

CITIES AND THEIR WATER INFRASTRUCTURES: FORCES FOR GOOD IN THE WATERSHED?

F. Jiang¹ and M.B. Beck²

- (1) Georgia Department of Natural Resources, Atlanta, GA 30334, U.S.A., email: fjiang@uga.edu
- (2) Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602, U.S.A., email: mbbeck@uga.edu

ABSTRACT

It is hard to conceive of cities as forces for good in the environment of their watershed. We present a case for promoting the principle of transforming cities from being perceived as inherent environmental “bads” to becoming environmental “goods”, albeit over generations. A city is commonly thought of as having a metabolism. This metaphor allows us to elaborate three strategically important criteria in judging the performance of the city and its water infrastructure against the environmentally benign component of the “triple bottom line”: one criterion is the ecological footprint (EF); a second has to do with the flux of materials passing through the city in its context of global material cycles; and the third, pulse rate, is cast in terms of the spectrum of disturbance frequencies to which the city’s environment is subject. In order to anchor our elaboration of the foregoing criteria, we report results from a computational case study in the redesign of the city’s existing wastewater infrastructure such that the infrastructure would assume the primary purpose of generating a “perfect fertilizer”. Crucial in our interpretation of how this goal might be realized is a strategic, stage-wise migration towards what is called source separation. Our computational studies demonstrate that source-separation strategies have advantages over current practice due to their lower EF, recovery of more nutrients and some energy, and an altered spectrum of perturbations of the city’s environment.

Key words: Ecological footprint, metabolism, pulse rate, source separation, sustainable city

1. INTRODUCTION

Stated in rudimentary terms, the metabolism of a city can be summarized as its intake of “daily bread” and “daily water”, and return of the residuals of this daily metabolism to the environment surrounding the city. Water, however, is also used very widely for the purposes of conveying these residuals out of the confined spaces of the city, thus enabling the city’s population to lead healthy and productive lives, but also inducing degradation of the aquatic environment, especially in respect of nutrient residuals of metabolism, hence typically eutrophication and the focus on installing technologies for removing nutrients (N and P) as “pollutants” instead of as “resources to be gainfully recovered” (for example, Beck, 2005; Beck and Jiang, 2006). Succinctly put, to paraphrase the words of Otterpohl *et al.* (1999): the purpose of an urban wastewater infrastructure, once a hygienic existence for people in the city has been secured, is to keep the soil fertile. Accordingly, using simulation models in this paper, we undertake some computational studies intended to achieve two goals: (i) further elaboration and substantiation of the technological scope for producing a perfect fertilizer from a “conventional” urban wastewater infrastructure (as originally conceived in Beck and Chen (1999)); and (ii) further elaboration – and application – of some evolving criteria of what constitutes greater/lesser sustainability in the behavior of a city and its water infrastructure (Beck and Jiang, 2006). We emphasize that these are preliminary studies, reflecting nascent quantitative and computational analyses of previously essentially conceptual work. This work in turn has the long-term aim of seeking to go beyond designing (waste)water infrastructures merely for the purpose of compensating for the environmental “bads” of the city, thus to enable the city instead to act deliberately as a positive force for good in the environment (Beck and Jiang, 2006). One technological option of particular interest is that of source separation, wherein different streams of wastewater are separated and treated with different pathways from their source onwards. Compared with current infrastructure, such a strategy would have the following advantages: (i) adequate treatment and utilization/recovery of wastewater contents; (ii) integration of agriculture as users of end-products; (iii)

utilization of the energy content of wastewater; (iv) reutilization of the separated flows, or their substitution.

2. METHODOLOGY

Wastewater from urban areas is usually collected from individual households and treated in a central wastewater treatment plant (WWTP). Because the crude sewage influent to the WWTP is a mixture of different wastewaters, these standard arrangements for the wastewater infrastructure will be called the “mixing strategy” herein. Since the Anaerobic/Anoxic/Oxic (A/A/O) arrangement of the common activated sludge system of biological wastewater treatment has a high efficiency of nutrient removal, it is selected here as representative of current treatment practice (Fig. 1).

Analysis of the individual sources of municipal wastewater shows that human excrement contains about 90% of the nitrogen, phosphorus, and potassium in household wastewater (Fittschen and Niemczynowicz, 1997). Thus, if we were to separate yellow water (urine) and black water (feces) from grey water (other household water), nutrient removal – or better, nutrient separation/recovery – in a WWTP should in principle become easier. We adopt two strategies for such source control: one is what we shall call the “ANS (Anthropogenic Nutrient Solution)-separation strategy”, wherein urine is separated from other sources of wastewater by a NoMix toilet (Lienert and Larsen 2004) (Fig. 2). The other, which we label “ANS-AHP (Anthropogenic Humus Precursor) separation”, involves separating both urine and feces from the other fluxes/sources of wastewater. The influent data for the source wastewater characteristics are typical of dry-weather conditions (Table 1), largely derived from the research conducted by Larsen and Gujer (1996) and Herrmann and Klaus (1997). We use WEST[®] (Hemmis nv, Kortrijk, Belgium) as the software platform for our simulation studies. At the core of the simulation is the biochemical, wastewater treatment plant model commonly referred to as Activated Sludge Model (ASM) No.2d (Henze *et al.*, 1999).

3. RESULTS AND DISCUSSION

In order to assess the advantages and disadvantages of different strategies, three criteria are adopted here: ecological footprint (Lenzen *et al.*, 2003); fluxes of materials passing through the city, i.e., a form of mass balance (not, as ideally conceived of, in terms of these fluxes in the context of global material cycles); and pulse rate, approximated here by conventional time-series plots (as opposed, ideally, to quantitative representation in terms of the spectrum of disturbance frequencies to which the city’s environment is subject; Beck, 2005). We acknowledge that all three criteria would come under just the single “environmentally benign” component of the triple bottom line accounting system (for sustainability). In these initial stages, we also assume that our three strategies are already in place, i.e., we have yet to assess the sustainability of the infrastructural transitions from the current arrangements (the mixing strategy) to the end-points of either of the other two strategies.

3.1 Ecological footprint

Ecological footprint (EF) involves determining the area of land and water (in various categories) required on a continuous basis to provide all the energy and material resources brought into the city and to absorb all waste discharged back from the city (Lenzen *et al.*, 2003). For the three strategies investigated in this research, we compared their areas of consumed and disturbed lands and their greenhouse gas emissions, from all of which their ecological footprints can be calculated (Table 2). We find that the mixing strategy occupies the largest land area, since the A/A/O process embedded therein needs large tanks (anaerobic and anoxic tanks) to effect biological nutrient removal. The ANS-separation and ANS-AHP-separation strategies recover most of the nutrients at their sources, so that very little land must be

consumed in any “downstream” processes of wastewater treatment. The disturbed land area is estimated using a ratio determined from the research of Lenzen *et al.* (2003), such that rankings on that account mirror those of the consumed land areas. Greenhouse gas emissions are estimated on the basis of three components: (i) CO₂ emission in wastewater collection and treatment processes; (ii) CO₂ emission in producing the energy consumed in these collection and treatment processes; (iii) CO₂ emission in producing the chemicals likewise consumed. The results show that the ANS-separation strategy has the lowest emission, due to its lowest energy consumption. The ANS-AHP-separation strategy has the largest emission, as a result of high energy consumption in the unit processes of Ultra-filtration (UF) and Reverse Osmosis (RO) (see Fig. 3 relative to Fig. 1 and Fig. 2). From these three factors – area of consumed land, disturbed land and greenhouse gas emission – the EF is estimated according to the method of Lenzen *et al.* (2003) (Table 2), giving thus the following ranking: ANS-AHP-separation (lowest EF); ANS-separation; mixing (highest EF). This is as expected, since mixing all wastewater streams (current practice) must use large treatment tanks to remove nutrients at low concentrations.

3.2 Metabolism

Simply put, we treat the metabolism of the city for the moment as being merely a matter of its material inputs and outputs. Comparing Figs. 4, 5, and 6, the mixing strategy has the highest levels of pollutants in its effluent and recovers no resources, whereas both the other strategies can recover nutrients from the wastewater. The ANS-AHP-separation strategy can recover more of the nutrients, along with some energy. However, the advantages of the ANS-separation and ANS-AHP-separation are not confined to recovery of nutrients and energy alone, for they have greater potentials to “close” the related global material cycles. Under current practice, i.e., our mixing strategy, we spend much effort and cost in fixing nitrogen from the atmosphere to produce fertilizer (upstream of the city, as it were), only then downstream in a conventional WWTP to expend further energy and cost to “shunt” nitrogen back into the atmosphere (instead of into the receiving water body) through nitrification-denitrification. This does not seem a sympathetic way of organizing the metabolism of the city and its compensatory wastewater infrastructure (Beck and Jiang, 2006). If we were to adopt a strategy of source-separation instead, the nutrients could be recovered at source and re-utilized rather more directly in agriculture, without having to be diluted with water and transported to the WWTP. Thus, the effort and cost spent on the fixation of nitrogen from air, and removing nitrogen through nitrification-denitrification, can be saved. As for phosphorus, its recovery is even more important, given its limited mineral reserves.

3.3 Pulse

Before the city exists, the aquatic environment is subject to certain “natural” regimes of hydrological, nutrient, and sediment perturbations and fluctuations. In the post-city condition that environment will be subjected to significantly altered such regimes – ones arguably with a higher proportion of faster disturbances, with strong weekly, daily, if not hourly periodic components (Beck, 2005; Beck and Jiang, 2006). As yet we are not in a position to gauge computationally the behavior of our three strategies according to this criterion of the frequency spectrum of environmental perturbations (although there are simple statistical procedures that will enable this). Instead, we shall investigate merely the temporal variability of in-stream water quality (at the point where the effluent from the city’s WWTP enters the river). We assume a background in-stream total suspended solids (TSS) concentration of 5 mg/l and a ratio of stream discharge to effluent discharge of 10. To make a start on capturing some of the spectrum of temporal variations in wastewater infrastructure behavior, we simulate the TSS responses in the river under three situations: (i) dry weather; (ii) wet weather; (iii) operational deterioration of sludge settleability (and, therefore, separation) in the WWTP. Assuming that a low average value of TSS in the river, with little temporal variation about this mean, is a positive (as opposed to negative) feature of behavior, the results of Figs. 7, 8, and 9 suggest that the ANS-AHP-separation has significant advantages over the other two alternatives. These latter both give rise to higher amplitude diurnal variations about the

longer-term trend, which amplitude is greater under the scenario of degraded sludge settleability (Fig. 9). They also give rise to much higher amplitude fluctuations as a function of the wet weather (Fig. 8), for which the speed (frequency) of variability can be described as lying somewhere between the diurnal and “longer-term trend” fluctuations. Such “sensitivity”, or vulnerability, in the mixing and ANS-separation strategies derives from the sensitivity of solids separation during clarification to hydraulic perturbations. That the effluent quality from the ANS-separation strategy is slightly better than that from the mixing (A/A/O) strategy, is a function of the slightly lower influent (hydraulic) flow of the ANS-separation strategy (because of the “removal” of ANS at source). Apparent marginal improvement in stream water quality – gauged according merely to TSS, *with* the ANS-AHP-separation strategy and city in place, as opposed to the pre-city reference condition of 5 mg/l (Figs. 7-9) – arises from the fact that the WWTP effluent is approaching zero in its TSS content, given the UF unit treatment process (Fig. 3). For constituents other than TSS, however, such as, for example, P and N, it *might* be that occasional (higher-concentration) pulses of these should be deliberately discharged to the river in order to mimic the kind of pre-city regimes of nutrient variations passing through the river system. Certainly, having access to the separated and recovered fertilizer production stream would facilitate realizing such actions in practice. This might at first sight appear as wanton, deliberate pollution of the river from time to time. Yet, in principle, it might better be seen as a deliberate action – by the city authorities – to reconstruct those regimes of nutrient perturbations that would have given rise to the “pristine” ecological status of the river, as it might have evolved over the decades, centuries, and millennia prior to urbanization of the watershed. And that could constitute, in effect, the city acting as a deliberate force for good in the environment of its surrounding watershed.

4. CONCLUSIONS

Three indicators, the ecological footprint, metabolism, and pulse of the city (and its compensatory wastewater infrastructure), have been employed to evaluate three strategies of wastewater infrastructure, using a simulation study. Given the particular interpretations placed on the results deriving from preliminary computational *approximations* of the more complete conceptual reasoning underpinning the second and third of these criteria, it is found that the ANS-AHP-separation strategy has the lowest EF, highest recovery of nutrients and energy, and most beneficial manipulation of the perturbation regimes of the city’s aquatic environment.

This, of course, is but a preliminary indication of the kinds of studies we plan to undertake of how to achieve less unsustainability in urban water management (Beck, 2005; Beck and Jiang, 2006). We have said nothing on matters of social legitimacy surrounding our candidate alternatives; there has been very little discussion of urban drainage; instead we have focused on nutrients and other materials in the fluxes circulating through the city and the biological residuals of its metabolism. Nevertheless, we believe such studies do indeed have promise in respect of answering, in the affirmative, our opening question – of whether cities can be made forces for good in the environment. Comparative assessments on this same quantitative basis of strategically different alternatives, such as a de-centralized as opposed to centralized wastewater infrastructure, the role of source separation therein, and paths of transition from current arrangements to these longer-term future alternatives, can be expected to be of considerable interest.

Table 1 The characteristics of influent

Strategy	Wastewater	Flow m ³ /d	COD mg/l	NH ₄ -N mg/l	TP mg/l	TSS mg/l
A/A/O	Mixed	19,600	321	29.25	5.36	199
ANS- separation	Grey + black	17,800	317	7.87	2.79	223
	Yellow	200	3,816	2,336	300	14
ANS-AHP- separation	Grey	12,800	163	4.41	2.19	93.6
	Yellow + black	240	17,667	2,250	334	11,667

Table 2 Ecological footprint of the three strategies

Strategies	Consumed land (ha)	Disturbed land (ha)	Greenhouse gas emission (kt)	Ecological Footprint (gha)
A/A/O	22.36	1573	4.76	1921
ANS-separation	15.16	1067	4.71	1405
ANS-AHP-separation	10.22	719	7.06	1213

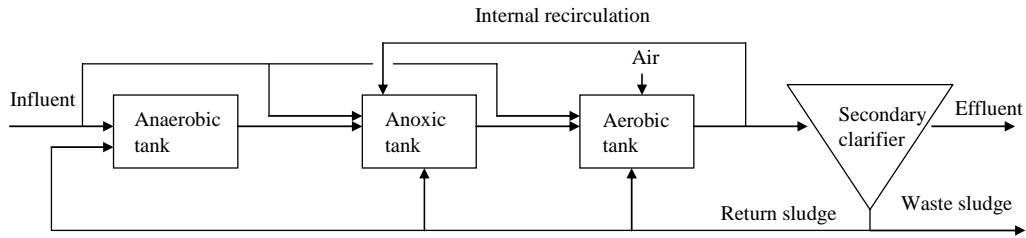


Fig. 1 Flowchart of A/A/O process (mixing strategy)

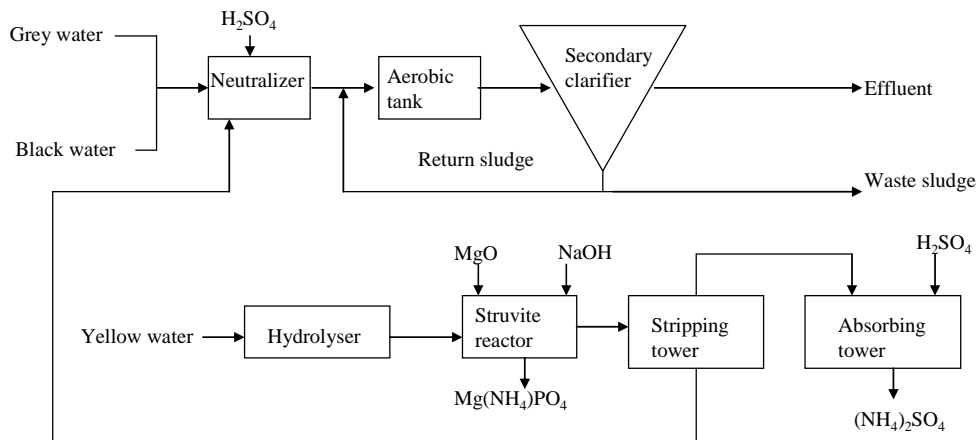


Fig. 2 Flow chart of ANS-separation strategy

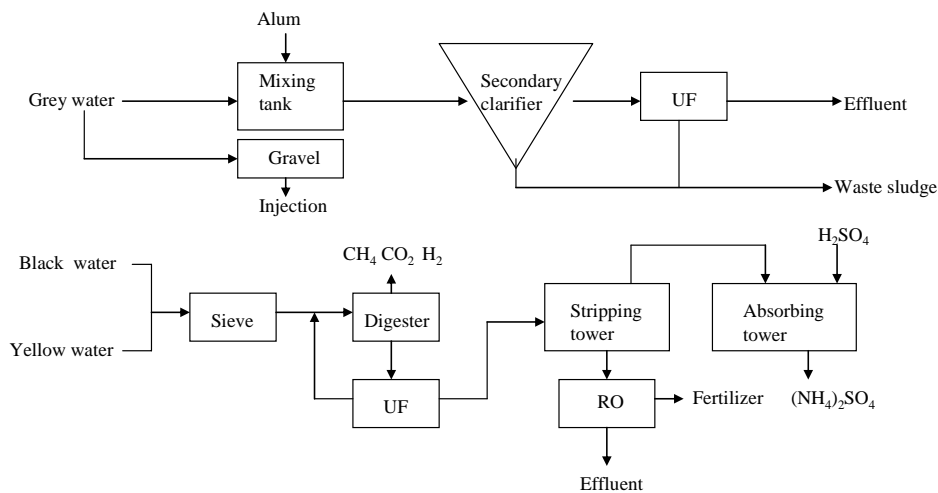


Fig. 3 Flow chart of ANS-AHP-separation strategy

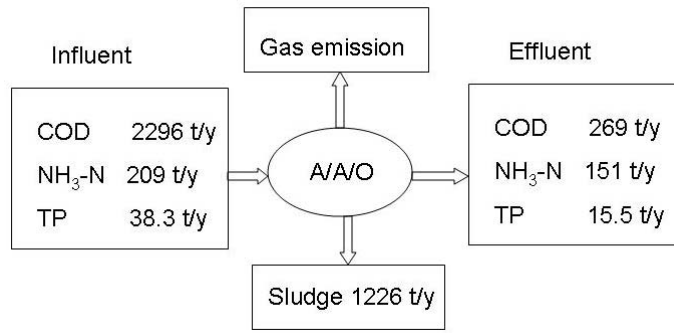


Fig. 4 The metabolism of city infrastructure with the mixing strategy

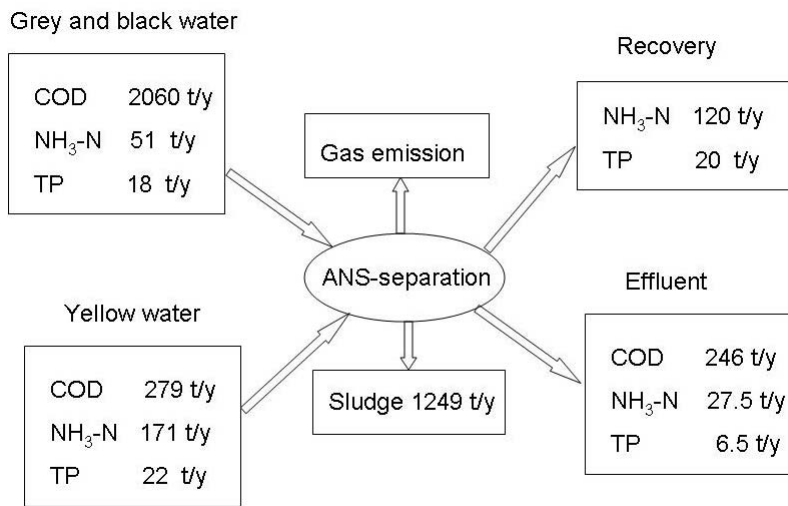


Fig. 5 The metabolism of city infrastructure with ANS-separation strategy

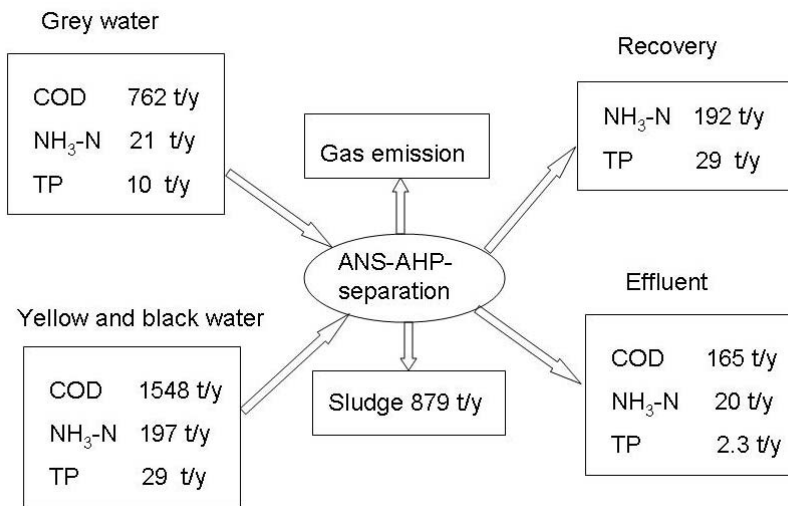


Fig. 6 The metabolism of city infrastructure with ANS-AHP-separation strategy

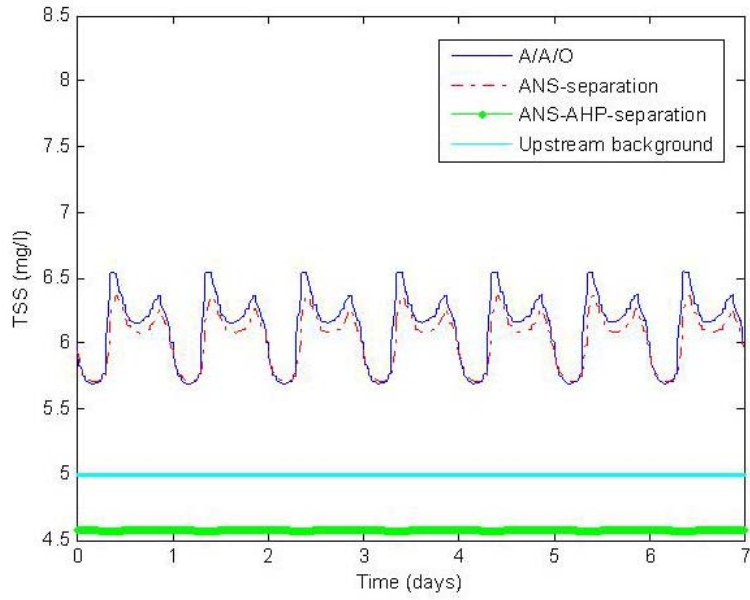


Fig. 7 The TSS concentration in river under dry weather

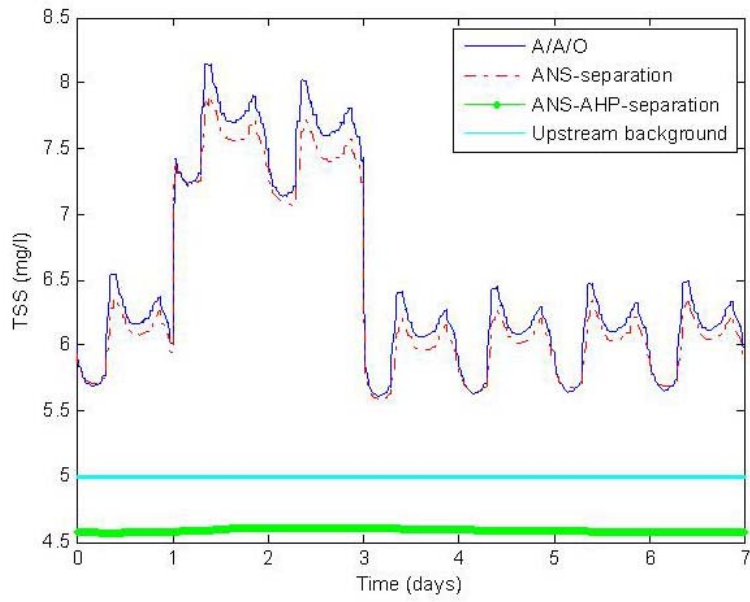


Fig. 8 The TSS concentration in river under wet weather

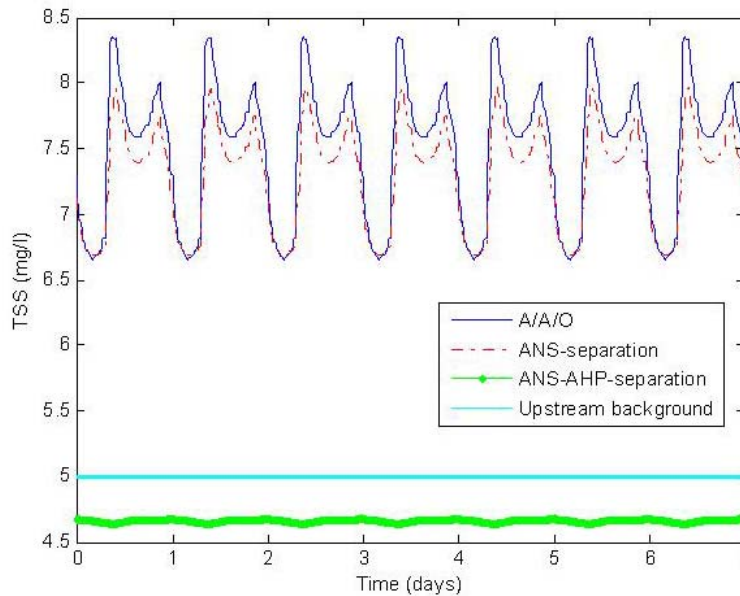


Fig. 9 The TSS concentration in river when sludge settling deteriorates

REFERENCES

- Beck, M.B. (2005). Vulnerability of Water Quality in Intensively Developing Urban Watersheds. *Environmental Modelling & Software*, **20**(4): 381-400.
- Beck, M.B. and Chen, J. (1999). Perfect fertilizer from urban wastewater infrastructures.
- Beck, M.B. and Jiang, F. (2006). 'Factor 10' engineering for sustainable cities – water. IABSE Henderson Colloquium, Cambridge, July 10 – 12, 2006.
- Fittschen, I. and Niemczynowicz (1997). Experiences with dry sanitation and greywater treatment in ecovillage Toarp, Sweden. *Wat. Sci. Tech.* **35**(9): 161-170.
- Henze, M., Gujer, W., Mino, T., Wentzel, M.C., Marais, G.v.R. and Loosdrecht M.C. M. V. (1999). Activated sludge model No.2d, ASM2d. *Wat. Sci. Tech.* **39**(1): 165-182.
- Herrmann and Klaus (1997). Fluxes of nutrients in urban drainage systems: assessment of sources, pathways and treatment techniques. *Wat. Sci. Tech.* **36**(8-9): 167-172.
- Larsen, T.A. and Gujer, W (1996). Separate management of anthropogenic nutrient solutions. *Wat. Sci. Tech.* **34**(3~4): 87-94.
- Lenzen, M., Lundie, S., Bransgrove, G., Charet, L. and Sack, F. (2003). Assessing the ecological footprint of a large metropolitan water supplier: lessons for water management and planning towards sustainability. *Journal of Environmental Planning and Management*, **46**(1): 113-141.
- Lienert, J. and Larsen (2004). Making the first step towards a more sustainable urban water management urban water management system – with the NoMix toilet. Technical Report.
- Otterpohl, R., Albold, A. and Oldenburg (1999). Source control in urban sanitation and waste management: ten systems with reuse of resources. *Wat. Sci. Tech.* **39**(5): 153-160.
- Otterpohl, R., Braun, U. and M. Oldenburg (2003). Innovative technologies for decentralized water, wastewater and biowaste management in urban and peri-burban areas. *Wat. Sci. Tech.* **48**(11-12): 23-32.
- WWF Europe Policy Office (2006). Europe 2005 the Ecological Footprint. <http://www.ewire.com/display.cfm/Wire-ID/2649>