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Dualistic water cycle pattern and its evolution in Haihe River basin

LIU JiaHong[1*], QIN DaYong[1,2], WANG Hao[1,2], WANG MingNa[1] & YANG ZhiYong[1]

[1] *China Institute of Water Resources and Hydropower Research, Beijing 100038, China;*
[2] *Research Center for Water Resources and Ecology of the Ministry of Water Resources, Beijing 100044, China*

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The Haihe River basin is widely recognized as an area in China which is most severely affected by human activities. The water resources utilization and recycling in the basin is very complex, and the characteristic of the dualistic water cycle is becoming more and more prominent. The ever-growing demand of water for modern industry and domestic life nearly dries up all the natural runoff. Meanwhile, industrial, agricultural and domestic wastewater discharges cause severe deterioration in water quality. Consequently, many of water courses are either dried out or being heavily polluted. Modern water resources management can no longer rely on the "monitoring-rehabilitation" model which was originally developed based on the natural water cycle. This paper analyzes the critical characteristics, water balance, and evolution of water flux process based on the theory of dualistic water cycle. Referring to the water cycle in the Haihe River basin, a schematic diagram was drawn to describe the dualistic water cycle pattern. Ten different parameters affecting mainly the evolution of water flux in the "dualistic water cycle" are closely examined using the newly-collected data. As a result, this paper proposes several water management and control strategies to achieve healthy water status for the Haihe River basin.

dualistic water cycle, water resources, social water cycle flux, human activities, Haihe River

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The water cycle in natural river basins is becoming increasingly complex with the ever expanding human activities in modern society. Natural water cycle traditionally relies on solar radiation and the Earth's gravity as the main driver. This has been changed to a dual-power driven, "natural-artificial" system. Water quality cannot be simply defined by relatively simple components of the natural organic compounds, minerals and sediment; there are thousands of chemical components added in water, including fertilizers, pesticides, industrial detergents, persistent organic compounds, medical antibiotics, hormones and many others. Thus, characteristics and signatures of "dualistic" water cycle in river basins are presented in both quantity and quality of water flux.

In 1997, Raskin et al. [1] developed one of the earliest global assessment models of freshwater resources. Their model did not consider the influence of human activities. Subsequently, another model, Water global assessment and prognosis (Water GAP) tool (Döll [2,3]) was developed to make up for the shortage. Water GAP consists of two modules: the world's water consumption module and the world's hydrological module; and it can be regarded as the first global "dualistic" water cycle model. In addition, the SWAT model [4,5] operates at a regional scale; Imbe's model [6] which simulates evaluation and rehabilitation of urban water cycle, operates at the city level.

In China, Wang et al. [7] proposed the theory of "dualistic water cycle" and developed the WEP-L model [8] to simulate the natural-artificial" dual water system for large river basins. The concept of "dualistic water cycle" and its application for water resources assessment were further enhanced and tested in the Heihe research project [9]. Wang et al. [10] developed an ecological water demand model for river water and water quality calculation based on the "du-

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*Corresponding author (email: liujh@iwhr.com) alistic water cycle" framework. Li et al. [11] analyzed the effects of artificial disturbance on the Taizi River based on a "natural-artificial" dual structure of the water cycle model. Previous studies adopted the notion that human impact on water cycle must be considered separately since it is not part of the natural water cycle. These studies explicitly attempts to describe the impact of human activities and socioeconomic factors on the amount of water flux, thus concentrating in understanding the relationship between various parameters that are used to describe human impacts and the effect of incorporating these parameters in simulation models.

1 Dualistic water cycle

In ancient times, when the natural water cycle was dominant and was not impeded by human activities, water cycle in natural river basin could be generally regarded as consisting of five main fluid fluxes (ocean-to-basin water flux, basin-to-outward water flux, precipitation, evapotranspiration and runoff) and four major state-variables (atmospheric water, surface water, soil water and groundwater).

In most part of the natural water cycle era, the annual fluid fluxes in circulation were relatively stable, with cyclical changes caused by fluctuations in solar radiation intensity and atmospheric movements; the four major state-variables also experienced cyclical changes over time, and they were in the states of dynamic balance.

As human gathered strength to transform nature via various activities (e.g. pumping water from riverside, construction of water reservoirs for further abstraction, exploitation of groundwater from greater and greater depths, interbasin water transfer and so on), the natural water cycle has been modified considerably. Such human activities induce the so-called five basic aspects of the artificial collateral circulation (also known as "social water cycle"): abstraction, transportation, utilization, drainage, and return.

Modern water cycle encompasses the two main components: the original natural water cycle driven by solar radiation and gravity and the artificial water cycle caused by human activities. Besides this change in driving forces, the water channel now includes both natural rivers and artificial channels with flow paths crisscrossing different parts of the system, forming an unmistakably "natural-artificial" dual water cycle. Figure 1 shows the "dualistic water cycle" in the Haihe River basin.

1.1 Definition

The "dualistic water cycle" pattern is an abstraction of the dual power-driven "natural-artificial" water circulation system shown in Figure 2. The water in the dual water circulation system is from two main sources: the ocean-to-basin water flux (W_{SC}) that comes with the monsoon; and the evapotranspiration flux from within the basin (W_{ET}).

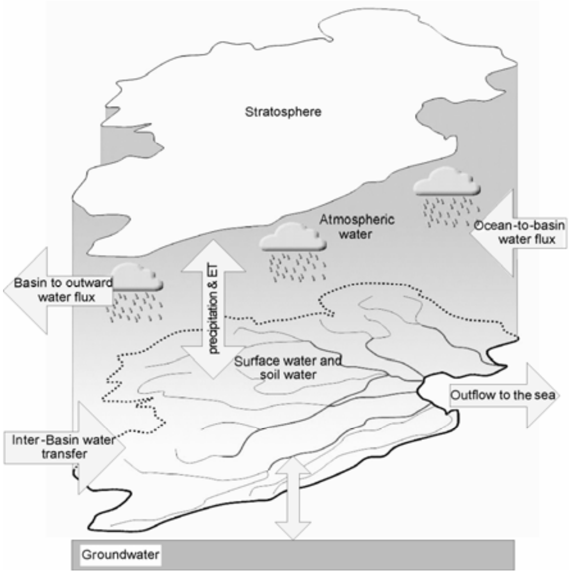

Figure 1 Dualistic water cycle in the Haihe River basin.

From Figure 2, water vapor reaches the ground through the condensation precipitation (W_p) and returns to the atmosphere or the ocean via three pathways:

(1) Precipitation → soil water (groundwater) → vegetation water → atmospheric water. The pathway is denoted as W_{ETN}.

(2) Precipitation → runoff (groundwater) → artificial water (pumping) → drainage (or evaporation) → discharge into the sea (or into the atmosphere). The pathway is denoted as W_S and can be subdivided into W_{ETA} (evaporation to the atmosphere pathway), W_I (groundwater recharge through infiltration pathway), W_{dr} (drainage into sea outflow pathway).

(3) Precipitation → runoff → sea. The pathway is denoted as W_{nr}.

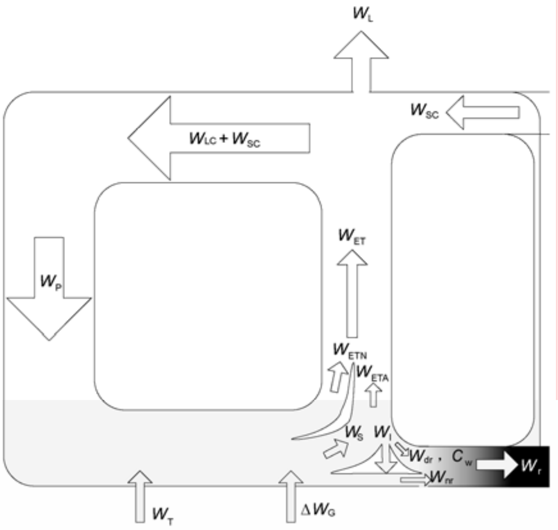

Figure 2 The schematic diagram of the dualistic water cycle pattern.

In subhumid and semiarid basin where precipitation (W_P) is relatively small, social water flux (W_S) due to industrial and agricultural production, and livelihood needs may be larger than local precipitation. Hence local water resource is insufficient to support the sustainable development of the basin. As the severity of human disturbance increases, there has been overexploitation of groundwater (ΔW_G) and interbasin water transfer (W_T) as two new sources of water. At the same time within the basin during the monsoon, water vapour will dissipate outward to form a dissipation of water vapour (W_L). In the evolution of water quality within the water cycle, as the industrial and agricultural production and the deterioration of life characteristics of water, "social water" contains large quantities of pollutants (C_W), hence the water quality of runoff into the sea (W_r) is very poor.

Water cycle can be divided into three types according to the space of occurrence namely, major cycle (also known as "sea-continent cycle"), marine cycle (also known as "inner sea cycle"), and land cycle (also known as "inner land cycle"). Since the "inner sea cycle" has negligible effects on the water cycle in river basin, it is omitted in the "dualistic water cycle". The "inner land cycle" refers to the transportation of water over different parts of land surface only [12]. As the catchment boundary is not entirely closed, water molecules that originates from within the basin do not necessarily confine to the same basin and it is possible dissipation outside the catchment; similarly, water molecules from outside the catchment may also fall within the catchment. In this aspect, the "inner land cycle" is in fact a relative concept which takes into the dynamic exchange within the catchment, and losses during circulation (W_L) should be included as losses of moisture dissipation. The "sea-continent cycle" refers to the water cycle from sea to continent and back to sea. Due to the global connectivity between atmospheric water vapour, water molecules from within the basin may not end up as runoff to the sea. They may return to the sea through other catchment or pathways. Hence such component is also credited to the dissipation of water vapour as W_L.

To facilitate the discussion, the following definitions are used in this paper: the unit for a hydrological period is typically one year; W_{LC}-Water flux (quantity) from the "inner land cycle" for a hydrological period; W_{SC}-Water flux (quantity) from the "sea-continent cycle" for a hydrological period.

The relationship between the different water fluxes can be given by the following equations:

$$W_P = W_{LC} + W_{SC}, \tag{1}$$

$$W_P + W_T + \Delta W_G = W_{ET} + W_r, \tag{2}$$

$$W_L = W_{ET} - W_{LC}, \tag{3}$$

$$W_{ET} = W_{ETN} + W_{ETA}, \tag{4}$$

$$W_S = W_{ETA} + W_I + W_{dr}, \tag{5}$$

$$W_r = W_{nr} + W_{dr}. \tag{6}$$

1.2 Key parameters/variables

The dualistic water cycle pattern evolved from the natural water cycle pattern, and has thus inherited many parameters of the natural water cycle such as five main fluid fluxes (ocean-to-basin water flux, basin-to-outward water flux, precipitation, evapotranspiration and runoff) and four major state-variables (atmospheric water, surface water, soil water and groundwater). At the same time, in order to consider human activities, five additional fluxes were added, namely: interbasin water-transfer, overexploitation of groundwater, social water cycle flux (quantity), wastewater discharge and outflow quantity. The dualistic water cycle pattern also includes capacities of artificial surface storage works such as reservoirs, dikes, levees, terraces, etc.

Artificial surface storage works serve to only change the spatial distribution of surface water bodies, without changing the water fluxes in the process. As water moves from upper reservoirs to downstream reservoirs, river channels may dry up in the process, and the two retention effects cancelled out each other. Hence in the "dualistic water cycle" model, artificial surface retention is not regarded as an independent factor, but is implied as part of the surface water flux/cycle. Within the "dualistic water cycle" pattern, water flux is the link that threads all the ten flux and four instantaneous states. The flux is the key factor that plays a decisive role, and the instantaneous state of the cycle is the result of dynamic flux.

1.3 The evolution process

There is no clear boundary between "dualistic water cycle" and the natural water cycle; however, it should be noted that the natural water cycle has been disrupted by human activities since historical times. It is predictable that water cycle will continue to evolve as society progresses, notably increasing the components of artificial water cycle; in subhumid and semiarid regions, the rate and quantity of abstractions from surface water may exceed the total available surface runoff, forcing inhabitants to extract precious deep groundwater that is difficult to replenish. Such overexploitation also affects water available to maintain ecological functions.

Figure 3 is a schematic diagram of the evolution of the five parameters/variables in the "dualistic water cycle". Since the industrial revolution in England in the 18th century, water usage and demand in social system (caused by increasing human activities) has been rising continuously. At the beginning of the 21st century, some developed countries were able to successfully impose water saving policies and convert their economy to be less reliance to water as a primary resource. As a result, the annual increase in total water consumptions was slowed down. The general trend of water discharge from the social water cycle mimics that of water abstraction. At the end of the 20th century, as the intensity of water shortage increased, there was a surge of interests in wastewater recycling and reuse. As a result, there is a drop in the wastewater discharge rate compared with the increase in the abstraction rate. This trend is also demonstrated in the water quality along the Thames River, England. Industrial waste polluted the river in the mid 19th century. The situation had not been changed until the 20th century, in which the trend of heavily polluted water was halted via the construction of major wastewater treatment plants.

Overexploitation of groundwater is not a phenomenon occurring recently: while first occurring in populated cities in the 1960s–1970s, extensively deep well abstractions were used in the 1980s due to advances in deep well irrigation technology. On the other hand, in order to alleviate water crisis and to maintain water balance, various interbasin water transfer schemes were implemented in the 1950s. Following the successes of these major water transfer projects and the degree of protection of groundwater, overexploitation of groundwater is predicted to disappear in the middle 21st century.

It can be seen from the evolution of components of the water cycle process that the changes from natural water cycle (single dimensional) to the pattern of the dualistic water cycle have experienced a quantitative to qualitative change. According to the data of UNESCO's "21st Century World Water Assessment" [13] report in 1995, the global social water flux (quantity of water) was about 3750 billion m^3, with wastewater discharge of 1480 billion m^3, the total global consumption of water was estimated to be around 8.4% of total available water. Due to the uneven distribution of water resources and population, 75% of the world's population lives in areas with a high level of water resources utilization, usually greater than 20%. In areas such as southern and central Europe, the utilization rate of water is around 24%–30%, the Niagara Falls area in the United States is around 28%, and the Haihe River basin in China is as high as 100% [14].

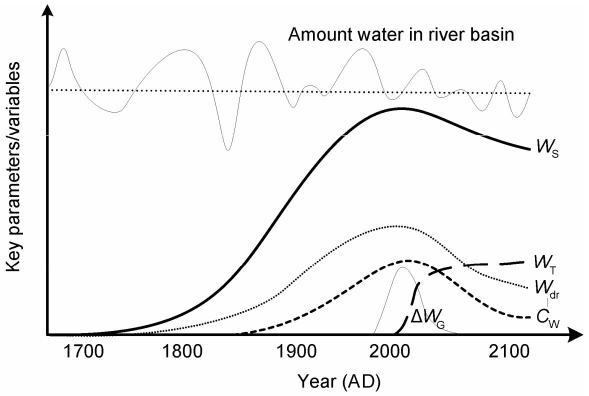

Figure 3 Schematic diagram of the evolution of key parameters/ variables.

2 Evolution of dualistic water cycle in the Haihe River basin

The Haihe river basin is one of the most severely disrupted regions in China, with prominent features of "dualistic water cycle" and typical evolution processes of "natural-artificial" water cycle. In this paper, the latest statistical data and published scientific data concerning the Haihe River basin were analyzed in order to determine the evolution characteristics of "dualistic water cycle" in the basin. However, since the first national census on pollution sources is still ongoing, the latest available data for the catchment are from the previous Haihe River basin water resources assessment report.

2.1 Ocean-to-basin water flux

The atmospheric circulation over the Haihe River basin consists mainly of convergence of main current from two directions: (1) South-east Pacific Ocean current; and (2) South-westerly Indian Ocean current. The main source of oceanic flux is from the South-westerly Bay of Bengal atmospheric current. Zhang et al. [15] simulated the Haihe River basin atmospheric circulation by an 8-layer model using data from the US Environment Protection Committee/National Centre for Atmospheric Research (NCEP/NCAR) (1949–2002). When confining to a region of 112°E –120°E, 35°N–43°N, with an area of about 610000 km^2, they found that the main atmospheric current entered the Haihe region from the south and west boundary and left from the north and east boundary.

Based on the results from Zhang et al. [15], further calculations were made for the volumetric oceanic water vapor input and output (Table 1). During the extremely wet years in the 1960s, the oceanic water vapor flux had a net positive surplus, and the Southerly current was greater than the Westerly by a ratio of 3:2. The net catchment water vapor flux in summer was about 139.6 billion m^3, which was 78% that of the average annual precipitation in the 1960s. Towards the end of last century (1990s), the global climate experienced a period of anomaly. The oceanic water vapour flux in summer decreased greatly by 80% to 27.2 billion m^3; the Southerly current water vapor flux reduced from 359.1 to 82.4 billion m^3; comparing this with the Westerly flux of 90.2 billion m^3, the dominant circulation was no longer from the Southerly current. In summary, over the last 50 years, the volume of ocean water entering the Haihe River basin followed a significant decreasing trend, mainly from the reducing influence of the southerly main current channel. It is important to note that after the 1990s, the water flux moving across the Yellow River to the Haihe region is very low.

The main reason for this situation is that there has been a rise in sea surface temperature from tropical east to the Pacific Ocean since the late of 1970s. It is an inter-decadal sea surface temperature anomaly that called the "El Niño" phenomenon. Since 1976, the West Pacific subtropical

Table 1 Vapor flux in the Haihe basin in summer

Period	Input boundary		Output boundary		Net vapor input	Net input in the Haihe Basin[a]
	South	West	East	North		
1960–1969	3591	2269	1677	1391	2792	1396
1990–2002	824	902	734	447	544	272
1949–2002	1992	1396	1302	858	1228	614

a) The area of the Haihe River basin is half of the calculation area, so we estimated the net vapor input in the Haihe basin as half of that in the calculation area.

pressure zone has a considerable diversion of southwest away from its normal location, which leads to a significant weakening of the East Asia summer monsoon. Such anomaly is not conducive to summer precipitation in North China [16,17].

2.2 Basin-to-outward water flux

As seen from Table 1, the catchment water vapour output mimics the reduction trend in oceanic water vapour input, although the rate in reduction for output is lower than that of oceanic input. In the 1960s, water output decreased by about 60%, while ocean water vapour input over the same period decreased by about 70%. This indicates that the net dissipation coefficient has increased which is likely to be related to large-scale water-related human activities in the Haihe River basin. Human activities typically increase the rate of evapotranspiration (ET) [18,19] which dissipates the storage within the catchment and creates a state of dynamic deficit for both surface and groundwater.

2.3 Precipitation

The Haihe River basin has a semiarid and subhumid climate with an average rainfall of 527 mm (from 1956 to 2007). Monthly distribution of precipitation within one year is uneven. The wet months (June–September) account for 75%–85% of the annual precipitation; and 56% of them concentrate in the wettest 30 days (accounting for 45% of the annual precipitation). There is also large inter-annual variation of precipitation, especially in between dry years. Since 1470 when yearly record began [20], there have been 3 occasions of consecutive drought that last more than 12 years; 15 occasions of consecutive drought that last more than 7 years; and 44 occasions of consecutive drought that last more than 3 years. Figure 4 shows the annual precipitation from 1956 to 2007. In general, there is a gentle downward trend of precipitation in the Haihe River basin. From 1978 to 2007, the average annual precipitation is only 499 mm, which is generally regarded as a drought period. The annual average precipitation is much lower than that between 1956–1977 (565 mm).

2.4 Evapotranspiration

Under the strong interference of human activities, actual evapotranspiration for the Haihe River basin shows an overall upward trend. Between 1956 and 1979, the average annual evapotranspiration is 470 mm (the first national water resources assessment results) [21], which is 90 mm less than that of the annual average precipitation for the same period. With the increasing human activities, coupled with a large number of interbasin water transfer schemes and exploitation of groundwater for various uses (such as socioeconomic systems, industrial and agricultural production, living and urban ecological water demand), the overall annual evapotranspiration of the Haihe River basin could be equal to or greater than the precipitation for the same period.

Based on the baseline data from the Haihe 973 project (National Basic Research Program of China), the evapotranspiration rate has increased by 20 mm (amounting to 6.4 billion m^3 around the Haihe River basin) compared with that for the 1950–1970s. Based on the water consumption ratio of 65% for human activities and the total water usage of 400 billion m^3, the estimated ET (evapotranspiration) due to human activities is 13 billion m^3.

2.5 Runoff

Due to the interference of human activities, the natural runoff of the Haihe River basin has reduced tremendously. Currently, most of the sea outflow from the Haihe River basin is industrial and domestic wastewater except for the Luan he River and the Tuhaimajia River which still have minimal natural runoff (refer to eq. (6)). In this paper, the term "surface water flow" (normally refers to the dynamic volumetric flow of surface water bodies including rivers and lakes) is used to represent the volumetric runoff from the Haihe River basin.

According to the first and second water resources assessment reports [22], the annual average surface water resources for the Haihe River basin for the period of 1956–1979 was 25.65 billion m^3 and that of 1980–2000 was 17.05 billion m^3, showing a reduction of 33.5%, and further reduced to 10.59 billion m^3 for the period of 2001–2007, with a decrease of 58.7%. The reduction to sea outflow from the Haihe River basin is even more alarming: from 1980 to 2007 the average annual outflow was 3360 million m^3, compared with 15.54 billion m^3 for the 1956 to 1979 period, which is a decrease of 78%. The average outflow volume was only 18.3 million m^3 from 1998 to 2007 (based on published data from various governmental sources). The reduction in runoff can be attributed to 2 main reasons: (1) global climate change resulting from the reduced precipitation; and (2) human activities causing imbalance in the distribution of natural water cycle, thus reducing the availability of water in the natural system for various functions.

2.6 Water use and consumption

According to a comprehensive report on the country's total

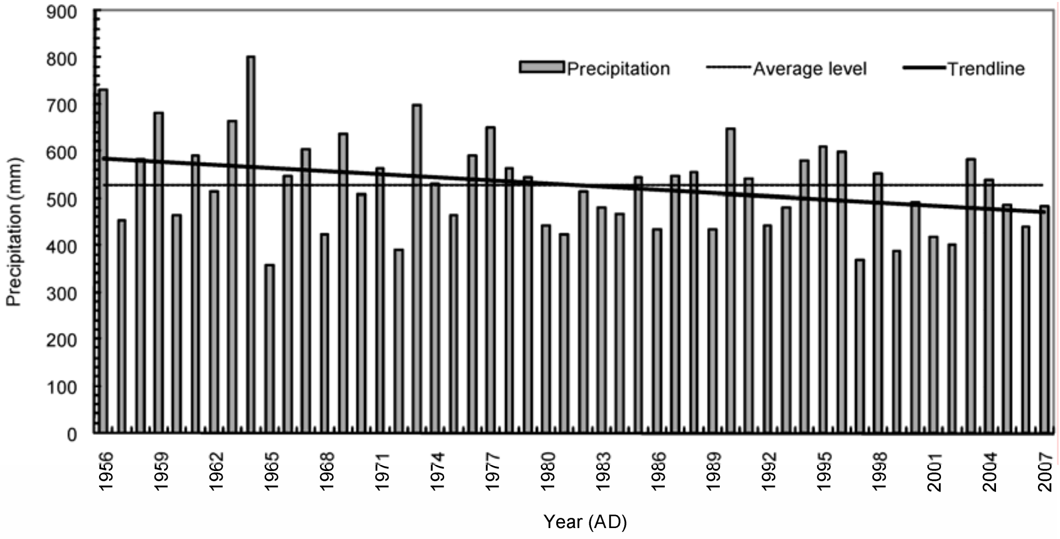

Figure 4 The precipitation series from 1956 to 2007 in the Haihe basin.

water consumption (which is part of the “China’s Water Resources Strategic Research on Sustainable Development”), water used in the Haihe River basin in 1949 was about 10 billion m^3. With the expansion of irrigated areas and industrial/domestic water consumption, water consumption increased year by year to more than double at the end of the 1950’s. In 1965, the water used was 26.8 billion m^3, which included the 5.0 billion m^3 water transferred from the Yellow river. Despite the water from the Yellow river, this quantity was still larger than the average annual surface water of 21.6 billion m^3. Thus, there was a frantic search for new surface water and groundwater as a potential source. The water used in 1980 was nearly 40 billion m^3, and since then, the range of water used has been between 34–44 billion m^3. The average water used is 39.9 billion m^3.

(1) Industrial water use. The Haihe River basin experienced a rapid rise and slow descent in industrial water use over the years as shown in Figure 5. The first half of 1990s is a period of rapid growth in terms of water usage of only around 7 billion m^3 constrained by a resource limitation. A decline then followed, especially in 2001 with the increasing acceptance of water saving devices and advances in water recycling technologies. After 2003, industrial water use dropped to 6 billion m^3, a decline of 1 billion m^3 from the peak.

(2) Domestic water use. It can be seen from Figure 6 that the domestic water use has been increasing since the end of last century. In 1980, the total water use was 2 billion m^3, but in 2006, it was 5.66 billion m^3. Since then, the total domestic use has been kept at around 5.63 billion m^3.

(3) Water used for ecosystem. Prior to 2003, ecological water use of the Haihe River basin fluctuated according to the availability of natural water resources. However, the ecological water use has been rising rapidly since 2003, because the society began to recognize the necessity to protect the ecological environment. Between the period of 2003 to 2007, the ecological water use increased by nearly two folds, reaching 0.56 billion m^3.

2.7 Wastewater discharge

Wastewater from the Haihe River basin comes mainly from two sources: agricultural discharge and urban discharge

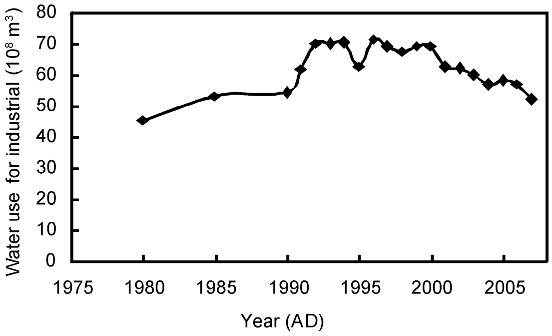

Figure 5 Annual amount of water use for industry in the Haihe River basin (1980–2007).

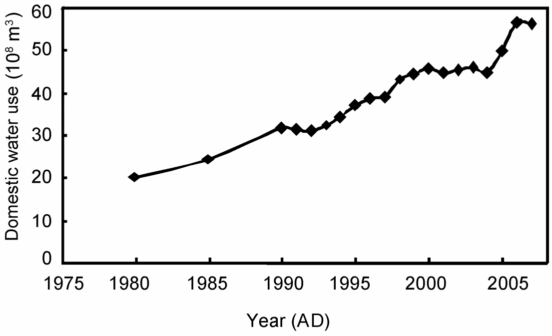

Figure 6 Annual amount of domestic water use in the Haihe River basin (1980–2007).

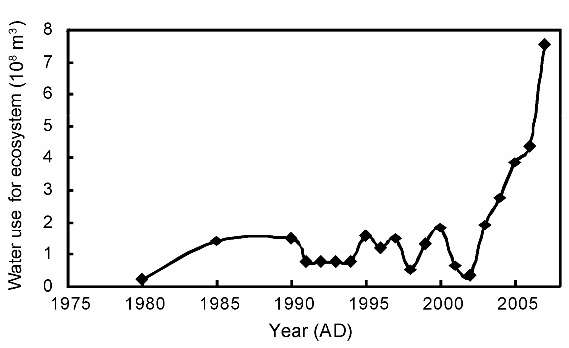

Figure 7 Annual water use for ecosystem in the Haihe River basin (1980–2007).

(comprising industrial and domestic wastewater). The main source of information for wastewater discharge is from the published "Haihe River basin water resources annual report" (1998–2006).

(1) Agricultural discharge. Table 2 shows the agricultural discharge of the Haihe River basin from 1998 to 2006. As the Haihe River basin consists of predominately dry lands, excess water from agricultural irrigation mainly infiltrates into the ground to form part of groundwater. There is very little evidence of direct runoff from agricultural land.

(2) Domestic and industrial discharge. Table 3 shows the domestic and industrial discharge from 1998 to 2006. It is evident that the difference between water used and water consumption was bigger than the total wastewater discharge, indicating that part of the discharge had been reused. In 1998, there was a high rate of water reuse but the amount of grey water recycling is relatively insignificant. This indicates that the mode of water reuse was predominantly that the wastewater discharge of the upstream was abstracted and reused by the downstream. Such a mode of water reuse is greatly affected by natural hydrological cycle; reuse in tensity in wetter years tends to be higher than that of drought years. The water reuse intensity for 2005 and 2006 was higher compared with other years due to widespread adoption of grey water recycling.

Domestic and industrial wastewater is commonly discharge directly into river courses, and there are three major pathways: (1) to replenish groundwater via river bed infiltration; (2) to enter the ecological water cycle in rivers (which also include water surface evaporation); and (3) to discharge into the sea. According to the data from the Haihe River basin water resources annual report, the annual average volume of domestic and industrial wastewater was around 1.84 billion m^3. Taking the natural runoff from the Luanue River and the Tuhaimajia River into account (approx. 0.2 billion m^3), the available water from domestic and industrial discharge was around 3.6 billion m^3, and 1.6 billion m^3 of them was consumed by river ecological system and the rest recharged the groundwater. In addition, the groundwater recharge from agricultural discharge was around 5.63 billion m^3, which put the total groundwater recharge to around 7.6 billion m^3 per year.

2.8 Interbasin water transfer

There are two major routes of interbasin water transfer for the Haihe River basin: the Middle Route of South to North Water Diversion Project and the Yellow River transfer scheme. Since the South to North Water Diversion Project is still not in full operation, only the Yellow River transfer scheme is considered in this study. Figure 8 shows the annual amount of water transfer for the period from 1994 to 2006, with an annual average of 4.7 billion m^3. The Yellow River transfer scheme could be divided into two major phases separated by the year 2000 (in which the Yellow River water regulation system was put into use): (1) before water regulation (1994–1999), the annual flow was 5.4 billion m^3; and (2) after regulation (2000–2006), considering ecological flow requirements in the Yellow River, the annual flow dropped to 4.1 billion m^3.

2.9 Pollution discharge

There are two main sources of pollutant discharge in the

Table 2 The amount of agricultural water drainage in the Haihe River basin (1998–2006) (10^8 m^3)

Year	1998	1999	2000	2001	2002	2003	2004	2005	2006	Average value
Agricultural water use	307.1	286.3	278.8	278.3	286.3	262.0	256.1	264.0	274.9	277.1
Agricultural water consumption	226.7	223.6	218.9	221.7	223.4	222.0	217.2	216.1	217.2	220.7
Agricultural water drainage	80.4	62.6	59.9	56.6	62.9	40.1	38.9	47.9	57.7	56.3

Table 3 The amount of domestic and industrial water discharge in the Haihe River basin (1998–2006) (10^8 m^3)

Year	1998	1999	2000	2001	2002	2003	2004	2005	2006	Average value
Used－Consumed	62.9	56.6	57.8	54.8	56.3	55.9	48.1	50.9	54.0	55.3
Industrial water drainage	56.1	56.2	54.0	54.0	53.6	51.1	48.0	44.9	48.3	51.8
The reused water	6.8	0.4	3.8	0.8	2.7	4.8	0.1	6.0	5.7	3.5

Haihe River basin: point source and nonpoint source. Point source pollutant discharges arise from domestic and industrial wastewater; and nonpoint source discharges arise from surface runoff, agricultural chemical fertilizers, rural area sewage, soil erosion, decentralized wastewater from livestock, etc. Table 4 shows the quantity of pollutant discharge for the year 2000.

2.10 Groundwater overexploitation

Large-scale overexploitation of groundwater in the Haihe River basin began from the 1980s: in the plain areas (excluding the Tuhaimajia River region) a total of 89.58 billion m^3 of groundwater was extracted between 1958 and 1998, comprising 47.1 billion m^3 from shallow aquifer and 42.5 billion m^3 from deep aquifer [23]. The shallow aquifer abstraction can be divided into 3 periods: 1958–1975 (0.86 billion m^3/a); 1975–1985 (1.38 billion m^3/a); and 1985–1999 (1.44 billion m^3/a). The deep aquifer abstraction can be divided into 4 periods: 1958–1975 (0.46 billion m^3/a); 1975–1985 (1.63 billion m^3/a); 1985–1999 (1.41 billion m^3/a) and 1999–2006 (4.15 billion m^3/a). Details are shown in Table 5. The total groundwater abstraction till 2006 is 122.8 billion m^3.

3 Scientific water management under the dualistic water cycle framework

3.1 Regional water balance

Regional water balance commonly refers to the conservation of masses in two main abstract water bodies/reservoirs (Figure 9): atmospheric and surface water corresponding to "atmospheric reservoir" and "surface reservoir". The body of "water" in "atmospheric reservoir" refers to mainly gaseous state; whereas the body of "water" in "surface reservoir" refers to mainly liquid state including conventional surface water, soil water and groundwater.

(1) Atmospheric water balance. Combining eqs. (1) and (3), we can obtain eq. (7), which conceptualizes the basic assumption of atmospheric water balance: the difference of the water storage in "atmospheric reservoir" is nil between the beginning and the end of a study year.

Table 4 The quantity of pollutant discharge to the Haihe River basin (2000) (10^4 t/a)

Source	COD	NH$_4^+$–N	Total-P
Point	133.06	11.04	0.60
Non-point	35.37	3.74	3.95
Total	168.43	14.78	4.55

$$W_{\mathrm{P}} = W_{\mathrm{SC}} + W_{\mathrm{ET}} - W_{\mathrm{L}}. \tag{7}$$

The summer weather in the Haihe River basin acts at a net importer of water, with the rest of the year acting as water dissipates. Based on the evolution of atmospheric water cycle, the average moisture dissipation for 1960–1969 and 1990–2002 were 109.2 billion m^3, 33 billion m^3 respectively. The average water depth for ET and precipitation were 470 mm and 565 mm for the period of 1960–1969; and 518 mm and 500 mm for the period of 1990–2002. This reduce tion in moisture dissipation was due to abnormal climate change resulting in less available water in summer. With a little change in wind speed over the period, less moisture dissipation indicates the increasing dryness over the autumn, winter and spring. This increase in dryness could also be due to the degradation in vegetation and reduction in wetlands and other ecological areas. From eq. (1) and Table 6, it can be seen that the internal land circulation flux, W_{LC} is 41.2 billion m^3, which is 23% of the total annual precipitation in the 1960s. While in the 1990s, W_{LC} increased to 132.8 billion m^3, i.e. 83% of the annual precipitation. This increase in internal land circulation indicates the increasing dominance of the land water cycle.

(2) Surface water balance. Eq. (2) is the equation for surface water balance. Prior to the 1960s, the amount of groundwater overexploitation ΔW_{G} and interbasin water transfer W_{T} were almost zero, and the precipitation was roughly equal to the sum of ET and runoff. In recent years (1997–2007), the annual groundwater exploitation was approx. 4.15 billion m^3; transfer from the Yellow River was 4.2 billion m^3; sea outflow was 1.4 billion m^3; the average

Figure 8 Annual amount of water transfer from the Yellow River to the Haihe River (1994–2006).

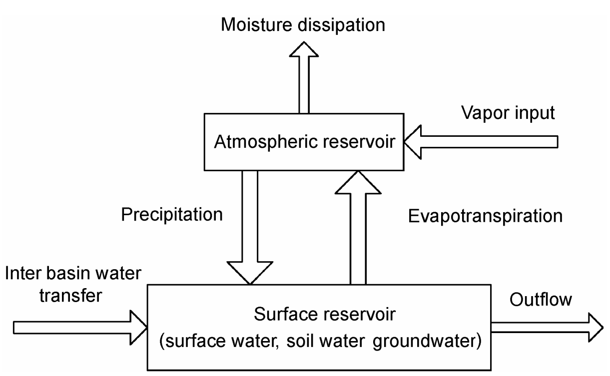

Figure 9 Sketch map of regional water balance.

Table 5 Over-exploitation of groundwater in the Haihe River basin (1999–2006) (10^8 m^3)

Year	1999	2000	2001	2002	2003	2004	2005	2006	Amount
Groundwater consumed	69.9 (75)[a)]	32.2 (28)[a)]	55.5 (54)[a)]	61.92	15.26	18.01	36.36	42.6	331.73 (331.13)[a)]

a) The data in parentheses comes from [24], and the others from [14].

annual precipitation was 150.2 billion m^3; ET was 157.1 billion m^3; and the ET caused directly by human activities was 26 billion m^3 (the total water used in the Haihe River basin was 40 billion m^3, and the water consumption ratio was 65%).

3.2 "Healthy" water cycle mode

Since the 1950's, the evolution of the Haihe River basin water circulation system can be summarized as "sea weak, land strong". "Sea weak" refers to the case that the ocean water vapour transport flux is low in summer and its strength is weakening; with the combined effects of human activities, surface water, soil water and groundwater, the innerbasin water dissipates quickly and results in a dry climate. "Land strong" the refers to the case that water flux on land is greatly enhanced (from 23% in the 1960s to the current 83%). The trend implies an enhanced inland water cycle in the Haihe River basin. The increase of the social water flux has also led to the increasing concentrations in the types of biochemical substances in surface water, soil water and groundwater, thus worsening water pollution.

The current state of "sea weak, land strong" of the Haihe River basin water cycle system has brought about an increase in water stress and water pollution, and this is the core issue of the deteriorating situation. This is also the focus of the scientific control in the "dualistic water cycle". In response to water deficit, necessary scientific measures are to increase the amount of interbasin water transfer; in response to the worsening water pollution, the necessary measures are to control the pollutant discharge and at the same time increase the ecological river flow, and to improve the pollutant carrying capacity of rivers.

Although there is not much room for manoeuvre in terms of inter-basin water transfer currently, once the Middle Routing of South to North Water Diversion Project is completed, the available amount of water to be transferred is 9.76 billion m^3 [25]. As a result, the total annual outflow from the Haihe River basin will increase by 4.1 billion m^3 to 5.5 billion m^3, take off the current groundwater over-exploitation (4.15 billion m^3) and add ecological demand by 1.5 billion m^3. With regard to pollution control in the river, an increase in sea outflow will increase the carrying capacity of pollutants and increase the self-purification capacity of the river. The major pollutants discharged from the Haihe River basin is shown in Table 8 below.

Table 6 Atmospheric water balance in the Haihe River basin (10^8 m^3)

Period	Vapor input in summer	ET	Precipitation	Vapor output in dry seasons
1960–1969	1396	1504	1808	1092
1990–2002	272	1658	1600	330

Table 7 Surface water balance in the Haihe River basin (10^8 m^3)

Period	Precipitation	Water transfer	Over exploitation	ET	Outflow
1960–1969	1808	0	0	1504	304
1999–2007	1502	42	41.5	1571	14

When comparing the pollutant loadings in Table 4, the carrying and self-purification capacity is too small – even if the pollutant standard is to be controlled according to the lowest standard (national grade-2 standard for drainage water, called D-2 in Table 8), it is still an uphill task to achieve the desire pollutant level. For example, COD will have to be reduced by 51% and total phosphorus by 88% from current levels.

On the social side of the dualistic water cycle, it is necessary to strengthen water demand management; maintain the basic stability of the water cycle flux W_S and prevent its continuous growth; strengthen the control on ET while reduce the amount of artificial ET (see eq. (5)); increase infiltration capacity W_I; recharge groundwater; reduce catchment water dissipation; maintain the inter-annual balance in surface water, soil water, and groundwater.

4 Discussion and conclusions

The adoption of a dualistic evolutionary approach in catchment scale water cycle is a product of the development of human society. A better understanding of the dualistic mode and its regular pattern will enable better management of the water cycle. And such is the premise of promoting a more natural state of the catchment, and it brings about healthy

Table 8 The carrying capacity for main pollutants related to different water quality standards (10^4 t/a)

Pollutant	III[a)]	IV[a)]	V[a)]	D-2
COD	11	16.5	22	82.5
$NH_4^- - N$	0.55	0.825	1.1	27.5
Total-P	0.11	0.165	0.22	0.55

a) are national standards for surface water.

economic and social development. In this paper, a theoretical summary of research results was included and the definition of the "dualistic water cycle" mode was put forward and reviewed. The key parameters/variables of the water cycle were explained in detail, taking the Haihe River basin as an example. The analysis of the relationship between the key parameters/variables was performed.

The "dualistic water cycle" pattern was applied to study the Haihe River basin. Based on the latest available data and having analyzed the key elements of the dual cycle and its evolution, the following preliminary points were concluded: (1) The main evolution of the dualistic water cycle in the Haihe River basin is due to a decline in marine water vapour transport in summer and the corresponding increase in land-based water vapour flux, i.e., "sea weak, land strong"; with the catchment water cycle gradually exhibiting the characteristics of inland river; (2) the "sea weak, land strong" phenomenon has led to the continuing water deficit within the Haihe River basin, showing signs of runoff attenuation, shrinking wetlands, groundwater exploitation, ecological degradation, deterioration of water quality, etc; (3) the social water cycle flux in the Haihe River basin continues to grow, partly enhanced by human activities. However, such growth is bounded by the natural constraint of total available water resources and eventually stabilized at about 40 billion m^3.

Based on the analysis of the pattern and evolution of the dualistic water cycle, this study proposed the interbasin water transfer and the reduction of pollutants into the river as two management measures for the Haihe water system. The proposed interbasin transfer via the Middle Route of South to North Water Diversion Project will be able to meet the designated water requirement. With the scale of water diversion, water loss within the Haihe River basin will be basically eliminated if the social water flux and artificial ET maintain stable. The interbasin transfer scheme will also be able to gradually replenish the overexploited groundwater. However, the reduction of pollution is still a very arduous task (COD to 51% of the current level; total phosphorus to 88% of the current level).

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