x_r, r in the model (1)-(2) are unknown but bounded.

It this study, it is used the method for stability analysis of a nonlinear model of wastewater treatment processes, proposed in [16]. It is assumed that instead of numerical values for parameters s_{in}, x_r, r, the parameter intervals $[s_{in}], [x_r], [r]$ are given, respectively.

The main idea of this paper is to study the input–output static characteristics $y_x(u) = x(u)$ and $y_s(u) = s(u)$ involving intervals in the parameters (s_{in}, x_r, r).

Using advanced techniques from recently developed interval analysis [16], it is computed the so called interval static characteristic which presents the set of all functions $y_x(u)$ and $y_s(u)$ for any values of the coefficients in the given intervals ($[s_{in}], [x_r], [r]$).

3. Interval static characteristics

The static model of the process is delivered from (1)-(2) by setting the right-hand side functions equal to zero. Thus it is obtained the nonlinear algebraic system with respect to s and x:

$$\mu(s)x + rux_r - (1+r)ux = 0$$

$$k\mu(s)x - u(s_{in} - s) = 0$$

or more precisely:

$$\left(\frac{\mu_m \cdot s}{k_s + s} + -(1+r)u\right)x + rux_r = 0 \tag{3}$$

$$k\frac{\mu_m \cdot s}{k_s + s}x - u(s_{in} - s) = 0 \tag{4}$$

By expressing $x = x(s, u)$ from (4) and substituting in (3) it is obtained the following the quadratic equation with respect to s [16]:

$$as^2 + bs - c = 0,$$

where

$$a = (1+r)u - \mu_m, \quad b = \mu_m krx_r - s_{in}((1+r)u - \mu_m) + (1+r)uk_s, \quad c = (1+r)uk_s s_{in}.$$

Its discriminant is given by

$$\Delta(u) = b^2 + 4ac = (\mu_m krx_r - s_{in}((1+r)u - \mu_m) - (1+r)uk_s)^2 + 4\mu_m krx_r(1+r)uk_s$$

Obviously, $\Delta(u) > 0$ for any $u \geq 0$ is valid. The two roots, $s_1(u)$ and $s_2(u)$ are then

$$s_1(u) = \frac{-b+\sqrt{\Delta(u)}}{2a} = \frac{2c}{\sqrt{\Delta(u)}+b}, \qquad\qquad s_1(u) = \frac{-b-\sqrt{\Delta(u)}}{2a}$$

Taking into account the biotechnological restriction $0 < s < s_{in}$, the second root $s_2(u)$ is excluded from further consideration. Moreover, $s_1(u)$ satisfies [16]

$$s(u) < s_{in} \qquad \text{and} \qquad \lim_{u\to\infty} s_1(u) = s_{in}.$$

Thus the (biologically reasonable) steady state is $s(u) = s_1(u)$ [16]:

$$s(u) = \frac{2k_s(1+r)us_{in}}{\sqrt{\Delta(u)}+\mu_m krx_r-s_{in}((1+r)u-\mu_m)+(1+r)uk_s} \tag{5}$$

Then (4) implies

$$x(u) = \frac{u(s_{in}-s(u))}{k\mu(s(u))} \tag{6}$$

The functions

$$y_s(u) = s(u) \quad \text{and} \quad y_x(u) = x(u) \tag{7}$$

are called input-output static characteristics of the dynamic activated sludge wastewater treatment process.

It is assumed now that the coefficients s_{in}, x_r, r in the model (3)-(4) are enclosed by the intervals $[s_{in}] = [s_{in}^-, s_{in}^+], [x_r] = [x_r^-, x_r^+], [r] = [r^-, r^+]$, respectively [16].

For arbitrary but fixed $u > 0$ it is considered $y_s(u) = y_s(u; s_{in}, x_r, r)$ and $y_x(u) = y_x(u; s_{in}, x_r, r)$ from (7) as functions of the variables s_{in}, x_r, r defined on the vector with intervals in the components (interval vector) $[\mathbf{z}] = ([s_{in}], [x_r], [r])$.

As a next step it will be computed the ranges of $y_s(u) = y_s(u; s_{in}, x_r, r)$ and $y_x(u) = y_x(u; s_{in}, x_r, r)$ on $[\mathbf{z}]$. The main difficulty here is the strong dependence (repeatability) on the uncertain parameters in the expressions for $y_s(u)$ and $y_x(u)$ [17]. To overcome it the monotonicity properties of the functions with respect to s_{in}, x_r, r are used. The gradients of $y_s(u)$ and $y_x(u)$,

$$grad(y_s) = \left(\frac{\partial y_s}{\partial s_{in}}, \frac{\partial y_s}{\partial x_r}, \frac{\partial y_s}{\partial r}\right) \quad \text{and} \quad grad(y_x) = \left(\frac{\partial y_x}{\partial s_{in}}, \frac{\partial y_x}{\partial x_r}, \frac{\partial y_x}{\partial r}\right)$$

have constant signs with respect to each one of the components on $[\mathbf{z}]$, that is

$$\frac{\partial y_s}{\partial s_{in}} > 0, \quad \frac{\partial y_s}{\partial x_r} < 0, \quad \frac{\partial y_s}{\partial r_r} > 0 \qquad \text{and} \qquad \frac{\partial y_x}{\partial s_{in}} > 0, \quad \frac{\partial y_x}{\partial x_r} > 0, \quad \frac{\partial y_{sx}}{\partial r_r} > 0$$

Then the ranges of $y_s(u) = y_s(u; s_{in}, x_r, r)$ and $y_x(u) = y_x(u; s_{in}, x_r, r)$ on the interval vector $[\mathbf{z}] = ([s_{in}], [x_r], [r])$ are presented [18] by

$$[y_s](u) = [y_s^-(u), y_s^+(u)] = [y_s(u; s_{in}^-, x_r^+, r^+), y_s(u; s_{in}^+, x_r^-, r^-)]$$

$$[y_x](u) = [y_x^-(u), y_x^+(u)] = [y_x(u; s_{in}^-, x_r^-, r^-), y_x(u; s_{in}^+, x_r^+, r^+)]$$

The functions $[y_s](u)$ and $[y_x](u)$ are interval-valued functions of the real variable u. They are called interval input-output static characteristics of the process (1)-(2) with respect to the outputs s and x, respectively. They present the hull of all static characteristics $y_s(u) = y_s(u; s_{in}, x_r, r)$ and $y_x(u) = y_x(u; s_{in}, x_r, r)$, when the coefficients s_{in}, x_r, r vary in the prescribed intervals.

The interval function $[y_s](u)$ is uniquely defined by its boundary functions $y_s^-(u)$ and $y_s^+(u)$ that is $[y_s](u) = [y_s^-(u), y_s^+(u)]$ with $y_s^-(u) \le y_s^+(u)$ for any $u > 0$. The explicit expressions for $y_s^-(u)$ and $y_s^+(u)$ will be now given. First, it is denoted [16]:

$$\Delta_1(u) = (\mu_m k r^+ x_r^+ - s_{in}^-((1 + r^+)u - \mu_m) - (1 + r^+)uk_s)^2 + 4\mu_m k r^+ x_r^+ x_r (1 + r^+)uk_s$$

$$\Delta_2(u) = (\mu_m k r^- x_r^- - s_{in}^+((1 + r^-)u - \mu_m) - (1 + r^-)uk_s)^2 + 4\mu_m k r^- x_r^- x_r (1 + r^-)uk_s$$

Then the boundary functions are presented by

$$y_s^-(u) = \frac{2k_s(1 + r^+)us_{in}^-}{\sqrt{\Delta_1(u)} + \mu_m k r^+ x_r^+ - s_{in}^-((1 + r^+)u - \mu_m) + (1 + r^+)uk_s}$$

$$y_s^+(u) = \frac{2k_s(1 + r^-)us_{in}^+}{\sqrt{\Delta_1(u)} + \mu_m k r^- x_r^- - s_{in}^+((1 + r^-)u - \mu_m) + (1 + r^-)uk_s}$$

The boundary functions $y_x^-(u)$ and $y_x^+(u)$ for $[y_x](u)$ can be computed similarly by substituting, $s_{in} = s_{in}^-$, $x_r = x_r^-$, $r = r^-$ and $s_{in} = s_{in}^+$, $x_r = x_r^+$, $r = r^+$ in $y_x(u)$, respectively.

4. Numerical experiments and discussion

Many simulations are carried out with different nominal values of the coefficients $(\mu_m, k_s, k, s_{in}, x_r, r)$ in the model (1)-(2) in order to analyze natural hazard impacts on activated sludge wastewater treatment processes. All computations and visualizations are performed in the computer algebra system *Maple* [16].

In the computer experiments the nominal values for the process coefficients are considered as centers of the intervals. The radii are given by $\rho_\alpha \alpha$, $\alpha \in \{s_{in}, x_r, r\}$ with $0 < \rho_\alpha < 1$; ρ_α is called deviation from α. Thus

$$[s_{in}] = \left[s_{in}(1 - \rho_{s_{in}}), s_{in}(1 + \rho_{s_{in}})\right], \qquad [x_r] = \left[x_r(1 - \rho_{x_r}), x_r(1 - \rho_{x_r})\right],$$

$$[r] = [r(1 - \rho_r), r(1 + \rho_r)].$$

Giving different values to ρ_α, intervals $[s_{in}]$, $[x_r]$, $[r]$ with different radii (widths) are obtained [16]. Assume first that only $[s_{in}]$ is uncertain, $s_{in} \in [s_{in}]$ and the other two coefficients x_r and r are exactly known, that is $\rho_{x_r} = \rho_r = 0$ (or equivalently $[x_r] = x_r$ and $[r] = r$). Figure 2 shows the boundary functions of the input-output static characteristics $[y_s]_{s_{in}}(u)$ and $[y_x]_{s_{in}}(u)$ with different deviations, taking into account impact of some natural hazard to the analyzed activate sludge process.

Figure 1 shows that the large increase of u leads to strong decrease of the activated sludge concentration x, so that x may become smaller than a technologically given minimal concentration x_{min}. This may cause instability and inefficiency of the bioreactor. The left picture presents the strong influence of s_{in} on $y_s(u)$ for small values of u, whereas large values for u retain the width $(y_s^+ - y_s^-)$ of $[y_s](u)$ near to the width $(s_{in}^+ - s_{in}^-)$ of $[s_{in}]$.
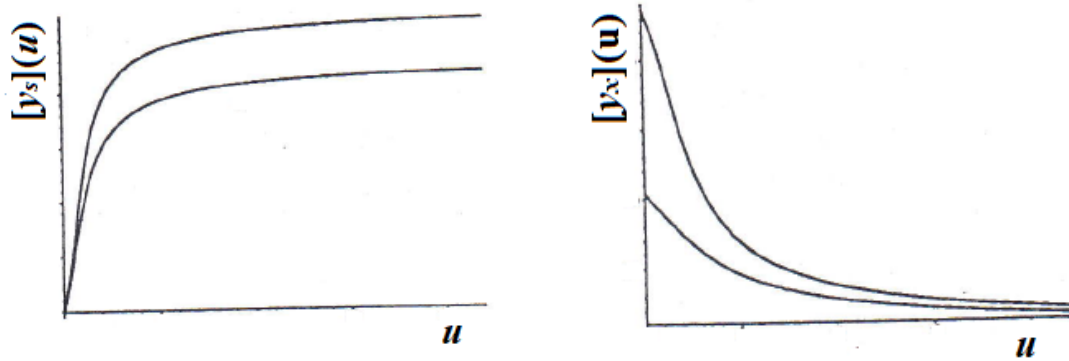
Figure 2. Simulations of the input-output static characteristics $[y_s](u)$ with $\rho_{s_{in}} = 0.1$ and $[y_x](u)$ with $\rho_{s_{in}} = 0.4$ [16].

Let be $x_r \in [x_r]$ and $[s_{in}] = s_{in}$, $[r] = r$. Figure 3 visualizes the interval input-output static characteristics $[y_s]_{x_r}(u)$ and $[y_x]_{x_r}(u)$.
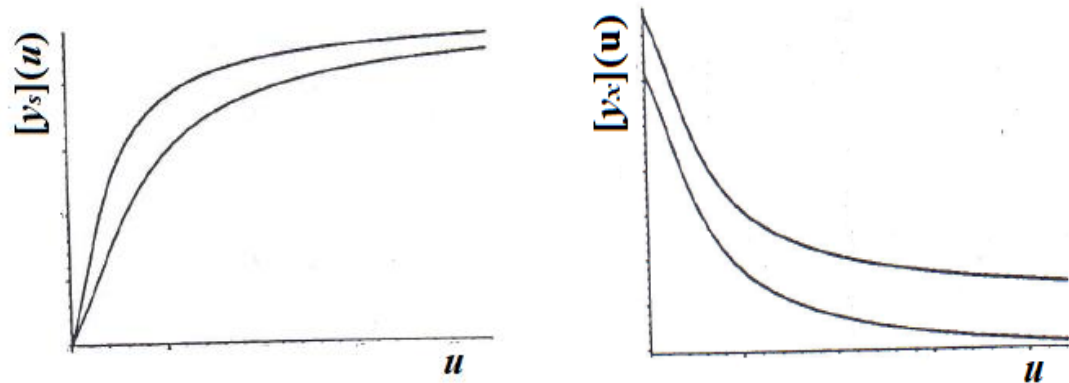
Figure 3. Simulations of the input-output static characteristics $[y_s](u)$ with $\rho_{x_r} = 0.3$ and $[y_x](u)$ with $\rho_{x_r} = 0.007$ [16].

For $r \in [r]$ and $[s_{in}] = s_{in}$, $[x_r] = x_r$ Figure 3 presents the boundary functions of the input-output static characteristics $[y_s]_r(u)$ and $[y_x]_r(u)$.
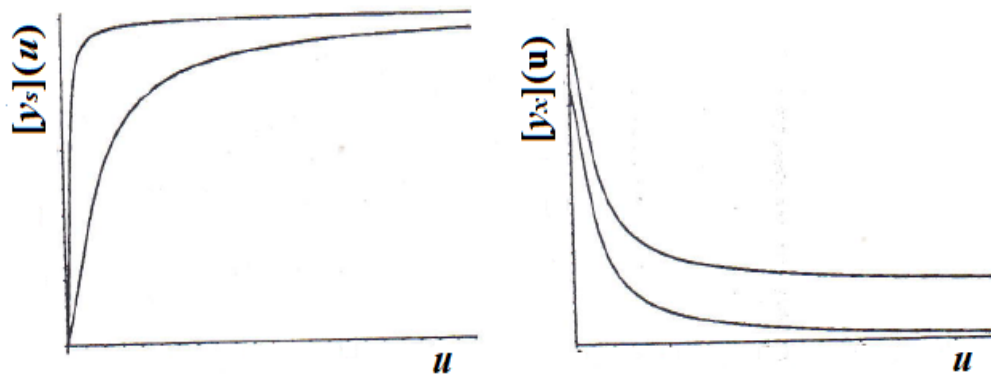
Figure 4. Simulations of the input-output static characteristics $[y_s](u)$ with $\rho_r = 0.9$ and $[y_x](u)$ with $\rho_r = 0.04$ [16].

Figure 3 shows strong dependence of the activated sludge concentration x with respect to recycled biomass concentration x_r. The simulation results of $[y_s](u)$ shows that the deviations in x_r have strong impact on $s(u)$ in the first (exponential) phase, but for large rates u it becomes negligible. Similar effects are observable on Figure 4.

The considered mathematical model of the activated sludge process affected from natural hazard does not require special bounds on the dilution rate u. In practice an operating admissible upper bound $\acute{u}$ for u always exists and depends on the technical characteristic of the bioreactor.

5. Conclusion

An approach for analysis of natural hazard impacts (climate change impacts) on wastewater treatment process with activated sludge is proposed. The approach is based on qualitative analysis of the input-output static characteristics of the activated sludge process, involving uncertainties in the inflow parameters of the aerobic bioreactor. The process model is described by the system from two nonlinear ordinary equations with interval coefficients. The impact levels of one natural hazard on the activated sludge process are defined as a deviation between the nominal and the affected input-output characteristics. The negative effects are described by variation in given intervals of some process coefficients and are calculated as percentages (deviations) from the nominal process coefficients. This analysis of natural hazard impacts on activated sludge wastewater treatment analysis is necessary in order to design and operate such system stable and efficiently.

6. Acknowledgments

7. References

[1] Sperling M 2007 *Basic Principles of Wastewater Treatment*, IWA Publishing, p 200.
[2] Riffat R 2012 *Fundamentals of Wastewater Treatment and Engineering*, Taylor & Francis, p 359
[3] Sokawa H 2016 *Management of Wastewater in Japan*, Japan Sewage Works Association, http://www.jswa.jp
[4] Mihelcic J R and Zimmerman J B 2014 *Environmental Engineering: Fundamentals, Sustainability, Design.* 2nd Edition, John Wiley & Sons, p 704
[5] Mittal A 2011 *Biological Wastewater Treatment*, *Water Today*, pp 32-44
[6] Olga Sanches (ed.) 2016 *Environmental Engineering and Activated Sludge Processes: Models, Methodologies, and Applications*, Apple Academic Press, p 63.
[7] Brdjanovic D et al (eds.) 2015, *Applications of Activated Sludge Models*, IWA Publishing, p 500.
[8] IWA Task Group on Good Modelling Practice 2012 *Guidelines for Using Activated Sludge Models*, IWA Publishing, p 312.
[9] Meijer S C F and Brdjanovic D 2012 *A practical guide to activated sludge modeling*. UNESCO-IHE Institute for Water Education, p 277.
[10] Tram V T, Ngo H H, Guo W, Zhou J L, Nguyen P D, Listowski A and Wang X C 2014 A mini-review on the impacts of climate change on wastewater reclamation and reuse. *Sci Total Environ* 494-495 pp 9-17.
[11] Tolkou A K and Zouboulis A I 2016 Effect of climate change in WWTPs with a focus on MBR infrastructure, *Desalination and Water Treatment* 57 (5) pp 2344-2354.
[12] Danas K, Kurdi B, Stark M and Mutlaq A 2012 *Climate change effects on waste water* treatment, CEE Jordan Group Presentation. http://courses.washington.edu/cejordan/
[13] McMahan E K 2006 *Impacts of rainfall events on wastewater treatment processes*, University of South Florida, http://scholarcommons.usf.edu/etd/3846
[14] Morgan-Sagastume F and Allen D G 2003 Effects of temperature transient conditions on aerobic biological treatment of wastewater, *Water Res. Sep* 37 (15) pp 3590-601.

[15]   Pl ός z B, Liltved H, Ratnaweera H. 2009 Climate change impacts on activated sludge wastewater treatment: a case study from Norway, *Water Sci Technol.* 60 (2) pp 533-541.

[16]   Zlateva P. and Dimitrova N. 2005 Stability analysis of a nonlinear model of wastewater treatment processes, NAA 2004, (Li Z. et al., Eds.), *LNCS* 3401, (Berlin: Springer – Verlag) pp 606-612.

[17]   Ratschek H. and Rockne J 1984 *Computer Methods for the Range of Functions*. (New York: Ellis Horwood Publ., Halsted Press).

[18]   Dimitrova N. 1996 On a numerical approach for solving a class of nonlinear systems, *Scientific Computing and Validated Numerics*, (Alefeld G. et al., Eds.), (Berlin: Akademie Verlag) pp 147-153.