

# Water District on a Fractal River Basin (original)

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## ABSTRACT

The increasing population and trend of urbanization in the world have resulted in water shortage and deterioration of water environment. The current ways of implementing the modern water system will not be affordable due to the limitation of available water and energy sources and have to be ceased. Toward the post-modern era, various new strategies have to be formulated based on the concepts of water metabolism on a characteristic regional natural hydrological cycle. The river basins which are the most important source for water supply and drainage are of fractal natures and can be characterized as a nested structure of lentic and lotic waters as proposed by Nakamura. A full consideration of the relationship between human habitation and the fractal river basins will bring about a new philosophy of water system design. The future urban water and sewage systems can be designed on the concept of water districts proposed by Tambo which are independent water metabolic systems using clean water only for potable purposes and harvesting non-potable water from various local water resources such as rains and reclaimed used water in a city area. The used water in such systems is reclaimed and supplied for various non-potable uses via various supply measures. Environmental lakes are introduced into the systems as quality and quantity buffers as the key lentic part of the aquatic system. The impact of water use in one water district on the downstream basins can thus be minimized and integrated river basin management and resource conservation can be realized in both domestic and international river basins.

*Keywords:* Water district; water metabolism; river basin; fractal nature; lentic and lotic water, post-modern era.

## 1. INTRODUCTION

We are living on a unique planet in the universe which is named the *Earth* by our human beings. With its equator radius as about 6,300 km, the earth's surface area is as vast as about  $510 \times 10^6$  km<sup>2</sup>. However, its real land area takes only about 29.2% ( $149 \times 10^6$  km<sup>2</sup>), while 70.8% ( $361 \times 10^6$  km<sup>2</sup>) is covered by the ocean. For this reason, the earth can be called a 'water planet'. The total water volume on this water planet amounts to  $1.36 \times 10^9$  km<sup>3</sup> which, if completely available for various water uses, can be considered as an almost limitless resource comparing with the number of all living creatures who rely on water for their lives. Unfortunately, about 97.2% of this volume is seawater while the freshwater value takes only about 2.8%. Of the total freshwater volume (if taken as 100%), about 75% is kept in the glaciers, and most of the remainder is groundwater. The volume of water in rivers and that in lakes, which are real source waters for human utilization, are merely about 0.03% and 0.3%, respectively. The percent of the groundwater that is really available for withdrawal also takes very low value. In addition to this, the uneven distribution of water resource further affects its availability. We have to say that the water planet is unable to provide sufficient water everywhere for unlimited water uses.

The above simple calculation provides the basis for evaluating the carrying capacity of the

Earth from the viewpoint of water environment. To consider the carrying capacity of the Earth, we need to review how human population increased in the process of civilization and modernization. As shown in Figure 1 (Tambo, 2002), human population grew very slow until 1,800 AD. If we take 1800s as a turning point from the pre-modern era to the modern era, fast human population increase (a high  $dP/dt$  rate shown in Figure 1) is an important symbol of the modern era. As a result, world population reached about 6 billion around 2,000 AD which is more than 6 times of the pre-modern population. The world population further reached 7 billion in 2011 and is still increasing. From now till the world population reaches the peak of more than 11 billion, what will be our world like?

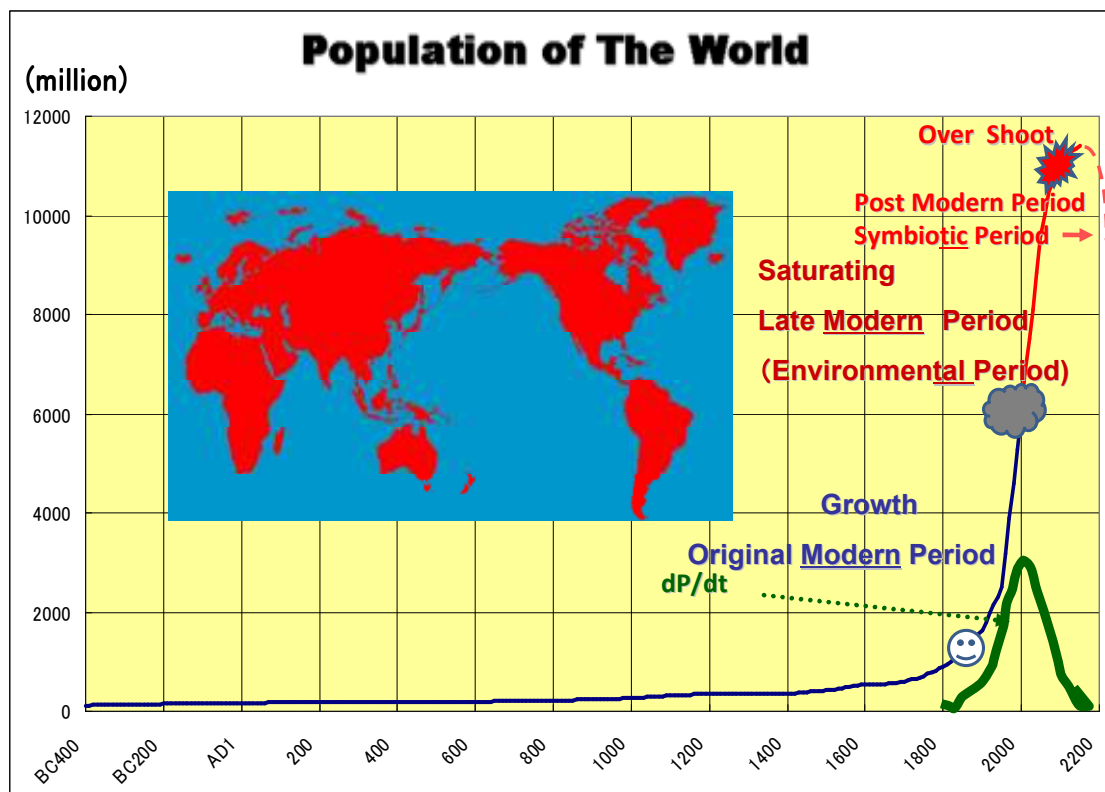


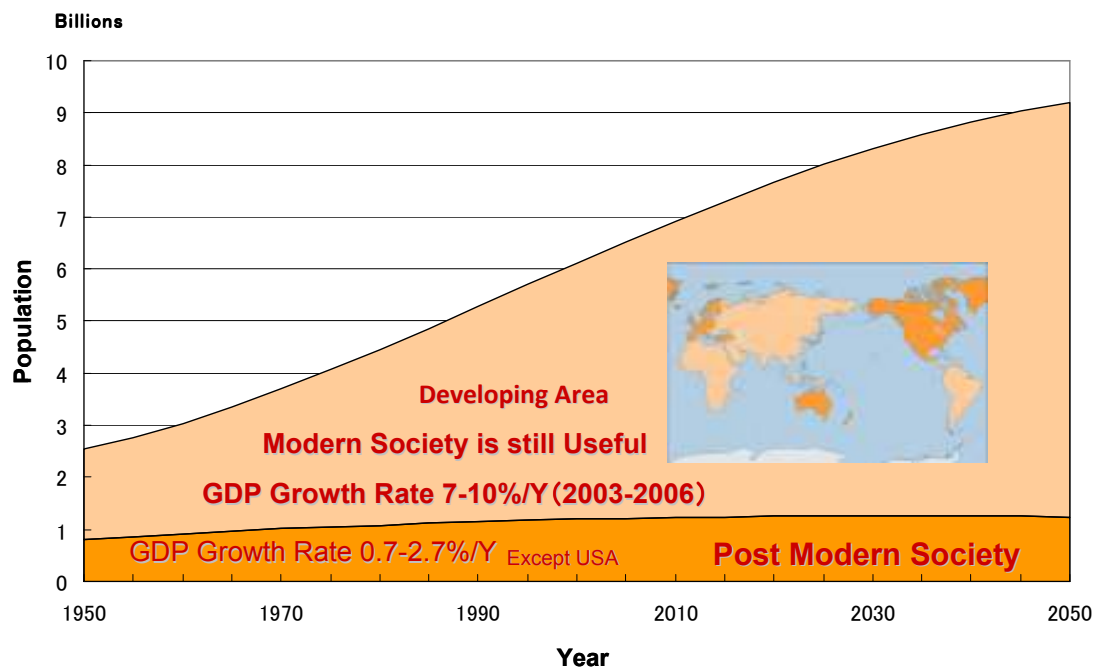
Figure 1 Population of the world

Historically, the Earth had been thought to be large enough for our human beings – no worry about water provision or water environmental problems, but the growth of the modern year in the past two centuries already made the Earth relatively smaller – water shortage, water pollution and water environmental problems shared by neighboring countries. Population growth and large scale urbanization are in any sense the major reasons for this, and globalization is going on not due to our human being's willing but the close linkage between nations under the limitation of available resources of which water is the most important one. People are confusing with the ways in which we are using water and other natural resources, wondering if the era of modern civilization should be ended, and thinking about a new model of social and economic development under the abovementioned constraints.

## 2. GLOBAL ISSUES

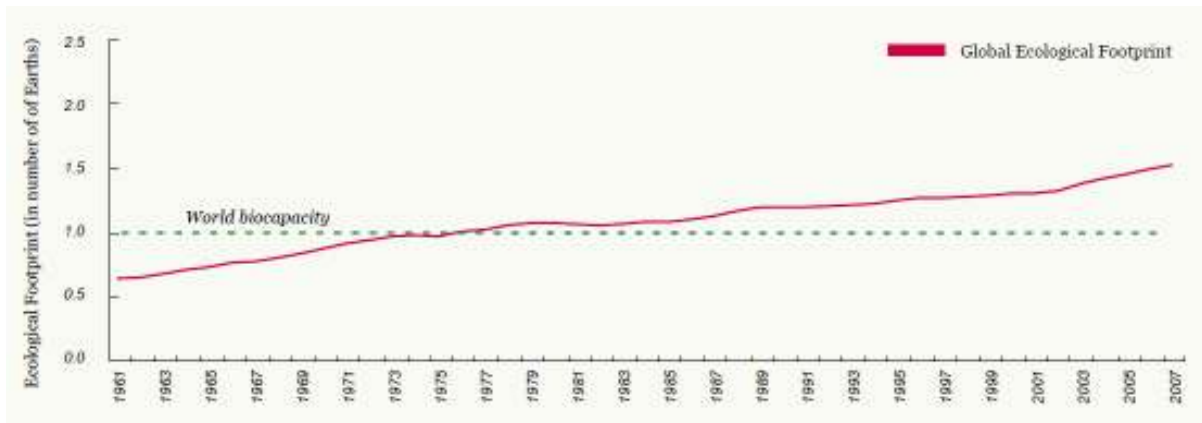
## 2.1 Two regions in the globalized world

Although we are living in a globalized world, different countries are in fact at different stages of development. Figure 2 (United Nations Secretariat, 2007) depicts the trend of population growth in the developing area (upper) and the developed area (lower). Of the developing nations, the BRICS (Brazil, Russia, India, China, and South Africa) represent the countries of the fastest economic growth, as high as 7-10% in annual GDP growth between 2003 and 2006. These developing countries are characterized by fast economic growth and still fast population increase, which was what experienced by the developed countries one century or several decades ago. To these countries the development mode of modern society may still be useful. Contrarily, the developed nations represented by the G7 (USA, Japan, Germany, France, UK, Canada, and Italy) are characterized by low economic growth (0.7-2.7% GDP growth rate) and low population increase, which is in a saturation state on modern civilization and can be considered stepping into the mode of post-modern society.



**Figure 2** Trend of population growth in different regions of the world

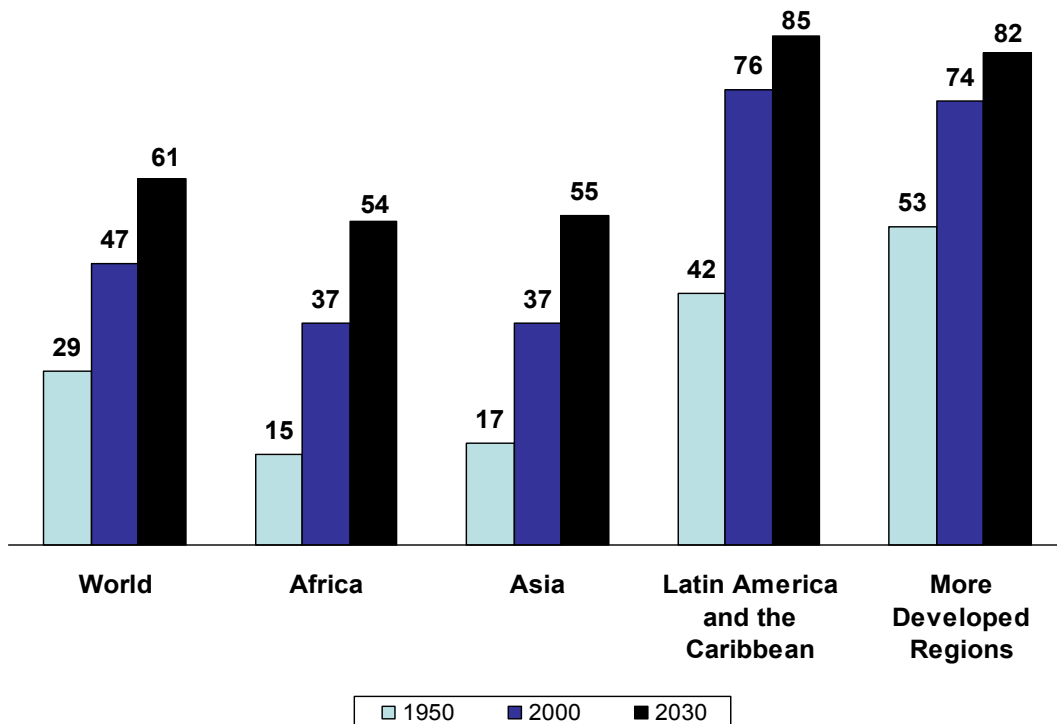
Taking Asia, the most populous continent in the world, as an example, the total population will continue to increase till a peak of about 9.1 billion around 2050. Such a continuous population increase plus the trend of fast urbanization as is happening in China and India inevitably has been bringing about an increase in the ecological footprint which measures whether a country, region or the world as a whole is living within its ecological means. As shown in Figure 3 (WWF, 2010), the global ecological footprint already surpassed the world biocapacity in the 1970s. Currently, we in fact need 1.5 earths to accommodate our human beings. It is also estimated that if all people in the world were living at the high income country level, 3.4 earths would be needed. Anyway, we have only one earth and no additional biocapacity can be provided from somewhere else. Therefore, the overshoot of human activities will only result in a degradation of the ecological system in the world.



**Figure 3** Global ecological footprint and biocapacity (1961-2007)

## 2.2 Large scale urbanization supported by industrialized agro-business

Percent of urban population is often a factor to reflect the level of industrialization as well as economic development. Figure 4 (United Nations, 2004) compares the degrees of urbanization in 1950, 2000 and 2030 for the whole world, several continents and the world's more developed regions. To the year of 2030, 61% of the world population will be concentrated in urban areas. Even in Africa and Asia, more than half of the people will live in cities, not to mention Latin America and the Caribbean, and the more developed regions where urban population will take a very high percent.



**Figure 4** Urban population in the world

To support the large scale urbanization, we have to categorize the Earth's space and its function

for the production of goods, growing food and biomass materials, and conservation of biodiversity. The corresponding areas can be named as urban-industrial area, productive area, and protective area as shown in Figure 5 (Tambo, 1986, 2002).

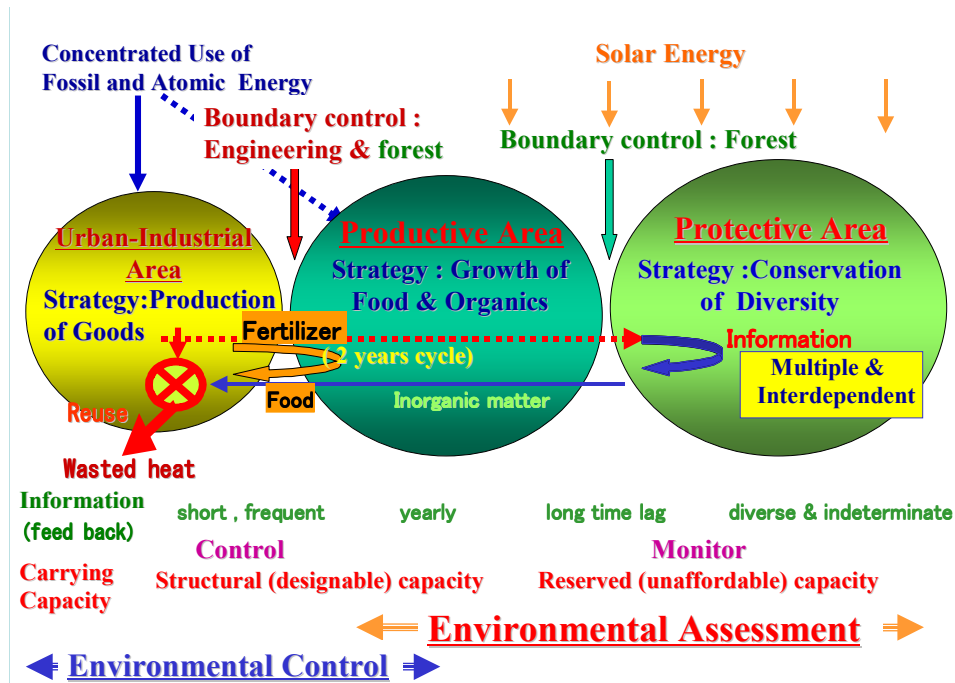


Figure 5 The three areas of the earth

The urban-industrial area is the space where human activities are most highly concentrated. It is characterized by the prevalence of industries involved in the production and distribution of material wealth as well as those dealing with information management. This area has little biological production functionality, and is driven by the intensive use of commercially available energy such as fossil and atomic power resources.

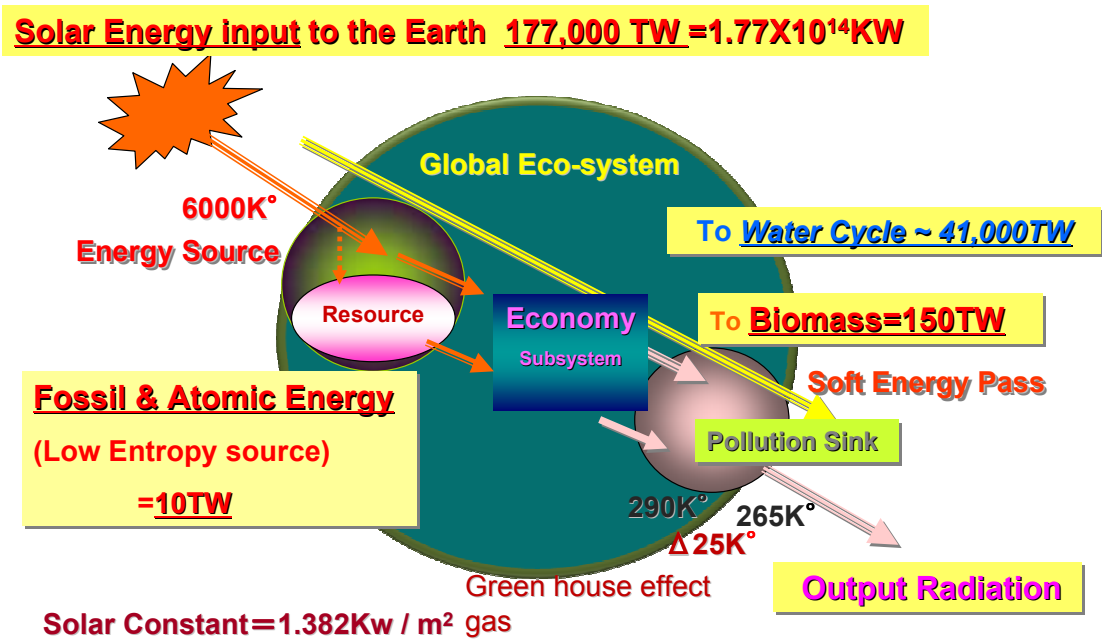
The productive area is the space where food and biomass are produced and supplied for people working in the urban-industrial area. The strategic goal of this area is to maximize the biomass production. People attempt to reap as much wheat grain as possible from each unit they sow. Although solar energy is the main driving energy for this area, machinery power and additional chemical fertilizer application have also significantly increased the productivity of biomass, giving rise to the Green Revolution in the modern era.

The protective area is used for ecosystem conservation where human involvement, unlike the other two areas, should be kept to the minimum necessary level, and material circulation is driven by solar energy and the forces of nature. The goal of this area is to help as many biological species as possible to make most of the solar energy and water in order to form and live in the diverse ecosystem.

### 2.3 Energy and water

Various systems on the Earth need their driving energies. The original energy source is from the

solar radiation which can be estimated as 177,000 TW. Such a huge amount of energy provides the driving energy mainly for the global climate system and ecological system. The protective area depicted in Figure 5 belongs to this category. Contrary to this, the productive area and the urban-industrial area can be taken as an economic subsystem in which much smaller amount of energy (about 12 TW) is consumed. Figure 6 shows roughly the energy balance on the Earth (Tambo 2002). The total energy consumed for the economic subsystem is estimated as about 12 TW which is much smaller than that consumed for sustaining the global eco-system. The direct use of solar radiation in the economic subsystem is only about 2 TW, and the remaining 10 TW is in the form of fossil and atomic energy. Although it is beyond the topic of this paper, the green house effect can also be explained by Figure 6 as a result of the pollution sink which causes an imbalance of the radiation temperature.

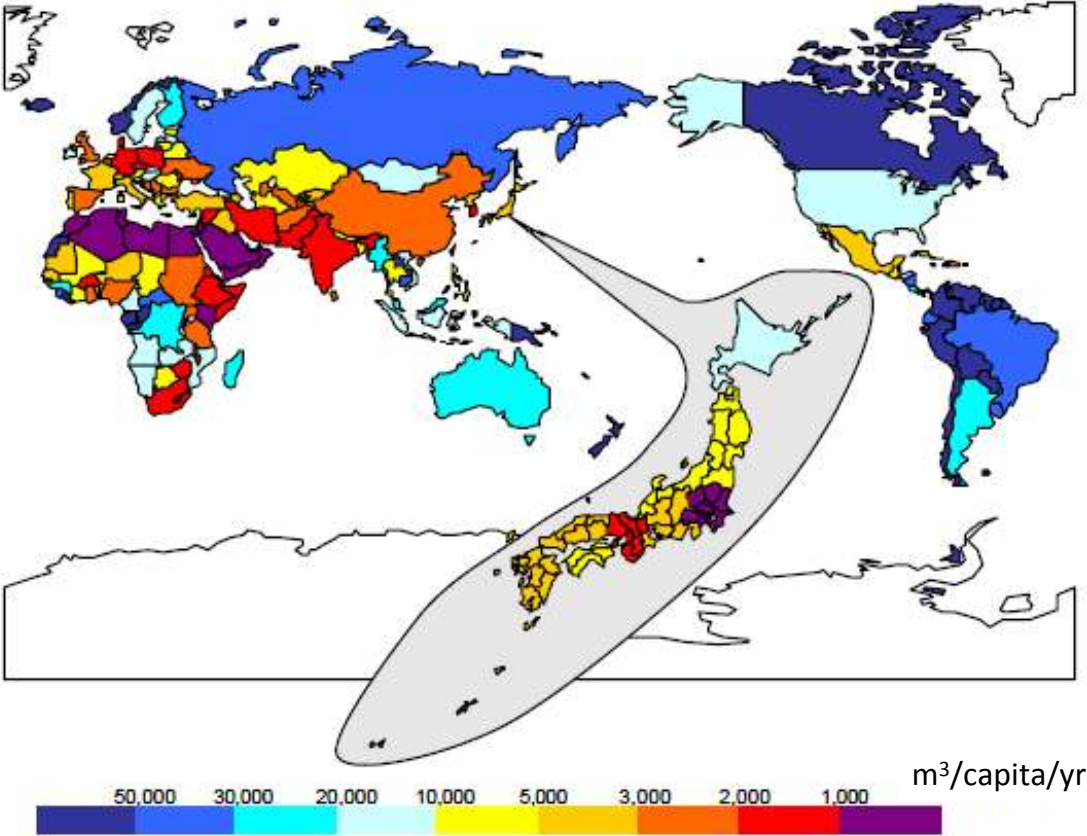


**Figure 6** Diving energy for the global eco-system and the economic subsystem

For many years, fossil energy has been the main energy source for the economic subsystem. Although the fossil energy, no matter in the forms of liquid (oil), gas (natural gas) or solid (coal), is originated from the solar energy, the process of transformation takes thousands of years. Therefore its renewal is very difficult. It is estimated by the Energy Information Administration (2000) that oil production has already outstripped the amount of oil discovered, and human beings will face serious oil scarcity in 2050 to 2075 if the current oil production speed continues. Atomic energy had been expected to play more and more important role in supplementing energy for the economic subsystem. However, due to lack of reliable measures to secure the absolute safety of atomic energy production, many industrialized countries decided to suspend nuclear power stations. How to supplement energy source for the economic subsystem is and will be a serious problem for our human beings.

Water, along with energy abovementioned, is also the most important consideration in achieving a sustainable world tomorrow. Figure 7 shows the per capita annual water availability in various parts of the world (Water Resources Department, Ministry of Land, Infrastructure, Transport and

Tourism of Japan, 2004). It is widely accepted that the per capita water resource can be used as a parameter for a reasonable evaluation of water supply conditions. Once a country's available water resources drop below 1,700 m<sup>3</sup>/capita/yr, the country can be expected to experience regular water stress – a situation in which disruptive water shortages can frequently occur; if the available water resource drops below 1,000 m<sup>3</sup>/capita/yr, the consequences can be more severe and lead to problems with food production and economic development; and if the amount of water available per capita drops below 500 m<sup>3</sup>/capita/yr, countries face conditions of absolute water scarcity (Engelman and Leroy, 1993; Falkenmark and Widstrand, 1992; United Nations Population Fund, 1997). According to the Water Resources Institute (2003), in 1995 approximately 41% of the world's population, or 2.3 billion people, lived in river basins under water stress, with the water availability below 1,700 m<sup>3</sup>/capita/yr. Of these, approximately 1.7 billion people resided in highly stressed river basins where water availability fell below 1,000 m<sup>3</sup>/capita/yr. By 2025, it is projected that, assuming current consumption patterns continue, at least 3.5 billion people – or 48% of the world's population – will live in water-stressed river basins. Of these, 2.4 billion will live under high water stress conditions.



**Figure 7** Water resources per capita in the world

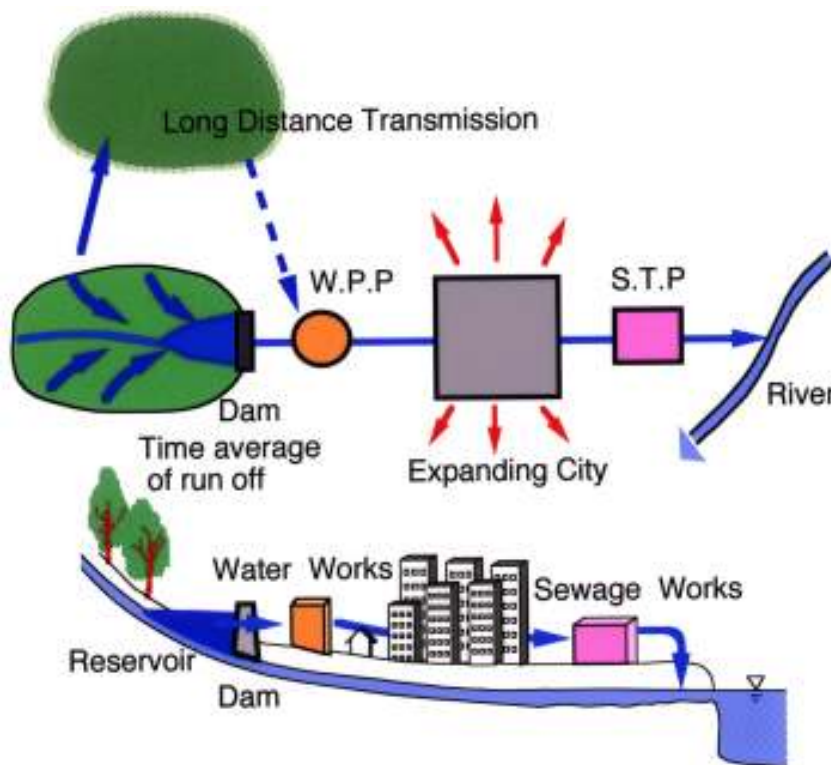
Per capita water availability also varies largely within one country due to varied conditions of precipitation, runoff and catchment storage capacity, population density and industrial scale. Taking the Kanto(Tokyo and its vicinity) region in Japan (the inserted graph in Figure 7) as an example, despite annual precipitation of 1,600 mm, it is one of the world's most water-deficient areas with a per capita water availability less than 1,000 m<sup>3</sup>/capita/yr. This low availability is

due to the enormous production output, with a population of roughly 41 million people with population density 1,300 person/km<sup>2</sup> and achieving a GDP close to that of Germany and higher than that of France. Such a large scale activity inevitably causes water shortage.

### 3. WATER DISTRICT CONCEPTS

#### 3.1 End of modern water use

A typical modern water system for a developed urban area can be depicted in Figure 8 (Tambo, 1994). Such a system has been widely used for more than one century since the industrial revolution which brought about the growth of large cities. The basic consideration for designing the urban water system is to supply high quality drinking water to every corner of the city under a principle of “meeting the demand of various water uses”, and to collect the sewage and then to treat it prior to its discharge into natural waters for meeting the needs of the public health, industrial growth and prosperity of the society. To meet the demand of various water uses, source water has to be transmitted to the city either from the dams constructed on the nearby rivers or by long distance channels or pipes. With the expansion of the city as is happening in many fast developing countries, still larger quantity of source water has to be provided. As the source water is from the nature, it can only be sustained by the natural hydrological cycle and therefore has its limitation in either quantity or quality within a river basin. This is one question we have to ask ourselves when implementing or upgrading a water system for a growing city.



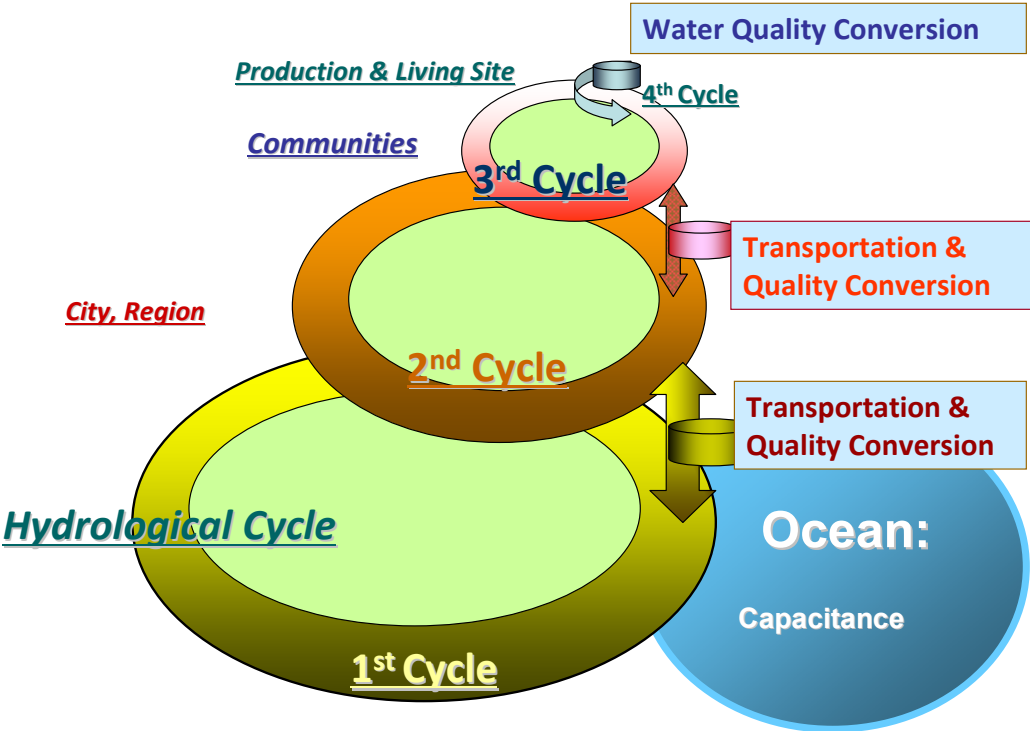
**Figure 8** Modern water system in a city

The impact of urbanization on the natural water environment can be viewed as overlying



multiple artificial water cycles upon the natural hydrological cycle. As shown in Figure 9 (Tambo, 2002), a large scale water utilization system implemented for a city or a region is the secondary water cycle directly overlying upon the hydrological cycle. Transportation and quality conversion are the main artificial actions. The secondary water cycle is further overlaid by the tertiary water cycle at community level, followed by the fourth water cycle at production and/or living site. In this way, the metabolic process in the hydrological cycle has been largely changed and it becomes more and more difficult to sustain a healthy water environment in the water basin, as well as in the global ecological system.

The operation of an urban water and sewage system is also accompanied by energy consumption. According to Tokyo Water and Sewage Works, the energy consumption for water and sewage as a whole is 0.82 kWh/m<sup>3</sup> of which 45% is for treatment and 55% is for transportation. Its breakdown for water supply and that for sewage works are 0.38 kWh/m<sup>3</sup> (20% for treatment and 80% for transportation) and 0.44 kWh/m<sup>3</sup> (67% for treatment and sludge disposal, and 33% for transportation). In some countries and cities, sea water desalination is practiced for supplementing water supply. The energy consumption can be as high as 2-5 kWh/m<sup>3</sup>.



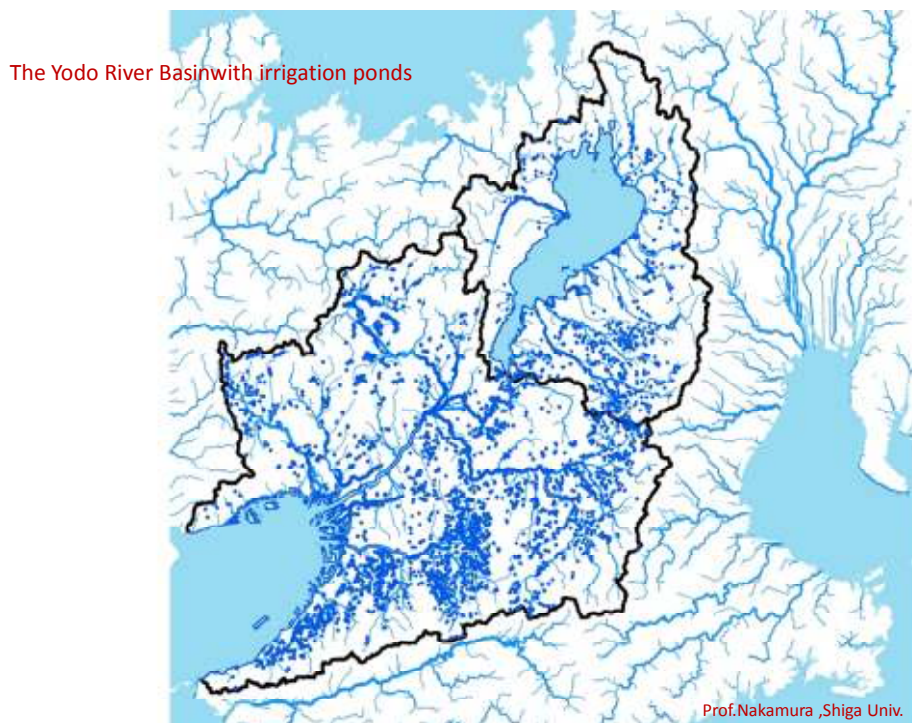
**Figure 9** Spectra of multiple hydrological cycles

No matter how we consider the modern water system, from the viewpoints of water availability, water environment, or energy consumption, its sustainability is questionable especially under the condition of further growth of world population and continuous urbanization. The way of modern water use may have to be ended and we have to consider a new manner of water use for meeting the future needs under the constraints of water availability.

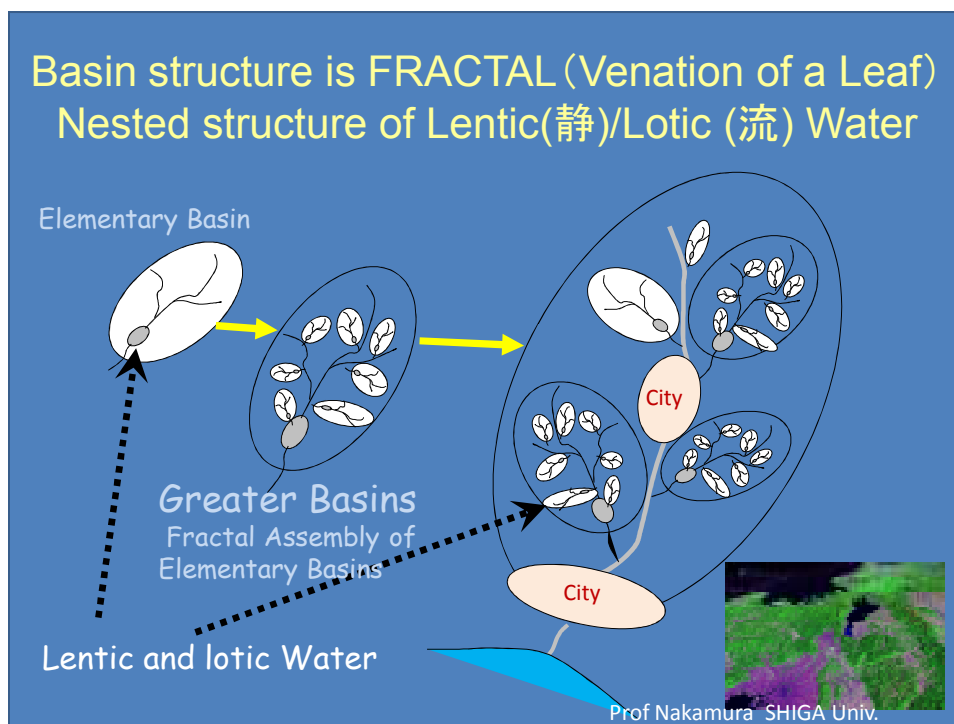
**3.2 Fractal nature of river basins**

Every city depends on river basins to provide fresh water source as well as various kinds of farmyards. The fractal nature of river basins has been well studied in the field of hydrological science and engineering (Kunigami, 1984) (Takara et.al, 1991) ( Rodriguez-Iturbe, I. and Rinaldo, A. 2001). River basins are three-dimensional landscapes organized around arborescent structures that constitute the drainage network to convey water from every site of the basin to a common outlet. The arborescent structure exhibits clear statistical self-similarity where sub-basins of different sized embedded among themselves and as part of the larger basin show topological and metric organizations independent of scale. Kunigami(1984) reported that fractal dimension of the river Amazon is 1.85, the Nile is 1.4. and of some other much smaller Japanese basins are in the range of 1.1-1.3. Takara et.al (1991) reported the fractal dimension of western and central Japanese rivers are in the range of 1.03 to 1.16. Any sub-basin, independent of its size or location, may be considered a self-contained hydrologic unit operating under the same hydrologic principles of “lentic and lotic “organization (Nakamura,2011). It is hypothesized that these principles are grounded in the metabolism of the river basin. From a hydrologic perspective, the metabolism of a river basin is defined as the set of processes that allow the basin to maintain its structure and respond to its environment through the physical and biological processing of the precipitation it receives. Green or biotic metabolism refers to the transformation undergone by precipitation in the process of carbon fixation by photosynthesis carried out by the basin vegetation. A quantitative measure of green metabolism is provided by the transpiration rate at any particular site. Blue or abiotic metabolism, that is different from the classical notion of metabolism as biochemical process, refers to the processes involved in the transport of runoff from every site to the outlet (Tambo, 2004). Understanding the fractal nature of river basins and their characteristics of water metabolism can help us to reconsider our ways for water use and to redesign water systems in harmony with fractal river basins.

Figure 10 shows one example of the fractal structures of the river basins in western Japan where Japanese ancient and medieval capital cities were located. Figure 11 shows a conceptual sketch of large river basins as the fractal assembly of elementary basins and exhibit a nested structure of lentic water (stagnant water as that in a lake) and lotic water (flowing water in the river channel) (Nakamura, 2010). Those lentic and lotic structure have been developed in the Yodo river basin with irrigation ponds and dispersed wet lands in the Western Part of Japan at where an ancient capital city Nara (Heijyo Kyo:710A.D) and medieval capital city Kyoto (Heian Kyo:794A.D.) were built wherein old Japanese civilization established. Sueish et.al. suggested importance of the lentic water in a river basin reviewing the characteristic nature of the old Japanese civilization to carry out a self sustaining water system. According to the location of a city in the river basins, the availability of the lentic and lotic waters may differ largely.



**Figure 10** Fractal structures of river basins (right) and conceptual sketch of large river basins as the fractal assembly of elementary basins



**Fig 11** Lentic- Lotec nature of Fractal river basin

### 3.3 Water districts for the post modern society

Figure 12 shows the schematic diagram of a water district proposed by Tambo (1976, 2002,

2010). It represents a proposal for the basic structure of cities in the post modern society. The system is with a setup much different from that shown in Figure 9, and can perform water metabolism independently with minimum energy consumption and environmental loading. In this way, harmonious relationships can be maintained with the downstream basins and the natural environment.

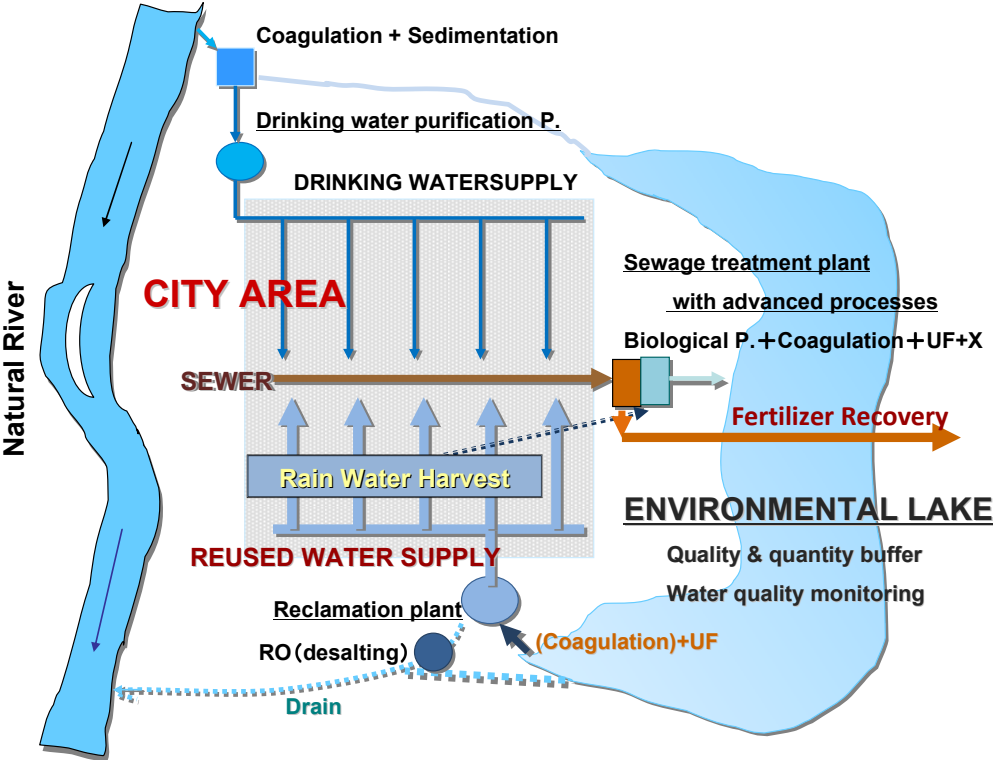


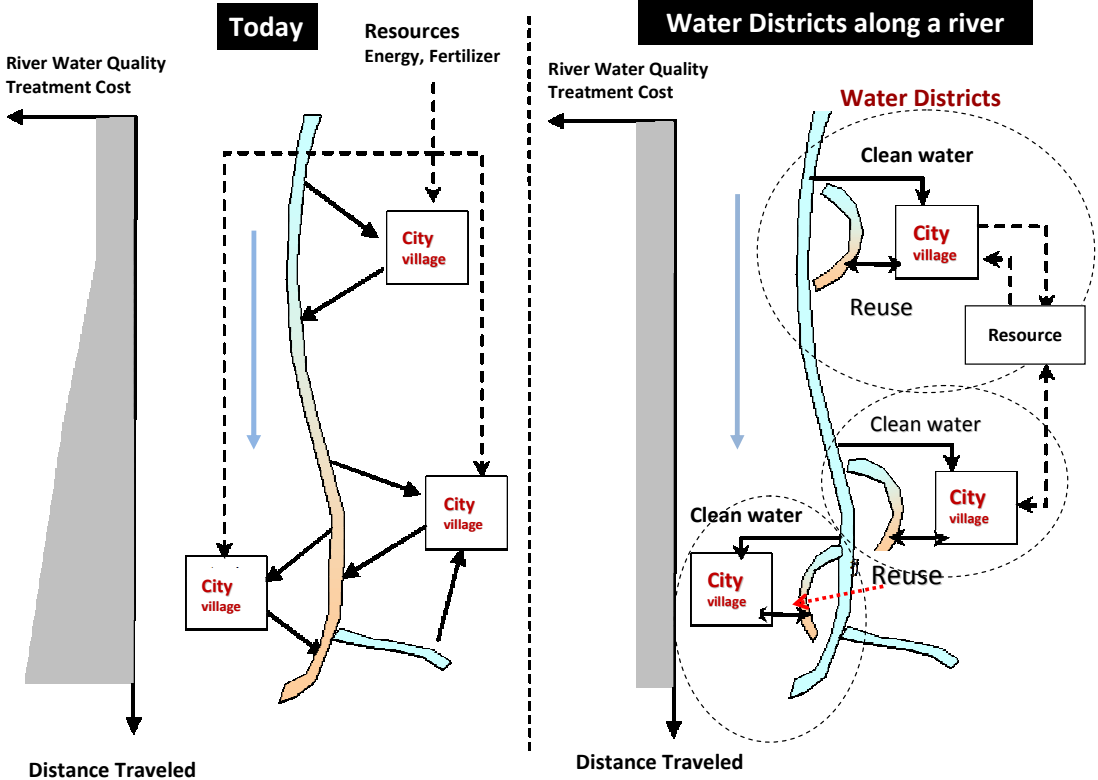
Figure 12 Water district for a city area

According to the United Nations (1992), a provision of 50 liters of clean water per capita per day to whole human beings is the goal toward sustainable development. This amount of clean water is considered to be essential for human life and hygiene and also sufficient in any society for potable purposes. If the precious fresh water in the world were preferentially supplied for potable use only, the worldwide water issues would not be as serious as it is nowadays. Unfortunately, in many developed countries as much as 300-400 liters of drinking water are consumed per person per day from the modern water supply system, because the high quality tap water is used for various purposes other than drinking, such as washing, bathing, showering, flushing toilets and watering plants. This not only wastes the fresh water resource, but also wastes energy for the treatment of large amount of water to meet the drinking water quality while only part of it is really used for drinking purposes. On the other hand, a large river is often shared by many cities from its upstream to downstream for fresh water supply. The downstream cities also have their demands on high quality source water, not to mention the protection of the river ecosystems. If we seek to coexist with nature, we cannot let people in the upstream areas to consume the high quality water to meet their needs for all purposes of water consumption.

Following this concept, cities should leave as much clean water as possible in river channels,

and collect only the minimum amount of high quality water that is necessary for potable purposes, such as 50 liters per person per day as abovementioned. For all non-potable water consumptions, the used water (a more suitable term than ‘sewage’) and rainwater can be recycled and used as far as possible. The environmental lake, which can be either natural or artificial, plays the key role of quantity and quality buffer in the water system as a lentic body in a fractal basin. It receives the treated used water and the harvested rainwater and becomes the secondary source for non-potable water supply. At the same time, the environmental lake can play landscaping and ecological functions in the city area. With the development of new advanced technologies such as membrane processes for water purification, it is possible to maximize the quantity of useful water from each source, to minimize the pollutant loading through drainage to downstream, and to perform integrated management of the water district for maintaining a sound water environment in the city area and the basin.

Figure 13 compares the conventional urban water systems and new urban water systems following the concept of water districts. As a long river may function as both the water source and receiving water body for all cities, towns and villages in its basin from upstream to the downstream, the conventional way of water use will inevitably bring about water quality deterioration which results in an increase of the costs for water purification along the flow direction as shown in the graph on the left. In contrast to this, it will be possible to keep the river water quality unchanged by adopting the new concept of water districts. Therefore, for all cities, towns and villages along the river, the unit cost of water treatment may not change as shown in the graph on the right.



**Figure 13** Water districts along a river comparing with conventional systems

### 3.4 Requests and measures

To realize the new urban water systems based on the abovementioned water district concept, we need innovations on the ways we use water, treat water and control the water environment. The minimum requests and measures may include the followings.

(1) *Clean water for potable & kitchen use only.* Here the clean water means good quality source water which after proper treatment can ensure safety water supply and high quality purified water which is produced through sophisticated treatment processes. From either the viewpoint of water conservation or that of energy and cost saving, such clean water should only be supplied for the water use directly related to human hygiene. Only potable and kitchen uses belong to this category. This may require a separated water supply system.

(2) *Rain water harvesting and grey water reuse for miscellaneous purposes.* Rain water and grey water are usually free from fecal pollutants. They are easy to be treated by simpler processes to a quality that meets the requirement of miscellaneous purposes other than drinking. This may require separated systems both for water supply as abovementioned and for differentiate grey water (from bathing and washing) from black water (from toilets).

(3) *Decentralized high performance treatment.* The conventional urban water and wastewater systems are usually highly centralized and unsuitable to source separation and reuse due to inevitable construction of long distance transfer pipelines. Contrary to this, decentralized systems can be flexible with suitable scales to meet the needs of onsite treatment and reuse and to get rid of unnecessary long distance water transfer. Careful selection of suitable technologies for high performance treatment will be required to achieve the goal of safety water reuse.

(4) *Resource recovery than pollution control.* The implementation of the new urban water system needs a change of the objective from merely pollution control to resource recovery. In the new system, every drop of water no matter where it comes from is the element of precious water resource but no longer the 'wastewater'. The recoverable resource also includes the useful materials such as nutrients contained in the water and/or the sludge. Energy recovery from wastewater treatment plants becomes a hot issue drawing wide attention (McCarty et al., 2011)

(5) *Ample natural flow conservation for living creatures.* The essence of the concept of water district is to create or maintain a harmonic aquatic ecosystem in the urban area and its surroundings. In a river or a lake, ample natural flow or water volume to meet the minimum requirement of all living creatures for their existence and reproduction is indispensable. How to conserve the natural water and maintain its condition as natural as possible is becoming tougher and tougher, but is a topic we always have to consider.

## 4. CONCLUSION

Our world is becoming smaller and smaller ideologically due to the change of human vision from regional to global, and physically due to the fast population growth and increasing demand

for energy and natural resources. Because we have only one earth to accommodate human beings and other living creatures, we cannot forget our task to conserve the global ecosystem while exploring resources to sustain our social and economic development. Since industrial revolution, our human beings have plundered too much from our mother earth and exerted too much damage on her intactness. We have already been at a time to rethink our ways to build our cities which are large sinks of natural resources and bad origins of pollutants. As water and energy are the most important resources for the survival of human beings, an analysis of the water and energy issues in this paper can let us realize the critic condition we are facing in the whole world. However, since our human beings are intelligent creatures, we can find ways to overcome difficulties. The concept of water district discussed in the former section can provide the basis for reforming our urban water systems toward the post-modern society.

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