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Incremental Infrastructure Transitions Towards Cities As Forces For Good In The Environment

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Abstract— **As source-separation has been proposed as a sustainable alternative to the current wastewater treatment strategy, the improvement in sustainability associated with such transition needs to be evaluated. However, given the difficulties and uncertainty in both technological and social aspects, such transition will most probably be happening gradually, step by step. Here with a computational case study based on the city of Atlanta within the Upper Chattahoochee watershed in the south-eastern United States, we simulated three steps of transition, i.e. 50%, 70%, and 100% ANS-separation (Anthropogenic Nutrient Solution) is reached. The economic sustainability of these transition strategies was evaluated with total annual economic cost (TAEC), and the environmental sustainability was evaluated with three indicators, i.e. ecological footprints (EF), flux of materials passing through the city in its context of global material cycles, and pulse rate in terms of the spectrum of disturbance frequency to which the city is subject. The simulation results showed that compared with the current strategy, the ANS-separation has significantly lower TAEC, lower EF, lower pollutant discharge, higher recovery of nutrient and energy, and more beneficial manipulation of perturbation regimes of the city's environment. These advantages increase with the rate of ANS-separation.**

Keywords—**ANS-separation, Total annual economic cost, Ecological footprint, metabolism, pulse rate, sustainable city**

I. INTRODUCTION

Although the current sewage system can dispose of wastewater with acceptable environmental impacts, the treatment of wastewater always lagged behind environmental problems such as eutrophication [1]. The current strategy mixes all streams of wastewater together, transport and treat them in the central wastewater treatment plant (WWTP). By analyzing the individual sources of municipal wastewater, it has been found that human excrement contains about 90% of the nitrogen, phosphorus, and potassium in household wastewater [2] but occupies less than 2% volume of wastewater [3]. The mixing of all streams of wastewater actually dilutes the human excrement with other wastewater. Consequently, when storm comes, combined sewage overflows (CSO) often lead to the pollution of receiving water. Furthermore, we have to spend high cost to remove the nutrients in the "diluted" wastewater in WWTP. For example, we need nitrification-denitrification to convert ammonia-nitrogen to nitrogen gas, and biological process (anerobic-anoxic-oxic or A/A/O process) or chemical process (addition of aluminum, iron, or calcium) to deposit phosphorus to sludge, and treat the sludge with incineration and/or landfill. On the other hand, we need to spend high cost to fix nitrogen from air to produce nitrogen fertilizer, and extract phosphorus from ore to produce phosphorus fertilizer for agriculture. Then, the nitrogen and phosphorus will enter wastewater through various pathways, and the mixing-dilution-discharge process will repeat. Obviously, the current strategy is neither efficient nor sustainable, and should be replaced by some more efficient, more reliable, and more sustainable strategies.

One of the possible solutions is the source-separation strategy that separates the yellow water and/or black water from gray water (other household water). The yellow water is also called "ANS (Anthropogenic Nutrient Solution) [4]. Though its volume occupies only 0.5% of the total wastewater, it has about 80% of the nitrogen and 50% of phosphorus in purely domestic wastewater [5]. If yellow water can be separated from other wastewater, we can greatly reduce the nutrient load in WWTP, and more importantly, close the nutrient cycle by returning the nutrients in the wastewater to agriculture. We have explored this ANS-separation strategy as one of our end-points [6] [7]. In the present research, we will explore some intermediate strategies between the current mixing strategy and the end-point ANS-separation strategy.

Although ANS-separation is superior to current strategy, it is not the only solution, and other choices are also possible. One alternative is the peak shaving strategy, which collects and stores 2 to 3 days' yellow water and deliver it via the existing sewer line using timers that release the stored urine at appropriate intervals to level out the delivery rate [8]. By this strategy, we can operate the WWTP more smoothly and efficiently. Another option is the more efficient water and sewage system proposed by Anderson [9]. For this system, residential water can be reused for garden watering and toilet flushing. Rainwater can be utilized for hot water service, bathroom and laundry use. Besides, dry sanitation is also

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proposed that uses no water or minor amount of water [2] [10], which made the central WWTP unnecessary.

Though there is a consensus that the current mixing strategy should be replaced by some innovative strategy, such a transition is by no means an easy task. For example, the implementation of source-separation strategy involves many stakeholders, therefore has not only technical but also social implications [11]. In each house, the current toilet needs to be replaced by NoMix toilet [4] that can separate yellow water and store it in a tank near the house. This transition will need both spending of additional cost and the change of people's habits of behavior (men need to sit when urinating) [12]. For the sanitary industry, the market needs to be sufficiently large to make commercial production worthwhile. For WWTP, it is necessary to modify the current facilities and operation to treat the wastewater with less nutrient, and recover most of nutrient in yellow water as fertilizer. Additionally, farmers concern about the price, odor, and hazard content of urine-based fertilizers [5]. Thus, it is unlikely to be cost-effective to replace all existing toilets at one time, and various transition scenarios are possible [8]. It is important to create scientific visualization of these scenarios, and make it easily reachable and understandable by general public to achieve social legitimacy [13].

II. METHODOLOGY

This research explores how to implement the ANS-separation strategy in the sewage system in the North part of Metro Atlanta, which is located in the Upper Chattahoochee River Basin in north-central Georgia. The wastewater of Atlanta is treated in several WWTPs, among which the R.M.Clayton water reclamation center (Clayton WRC) is the largest one and treats most of the wastewater in the North part of Atlanta (above the interstate highway I-20, see Figure 1). Totally there are 4 combined sewage overflows (CSO) in this area, namely the Greenferry CSO, the North Avenue CSO, the Tanyard CSO, and the Clear Creek CSO. Currently, the storm water in Greenferry is separated from the sewage system, and a tunnel is constructed to store the overflow from other three CSOs. The stored overflow will be gradually released to a new treatment facility (near Clayton WRC) after each storm. For this research, we still include these CSOs in the system so we can analyze the impact of source-separation strategy on the whole sewage system before the measures of CSO separation and treatment are implemented.

In order to explore the whole water system in the North Atlanta, we simulated the sewage system, the WWTP, and the Upper Chattahoochee Watershed with different models.

First, we selected Storm Water Management Model (SWMM) [14] to simulate the sewage system in the North Atlanta. We simulated the runoff, infiltration, and wastewater from this area. The 2006 actual data were used to calibrate the model. Later the model was used to simulate the sewage generated in 1986, which was a typical dry year in Georgia.

Then, we used WEST® [15] to simulate the treatment process in the Clayton WRC. The current treatment includes the A/A/O and filtration process (See Figure 3). For the ANS-separation strategy, we consider 3 scenarios: 50%, 70%, and 100% yellow water is separated. When 50% or more yellow water is separated, the anaerobic and anoxic tanks (used in the A/A/O process) are no longer needed and the A/A/O process can be reduced to activated sludge (AS) process. Thus, totally we simulated 4 scenarios: (1) A/A/O process plus filtration (current process); (2) AS process plus filtration and 50% ANS-separation; (3) AS process plus filtration and 70%ANS-separation; (4) AS process plus filtration and 100%ANS-separation (Figure 4). The structure of the biochemical portion of the model is that of Activated Sludge Model (ASM) No.2d [16]. The behavior of the clarifier was simulated with the double-exponential settling functions in a 10-layer model [17]. For the method of the transport of the separated ANS, Larsen and Gujer [4] proposed the utilization of current sewage system. The separated ANS is stored in a storage tank of each house. At midnight, a signal is sent to all houses to open the valve in each house, and the separated ANS is transported to the central treatment facility simultaneously through the current sewage system. We did not adopt this idea because it is still highly speculative [8], and urine scaling may lead blockages [12]. Additionally, as most of the current sewage systems are leaking, the transport of the yellow water through such a system will most probably lead to the dilution of the yellow water and more serious leaking pollution. Instead, we adopted the tanker lorry transportation that was already implemented in practice [18] [19].

Last, simulation of watershed pollutant behavior is achieved through BASINS-HSPF (Hydrologic Simulation Program – FORTRAN) [20] and the Sediment – Transport – Associated Nutrient Dynamics (STAND) model [21]. The former was used to estimate pollutant loads from nonpoint sources, and the latter was used to simulate the receiving river quality resulting from the discharge from Clayton WRC and non-point sources. The STAND model was evaluated against several sets of field data for adjacent river systems [21], presently covers an 191 km stretch of the Chattahoochee from Buford Dam, the outlet from Lake Lanier, to Lake West Point, to the south of Atlanta (see Figure 2). The model is part of a study in developing schemes for point/nonpoint-source nutrient trading — under uncertainty — in that 4250 km^2 segment of the Upper Chattahoochee watershed [22], with a special focus on accommodating in a compatible manner high-frequency fluctuations in the behavior of both the point and nonpoint discharges to the river.

Additionally, we employed the FFT function of Matlab [23] to analyze the spectrum of the total phosphorus (TP) of the Chattahoochee River at the downstream of the Clayton WRC. FFT(X) is the discrete Fourier transform (DFT) of vector X. For length N input vector x, the DFT is a length N vector X, with elements

$$X(k) = \sum_{n=1}^{N} x(n)*\exp(-j*2*\pi*(k-1)*(n-1)/N), 1 \le k \le N.$$

For the economic analysis, we analyzed capital cost, operation and maintenance cost (O & M), and the total annual economic cost (TAEC). The method for the cost estimation can be found in our previous paper [24] [25].

III. RESULTS AND DISCUSSIONS

With respect to the sustainability of water resource management in urban areas, the water infrastructures play a central role because they not only provides essential services to enable economic and social development, but also strongly affects the way society handles water as one of the most precious and limited resources [26]. For the evaluation of such sustainability, many indicators are possible [27][29]. Apart from protecting the water resources, future developments must also consider all other resources, including capital, energy and nutrients [11]. For the assessment of the transition strategies, we evaluated the economic sustainability with their costs, and the environmental sustainability with three indicators: ecological footprint [28]; fluxes of materials passing through the city, i.e., a form of mass balance (not, as ideally conceived

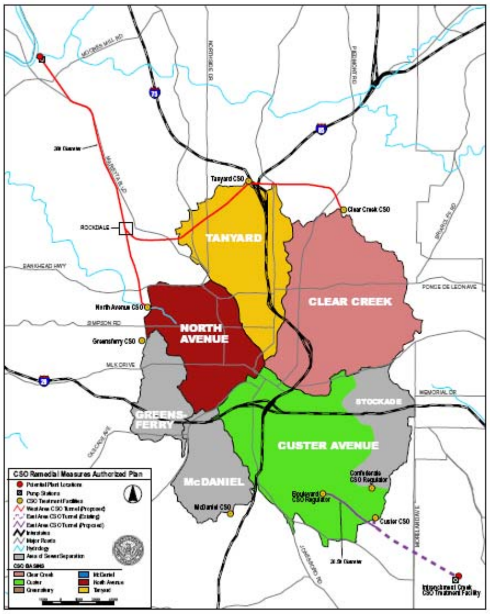

Figure 1. The CSO area in Atlanta area [37]

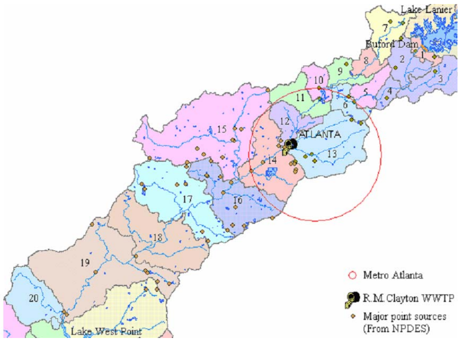

Figure 2. Metropolitan Atlanta and the Chattahoochee watershed in the south-eastern United Sates.

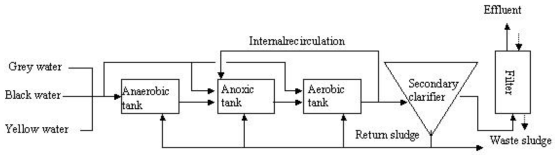

Figure 3. Flowchart of A/A/O and filtration process (current strategy)

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	242858	200	13.4	2.99	123
50%ANS_separation	Grey + black + 50%yellow	239043	196	8.86	2.60	121
	50%yellow	531	3816	2336	300	14
70%ANS_separation	Grey + black + 30%yellow	237449	195	6.99	2.49	120
	70%yellow	744	3816	2336	300	14
100%ANS_separation	Grey + black	234940	193	4.11	2.32	118
	100%yellow	1063	3816	2336	300	14

TABLE 2 COMPARISON OF ECONOMIC SUSTAINABILITY

Strategies	Capital cost (added) (million USD)	O & M cost (million USD/year)	TAEC (million USD/year)
A/A/O	0	7.83	9.95
50%ANS-separation	1.66	7.71	9.71
70%ANS-separation	1.71	7.61	9.61
100%ANS-separation	1.76	7.44	9.44

TABLE 3 ECOLOGICAL FOOTPRINT OF STRATEGIES

Strategies	Consumed land (ha)	Disturbed land (ha)	Greenhouse gas emission (kt)	Ecological Footprint (gha)
A/A/O	3.89	272.3	23.23	1867
50%ANS-separation	3.13	219.1	17.70	1435
70%ANS-separation	3.13	219.1	17.18	1399
100%ANS-separation	3.13	219.1	16.22	1333

of, in terms of these fluxes in the context of global material cycles) [29]; and pulse rate, approximated here by both conventional time-series plots and the spectrum of disturbance frequencies to which the city's environment is subject [30]. We acknowledge that we miss the social component of the triple bottom line accounting system (for sustainability), which may be investigated in our future research.

A. Economic Sustainability

Economic sustainability implies paying for itself, with costs not exceeding benefits. Theoretically it should include all resources (including environmental and social values), but in practice the analysis includes only financial costs and benefits [27]. Here we selected capital cost, O & M cost, and TAEC as the indicators of economic sustainability, which is summarized in Table 2. The capital cost refers to the cost needed to implement the ANS-separation strategies, which includes the cost of ANS transportation (by tanker lorry) and treatment (installment of facilities). The energy needed for transport of yellow water is derived from previous research [18]. We did not include the cost of NoMix toilet here because the current price (around 1000 USD) is not reasonable and may fall rapidly after mass production. From the results it is found that the construction cost increases with the rate of ANS-separation because the scale of ANS transport and treatment is enlarged. However, as the rate of ANS-separation increases, the energy consumption needed for nutrient removal will decrease, and the nutrient recovery will increase. Consequently, the O & M cost and the TAEC fall, which indicate that the ANS-separation strategy has economic advantage over the current strategy. These results are in agreement with the research conducted by Lundin *et al.* [18] and Dockhorn and Dichtl [19], who showed that the ANS-separation system combined with conventional treatment of black and gray water has economical advantage over the conventional (mixing) strategy.

B. Environmental Sustainability

The long-term viability of natural environment should be maintained to support development by supplying resources and taking up emissions. Environmental sustainability refers to the ability of the environment to sustain human ways of life [27]. There are many indicators available for the assessment of environmental sustainability. For this research, we select the ecological footprint, flux of materials passing through the city and pulse rate of city's aquatic environment.

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 [28]. For the 4 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 3). The results showed that the current strategy has the largest EF, since the A/A/O process has the highest energy consumption, and correspondingly has the most CO_2 emission. Besides, A/A/O also needs large tanks (anaerobic and anoxic tanks) to effect biological nutrient removal, and occupies most land. If 50% yellow water is separated from other wastewater, the A/A/O process can be reduced to AS process, because it no longer needs the big anaerobic tank and anoxic tank to help removing the nutrients. Therefore, the occupied land is greatly reduced. Similarly, the CO_2 emission falls because the energy consumption is reduced. If 70% and 100% yellow water is separated from other wastewater, the energy consumption and CO_2 emission will become further lower. However, because the facilities of AS process are not significantly modified, the occupied land remains unchanged.

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.* [28] (Table 3). It clearly shows that the EF is significantly reduced as more yellow water is separated from other wastewater. If 50% to 100% yellow water is separated, the EF can be reduced by 23% to 28%, which is a significant improvement of sustainability. It is also noted that the decrease of green house gas emission makes more contribution to the decrease of EF than the decrease of consumed and disturbed land, which implies that the benefit of ANS-separation is much more than elimination of some tanks.

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 Figures 5, 6, 7 and 8, the current strategy has the highest levels of pollutants in its effluent and recovers no resources. As more and more yellow water is separated from other wastewater, less pollutant will be discharged with the effluent, which is beneficial to the receiving water. Wastewater handling in WWTP will become simpler and cheaper because nutrient elimination is rendered unnecessary, and part of the nutrients can be recovered as fertilizer for agriculture, and part of water (used in toilet) can be saved [12]. It is worthy to be noted that the advantages of the ANS-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 (A/A/O process), 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 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 of organizing the metabolism of the city and its compensatory wastewater infrastructure [32]. 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 efforts 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, because the remaining mineral sources of phosphorus have a high heavy-metal content [12], and they will be exhausted within approximately 124 years at the current extraction rate [33]. Additionally, ANS-separation represents an excellent way of improving the quality of reused water and increases the flexibility of wastewater treatment as the micropollutants in urine can be removed without being mixed with other wastewater [5].

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 [30] [32].

Figure 9 shows the time-series of TP for 1986 in the Chattahoochee River immediately downstream of the discharge from Clayton WRC. Results refers to a sampling interval of 0.02 days and illustrate how the presently "disturbed" condition of the river, where the treatment plant is operating according to the current strategy, can be successively restored through the installation of the ANS-separation strategies. The daily and weekly oscillations in the time series are a function of the variations in the point discharge from the Clayton WRC and the upstream boundary conditions, which are dominated by the manipulation of the releases from Lake Lanier at Buford Dam for the purposes of hydro-electric power generation.

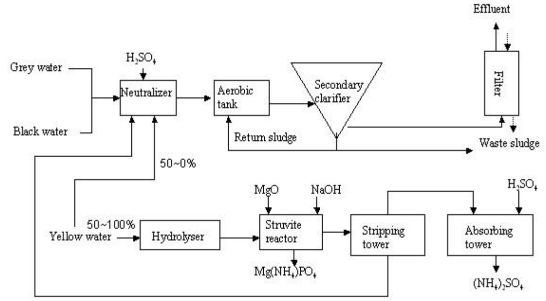

Figure 4. Flowchart of AS and filtration process plus 50~100% ANS-separation

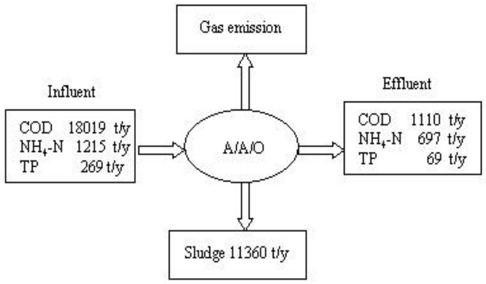

Figure 5. The metabolism of city infrastructure with the current strategy

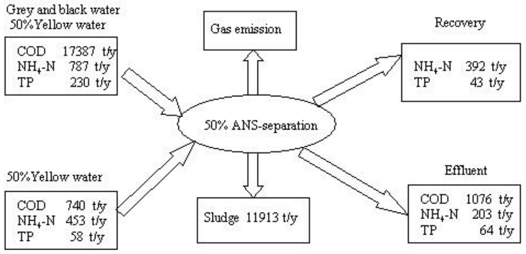

Figure 6. The metabolism of city infrastructure with 50% ANS-separation

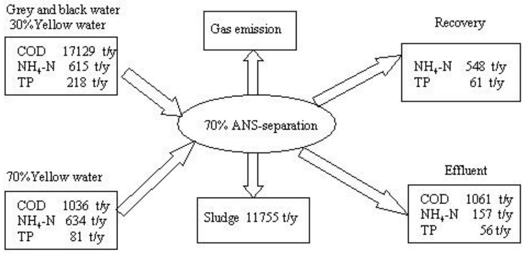

Figure 7. The metabolism of city infrastructure with 70% ANS-separation

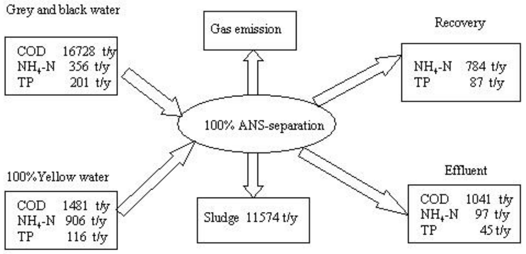

Figure 8. The metabolism of city infrastructure with 100% ANS-separation

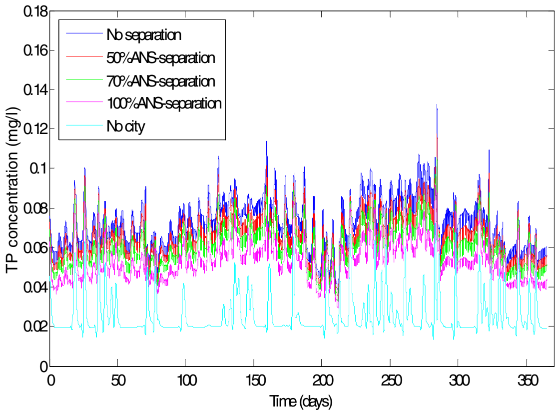

Figure 9. Simulated variations in total-P concentration for 1986 in the Chattahoochee River immediately downstream of the discharge from the R M Clayton facility under a variety of conditions

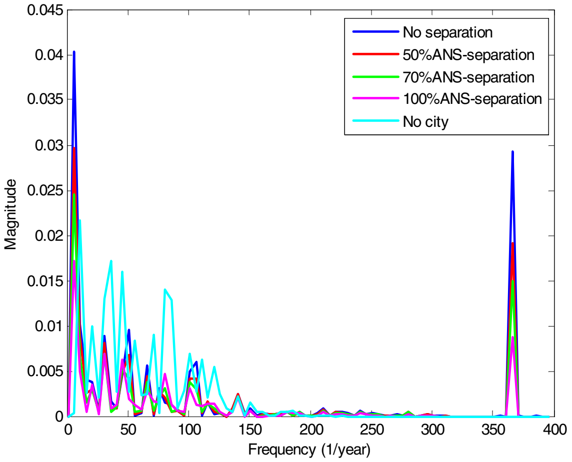

Figure 10. Frequency spectra for simulated time-series of Figure 9 for variations in total-P concentration for 1986 in the Chattahoochee River immediately downstream of the discharge from the R M Clayton facility, under a variety of conditions

Figure 10 shows the spectral transformation of the four time-series of Figure 9, i.e. the synoptic representations of the pulse of the city-watershed system. It is abundantly clear that the presence of the city transfers some of the magnitude in the signal of the "undisturbed" watershed from the lower frequency components (left) to the high–frequency components (right), especially at the diurnal frequency. It is also noted that with higher rate of ANS-separation, the magnitude of the high-frequency components becomes lower. However, even if 100%ANS-separation is reached, the magnitude of the high-frequency component is still higher than that of "No city" situation, which results from the fact that only about 50% phosphorus is associated with yellow water [5].

IV. CONCLUSIONS

Both economic and environmental sustainability indicators have been employed to evaluate three incremental transitions from current strategy to future source-separation of wastewater infrastructure, using a simulation study. From our simulation results, it is found that the ANS-separation strategy has advantage over the current strategy because of lower TAEC, lower EF, higher recovery of nutrients and energy, and beneficial manipulation of the perturbation regimes of the city's aquatic environment. From the perspective of sustainability, the ANS-separation is preferable to the current strategy, and the advantages increase with the rate of the ANS-separation.

This, of course, is only one step of the kinds of studies we plan to undertake of how to achieve less unsustainability in urban water management [30] [32]. For the implementation of the ANS-separation in Metro Atlanta, the ANS storage tank and the treatment facilities (including hydrolyzer, struvite reactor, and stripping and absorbing towers) need to be built at or near Clayton WRC. Many problems remain to be solved for such implementation. One of such problems is the transport of the separated ANS. Either installing new pipes or transporting by tanker lorry would be complex and costly undertaking [5]. Besides the three transition steps we simulated here, there are many ways to make and maintain the urban water infrastructure efficiently and sustainably [34] [35] [36]. These transition scenarios may also be subject to changes in the process of implementation. We also acknowledge that we have said nothing herein of judgments according to the social legitimacy of these strategies. Nevertheless, we believe such studies do indeed have promise in respect of answering our opening question – of how cities can be made forces for good in the environment step by step.

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