Part II

New Paradigm of Systems Thinking and Technology Advances

Chapter 6

Water cycle management for building water-wise cities

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6.1 INTRODUCTION

Water is a chemical substance with a simple but stable molecular structure of H_2O. It cannot be generated or eliminated under normal conditions, so the total mass of water in the whole world is constant. Water itself is transparent, tasteless, odorless, and nearly colorless, but can dissolve various inorganic and organic solutes, and carry fine particulate solids as it flows. All these foreign substances the water carries are called 'impurities' which can enter the water mass and conversely be removed through various natural or artificial actions. Water is essential to human and all living organisms, but any consumption and utilization of water cannot result in any true loss of the water mass. This means that after water use, the water molecules are still there and the only alteration is in their quality, location of existence, and existing state (liquid, gaseous or even solid forms). However, the usability of water may not merely depend on its quantity, but more importantly its quality. Contaminated water cannot be directly supplied for most purposes of water use. In this sense, the problem of water shortage we

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are discussing in several chapters of this book may not only mean a shortage of water mass in most cases, but the shortage of water with quality to meet the requirement of water use.

Fortunately, water is always moving or being moved in different ways and scales. Naturally, the global scale water movement is driven by solar energy and gravitational energy, and brings water mass back to every water body where water can stay. The water movement is also associated with many processes of quality conversion which results in an almost stable water quality in each waterbody under natural conditions.

Human beings are utilizing the abovementioned natural water cycle to obtain source water. To facilitate water use for various purposes, artificial measures are taken for water conveyance and additional quality conversion by consuming energy. The water to be used is from nature and after use it is returned to nature, thus forming various scales of additional artificial water cycles.

Let us come back to the topic of building water-wise cities. We understand that cites are basin connected (the second level action in the IWA Principles for Water Wise Cities), so the water sources provided to us are sustained by the natural water cycle. On the other hand, the water-related infrastructures built for cities are artificial patches to the natural water cycle. In this viewpoint, water cycle management can be proposed as the core concept for formulating strategical schemes for building water-wise cities.

6.2 THINGS TO LEARN FROM THE NATURAL HYDROLOGICAL CYCLE

6.2.1 Natural hydrological cycle

The most important reason for the survival of human beings on the planet Earth through several generations is the presence of plentiful water to support life. With a total surface area of about $5.1 \times 10^8\,km^2$, about 71% of which is ocean surface and 29% land surface, the total volume of water on Earth amounts to about $1.39 \times 10^9\,km^3$ (Agarwal *et al.*, 2019; Nazaroff & Alvarez-Cohen, 2000). If all of Earth's crustal surface were at the same elevation as a smooth sphere, then the resulting water depth covering the Earth would be over 2700 m. This huge amount of water is distributed in a hydrosphere, namely the combined mass of water found on, under, and above the surface of the Earth, including water in liquid and frozen forms in groundwater, oceans, lakes, and streams. Saltwater accounts for almost 97.5% of this amount, whereas freshwater accounts for only about 2.5%. Of the freshwater, 68.9% is in the form of ice and permanent snow cover in the Arctic, Antarctic, and mountain glaciers and 30.8% is in the form of fresh groundwater. Only 0.3% of the freshwater on Earth is in readily accessible lakes, reservoirs, and river systems (Chawla *et al.*, 2020). Table 6.1 shows the distribution of fresh and saline water in the Earth's hydrosphere.

Table 6.1 Distribution of fresh and saline water in the Earth's hydrosphere.

Site	Volume (km^3)	Percent (%)
Ocean	1,350,000,000	97.29
Polar ice caps and glaciers	29,000,000	2.09
Groundwater	8,300,000	0.6
Freshwater lakes	125,000	0.009
Saline lakes and inland seas	104,000	0.0075
Soil and subsoil water	67,000	0.0048
Atmospheric water vapor	13,000	0.00094
Living biomass	3000	0.00022
Stream channels	1000	0.00007
Total	1,390,000,000	100

Source: Nazaroff and Alvarez-Cohen 2000.

Water in the hydrosphere is continuously transformed through various phases in a process called the water cycle or hydrological cycle at global or watershed scales.

6.2.1.1 Global hydrological cycle

Figure 6.1 depicts the major processes in the hydrological cycle on a global scale. As oceans and seas are covering 71% of the Earth's surface, the solar radiation heats the

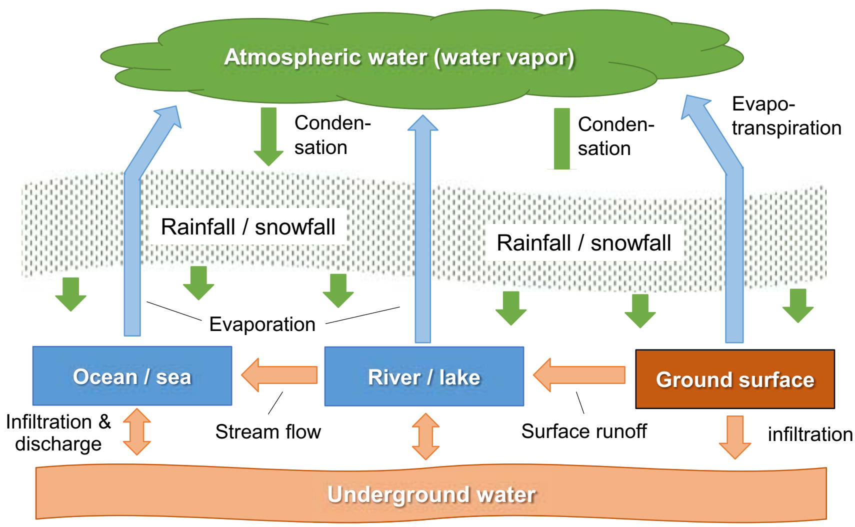

Figure 6.1 Major processes of water movement and transport in the hydrological cycle at the global scale (figure by authors).

seawater and forces it to evaporate as water vapor into the air. A similar process also occurs on other water surfaces, such as rivers, lakes, and other surface water bodies. Water may also be transpired by plants and evaporated from the soil through a process called evapotranspiration. However, the majority of the water vapor from the Earth's surface into the atmosphere is due to seawater evaporation.

As the water molecule has a smaller molecular mass and is less dense than the major components of the atmosphere, such as nitrogen and oxygen gases, the evaporated water vapor is driven by buoyancy and goes upward to a height of 600–1000 m above ground in a humid area or up to 3000 m in a dry area. As altitude increases, air pressure decreases, and the temperature drops. The lower temperature causes water vapor to condense into tiny liquid water droplets which are heavier than the air, and fall unless supported by an updraft. A huge concentration of these droplets over a large space up in the atmosphere becomes visible as a cloud.

Atmospheric circulation moves water vapor around the globe, and cloud particles collide, grow, and fall out of the upper atmospheric layers as precipitation falling to the Earth as rain and/or snow. Most of the precipitation may fall back into the ocean, thus resulting in a shorter cycle of 'seawater evaporation – condensation – precipitation back to the sea.' Moreover, a part of the precipitation may fall onto land, where the water flows over the ground as surface runoff. A portion of the runoff may enter rivers in valleys, with streamflow moving water towards the ocean, resulting in a longer cycle of 'evaporation – condensation – precipitation – surface runoff – streamflow back to the sea.' Runoff may be stored as freshwater in some surface water bodies with ample storage volumes, such as lakes and reservoirs. Not all the runoff enters surface water bodies, and much of it may soak into the ground through infiltration. Some water infiltrates deep into the ground and replenishes groundwater aquifers, while some stay close to the land surface and can seep back into surface water bodies (including the ocean) as groundwater discharge (Cui *et al.*, 2018). In river valleys and floodplains, there is often continuous water exchange between surface water and groundwater in the hyporheic zone, and the time for the water to return to the ocean may be very long. Anyway, no matter how complicated the processes are, the ocean is always the final destination of the water movement where the next water cycle continues.

6.2.1.2 Hydrological cycle of a watershed

A watershed is a drainage basin with a defined area of land where precipitation collects and drains off into a common outlet, such as into a river, bay, or other water bodies. In a watershed, there is still a water cycle with similar hydrological processes as discussed in Section 6.2.1.2. However, as the water cycle in each watershed is a subsystem or a hydrological element of the global water cycle, it is not completely independent of the global water movement. First, the amount of precipitation to the watershed may not be equivalent to the amount of evaporation and evapotranspiration from the watershed area because of the atmospheric movement of water vapor in the broader area. Second, the watershed has an outlet where surplus water flows out of the watershed area (Hester & Little, 2013). Due to these two reasons, the hydrological cycle of a watershed is not a closed water loop but follows a relationship as below:

$$\text{Precipitation} - (\text{Evaporation} + \text{Evapotranspiration}) - \text{Outflow} = \text{Increase in storage} \quad (6.1)$$

where 'Precipitation' is the precipitated water volume within the watershed area, 'Evaporation + Evapotranspiration' is the amount of water evaporated from the watershed area, 'Outflow' is the amount of water that drains off from the outlet of the watershed, and 'Increase in storage' includes the amount of water added to surface water bodies, groundwater aquifers, soil moisture and so on within the watershed area in a given time.

Equation (6.1) is a mass balance relation of water for a watershed. As the precipitation may be affected by weather conditions, the amount of water stored in the watershed may not always be secured. This can explain why droughts occasionally occur in many watersheds worldwide. On the other hand, as the maximum storage volume of water bodies (e.g. lakes and reservoirs) is limited and so is the capacity of outflow through the outlet of the watershed, if the amount of precipitation is abnormally large, the precipitated water may not drain off smoothly and surface flooding may inevitably occur.

6.2.2 Functions of the hydrological cycle

The hydrological cycle has two important functions from the viewpoint of human needs for water resources. One is to secure the quantity of renewable water resources on the earth's surface under a dynamic equilibrium condition, and another is to secure the quality of the water resources.

6.2.2.1 Water quantity secured by the hydrological cycle

It is estimated that the average annual evaporation (including evapotranspiration) amounts to 577,000 km^3, of which 503,000 km^3 evaporates from the oceans and the remaining 74,000 km^3 is from the land by evapotranspiration. As water molecules cannot be naturally created nor destroyed but can only possibly transform from one state to another, the same amount of water (577,000 km^3) returns to earth as a result of precipitation. However, the amount of water that directly precipitates over the oceans is 458,000 km^3 while that over the land is 119,000 km^3. By a simple calculation of the difference between the precipitated amount and the evaporated amount on land, it can be estimated that the net amount of water annually transported from the oceans to the land is 45,000 km^3. This is the principal source of renewable freshwater for all organisms on earth.

Of course, an equivalent amount of water eventually discharges to the oceans through surface flows (rivers) and subsurface flows (groundwater outflow) to maintain the mass balance of water circulation in the global hydrological cycle, as discussed in Section 6.2.1.2.

According to the Food and Agriculture Organization of the United Nations (FAO, 2003), the total water resources of the world are estimated at 43,764 km^3 per year, which is roughly the amount of water annually transported from the oceans to the land (45,000 km^3 as calculated above). This amount of water is called the annual renewable water resource, which, by definition, is the water replenishable to replace the portion of water depleted by usage and consumption for various purposes. If the current world population of 7.7 billion is considered, then the average per capita water resource is about 5700 m^3 per year. However, water resources are unevenly distributed throughout the world. America (including North, South, and Central) possesses about 45.3% of the world water resources, but its population accounts for only 13.5% of the world population. In contrast, Asia has the largest population (about 60% of the world population) while it possesses only about 28.5% of the world's water resources.

As the annual precipitation amount significantly influences the amount of annual renewable water resources, there is a fluctuation in the amount of world water resources. We do not have reliable worldwide data to show such kinds of fluctuation but can take China as an example to see how the amount of water resources varies in the territory of this large country. Figure 6.2 is depicted using the data from the National Bureau of Statistics of China (NBSC, 2020) from

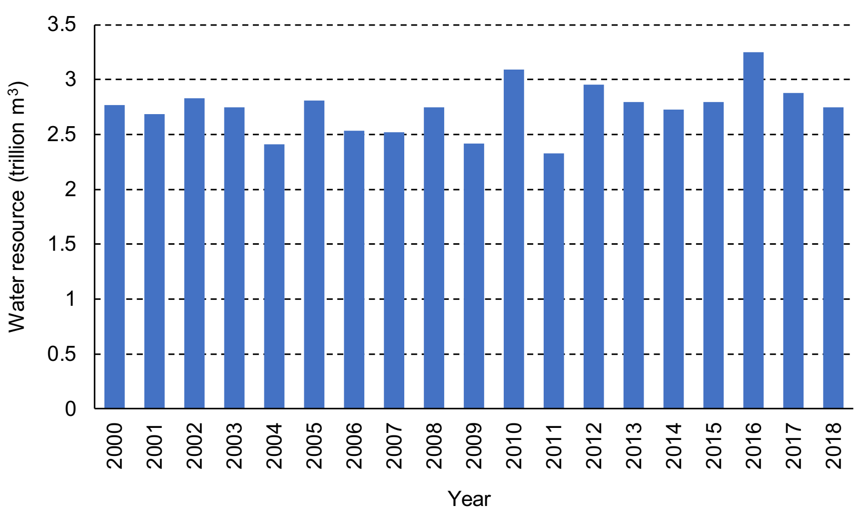

Figure 6.2 Annual water resource in China from 2000 to 2018 (data source: NBSC, 2020).

2000 to 2018. Historical data show that the long-term average of total water resources in China amounts to 2829.6 km^3 (2.8296 trillion m^3) per year. However, the short-term average of total water resources in the past 19 years is calculated as 2.7380 trillion m^3 per year, indicating an apparent decline in water resources compared with the long-term average. Very low amounts of total water resources occurred in 2004, 2009, and 2011, at about 2.41, 2.42, and 2.33 trillion m^3, respectively, which are 14.8, 14.5, and 17.7% below the long-term average. These years are known as extremely dry years in the past two decades. Nonetheless, in wet years, such as 2010 and 2016, the amount of total water resources shows increases over the long-term average.

The renewable water resources for the whole world and any country or region include surface water resources (from rivers, lakes, reservoirs, etc.) and groundwater resources (from exploitable groundwater aquifers). Water in all these water bodies is replenished through the processes in the hydrological cycle as discussed in Section 6.2.1.

6.2.2.2 Water quality secured by the hydrological cycle

The turnover of water from the oceans to land through evaporation and precipitation is accompanied by the conversion of saline to freshwater, which is the most important process of 'water treatment' for removing salts and all impurities to obtain pure H_2O molecules. Driven by solar radiation, the cleanest natural energy, the water purified amounts to 45,000 km^3 per year, or about 123.3 km^3 per day, on average, and provides high-quality water to replenish surface and subsurface water bodies. This is the primary step of water purification through the hydrological cycle.

After reaching the land, natural elements, of which many are minerals essential to the health of human beings and other living organisms, are dissolved from soils, rocks, and other mineral media into the precipitated water during surface runoff, streamflow, and underground movement in groundwater aquifers. This is a secondary step of water quality adjustment through the hydrological cycle.

During flow in waterways, e.g. streams and rivers, and storage in water realms without apparent flow, e.g. lakes and reservoirs, impurities in the water can be removed and/or assimilated under a series of natural physical (sedimentation, entrapment, etc.), physicochemical (natural coagulation, complexation, and precipitation, filtration, adsorption, ion-exchange, etc.), chemical (oxidation, etc.), and biological (decomposition, degradation, etc.) actions (Korenaga *et al.*, 2017; Oki & Kanae, 2006). Nowadays, we use the terminology of 'self-purification' to explain the function of water quality conversion within waterbodies. The most classic work was carried out by Streeter and Phelps (Long, 2020) who considered both organic matter and dissolved oxygen in a stream and developed partial differential equations for modeling organic decay during streamflow. Various studies have also been conducted for characterizing natural processes in streams, lakes, and groundwater aquifers to remove organic matter, nutrients, and other pollutants (Dai, *et al.*, 2020; Tong *et al.*, 2019). Natural purification is the subsidiary function of water quality stabilization through the hydrological cycle.

6.2.3 Thermodynamic characteristics of the hydrological cycle

Let us consider again the global hydrological cycle regarding its thermodynamic characteristics. First, water movement through the hydrological cycle is driven by solar energy and gravitational potential energy. The former transforms water from its liquid state to gaseous state (the water vapor) and drives it up to the atmosphere. The latter forces the liquid droplets condensed from the water vapor to fall as rainfall or snowfall, and then forces the precipitated water to move along the ground slope, forming surface runoff and streamflow. Water infiltration down to subsurface and groundwater movement are also due to gravitational force. Both solar energy and gravitational potential energy belong to green energy or sustainable energy, which, by definition, can never be exhausted so that it always meets the needs of the present without compromising the ability of future generations to meet their own needs (Stassen *et al.*, 2019).

Second, as water in various states (liquid, vapor, or even ice) are all confined in what we call the hydrosphere, the combined mass of water found on, under, and above the surface of the Earth, there is not any inflow to or outflow from the hydrosphere during any process in the hydrological cycle. Therefore, taking the out layer of the hydrosphere (several thousand meters above the Earth's surface) as the boundary for mass balance analysis of water molecules, the referred system (a spherical volume with the Earth in it) is a closed system with no exchange of water molecules without space, and the total mass of water remains constant. Therefore, the movement of water through the hydrological cycle is reversible, namely a reversible cycle with a cyclical reversible process in which the system and its surroundings will be returned to their original states.

With the above characteristics, it can be concluded that the hydrological cycle can spontaneously maintain a dynamic equilibrium condition without any unnatural interference. It is virtually a thermodynamically sound system with each hydrological element (e.g. each surface or subsurface water body) in it also in a dynamic equilibrium state.

6.2.4 Human disturbance of the hydrological cycle

The discussions above are based on a primitive assumption of the state of the hydrological cycle with unnatural interferences. From ancient times, human beings have depended on water of relatively stable quantity and quality from various water bodies to support their domestic and productive water use. However, according to the scale of water use, human activities inevitably impose impacts or disturbances on the hydrological cycle.

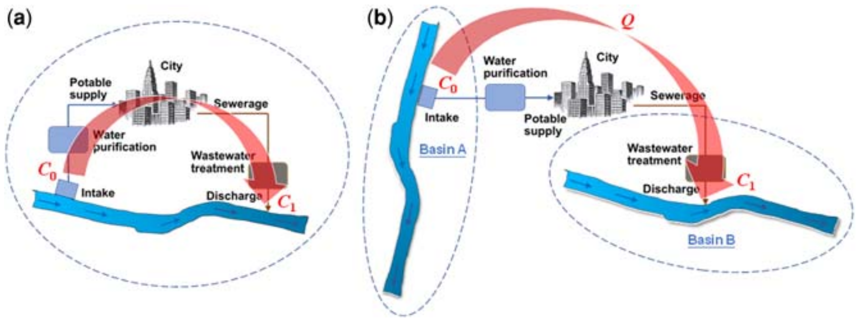

Figure 6.3 Disturbance of natural streamflow due to urban water supply and sewage discharge (figure by authors). (**a**) Intra-basin disturbance. (**b**) Inter-basin disturbance.

Figure 6.3 shows the possible disturbance of natural streamflow due to urban development under an assumption that a city depends on a river for water supply from its upstream and discharges the used water to its downstream (Figure 6.3 (a)), or a city takes water from a river in basin A for urban supply and discharges the used water to another river in basin B (Figure 6.3(b)).

In the case of Figure 6.3(a), the major disturbance to the natural streamflow of the river is the change of water quality from C_0 at the upstream section where water is withdrawn to C_1 at the downstream section where the used water (treated or untreated effluent) is discharged. The stream flowrate may not change so much for the river as a whole. This is a typical case of 'intra-basin disturbance', usually for a riverside city. According to the scale of water supply and the remaining pollutant loading in the discharged flow into the river, the water quality downstream may be severely deteriorated.

In the case of Figure 6.3(b), the disturbance to the natural streamflow of the river in basin A is the loss of flowrate Q due to water supply to the city, while that to the natural streamflow of the river in basin B is an increase of flowrate Q at the section of discharge and an increase of pollutant loading to the stream. This is a typical case of 'inter-basin disturbance.' It brings about significant changes in the hydrological conditions of the two rivers in different basins.

6.3 URBAN WATER CYCLE

In Section 6.2, we discussed the hydrological cycle at both the global and watershed scales. We learnt that all the natural processes involved in the hydrological cycle perform functions either to ensure water quantity and/or to ensure water quality in all freshwater bodies. Such a natural water cycle, on the whole, is a thermodynamically sound system under a dynamical equilibrium state. Human beings, as well as other living organisms in the world, are enjoying the grace of nature for obtaining water to support their lives. However, our large-scale utilization of water resources has more or less disturbed the hydrological cycle, especially after people began to live in densely populated settlements – the cities. As indicated in Figure 6.3, human consumption of freshwater from nature will not cause water to disappear, but create a water bypass and alter its quality before returning it to nature. This also forms a water cycle due to artificial elaboration.

6.3.1 Characteristics of the urban water cycle

Figure 6.4 is a conceptual depiction of the process of human utilization of water, the engineered system to facilitate water use, and how this engineered system is connected with natural waters. The basic process of human utilization of water consists of four sub-processes, namely water intake, water supply, water use, and used water disposal. In prehistoric times or even nowadays in remote areas, all these are conducted by using manpower, such as fetching water from a stream or well with a bucket, carrying the bucket back home, using the water at home, and finally discarding the used water randomly. Conversely, for modern cities, an engineered system with the four subsystems shown in Figure 6.4 is provided. Such an engineered system connects with natural waters at least at two locations – one at the start of the water resource subsystem where freshwater is withdrawn, and another at the end of the wastewater and drainage subsystem where used water is discharged back to natural waters. This engineered system and the connected natural waters form a water loop is named as an 'urban water cycle'.

We take the engineered system as the artificial (engineering) component of the urban water cycle because water is mechanically forced to flow through artificially built facilities to facilitate human water use. The function of each component (subsystem) of the engineered system is summarized as follows: (1)

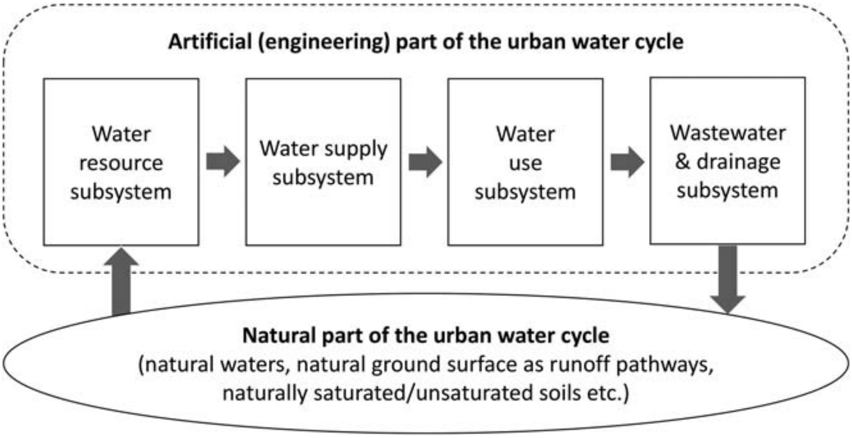

Figure 6.4 Urban water cycle consisting of artificial (engineering) and natural components (figure by authors).

the water resource subsystem provides sufficient raw water to a city by booster pumps and conveyance pipelines, (2) the water supply subsystem consists of water purification plants for treating the raw water to meet the quality requirement for human use (usually for drinking), and a distribution network to supply the treated water (potable water) to users, (3) the water use subsystem usually covers the whole city with various apparatus to facilitate water use for all purposes, and (4) the wastewater and drainage subsystem consists of sewage networks for collecting the used water (conventionally called wastewater) and send it to wastewater treatment plants where pollutants are separated from the wastewater and the treated effluent is finally discharged. This subsystem also includes facilities for urban drainage during rainy days through separated and/or combined pipelines for smooth drainage of surface runoff (Bach *et al.*, 2014).

As shown in Figure 6.4, the engineered system discussed above is connected with natural waters at least at two locations, namely the waterbody that provides source water and the waterbody that receives the used water (treated wastewater) and urban drainage. In fact, in the urban area, the natural ground surface provides surface runoff pathways and the naturally saturated and/or unsaturated soil provides pathways for water infiltration into groundwater aquifers. The source for water supply to the city and the urban discharge/drainage receiver may be the same waterbody as that depicted in Figure 6.3(a) or water bodies in neighboring watersheds as that depicted in Figure 6.3(b). In either case, if the human disturbance has not brought about a significant variation of the dynamic equilibrium state of the local hydrological system (with related waters in it), this natural component of the urban water cycle can be capable of continuous provision of source water and accommodation of urban discharge/drainage. On the other hand, with the rational design of the artificial component of the urban water cycle (the engineered system with application of up to date technologies), the human disturbance can also be reduced to a permissible extent so that the whole urban water cycle can be maintained in a healthy state, or in other words, a dynamic equilibrium state, in terms of both water quantity and quality.

6.3.2 Conventional modern urban water system

We use the expression of ‘conventional modern’ to characterize the urban water system widely built over the world from the late 1800s or early 1900s till nowadays, where ‘conventional’ means the manner widely accepted or standardized, and ‘modern’ differentiates the past time of more than one century from earlier times. The conventional modern urban water system, formulated as a result of the industrial revolution, is characterized by centralized potable water supply to provide water of sufficient quality to meet various demands for water use, and centralized sewerage for collecting and transporting human wastes swiftly out of the urban area (Tambo, 2004). In addition to the provision of large water distribution and used water collection networks, the introduction of water purification facilities (first by slow sand filtration and later by rapid sand filtration with disinfection) and wastewater treatment (symbolized by the activated sludge process) are important innovations in water and sanitation for urban societies (Li *et al.*, 2018). As the main objective of the system design was to satisfy the human desire for comfort and better sanitation, the maximized utilization of available water sources and the use of water bodies for the assimilation of discharged wastes has been commonly practiced everywhere. However, the shortcomings become more and more obvious with the increasing world population and growth in the number and scale of cities. These include but are not limited to the following:

(1) Indiscriminate use of high-quality water: In almost all cities, the total quantity of water supplied to users is of potable quality, but less than half of it is used for drinking, cooking, or other purposes that really require high quality.
(2) Endless requirements for quality improvement: In the late 1800s or early 1900s when the conventional urban water system was put into operation, the processes for drinking water purification and wastewater treatment were 'conventional' with applications of basic technologies. This is not because of the lack of advanced technologies at that time, but mainly due to the easiness to obtain good quality source water and sufficient self-purification capacity of the waters to receive wastewater discharge. However, as water pollution became increasingly severe in many countries and regions, especially in the vicinity of large cities, more and more sophisticated treatment was required for the provision of safe drinking water and the reduction of pollutant loadings to receiving waters. High costs of water and wastewater treatment have increased economic difficulties in many cities.
(3) Continuous or limitless system expansion: As coverage of the whole service area is the task for a centralized urban water system, it always needs expansion and/or upgrading to meet increasing demands due to the enlargement of urban areas and population growth. Even the maintenance and rehabilitation of the massive water and wastewater networks are heavy tasks in many cities.
(4) Difficulties in practicing water reuse and resource recovery: The conventional urban water system was designed following an 'end-of-the-pipe' model, characterized by a sequence of production-utilization-wastage because water reuse and resource recovery were not topics at all for all the cities developed decades ago. However, when the water resource is no longer plentiful, and its reclamation and reuse become necessary, the conventional system is found to be unsuitable to meet this new requirement. On the other hand, although we have realized for a long time that water, fertilizers, and other resources from the wastewater

stream can be reclaimed for various uses because most wastewater treatment plants are located outside the city, the reclaimed water and resources have to be sent back to the city area by long-distance transportation, which needs additional energy and/or cost input.

(5) Lack of harmonic relation with natural waters: In urban water system design, natural waters are usually taken as source providers and waste receivers but not important components of the urban water cycle. The harmonic relation between engineered facilities and nature was seldom taken into consideration in planning the whole system.

6.3.3 Urban water system toward a new paradigm

From a historical view, human utilization of water has so far roughly undergone two distinctive paradigms. The first is almost nature-dependent, while the second is largely engineering-dependent. The nature-dependent paradigm is the paradigm of very basic water supply by fetching water directly from surface waters and/or wells, with the use of streets and simple street drainage for stormwater and wastewater conveyance. Water quality at that time was generally excellent due to sufficient natural purification capacity of streams and/or groundwater aquifers to assimilate pollutants. The timeline for this paradigm is not very clear but can date back to the period from B.C. to the Middle Ages. It can still be found in remote areas nowadays. The engineering-dependent paradigm is the paradigm of water supply by engineered systems. It also has not a clear start time in history but gradually evolved from nature-dependent to more engineering-dependent (decrease in nature dependence and increase in engineering dependence), as depicted in Figure 6.5, with rough periods and typical engineered facility types for water supply and sewerage.

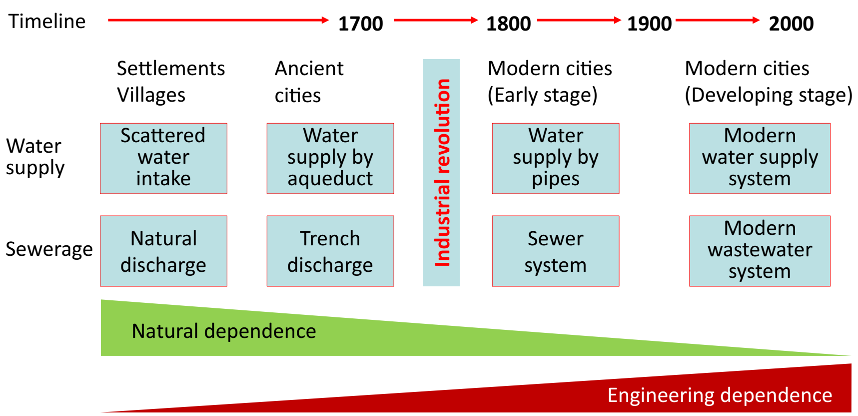

Figure 6.5 Evolution of urban water and wastewater systems with a decrease of nature dependence and increase of engineering dependence (figure by authors).

Now we come back to continue our discussion of the urban water cycle, as depicted in Figure 6.4, regarding the functions of the natural and artificial components. Since the natural component belongs to the hydrological cycle, as discussed in Section 6.2.2, its function is, first, to secure a sufficient quantity of water for the city. The second function is to secure the water quality of both the source water and the receiving water. In contrast, the function of the artificial or engineering component is to supply water for various uses and bring the used water back to nature. In terms of water quantity, a balance between the withdrawable water source and the demand for water supply should be reached. Conversely, in terms of water quality, the pollutant loading of the discharged wastewater and urban drainage should not exceed the carrying capacity of the receiving waterbody. The installation of wastewater treatment facilities is, in principle, for the protection of the receiving waterbody. However, if the qualitative balance between the natural and artificial components is broken, the urban water cycle will enter a vicious circle: pollution of natural water results in deteriorated source water quality so that more sophisticated drinking water treatment is required, and to protect natural waters, wastewater treatment facilities have to be upgraded to achieve higher pollutant removal goals. Such a condition is currently encountered by many cities.

It is widely recognized that we need a paradigm shift in building our urban water systems. The tendency of decreasing nature dependence and increasing engineering dependence, as shown in Figure 6.5, has to be changed so that a new paradigm toward the future may take the form of 'engineering in nature' with the following characteristics:

(1) A city is located in a watershed within the natural hydrological cycle and the watershed determines the hydrological boundary of the city.
(2) Any engineered facility provided for utilization of water in the city is designed in a way first not to bring about any irreversible damage to the hydrological process and second to meet the reasonable requirement of urban service.
(3) Urban aqua-ecological service is provided to the city first by the favorable natural property of the watershed and second by an artificial elaboration in harmony with nature.
(4) The urban water cycle as depicted in Figure 6.4 is a healthy water loop with sufficient metabolic capacity to accommodate and assimilate its endogenous pollutant loading and with no pollution export to neighboring watersheds and/or hydrological cycle at a larger scale.

To realize such a paradigm shift, we need to introduce a brand-new concept of water cycle management.

6.4 CONCEPTUAL SCHEME OF WATER CYCLE MANAGEMENT

Table 6.2 shows a conceptual scheme of water cycle management (WCM) for cities. It includes the management of water sources, water quality, water use, and waste discharge, each with specific objectives, with the overall management aiming at urban water sustainability.

6.4.1 Resource management

The primary water source for urban water supply is the natural waters within the watershed where a city is located. In cases where the city and the source water are hydrologically located in adjacent watersheds, we would like to put all of them into the scope of the urban water cycle for the discussion. The primary source of water is usually the available freshwater suitable for drinking water supply and other applications. In addition to such types of 'conventional' water source, there are also 'alternative' water sources that can be made applicable for cities, such as the harvestable rainwater, reclaimed used water (alternative terminology of 'wastewater'), and even water from saline or brackish sources.

The utilization of conventional water sources is usually prioritized because of their favorable quality. However, every freshwater body has its limit of water withdrawal beyond which its aquatic environmental condition will be deteriorated

Table 6.2 Conceptual scheme of WCM for cities.

Item	Coverage	Objectives
Resource management	Conventional water source Alternative water source	Meet the reasonable requirement of urban service without irreversible damage on natural waters
Quality management	Quality for water use Quality for ecological health	Meet the quality requirement of water for various water uses and ecological safety
Water use management	Potable water use Non-potable water use	Fit-for-purpose water use and minimization of freshwater consumption
Discharge management	Urban floods Pollutant loading Recycle & reuse	Urban flooding control, minimization of pollutants discharged to natural waters and maximization of resource recovery
Overall management		Sustainable water service and urban water environment protection

(Schornikov *et al.*, 2014). Therefore, the restriction of overexploitation of source water is the main point of conventional water resources management. In case the conventional source water is insufficient for urban water supply, the utilization of alternative water sources should become a realistic option.

Alternative water sources development encompasses the utilization of the hydrological cycle and/or urban water cycle. For example, rainwater harvesting collects water directly in the processes of precipitation and/or surface runoff (Figure 6.1), while water reclamation from the discharged used water stream is through an interception of the outflow from the artificial component to the natural component of the urban water cycle (Figure 6.4). As rainwater is a seasonally obtainable source, its potential for utilization much depends on the natural and artificial storage capacity in the local area. In contrast, the reclaimed water can be viewed as a stable water source because an almost fixed amount of the used water is collectible daily. As far as economically and technologically permissible, there is no limit to water withdrawals from these alternative sources (Hiratsuka & Wakae, 2019).

6.4.2 Quality management

Quality management of water for meeting the requirement of water use has so far been a prioritized task. Of the various purposes of urban water use, drinking water requires a quality that should not cause any negative effect on human health after daily oral intake (Goncharuk *et al.*, 2018). Historically this was not difficult because water from natural sources was usually clean and after removing the naturally originating turbid and colored substances (usually by physicochemical processes of coagulation, sedimentation, and filtration when surface water was the source) and carrying out disinfection to inactivate pathogenic bacteria (usually by chlorination), the water could be made drinkable for tap water supply (Han *et al.*, 2020). Although additional treatment, such as carbon adsorption and more sophisticated processes including advanced oxidation, membrane filtration, and so on, have been required in many water purification plants due to source water contamination, the conventional coagulation-sedimentation-filtration treatment is still the basic process of water purification. For safe drinking water supply there is always a dilemma between source water protection and upgrading of drinking water treatment processes. From the viewpoint of water cycle management, the upmost principle should be to prevent foreign pollutants from entering the urban water cycle, so source water protection should be a wise choice.

The target of water quality management should also be placed on urban ecological health. As an urban planning term, ecological health refers much to the 'greenness' of cities for which the visibility of water is a very important factor (He *et al.*, 2020).

In fact, the quality for water use and that for ecological health are closely interrelated because when we put a city into its related watershed and consider them as a whole, without an ecological healthy condition for the watershed we may not obtain good source water to ensure good quality for various water uses.

6.4.3 Water use management

The conventional manner of urban water use is characterized by using tap water of drinkable quality for most or almost all domestic and municipal purposes. Although many cities have been practicing water-saving to reduce per capita and total water consumption, a large amount of high-quality tap water is still wasted because it is not consumed for potable use. In Section 6.4.1.1 we added alternative waters into the water resources for management. In most cases, these alternative waters are of inferior quality compared to freshwater. Unless necessary, it may not be an apt option to convert the quality of the harvested rainwater, or that of the reclaimed water, to drinkable level through sophisticated treatment processes and with high energy consumption. Therefore, 'fit-for-purpose' water use should be the principle of urban water use management.

Fit-for-purpose is a common term to describe the ideal level of quality for a given use (Coonrod *et al.*, 2020). Regarding water use, it first stresses the importance that various source waters should be rationally utilized. Freshwater from nature should be preferentially used for potable purposes while alternative waters, usually as supplemental sources, should mainly be used for non-potable water supply. Taking domestic (household) water supply as an example, of the per capita water demand ranging from several ten liters to several hundred liters per day in different countries and regions of the world (Kuski *et al.*, 2020), the amount actually used for drinking (including cooking) is no more than 20 liters. If the water for in-house washing, bathing, and toilet flushing is also accounted for, the required amount will be up to 50–80 liters (Tamura and Ogawa, 2012). The considerably higher per capita water demand or consumption than this required amount in many countries is an indication of overconsumption of tap water for other purposes, such as gardening, etc. which may not really need high-quality tap water. Dual-pipe water supply, one for potable and another for non-potable, can be an option for minimizing freshwater source utilization and facilitating alternative water use (Hambly *et al.*, 2015).

On the other hand, fit-for-purpose water use also implies that water quality conversion (treatment) before being supplied for a given use should meet the given quality criteria but not require over-processing. Taking water reclamation from discharged wastewater as an example, technologically it is possible to transform domestic wastewater into a potable quality level, such as what is done in Singapore for NEWater production (Schnoor, 2009). However, in most cases, the reclaimed water is used for gardening and urban irrigation, replenishing urban lakes/streams, and other environmental purposes. Therefore, the required treatment processes should be the most appropriate ones but not the most sophisticated ones, as long as water reuse may not result in negative environmental impacts (Wang *et al.*, 2018).

Water use management for minimizing freshwater consumption is an important task especially for cities facing water shortage problems.

6.4.4 Discharge management

In the urban water cycle depicted in Figure 6.4, the water to be discharged back to natural water bodies includes the used water and stormwater from the urban area, and related watershed. The task of discharge management to be discussed here deals with the quantitative and qualitative aspects.

Quantitatively, the used water discharged from various users is with an almost constant average flowrate, on a daily basis, and the urban sewage system, including sewer network, transfer pipelines, and treatment facilities, is designed with a capacity for the smooth conveyance of the sewage flow under ordinary conditions (e.g. in the dry weather). Parallel to the sewage system, an urban drainage system is also to be provided for discharging surface runoff on rainy days. The design of the drainage system is usually based on a given rainfall intensity corresponding to a prescribed return period (Hou & Ning, 2007). There are also cases of combined sewers that are designed to simultaneously collect surface runoff and sewage water in a shared system, especially in many older cities (Kamei-Ishikawa *et al.*, 2016). During dry weather or small storms, all flows are handled by the treatment facilities, while during large storms, some of the combined stormwater and sewage is allowed to be discharged untreated to the receiving waterbody. For diverting flows in excess of the peak design flow of the sewage treatment facilities, relief structures, which are called stormwater regulators or combined sewer overflows, are constructed in combined sewer systems. When constructed, combined sewer systems are typically sized according to a prescribed interception ratio (the capacity to carry a mixed flow of sewage and surface runoff over the average dry weather sewage flow). For either the separate or combined systems, smooth transmission of the sewage and surface runoff flows to prevent urban flooding is the main objective of discharge management in the quantitative aspect.

As the discharged flows eventually enter the receiving water bodies which are usually important water environmental elements of a city, their quality management is also required. For most cities, the reduction of pollutant loading of the sewage flow by proper wastewater treatment is the main measure to be taken. Many nations have put forward strict regulations on effluent discharge from treatment facilities for water environmental protection. Another trend is to incorporate water reclamation and useful materials recovery into the treatment scheme (Kog, 2020). On the other hand, surface runoff during a storm may carry pollutants from nonpoint sources to result in pollution of the receiving waters as well. Therefore, various measures are also taken within the scheme of low impact development (LID) and others for reducing pollutants (Eckart *et al.*, 2018). In the case of combined sewers, serious water pollution can be caused during combined sewer overflow (CSO) events when combined sewage and surface runoff flows exceed the capacity of the sewage treatment plant, or of the maximum flow rate of the system which transmits the combined sources (Rathnayake & Faisal, 2019). CSO management, thus, becomes very important for some older cities where combined sewers are still in service.

6.4.5 Overall management

Under the WCM principle, we should also stress the systematic management of the whole urban water cycle, targeting sustainable water services and urban water environmental protection. Each of the subsystems shown in Figure 6.4 is linked with others, as well as the natural elements of the watershed. Water from each of the utilizable sources is with its characteristic quality which meets the requirement of a specific purpose of water use after a minimum or simplest quality conversion process. The treated effluent from sewage treatment facilities and harvestable stormwater are also alternative sources for water use. Therefore, the discussions in Sections 6.4.1–6.4.4 for resource, quality, water use, and discharge management should be put into an overall management scheme.

6.5 WCM CONCEPT APPLICATION FOR WATER SOURCE ENLARGEMENT TO RESTORE A WATER CITY

6.5.1 Background

As an example of the WCM concept application, we introduce a case of urban water system planning in Xi'an, a megacity in northwestern China, to solve the problem of water shortage and the restoration of an aquatic city.

Xi'an was the ancient capital city of China. In ancient times, there was plentiful water running down from the nearby Qinling Mountains, feeding many rivers passing near the city and forming the ancient beauty of 'Eight Rivers Surrounding the Capital.' Over time, climate change, hydrogeological variation, rapid industrialization and urbanization, overuse, and improper management of the water resources all resulted in the disappearance of the ancient water quality and abundance. Located in the middle of the Yellow River basin, the annual precipitation in Xi'an is about 550 mm, yet the evaporation amount far exceeds this amount of rainfall. Although the Wei-River passing through the northern suburb of the city is the largest tributary of the Yellow River, due to the overconsumption of the river water in the upstream area, it is almost impossible, nowadays, to withdraw surface water for water supply to Xi'an. Groundwater used to be important source water, but for the prevention of ground subsidence, its development has to be strictly prohibited. Since the 1990s, more than 70% of the water supply to the central urban area has depended on water transfer from a set of dams about 140 km away, built on rivers originating from the Qinling Mountains.

Within the recent urban development plan, a major governmental investment project has been implemented. Aiming at a restoration of the ancient water city, the so-called 'Eight-Rivers Regeneration' project includes the construction of water supply lines, restoration of seven wetlands, rehabilitation of eight river channels, and reconstruction of 28 lakes and ponds, including some surrounding parks designed to imitate Tang Dynasty (AD 618–907, the most prosperous time of Xi'an as the ancient capital city) landscapes known from ancient illustrations. The project also includes the expansion of urban green spaces to make the city more resilient and environmentally sustainable. Figure 6.6 shows the general plan of the project.

However, one of the bottlenecks to this large project is the supply of sufficient water for maintaining a healthy urban water system, especially the 28 lakes/ponds that need water replenishment regularly to maintain their favorable environmental and landscape values. Under the current conditions, domestic, municipal, and industrial water demands are continuously increasing in this megacity of circa 10 million population and only a limited amount of water from natural resources can be allocated for environmental uses. Associated with the

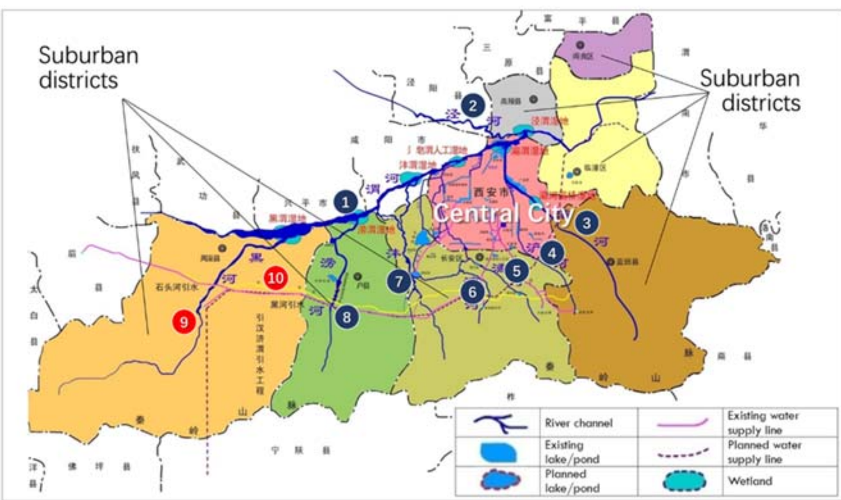

Figure 6.6 General plan of the 'Eight-Rivers Regeneration' project. For the river channels, Nos. 1–8 are the historical 'Eight Rivers' of Wei (a tributary of the Yellow River), Jing, Ba, Chan, Jue, Hao, Feng, and Lao; No. 9 is the source water river for water supply to Xi'an, and No. 10 is the water transfer channel (adapted from Xi'an Water Authority, 2013).

implementation of the project, a water source enlargement plan has been formulated following the WCM concept.

6.5.2 Water source enlargement plan

6.5.2.1 Requirement of source enlargement

For the 'Eight-Rivers Regeneration' project, water source enlargement solely targets replenishing the 28 lakes/ponds. Table 6.3 summarizes the results of water budget analysis for evaluating the required amount of water to be supplemented.

The average available water resources for Xi'an amounts to 2347 million m^3/yr (Xi'an Water Authority, 2019). If the current total population of 10.2 million is considered (Xi'an Municipal Bureau of Statistics and NBS Survey Office in Xi'an, 2020), the per capita water resource is only about 230 m^3/yr, indicating a severe water shortage condition for this city. As water resources should be prioritized for domestic and production water supply, the amount of water allocated for the environment is very limited. As shown in Table 6.3, the currently available water source of 141 million m^3/yr, mainly from natural stream flows, for replenishing these lakes and ponds is far below the total demand of 304 million m^3/yr, which is calculated based on the requirement to maintain a favorable landscape for each lake or pond.

6.5.2.2 Source enlargement measures

There are generally two categories of measures to be taken for the enlargement of water sources for replenishing urban lakes/ponds, namely, alternative water resource development and increasing water use efficiency.

Table 6.3 Results of water budget analysis for lakes/ponds replenishment.

No	Item	Unit	Value	Remarks
1	Water surface area	ha	2060	
2	Storage volume	million m^3	65	
3	Annual net evaporation loss	million m^3	5.4	Evaporation – Precipitation
4	Annual leakage loss	million m^3	4.6	Local experiential data
5	Replenishment plan	time/yr	4~6	Lake/pond specific
6	Annual replenishment amount	million m^3/yr	294	Sum of all lakes/ponds
7	Total water demand	million m^3/yr	304	Sum of items 3, 4 and 6
8	Currently available water source	million m^3/yr	141	Mainly from streamflow
9	Annual water deficiency	million m^3/yr	163	Deference of items 7 and 8

6.5.2.2.1 Alternative water resource development

As a megacity, there are currently 22 centralized domestic wastewater treatment plants in operation and the volume of wastewater treated amounts to about 2.2 million m^3/d. About 0.385 million m^3/d of this wastewater is produced as reclaimed water with quality meeting the standard for environmental reuse including recreational water replenishment (Xi'an Municipal Bureau of Statistics and NBS Survey Office in Xi'an, 2020). The potential of reclaimed water use for non-potable supply is about 140 million m^3/yr at present and will increase to about 215 million m^3/yr in 2030. This is the most promising alternative water resource for the project.

Another alternative water resource can be from rainwater harvesting. Although most of the lakes/ponds do not have considerable catchment areas for receiving sufficient amounts of natural runoff, as they are mostly built on low-lying lands, it is possible to implement measures that connect their inlet structures with local stormwater regulation and drainage facilities. For effective harvesting of rainwater or stormwater runoff, the provision of sufficient storage volume is usually required. Fortunately, these lakes and ponds have their own storage volume to meet this requirement.

6.5.2.2.2 Increasing water use efficiency

One important characteristic of landscape water use is that there is no actual water loss other than surface evaporation and subsurface leakage. The main purpose of water replenishment is to renew the lake water so as to prevent water quality deterioration due to long-term stagnation. In the project area, the hydraulic retention time (HRT) for small-scale urban lakes or ponds is preferably two months, whereas that for a larger lake can be up to three months, from past experiences (Chang *et al.*, 2020). As shown in Table 6.3, the required amount for replenishment is far larger than that for evaporation and leakage. As long as the water quality can be secured, water may be used more than once for replenishment purposes. Cycling flow may be a measure for individual lakes or ponds, but it may be more feasible to practice cascading water use between lakes if elevation difference can be utilized for gravity flow. On the other hand, water use efficiency may also be increased by flow regulation between streams connecting lakes and ponds.

6.5.2.3 Formulation of a quasi-natural water cycle for water source enlargement

Putting all the available natural and alternative sources into an integrated application scheme, a quasi-natural water cycle is conceptually formulated as shown in Figure 6.7.

This water cycle covers the watersheds where Xi'an city is located (approximately the whole area shown in Figure 6.6). The natural component of

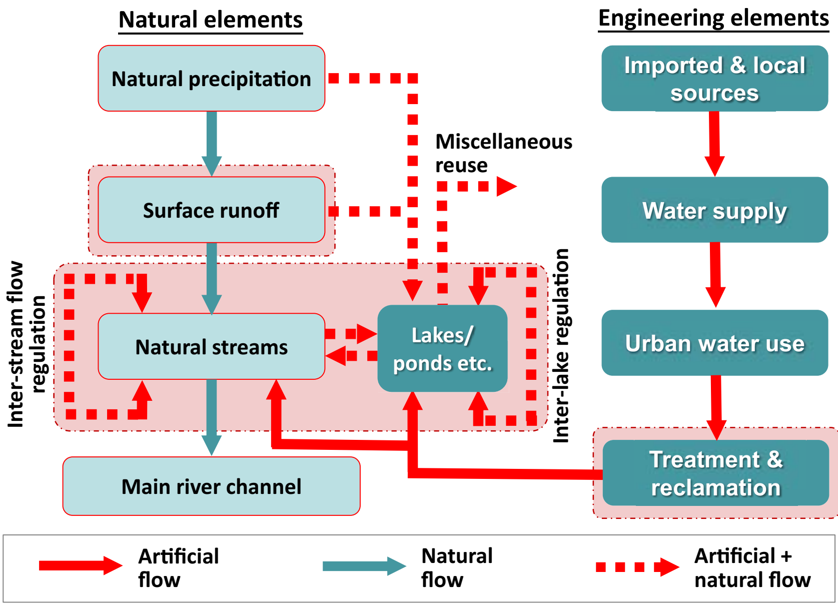

Figure 6.7 A quasi-natural water cycle for integrated water management to enlarge water sources for the 'Eight-Rivers Regeneration' project. A, B, and C are the three measures of water source enlargement as water reuse, rainwater harvesting, and cascading water use, respectively (figure by authors).

the water cycle includes all the hydrological elements, such as atmospheric precipitation, surface runoff, and natural streams shown in Figure 6.6. The Wei River (No. 1 in Figure 6.6) is the main river channel receiving all stream flows. The artificial or engineering component of the water cycle includes all the engineering facilities for water sources, water supply, water use, and wastewater treatment, and final disposal. For this project, as special attention is paid to the lakes and ponds which need water replenishment, these water bodies become hydraulic nodes between the natural and engineering components. On one hand, as open water bodies, they may receive natural precipitation, stormwater runoff, and/or stream water replenishment. On the other hand, the reclaimed water from domestic wastewater treatment facilities can become an important source for water replenishment.

Within such a quasi-natural water cycle, source enlargement can be fulfilled by three measures, namely water reclamation from domestic wastewater (A in Figure 6.6) which is a source with almost constant flow, rainwater harvesting from surface runoff (B in Figure 6.6) which is a seasonal water source, and cascading water use (C in Figure 6.6) including inter-stream and inter-lake flow regulations. The lakes and ponds, as well as the river channels, also provide a water storage volume buffering between water supply and uses.

6.5.2.4 Implementation plan

Following the source enlargement measures discussed in Section 6.5.2.2 and the scheme of the quasi-natural water cycle discussed in Section 6.5.2.3, engineering implementation plans have further been formulated.

6.5.2.4.1 Water supply network

A water supply network is provided by utilizing the rehabilitated river channels, water transfer channels, and pipelines, and with River Wei as the receiving water (Figure 6.8). This network links between six domestic wastewater treatment plants where reclaimed water is supplied, three local reservoirs where the stored natural flow is supplied, a number of outlets from the urban drainage system where stormwater can be supplied as needed, and inlets of the lakes and ponds that need water supply for replenishment. Such a network enables systematic management of the available natural and alternative source water for the project.

6.5.2.4.2 Source water distribution

The lakes and ponds shown in Figure 6.8 are fed with river water, water from local reservoirs through water supply lines, reclaimed water from nearby WWTPs, local rainwater harvesting facilities (not shown in Figure 6.8 in detail), or multiple sources depending on their locations and source availability.

For lakes and ponds adjacent to the rehabilitated river channels, direct use of the river water is preferable from both the quantity and quality aspects. In addition to

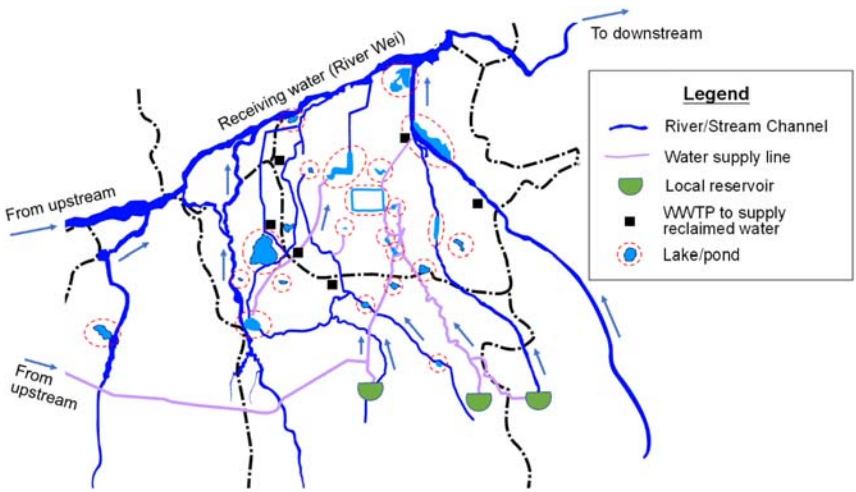

Figure 6.8 Water supply network with river/stream channels linking between local reservoirs, WWTPs, and lake/pond inlets and outlets for natural/alternative water supply and receiving outflows (adapted from Xi'an Water Authority, 2013).

these natural rivers, several drainage channels in the central urban area are also utilized for source water distribution. In rainy seasons their main functions are still stormwater drainage while in dry seasons they become water channels for transferring reclaimed water from WWTPs and/or harvested rainwater from storage facilities to lakes/ponds as alternative sources for water replenishment.

6.5.2.4.3 Realization of cascading water use

Topographically, Xi'an has a ground slope from the mountain foot to its south to the main channel of River Wei to its north. For a group of lakes with their elevations of water surface descending along the ground slope, cascading water use can be made possible between them by using the outflow from a lake at the upstream side as the inflow to another lake at the downstream side. This is mainly for the case of a series of lakes supplied with natural water from the same local reservoir for a reduction of the total demand for such types of high-quality source water.

With the water supply network shown in Figure 6.8, water regulation between different river/stream channels for mitigating the imbalanced demand-supply relationship can also be made possible for more reasonable and efficient use of the limited water resource.

6.5.2.4.4 Water quality protection

The formulation of the water network shown in Figure 6.8 has well realized the basic consideration of a quasi-natural water cycle of Figure 6.7. It fully utilizes part of the urban watershed where a number of natural streams flow toward a common receiving water. All artificial water structures, including the water lines, lakes, and ponds, are harmoniously superimposed onto the natural flow system and add its new hydrological elements without altering the hydrological characteristics of the original watershed. Such a water system not only enables the smooth distribution of water to each of the lakes and ponds for replenishment but also assists water quality protection and even improvement because the good flow and circulation of water in the whole system significantly increase the self-purification capacity.

Water from natural streams and local reservoirs are of good quality in terms of organic content (COD or BOD) and nutrients (P and N) as the most favorable water source for lake replenishment. The harvested rainwater, if the initial surface runoff with high pollutants concentration is not included, is also good for lake replenishment. In contrast, the water reclaimed from domestic wastewater, though well treated in WWTPs, is usually with higher concentrations of organics and nutrients. This is, in many cases, an obstacle for using reclaimed water as the sole source for replenishing landscape lakes due to the possible occurrence of water eutrophication. Through the water network shown in Figure 6.8, water quality deterioration is prevented by: (1) allocation of larger amounts of flow to the lakes that are solely replenished by reclaimed water so as to shorten their hydraulic retention time for the prevention of algae growth; (2) dilution of the reclaimed water with water from other sources during water distribution; and (3) artificial flow circulation within the water body or between water bodies.

6.5.3 Effects of water source enlargement

The implementation of the water source enlargement plan through the quasi-natural water system discussed above has mitigated the problem of water shortage for the replenishment of lakes and ponds restored and/or built within the 'Eight-Rivers Regeneration' project. Table 6.4 summarizes the overall effects. The conventional source includes water directly from natural streams and local reservoirs, which amounts to 141 million m^3/yr, as indicated in Table 6.4. The alternative sources include the amount of water supplied to some of the lakes through cascading water use (amounting to 56 million m^3/yr), water harvested from surface runoff in rainy seasons (amounting to 24 million m^3/yr), and reclaimed water from WWTPs (amounting to 86 million m^3/yr). The total amount of water from alternative sources reaches 166 million m^3/yr and has covered the annual water deficiency of 163 million m^3/yr indicated in Table 6.4. This indicates that by the management of the quasi-natural water cycle shown in Figure 6.7, the available water source can be enlarged to meet the needs for replenishing the 28 lakes and ponds. Of the total amount of 307 million m^3/yr to be supplied for lakes/ponds replenishment, that from the conventional water sources, namely stream flows, takes 45.9%, while that from alternative sources takes 54.1%.

It is notable that cascading water use virtually covers 18.3% of the water supply for some of the lakes and ponds. Although this is not truly an amount of water adding to the water source, an equivalent amount of high-quality stream flow is effectively saved due to the improvement of water use efficiency.

For environmental water use in a megacity in water-deficient regions, reclaimed water is an important alternative source. For this project, reclaimed water covers 28% of the water supply for lakes/ponds replenishment. Through the water

Table 6.4 Water supply for lakes/ponds replenishment by various water sources.

Water source		Annual supply (million m^3/yr)	Percent of supply (%)
Conventional source	Streamflow[a]	141	45.9
Alternative source	Cascading water use[b]	56	18.3
	Rainwater harvesting[c]	24	7.8
	Reclaimed water[d]	86	28.0
Total		307	100.0

[a]From natural streams and local reservoirs.
[b]For lakes/ponds in series.
[c]Combining with utilization of urban drainage system.
[d]Supplied from domestic wastewater treatment plants.

supply network shown in Figure 6.8, reclaimed water use is practiced either by using it as the sole source or mixing it with water from other sources. With the increased percentage of reclaimed water use, more frequent replenishment is required for maintaining a favorable landscape condition (Ao *et al*., 2018).

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