Urban Water Balance Analysis by Holistic Approach

Shuping Li, Weiming Yu

College of Environmental Science and Engineering, Tongji University, Siping Road 1239, Shanghai, 200092, China

Email: lishuping@tongji.edu.cn，yuyuyuf630@163.com

Abstract: Now there are a number of key challenges for management of urban water systems common to all towns and cities, such as providing safety drinking water, protecting from flooding, and efficiently removing wastewater. So we need take a holistic approach to manage urban water system. The water balance model developed in this study provides the framework for evaluating the demand for water supply, the availability of stormwater and wastewater, and the interactions between them. First, different levels of water balance model were presented, which are in house level, property level, district level, and urban level. Second, urban water performance indicators were introduced, which categorized to environmental, economical and social service aspects. At last, SH City was taken as a case to study; and the computing result showed that the water balance model is reasonable and practicable.

Keywords: Urban water system; water balance model; performance indicators

1 Introduction

Water is the requisite for urban living and development, it is a part of urban landscape and culture, and it is the basic container of pollutant transportation. Urban water system is the infrastructure about flood protection, water source development, water supply, water use, waste water drainage, sewerage treatment and reuse, etc. Urban water system is a large, complex system, and it is important to study as integrated (Shao, 2004; Li, et al., 2006; Li et al., 2007). The appropriate mathematic model is needed to build for analysis.

Water balance model is a tool to understand water transporting in urban areas. During the analysis, the different level models are built first, then the performance indicators for evaluating urban water system in environmental, economical and social services aspects. At last, the City SH is taken as a case to study and the water quantity problem is analyzed.

2 Urban Water Balance Model

A water balance is the systematic presentation of data on the supply and use of water within a geographic region for a specific period of time. In hydrology, a water balance equation can be used to describes the flow of water in and out of a system. A general water balance equation is:

$$P = Q + E + \Delta S$$

Here, P is precipitation; Q is runoff; E is evapotranspiration; and ΔS is the change in storage (in soil or the bedrock).

There are many ways to integrated drinking water, stormwater, wastewater and reusing water within an urban area (Mitchell, 2001; Wenzel, 2005). In order to make a wide variety of schemes, several nested spatial scales were selected for this study, which starting from simple and go step by step to more complicate. The simplest case is the house level model, where water is imported, used and maybe recycled, and wastewater discharged outside of the house boundaries. Next is property level and distribution level. Finally, urban level is achieved, which includes residential area, industrial area, public area and park area.

2.1 House level

House is the unit construction in urban area. House level represents in an apartment or a house without garden. Usually, water system at house level contains three components, which are water input, water consumption and water out. Water input contains all kinds of water goes into house, such as piped water, bottled water, even water contained in fruit. After domestic consumption, most of water will leave the system in certain forms such as evaporation, sewerage, etc.

2.2 Property level

Property here refers to house and garden, it is another kind of water consumption unit in urban area. In this level, the water balance model is built on three components, which are precipitation, evaporation and runoff. Therefore the water cycle could be described as precipitation introduces water into property level system, and by means of evaporation and runoff, water out of this system. Generally, runoff is supposed to be drained out of property area as quickly as possible. On the contrary, precipitation could be harvested as a resource. Maybe it is need to equip a retention tank for ground water infiltration or storing rain water for irrigation. In addition, building a green roof in one's property could create a better landscape and reduce runoff onsite.

2.3 Developed district level

A developed district is defined as a system, which combines components of house level and property level. Developed district contains larger population and more

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municipal construction, therefore, balance counting is considered in a longer time span and in a larger area size.

There are three essential options for developed district level analysis as follows. Alternative 1: initial urban lands plan without any structure water management; it may be works well and need little investment. Alternative 2: employing recycle strategy indoor and building a detention tank outdoor. As a result, the investment in water facilities is higher than option 1. Provided more designs in alternative 3, one of them is the green roof, which create a better landscape and it is benefit for citizen's aesthetic demanding.

2.4 Urban level

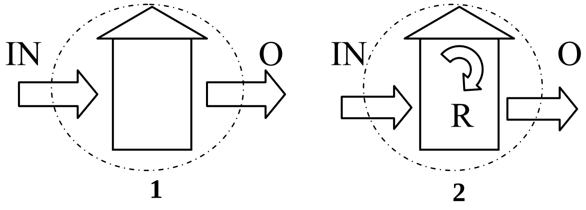
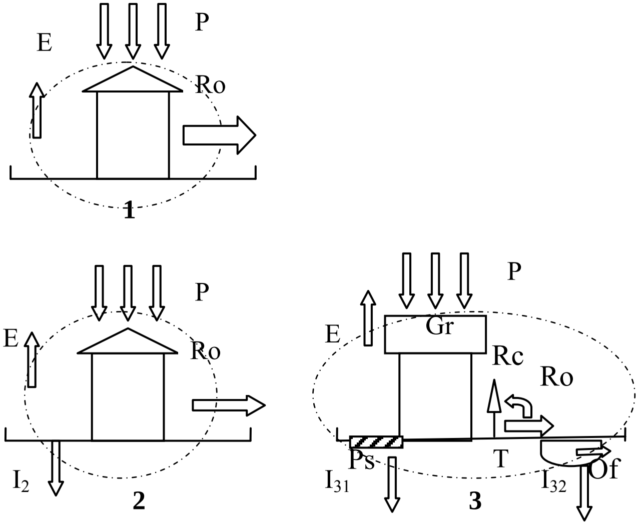
According to different function, a city could be divided into three types of areas, which are defined as residential area, industrial area, and public area. Usually, water cycle in city includes the three major parts: surface and ground water flow, atmospheric circulation, water related substance trading.

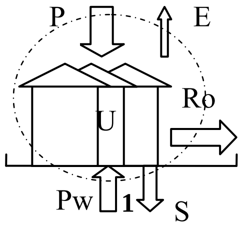
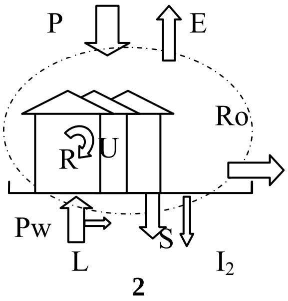
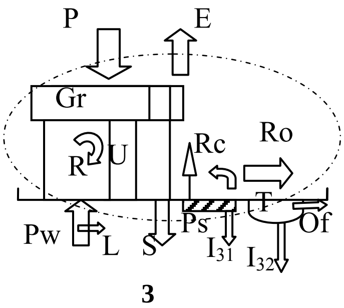
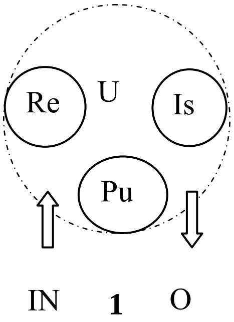
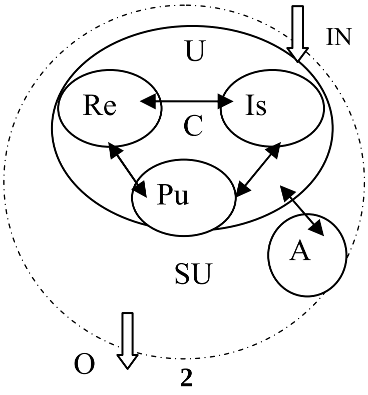
With urban water system, three function units are taken as separated subsystems; they are residential area, industry area and public area. Within each function unit reusing or recycling could be employed. Also water management could be discovering new water resource, employing facilities to integrate all the resource including grey water, precipitation and parts of waste water which might be reclaim in lower water quality demanding departments. Take a paper industry for example, there are various product line in a paper industry, some parts demand fresh water, while some processes only ask for lower quality water, therefore, water could be reused or reclaimed in some parts, and saving a mount of potable water.

2.5 Development of water balance formula

Based on water balance, formula of the relationship between elements is developed in draft on left in Table 1. Since water systems have been defined, it is possible to calculate water quantity by water balance (Yu, and Schubert, 2007).

Table 1. urban water balance in different level

Level	Formula
House level  	**1:** IN = O, **2:** IN = O. **Comparison between 1 and 2:** $IN_1 > IN_2$, $IN_1 = IN_2 + R_2$, $O_1 > O_2$, $O_1 = O_2 + R_2$.
Property level  	**1:** P = Ro + E, **2:** $P = Ro + I_2 + E$, **3:** $P = Ro + I_{31} + T + E + Gr$, $Ro = T + Of + I_{32}$. **Comparison among 1, 2 and 3:** $Ro_1 > Ro_2 > Ro_3$, $I_2 < I_{31}$, $E_1 < E_2 < E_3$.
Developed district level	**1:** P + Pw = Ro + S + E. **2:** $P + Pw – L = Ro + S + E + I_2$. **Process 2:** P = Ro + I + E U = Pw – L+ R. **3:** $P + Pw – L = Ro + S + E + I_{31} + I_{32} + Gr + T$.

  	**Process 3:** $Ro = Of + I_{32} + Rc + T$, $U = Pw - L + R + Rc$. **Comparison among 1,2 and 3:** $Ro_1 > Ro_2 > Ro_3$, $E_1 < E_2 < E_3$. $L_2 > L_3$
Urban level  	**1:** $IN = U = Re + Is + Pu= O$, **2:** $IN = Re + Is + Pu + A - eri - erp - eip- eac= O$. $U = Re + Is + Pu + A$ **Comparison between 1 and 2:** Assumption: $U_1 = U_2$, then $IN_1 > IN_2$, $O_1 > O_2$,
Explanations	
1,2,3—draft 1, 2, 3, IN—water in, O—water out, U—use, R—recycle, P—precipitation, T—tank increased volume, E—evaporation, Gr—green roof retention, eri—exchange between residential areas and industrial areas, erp—exchange between residential areas and public areas, eip—exchange between industrial areas and public areas.	Ro— runoff, Pw—potable water, S—sewage, L—leakage, Ps—pervious pavement, Of—overflow, Rc—reclaim, C—city area, SU—suburban, Is—industrial areas, Re—residential areas, Pu—public areas, A—agriculture areas.

2.5.1 Water balance figure and formula

Water balance level and their alternatives are drafted in left column, where dashed circle qualifies each system. And right column shows balance equations as well as elements comparison between alternatives.

2.5.2 Comparison of elements in each figure

Each level contains at least two alternatives. Basically, alternative 1 in each level is relatively simple; it shows a traditional water system. Comparing to alternative 1, some elements represent new facilities are added in at alternative 2 and 3. In right column, a comparison between elements in the same water balances level is given.

3 Urban Water Performance Indicators

When the model purpose has been defined and the system boundaries agreed on, appropriate performance indicators can be selected based on criteria (e.g. validity, feasibility, and interpretability) or from case studies, literature reviews and existing indicators already in use within the field. Indicator is a parameter, or value derived from a parameter; which points to: provides information about, or described the state of a phenomenon, environment, or area with a significance extending beyond that directly associated with a parameter values (Bergquist, 1996).

For urban water balance model, the indicators can be divided into three categories, environmental, economical and social services, as shown in Table 2. Environmental indicators focus on water resource, water using and discharging, mainly in percent; Social service indicators are corresponding to population; and economical indicators focus on infrastructure cost and GDP.

Table 2. Performance indicators for urban water balance evaluation

<table>
<tr><th>Indictors</th><th>Category</th><th>Units</th><th>Definition</th><th>Remarks</th></tr>
<tr><td>Mean annual runoff</td><td rowspan="12">Environmental indicators</td><td>mm</td><td>Annual surface runoff/area</td><td>Represent sector’s surface water quantity. Based on China runoff zone category standard: annual runoff height is more than 900 mm, it is abundance zone; 200~900 mm is more water zone; 50~200 mm is transitional zone; 10~50 mm is less water zone; and runoff height is less than 10 mm, is scarcity zone.</td></tr>
<tr><td>Modulus of groundwater flow</td><td>10^4 m^3/km^2</td><td>Groundwater resource amount/land area</td><td>Represent district groundwater amount. The grading standard is 30×10^4 m^3/km^2·a is abundance line, 2×10^4 m^3/km^2·a is poor line, and 5 ~ 20×10^4 m^3/km^2·a is middle line.</td></tr>
<tr><td>Water producution coefficient</td><td></td><td>Zone water resource amount/zone annual precipitation</td><td>Reflect the impact of climate change on water resource. 0.10 is the lower level, 0.60 is the higher level, and 0.50 is middle to higher level.</td></tr>
<tr><td>Water resource development rate</td><td>%</td><td>100%×water resource development amount /water resource amount</td><td>Reflect district water resource development status. General considered that < 20% is sustainable, 20~30% is vulnerable, and > 30% is unsustainable.</td></tr>
<tr><td>Surface water control and application rate</td><td>%</td><td>100%×surface water apply/surface water resource</td><td>Reflect surface water development and using status. 10% is the higher level, 50% is the lower level and 20~30 is the middle level.</td></tr>
<tr><td>Groundwater application rate</td><td></td><td>Actual exploit groundwater/groundwater available</td><td>Measured by shallow ground water exploit. 30% is the lower exploit rate, 100% is the severe excess exploit level.</td></tr>
<tr><td>Domestic water use ratio</td><td>%</td><td>100%×zone domestic water use /zone total water use</td><td rowspan="2">Zone water use ratio for different income level (%)<table><tr><th></th><th>Domestic</th><th>Industrial</th><th>Agricultural</th></tr><tr><td>Low income zone</td><td>4</td><td>5</td><td>91</td></tr><tr><td>Middle income zone</td><td>13</td><td>18</td><td>69</td></tr><tr><td>High income zone</td><td>14</td><td>47</td><td>39</td></tr></table></td></tr>
<tr><td>Industrial water use ratio</td><td>%</td><td>100%×zone industrial water use/zone total water use</td></tr>
<tr><td>Industrial water reuse rate</td><td>%</td><td>100%×reuse water amount/(new water + reuse water)</td><td>30 % is the lower line, 90% is the higher line, and 40~70 is the middle line.</td></tr>
<tr><td>Legal industrial wastewater discharge rate</td><td>%</td><td>100%×industrial wastewater discharge amount that meet the standard/total industrial wastewater discharge</td><td>Demonstrate that industrial wastewater treatment efficiency. Based on National Environmental Protection Ministry, the indicator value should be 100%.</td></tr>
<tr><td>Ratio of wastewater to runoff</td><td></td><td>Wastewater discharge/surface runoff</td><td>To some extent reflect the pollutant status and degree of surface waters such as river, lake and reservoir. General considered that when wastewater and runoff ratio is more than 0.05, it is severe polluted.</td></tr>
</table>

reuse rate of treated wastewater		%	100%×the amount meet reuse water standards/total treatment wastewater amount	Shows wastewater reuse status after the treatment.
Qualified urban drinking water source ratio	Social service indicators	%	100%×qualified urban water source number/total urban water source number	90% is the lower level, and 100% is the target.
Average water resource per capita		m^3 /cap.	Zone water resource/zone population	Measuring the freshwater statues of one country and district internationally. Now take capital water resource 1700 m^3 as scarcity warning line.
Integrated water use per capita		m^3 /cap.	Zone annual water uses / zone population	Integrated water use per capita is varying with living conditions. 510 m^3 /cap. is higher level, and 100 m^3 /cap. is the lower level.
Access to piped water		%	100%×population accessed to piped water/total population	The maximum value is 100%
Water leakage rate		%	100%×（annual water supply— annual efficient water supply）/ annual water supply	Reflect the water supply efficient. Generally considered that < 12% is sustainable, 12%~18% is vulnerable, and > 18% is unsustainable.
Water use elastic coefficient	Economic indicators		Zone water use growth/GDP growth	Reflect elastic effect of water use on economic growth, it is the indicator to judge the water conservation level and water reuse, and the value should be less than 1.0. Generally, 1.0 is the lowest level, and 0.00 is the highest level.
New water source exploit		m^3 /￥10^4	New water quantity/infrastructure funding	Generally, infrastructure funding of water conservation should be less than that of adding water use.
Water conservation efficient		m^3 /￥10^4	Water conservation quantity /infrastructure funding	

4 Case Study

Base on urban water system model and water balance equations, using Microsoft Excel software, the urban water balance worksheet is built. The operation data compile in several modules, they are “water sources”, “house water system”, “property water system”, “developed district water system”, “urban water system”, “economic”, “references”, “terms” and “results”. By VBA language, the data is interconnected and can be auto calculated, and using the hyperlink and controls to exchange the pages.

4.1 Catchment description

City SH is 6 340.5 km^2, it is 120 km long from south to north, and 100 km wide from east to west. The downtown area is 2 643.06 km^2 and suburb area is 3 697.44 km^2; land area is 6 219 km^2 and water area is 122 km^2. City SH belongs to sub-tropical climate. The annual temperature is about 16℃. Frost free period is about 230 days, the annual precipitation is about 1200 mm. 60 percent precipitation is concentrated between the month of May and September.

4.2 Water data treatment

Majority data is derived from Water Authority of SH City 2007. Some parameters in the model are appropriate assumed, and the part of analysis results is shown in Table 3 and Table 4.

In the statistical data of domestic and industrial water uses (Table 3), two water use patterns were designed. Water use data in “House 1” item is more than “House 2”, but the number of “House 1” is ten times of “House 2”; it shows that domestic with water conservation is less. The process water use items in “Industrial 1” and “Industrial 2” is the same, but the scale of “Industrial 2” is 7 times of “Industrial 1”, and the recycle water ratio is 1.6 times. So the water consume in “Industrial 2” is more than “Industrial 1”, and the computing result is 4 times. But in the water use item of “Special Industry” and “Institute” only designed one water use pattern, the statistic value of “Special Industrial 2” is 0.

Table 3. Monthly house water use

Description	Water supply [10^4 m^3]	Discharge [10^4 m^3]	Water consumption [10^4 m^3]	Water use [10^4 m^3]	Grey water recycle rate [%]	Grey water (or recycle water [10^4 m^3]
House 1	5 647	5 082	564.7	Household		
House 2	333.9	300.5	33.39	5 981	2.73	1.00
Industrial 1	2 000	1 800	200.0	General Industry		
Industrial 2	7 199	6 479	719.9	9 199	77.56	69.59
Special Industrial 1	54 200	48 780	5 420	Special Industry (e.g. Thermal Power Plant)		
Special Industrial 2		0.00	0.00	54 200	97.50	52 845
Institute	7 000	6 300	700.0		20	1400
Sum[10^8 m^3]	7.64	6.87	0.76			

Table 4. Annual wastewater discharge and surface runoff

Wastewater discharge （10^8 m^3）	Industrial wastewater treatment （10^8 m^3）	Urban water treatment （10^8 m^3）	surface runoff （10^8 m^3）
22.37	4.83	15.57	28.32

4.3 Performance indicator analysis

The analysis of all performance indicators in Table 2 needs more data to compile. Here only three indicators is presented for illustrating which are domestic water use ratio, domestic greywater reuse ratio and the ratio of wastewater to runoff.

1）Domestic water use ratio

$$[(5647+333.9)+7000\times 50\%]/76400\times 100\%$$
$$=12.42\%$$

The value is approach to the domestic water use level of mid-income country (13 %).

2) Domestic greywater reuse ratio

$$\frac{1600\times 3000\times 30\times 0+1600\times 300\times 30\times 30}{1600\times 3000\times 30+1600\times 30\times 30}$$
$$=2.73\%$$

The better value of this indicator is 60%, so it is shows that City SH need enforce the strategy for the indicator, such as education about waste water reuse, adoption reuse devices.

3) Ratio of wastewater to runoff

$$\frac{22.37-4.83-15.57}{28.32}=6.95\%$$

The value is more than the limit value 0.05, surface water maybe severe polluted. The value shows that wastewater treatment should be enforced.

5 Conclusions

This research has defined water balance levels for different scales, which are house, property, and developed district level. The model of urban water balance provides a benchmark for assessing amount of water supply and demand, rainwater and wastewater reusable, and the interaction between water supply, wastewater and rainwater. Urban water balance provides the good start point for integrated water management design and operation. The balance model is represented by graph and equations. Take a case study, it is shown the practicability and operability of urban water balance model.

Some aspects need to enforce for urban water balance model are: (1) the calculation needs large long-term accumulated high quality data. 2) urban water balance model need to calibration and verification, in order to provide sufficient data support for decision. 3) Urban water performance indicators need to be refined, in order to reflect the real conditions of urban water system.

Acknowledgements

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