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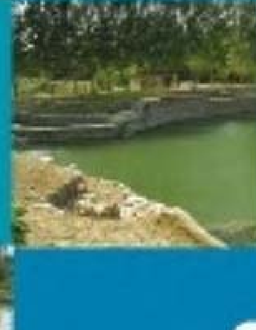

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Water Metabolism Concept and its Application in Designing Decentralized Urban Water Systems with Wastewater Recycling and Reuse

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Abstract In order to reconsider the configuration of an urban water system to meet the needs for sustainable water use and water environmental improvement in our water stringent world, the concept of water metabolism which stresses the harmony of the artificial water cycle with the natural hydrological cycle is discussed. By using the Second Law of Thermodynamics as a theoretical tool, the natural water cycle with minor human disturbance is considered to be a pseudo-reversible system with minimum entropy change from endogenous contribution. The minimization of entropy increase corresponds to the maximization of the metabolic capacity of a system. Two baselines can thus be proposed for the design of an urban water system: one is to decrease the entropy increase from human disturbance and another is to make the artificial or engineering part of the water system as close to the nature as possible. These principles are applied in two model cases of decentralized urban water systems that demonstrate a harmonic integration of water supply, sewerage, water reuse, and local water environment within one framework. Sound water environment is well sustained with minimized freshwater supply. The water metabolism concept and its application may direct a new paradigm for urban water system design towards the future.

Keywords Water metabolism, thermodynamics, urban area, decentralization, water reuse

INTRODUCTION

The total renewable water resource in the world amounts to about 55000 km^3 (World Resources Institute, 2005). Taking into account a total population of about 6.67 billion (World Resources Institute 2008), the per capita water resource can be calculated as more than 8200 m^3/person. However, due to uneven distribution of both the water resource and population, in different area of the world the availability of water resource differs from each other. The per capita water resource can be as high as 45000 m^3/person or more in South America and Oceania, while it can be as low as about 1400 m^3/person in the Middle East and North Africa (World Resources Institute, 2005). The distribution of water

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resource is also uneven within one area or one country. For example, in China the average per capita water resource based on the 2008 data (Ministry of Water Resources, 2010a; National Bureau of Statistics of China, 2009) is 2066 m^3/person, while of the 10 major river basins those in the northern China such as the Liaohe River, Yellow River, Huaihe River, and Haihe River, the per capita water resources are only 711 m^3/person, 510 m^3/person, 443 m^3/person, and 164 m^3/person, respectively. Due to low availability of water resources, over withdrawal of surface water or groundwater is commonly practiced in these basins. The direct result of over withdrawal is the decrease of water flow in the river channel and/or the decline of groundwater table. This results in deteriorated water quality because of insufficient water quantity for diluting pollutants.

In China surface water quality has been categorized into five classes according to its suitability for drinking water supply (Class I to Class III), industrial water use (Class IV), and agricultural water use (Class V). By a calculation using the national river water quality monitoring data of 2008 for all the major river basins (Ministry of Water Resources 2010b), Figure 1 can be obtained to show the relationship between the river water quality and per capita water resource. There is an apparent tendency that the % of polluted water (water quality worse than Class V) decreases with the increase of per capita water resource, indicating that water pollution often occurs simultaneously with water shortage.

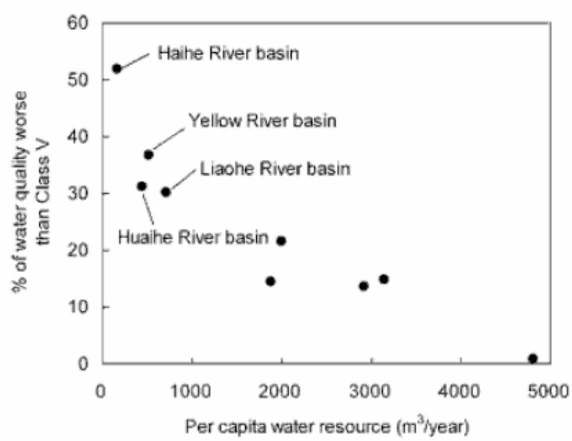

Figure 1 Relation between per capita water resource and % of water quality worse than Class V in major river basins in China (calculated according to 2008 surface water quality monitoring data)

In China there are more than 400 cities, most in the northern region, suffering from both water shortage and serious water pollution (Wang and Jin, 2006).

Although various actions have been taken recently such as development of new water resources, long distance water transfer and so on, it is widely recognized that in most cases water reuse is the most feasible option for mitigating urban water shortage.

When treated wastewater becomes part of the usable water resource in an urban area, how to design the urban water system may become a newly encountered problem because the traditional philosophy of system design for urban water supply is no longer completely apt to the current circumstance. Firstly, as water supply will be through at least two qualitatively different sources, i.e. freshwater and reclaimed water, the water demand has to be accounted both quantitatively and qualitatively. Secondly, as water shortage often occurs simultaneously with water pollution, restoration of a sound water environment should be one of the main objectives of water reuse. Thirdly, sustainable utilization of water resources should be the sole principle of urban water system design.

A detailed discussion on the above mentioned issues may need the development of an innovative philosophy by looking at the natural behaviour of water in the world. It thus becomes the topic of this chapter to introduce the concept of water metabolism into urban water system design. Examples of applying this concept to the design of decentralized urban water system with wastewater recycling and reuse are also presented.

CONCEPT OF WATER METABOLISM

Metabolism and Metabolic Capacity of Natural Waters

Let us consider what happens in the natural hydrologic cycle which is the cycling of water through the environment following a simple pattern. Moisture in the atmosphere condenses into droplets that fall to the Earth as rain or snow. Water, flowing over the Earth as surface water or through the soil as groundwater, returns to the oceans, where it evaporates back into the atmosphere to begin the cycle again. Such a water cycle is important for keeping a worldwide or regional circulation of water in various water bodies such as rivers, lakes, and groundwater aquifers. On the other hand, the water cycle is also a process of water purification that ensures the provision of fresh water resources in the cycle by a series of physical, chemical, and biological reactions. As a result, various water bodies can be kept "healthy" to perform their environmental functions well.

These processes in the hydrological cycle can be considered metaphorically as "metabolism" which, by definition, is the set of chemical reactions that occur in living organisms to maintain life (Smith and Morowitz, 2004). Such a metaphor was first used by Wolman (1965) in his famous paper "The metabolism of cities", and then by Tambo (2004) who proposed the "urban water district" as a water metabolic space within the hydrological cycle. We may thus give "water metabolism" a terminological definition as the set of natural purification reactions to maintain a water system in a living condition. The capability of a water system to perform natural purification may be called "metabolic capacity" which is its capacity of natural purification to maintain a healthy condition.

Human Disturbance on Natural Water Cycle

As human beings depend on natural water for sustaining life, the scale of human disturbance on the natural hydrological cycle became larger and larger with urban development. From ancient time people found traditional ways to take water from various water bodies for daily use and then discharge the used water which goes back to the water bodies through various routes. Because the scale of the traditional water use is very small, the disturbance on the natural water cycle is minor. However, in a modern city the human disturbance is no longer negligible and a large scale artificial water cycle is added to the natural water system (Figure 2). The pollutant loading from the artificial cycle to the natural cycle may be beyond the metabolic capacity for the water bodies to maintain "healthy". For these reasons, human beings have nothing to do but to take engineering means to "protect" or "cure" the natural water bodies, such as to practice water purification and wastewater treatment.

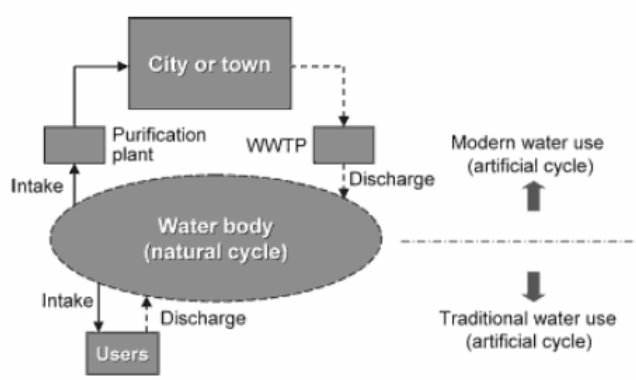

Figure 2 Artificial cycles added to the natural hydrological cycle (lower part: small artificial cycle by traditional water use; upper part: large artificial cycle by modern water use)

Concept of Water Metabolism Relating to Urban Water System Design

A thermodynamic consideration

The thermodynamic principles have been widely used for evaluating aquatic ecosystems (Ludovisi and Poletti, 2003; Aoki, 2006; Aoki, 2008), agro-ecosystems (Steinborn and Svirezhev, 2000), and water resources availability (Kawachi *et al.*, 2001; Maruyama *et al.*, 2005). In order to evaluate an urban water system in a similar way, we can consider the water system shown in Figure 2 to be principally an ecosystem. According to the Second Law of Thermodynamics, the entropy increase in the ecosystem can be written as

$$\Delta S = \oint_B \frac{\partial q}{T} \tag{2.1}$$

where ΔS is entropy increase, B is the system boundary, ∂q is any small change of energy or heat, and T is absolute temperature.

For an isolated system, it is considered to be reversible if

$$\Delta S = 0 \tag{2.2}$$

or it is considered to be irreversible if

$$\Delta S > 0 \tag{2.3}$$

However, since no ecosystem could ever exist as an isolated system, the second law of thermodynamics cannot be applied without adaptation. One prevailing method is to consider that the change in entropy for a non-isolated ecosystem is composed of two parts: an external contribution from outside as $\Delta_e S$ and an endogenous contribution due to the internal processes as $\Delta_i S$ (Ludovisi and Poletti, 2003).

From a worldwide viewpoint, all the natural processes in the hydrological cycle can be considered as internal processes that bring about endogenous contribution to changes in entropy, i.e. $\Delta_i S$ within the large natural aquatic ecosystem, while the external contribution of $\Delta_e S$ is considered to be from only human disturbances. Strictly speaking, any natural process can only progress in a direction which results in an entropy increase (Ludovisi and Poletti, 2003). However, it may be reasonable to assume that the natural hydrological cycle as discussed in 2.2.1 is a pseudo-reversible process by its nature of self maintenance of water and materials balance. Of course, such an assumption should be restricted to a comparatively short time span (e.g. the time scale of human life) but not a long time span (e.g. the time scale of natural evolution). In this way, we assume that the following condition almost holds for the natural hydrological system:

$$\Delta_i S \rightarrow 0 \tag{2.4}$$

We can thus bridge between the concepts of water metabolism and the thermodynamics a simple relationship as:

"Maximized metabolic capacity" = *"Minimized entropy increase"* (2.5)

Theoretical strategy of urban water system planning

An urban water system is closely related to the natural hydrological cycle (Figure 2). From what discussed above, there would be two baselines we have to follow in urban water planning. The first baseline is to decrease as far as possible $\Delta_e S$ which is the entropy change resulted from human disturbance on the natural hydrological cycle, and the second baseline is to make the artificial part of the urban water system as close to the natural part as possible so that the nature of $\Delta_e S$ can be modified in the way as we discussed for $\Delta_i S$. From the former, the envisaged strategy is to protect the natural watershed or water bodies such as lakes and streams and decrease human disturbance on them. This coincides with the principle of low impact development (LID) for local water system design (van Roon 2007) and for combined sewer overflows control (Montalto *et al.*, 2007). From the latter, the strategy is to learn more from the nature and try to build the artificial or engineering components of the urban water system in a natural manner.

Here we have to say that the conventional ways of urban water planning are often against the abovementioned principles. Under the human-centric consideration of supply of high quality drinking water, collection of sewage and storm water and advanced treatment of the collected water prior to discharge into natural water bodies to meet the needs of the public health, industrial growth and prosperity of the society (Wilderer, 2001), centralized water supply and sewerage networks become the central part of the urban water system almost in every city or metropolitan in the world. For water supply, "to meet the demand of water use" is the basic philosophy and the water supply network should cover every corner of the city to ensure water provision. For the sewerage work, "to collect and discharge the used water quickly and smoothly" is the basic philosophy and a sewerage network covering the whole water supplied area should also be provided in the city. In such an urban water system, water is in fact taking a journey through the artificial networks in a way as shown in Figure 3.

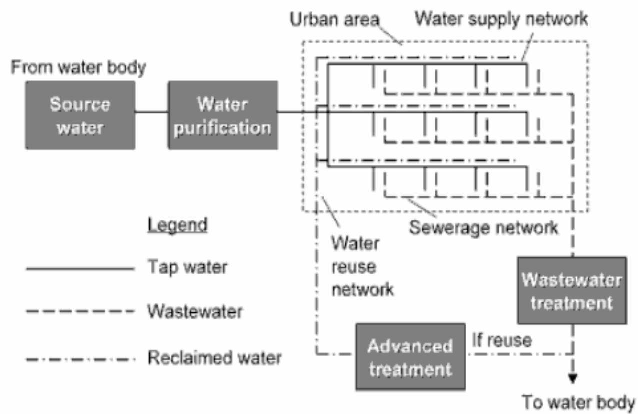

Figure 3 A conventional urban water system which composes of water supply network, sewerage network, and additional water reuse network as treated water reuse is practiced

As the source water is usually at a discrete location upstream of the city while the wastewater treatment plant is at another discrete location downstream of the city, long distance water and wastewater transfer pipelines have to be constructed for the water to take a long journey. When treated water reuse is to be practiced, a third network shown in Figure 3 will have to be constructed for bringing the reclaimed water back to the city area again for various purposes of reuse. The discrepancies between different parts of the artificial urban water system result in large amount of energy consumption which inevitably brings about additional increase of entropy as $\Delta_e S$. This is against the abovementioned first baseline. Another thing noticeable in Figure 3 is that such an artificial urban water system is related to the natural water only at the beginning and end points of the system, i.e. the source water which locates at upstream of the city and the water body which locates at downstream of the city to receive urban discharge. This is against the abovementioned second baseline.

Configuration of a Local Water System Under the Concept of Water Metabolism

Now we consider the configuration of an urban water system under the concept of water metabolism. Following the strategies discussed above, the basic policies for configuring such a system are (i) it should be a harmonic integration of the subsystems of water supply, sewerage, water reuse, and urban water environment; (ii) decentralization should be an important option for system selection; (iii) the system should be as close to the nature as possible; and (iv) the principle of ecological design should be applied.

A conceptual configuration of a local water system can then be proposed as shown in Figure 4. Comparing with a conventional urban water system, this system has the following features:

- It is an enclosed water system with minimized supply of fresh water and minimized discharge of wastes across its boundary.
- The primary objective of wastewater treatment is for water reuse. Therefore, as long as economically and technologically feasible, non-potable water use and environmental water use should be covered by reclaimed water.
- Where applicable, natural or artificial water bodies, such as lakes, ponds, streams, can be introduced into the system. They use the reclaimed water as source for water replenishment, and meanwhile play the functions of regulation basin and water quality polishing before being used for miscellaneous purposes.

Although at this stage there is yet a mathematic tool available for quantitative thermodynamic calculation of the system, it conceptually follows the two baselines we discussed, i.e. human disturbance on the nature being minimized, and the system itself being close to the nature.

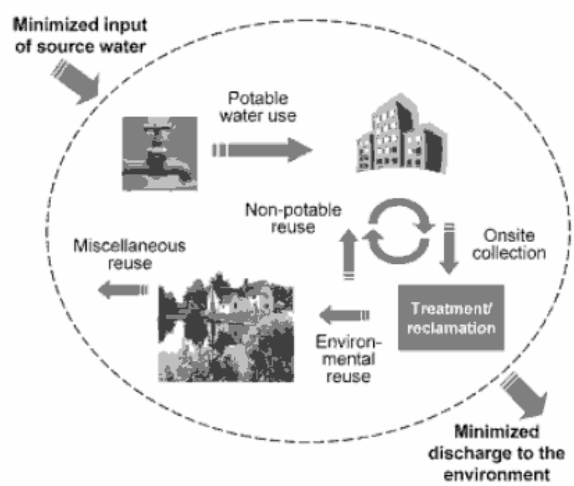

Figure 4 Conceptual configuration of a local water system under the concept of water metabolism

MODEL CASES FOR THE APPLICATION OF THE CONCEPT OF WATER METABOLISM

A Decentralized Water Environmental System with Grey Water Reuse

This model case is a decentralized water environmental system in a newly developed residential community in Xi'an, China. Environmental reuse of the treated grey water, including replenishment of an artificial pond and green belt gardening, is the main purpose. The total households in the project area are 400 and the total population is about 1600 people. The green belt covers 6400 m^2 and the artificial pond is with a water surface of 6500 m^2 and an average water depth of 0.5 m.

Figure 5 shows the system provided for the residential community. In the 6 residential buildings, dual pipe collection system is installed for separate collection of black water and grey water. The black water is treated by a septic tank system while the grey water is treated for local environmental reuse. The treated grey water is led to the artificial pond for water replenishment. The pond also performs the function of a regulation tank for other reuse purposes. In order to control the pond water quality, part of the stored water is circulated. The average retention time of the pond water is about 15 days.

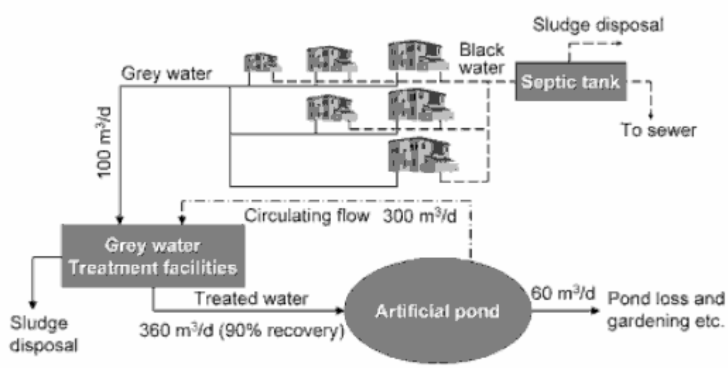

Figure 5 System composition of the decentralized water environmental system with grey water reuse

The grey water is treated by a process combining enhanced primary treatment with ozone enhanced flotation. The enhanced primary treatment is performed by a fluidised pellet bed bioreactor which is a specially designed wastewater treatment device for onsite wastewater treatment and can perform chemical coagulation, biological degradation, particle pelletization and separation in one unit (Wang *et al.*, 2007). The ozone enhanced flotation is performed by a dispersed-ozone flotation separator which is a compact device combining coagulation, ozonation and flotation in an integrated unit (Jin *et al.*, 2006). As for the circulated pond water, it only enters the ozone enhanced flotation unit for treatment.

Decentralized Water and Wastewater System Serving a College Campus

This model case is a project in a college located in the southeast suburban area of Xi'an, China. The campus is on top of a hill covering an area of about 87 hectares of which 45 hectares are green belts. About 30 thousands students are living in the campus. The college is away from the centralised urban water supply system and urban drainage system. Available water source is only several groundwater wells with a maximum water supply capacity of 3000 m^3/d.

Figure 6 shows the system composition of the decentralized water and wastewater system serving the college campus. As the fresh water source is unable to cover the total water demand for various uses, it is decided that the available groundwater should only be used for potable water consumption and all water for non-potable consumption should be covered by wastewater treatment and reclamation. In order to meet the high demand for toilet flushing (1200 m^3/d), lake replenishment (650 m^3/d), and gardening and road washing (1800 m^3/d) which much surpassed the reclaimable quantity based on the freshwater supply, several measures are taken in this system for increasing the recovery ratio of water reclamation, such as 100% recycling the toilet flushing water and partially escalated water use between lake replenishment and gardening. Another feature of this system is the practice of dual-quality reclaimed water supply to meet the requirement for different water uses, i.e. high quality for indoor toilet flushing and lake water replenishment, and normal quality for gardening and road washing. The water budget of the whole system is also shown in Figure 6. It shows that the total water consumption of more than 6000 m^3/d is well covered by the freshwater supply of merely 3000 m^3/d through this system.

Wastewater treatment and reclamation in this system is through two units. In the first unit with a treatment capacity of 1500 m^3/d, an anaerobic-anoxic-oxic (A2O) process is employed to produce the normal quality reclaimed water to meet the need for gardening and road washing, while in the second unit with a treatment capacity of 2000 m^3/d, a hybrid process of A2O combined with membrane bioreactor (MBR) is employed to produce the high quality reclaimed water to meet the need for toilet flushing and lake water replenishment.

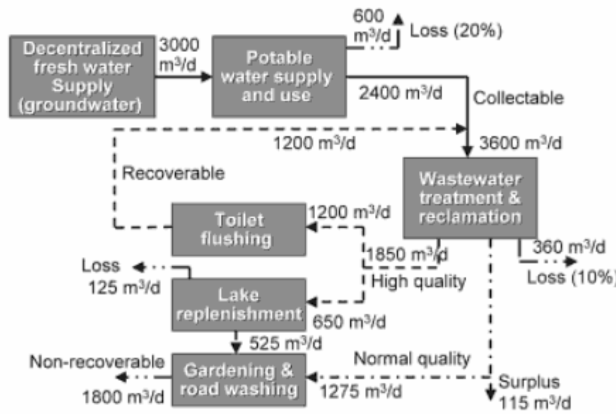

Figure 6 System composition of the decentralized water and wastewater system serving the college campus

CONCLUDING REMARKS

Water metabolism concept has been discussed in this paper. It stresses the harmony of the artificial water cycle with the natural hydrological cycle in the urban area. The Second Law of Thermodynamics can be used as a theoretical tool for analysing either a natural water system or an artificial water system. Under an assumption that the change in entropy for a water system is composed of an external contribution from outside and an endogenous contribution due to the internal processes, the natural water cycle with minor human disturbance can be taken as a pseudo-reversible system due to its nature of self maintenance of water and materials balance, which is a condition equivalent to $\Delta_i S \rightarrow 0$. It can be bridged between the water metabolism and thermodynamic concepts a relationship that minimization of entropy increase equals to the maximization of metabolic capacity. Two baselines thus have to be followed for the design of an urban water system: firstly to decrease the entropy increase from human disturbance and secondly to make the artificial part of the system as close to the nature as possible.

Harmonic integration of water supply, sewerage, water reuse, and urban water environment should be taken as the basic policy for urban water system design. These principles are applied in two model cases of decentralized urban water systems. The first case of grey water treatment and environmental reuse in the residential area is characterized by the application of treated grey water for replenishment of artificial pond and gardening in the residential area, and the maintenance of a sound local water environment. The second case of decentralized water and wastewater system serving a college campus is characterized by a harmonic integration of local water supply and water environmental system in which dual-quality water reclamation is practiced to meet the requirement for different reuse purposes. It is made possible to use the limited available freshwater resource to sustain the water demand of doubled scale. Zero discharge of wastewater is thus realized. The water metabolism concept and its application may direct a new paradigm for urban water system design in the future.

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