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FRAMEWORK OF A NEW URBAN WATER AND ENERGY BALANCE SCHEME

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ABSTRACT

Influenced by the increasing human activities, the urban water balance system and energy balance system have undergone significant changes. The interaction between urban water system and energy system is more significant. Based on the traditional urban water-heat coupling scheme, urban water consumption and urban anthropogenic heat emission are considered in the process of the water balance and energy balance in this study. A new coupling scheme of urban water balance and energy balance is constructed. It provides technical support for urban water-heat coupling simulation.

Keywords: Water balance, Energy balance, urban ,scheme

NONMENCLATURE

Abbreviations	
N-P	Noilhan-Planton
Symbols	
n	Year

1. INTRODUCTION

Due to the rapid urbanization, the water and energy character has changed in urban areas. The interaction between water and energy has also changed significantly. The relationship between urban water and energy balance has also changed accordingly. Many experts have done several relevant study on the water and energy balance in urban areas. For the urban water balance, many researchers pointed out that urban underlying surface is a key factor affecting urban water cycle[1-3]. The change of underlying surface causes the change of evaporation, runoff and water storage in urban water balance equation[4-6]. For the urban energy balance, significant changes have taken place in the components of the ground-building-atmosphere system equilibrium. Urban anthropogenic heat emissions also change the distribution of components in urban energy balance. In view of the phenomenon that the process of urban water and energy changes, this study attempts to construct a water and energy balance model considering the complex underlying surface, urban water consumption and urban anthropogenic heat change. The model consists of three parts: urban water balance scheme, urban energy balance scheme and urban water-energy interaction scheme.

2. THE MODEL

2.1 Urban Water Balance Scheme

Urban water balance is the basic theory and scientific basis of urban water cycle. For different spatial scales of urban areas, the water balance equations are different. In this model, the spatial boundary of urban water balance equation is defined as the urban canopy boundary. Based on the analysis of the amount of water entering the urban canopy and excluding the urban canopy, the urban water balance equation can be expressed as shown in equation 1[7].

$$P+D+F=E+R+\triangle S \tag{1}$$

In equation (1), P is precipitation, D is the water supply, F is the anthropogenic water emission (e.g. combustion, air conditioning, human emissions from breathing), E is the evaporation (which includes transpiration), R is the runoff, and $\triangle S$ is the net change in water storage (e.g. changes in soil moisture, detention ponds) within the study area.

Urban canopy refers to the floor from the ground to the roof of a building. From the vertical view, urban water cycle includes six main parts: roof interception, vegetation interception and evaporation, surface interception, soil infiltration, greenbelt interception and evaporation.

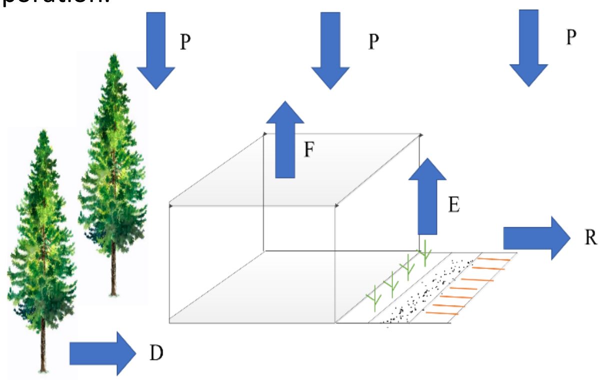

Fig 1. Urban Water Balance Map

2.1.1 Roof interception and rainfall evaporation

Roof interception is an important process in urban cycle. The water balance relationship is used for roof interception calculation[8]. The specific calculation methods are shown in equation 2 and 3.

$$P=R_r+E+\triangle S \quad (2)$$

$$R_r=P*n \quad (3)$$

While P represents the precipitation, R_r represents the roof water interception, n represents the runoff coefficient, E represents the evaporation, △S represents the roof water variable storage. For the un-greened roof △S equals 0. For the greened roof △S equals to soil water accumulative storage variables.

2.1.2 Vegetation interception and evaporation

The vegetation interception and evaporation is a crucial part in the urban water cycle. It includes the calculation of water interception by vegetation, the vegetation evaporation and transpiration. The vegetation water interception was calculated by considering vegetation saturation and Horton interception mechanism[9-10]. The Penman formula was used to calculate vegetation transpiration[11]. Vegetation interception evaporation was calculated by N-P formula[12].

$$P=I_c+E_p+E_i+R_{vi} \quad (4)$$

$$I_c=\frac{C_{ts}-C_0}{p_s}p+\frac{e}{p_s}tp \qquad t\leqslant t_s \;\; p\leqslant p_s \quad (5)$$

$$I_c=C_{ts}-C_0+et \qquad t>t_s \;\; p>p_s$$

$$E_p=\frac{(R_n-G)\Delta+\frac{\rho_a C_p \delta_e}{r_c}}{\lambda\left[\Delta+\Upsilon\left(1+\frac{r_c}{r_a}\right)\right]} \quad (6)$$

$$E_i=Veg\times I\times E_w \quad (7)$$

In equation 4, I_c represents the vegetation interception rainfall, E_p represents the vegetation transpiration, E_i represents the vegetation interception evaporation, R_{vi} represents the water flow downward through vegetation.

The model uses analytical model to calculate the vegetation transpiration. In equation 5, I_c represents the water interception by vegetation, C_{ts} represents the saturated water storage of vegetation; C_0 represents the vegetation water storage before rainfall; t_s represents the rainfall duration of vegetation saturation; p represents the secondary rainfall; p_s represents the rainfall saturated the canopy; t represents the rainfall duration; t_s presents the rainfall duration to saturate canopy; e represents the average vegetation evaporation during rainfall.

The Penman formula is used to calculate vegetation transpiration in the model. In equation 6, R_n represents the surface net radiation; G represents the soil heat flux; ρ_a represents the air density; C_p represents the specific heat of air at constant pressure; δ_e represents the difference of saturated water; r_a represents the aerodynamic resistance from ground to canopy height; r_c represents the impedance of plant community; △ represents the slope of temperature and saturated water pressure curve; λ represents the latent heat of evaporation; ϒ represents the dry-wet meter constant.

The N-P formula is used for calculate the vegetation interception evaporation. In equation 7, Veg represents the crop coverage, I represents the area ratio of wet leaf surface; E_w represents the water surface evaporation.

2.1.3 Surface interception

Urban surface runoff process is the key link of urban water cycle. The traditional calculation of surface water balance mainly considers evaporation, seepage and savings in depressions. The mechanism of rainfall runoff generation is taken into account in the calculation of runoff generation from urban underlying surface[13]. The calculation of evaporation term takes into account surface evaporation and urban water dissipation. The water balance equation for can be seen in equation 8.

$$P=E_s+R+D \quad (8)$$

$$R=\sum_{i=1}^{n}(i-f)\triangle t_i \quad (9)$$

$$E_s=P_s+(1-n_i)(P-P_s) \quad (10)$$

In equation 8， E_s represents the surface rainfall evaporation; R represents the surface runoff; D represents the water in depressions. For equation 9, i represents rainfall intensity; f represents infiltration intensity. The calculation methods of E_s on different underlying surfaces are different. P_s represents the critical precipitation for groundwater production. n_i represents the runoff coefficient of the type i underlying surface.

The calculation methods of soil infiltration refer to roof interception and grassland interception refer to vegetation interception.

2.2 Urban Energy Balance Scheme

The complex urban ground-building-atmosphere system results in the non-uniformity of power and heat[14]. The urban energy balance can be expressed as shown in equation 11.

$$Q_a+Q_F=Q_E+Q_H+\triangle S \quad (11)$$

In this equation, Q_a refers to the net all-wave radiation， Q_F refers to the anthropogenic heat, Q_E refers to the latent heat flux, Q_H refers to the turbulent sensible heat flux, $\triangle S$ refers to the net storage heat flux.

2.2.1 Net all-wave radiation

The net all-wave radiation comes mainly from solar energy and atmospheric emissions. It can be calculated by using vorticity correlation method[15]. It can be seen from equation 12 to 15.

$$Q_a=R_s-R_l \quad (12)$$

$$R_s=(a_s+b_s\frac{n}{N})R_a \quad (13)$$

$$R_a=\frac{S_0}{\rho_0} \quad (14)$$

$$R_l=2.45*10^{-9}(1.35\frac{0.25+0.5\frac{n}{N}}{(0.75+2*10^{-5}H)}-0.35)(0.34-0.14ed)(Tk^4+Tx^4) \quad (15)$$

In equation 12, R_s represents net shortwave radiation, R_l represents net longwave radiation. In equation 13, a_s represents the proportional coefficient of surface radiation and astronomical radiation in cloudy sky, b_s represents the proportional coefficient of surface radiation and astronomical radiation in sunny day. S_0 represents the solar constant. ρ_0 represents the average distance between the sun and the earth.

2.2.2 Anthropogenic heat

The source inventory method is the most commonly used method to calculate anthropogenic heat at different scales .Based on a certain hypothesis, the heat value of the energy consumption data is allocated to the study area of different scales. The annual emission data is usually refined into a monthly or diurnal variation coefficient, which reflects the temporal and spatial characteristics of the anthropogenic heat in the region[16]. In this study, anthropogenic heat(QF) is divided into 4 parts, including, industry heat(QI), transportation heat(QV), human metabolism (QM)and building heat discharge (QB) according to the different heat sources.

$$Q_F=Q_I+Q_V+Q_M+Q_B \quad (16)$$

Industrial anthropogenic heat emission: Industrial anthropogenic heat calculation is to transform other industrial heat sources into coal equivalent. By calculating industrial equivalent and standard coal heating value to get industrial anthropogenic heat. The specific calculation method is as equation 17. In this formula, C refers to annual consumption of standard coal equivalent in industry; $\varepsilon\varepsilon cc$ refers to Calorific value of standard coal. According to “Beijing statistical yearbook”, relevant parameters can be estimated.

$$Q_I=C\varepsilon_c \quad (17)$$

Transportation heat emission: Traffic anthropogenic heat is calculated by weighting the heat emission from different types of vehicles. The specific calculation method is listed as follows:

$$Q_I=C_f\varepsilon_f+C_d\varepsilon_d+C_L\varepsilon_L \quad (18)$$

Human metabolic heat emission: The anthropogenic heat released by metabolism is a function of factors such as population quantity, age, exercise volume, work and rest system. it is simplified as a function of population density when estimating the anthropogenic heat. The calculation method is listed as follows:

$$Q_M=\frac{PH_M}{A} \quad (19)$$

Building heat discharge: A model is built to estimate the anthropogenic heat by using different building functions, occupying area, floor height and building materials. The calculation method is listed as follows:

$$Q_B=\sum_{i=}^{n}\left(A_i\sum_{j=1}^{m}EUI_jP_{ij}\right) \quad (20)$$

2.2.3 Heat flux

The latent heat flux Q_E, the turbulent sensible heat flux Q_H, the net storage heat flux $\triangle S$ can be calculated by using Bowen's specific energy balance method[17]. The calculation method can be seen from equation 21 to 26.

$$Q_E = -\rho C_p K \frac{\partial \dot{\theta}}{\partial z} \quad (21)$$

$$Q_H = -\rho L_v \frac{\varepsilon}{p} K \frac{\partial \dot{e}}{\partial z} \quad (22)$$

$$\Delta S = -C_m K_s \quad (23)$$

In equation 21, ρ is the air density, C_p is the specific heat of air at constant pressure, K is the Turbulence exchange coefficient of heat and water vapor, $\frac{\partial \dot{\theta}}{\partial z}$ is the potential temperature of air. In equation 22, L_v is the latency for vapouring water, ε is the molecular ratio of water vapor to dry air, p is the atmospheric pressure, $\frac{\partial \dot{e}}{\partial z}$ is the water pressure. C_m is the soil thermal capacity, K_s is the soil thermal diffusivity, $\frac{\partial e\dot{T}_g}{\partial z}$ is the soil temperature gradient.

2.3 Urban water-energy interaction scheme

The interaction between water system and energy system is mainly focus on Focus on four parts including the water supply, water using, water consumption and drainage. Water evaporation and water dissipation are the bridges between water system and energy system[18]. The interaction between urban water system and urban energy system is shown in Figure 2.

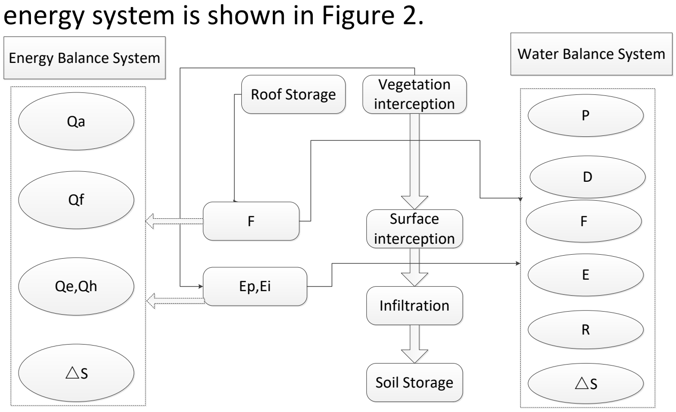

Fig 2. The relationship between water balance system and Energy balance system

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REFERENCE

[1] Ocampo-Martinez C, Puig V, Cembrano G, et al. Application of predictive control strategies to the management of complex networks in the urban water cycle [J]. Control Systems IEEE, 2013, 33(1):15-41.

[2] Venkatesh G, Brattebø H. Energy consumption, costs and environmental impacts for urban water cycle services: Case study of Oslo (Norway)[J]. Energy, 2011, 36(2):792-800.

[3] Lee J, Pak G, Yoo C, et al. Effects of land use change and water reuse options on urban water cycle[J]. Journal of Environmental Sciences, 2010, 22(6):923-928.

[4] Ramamurthy P, Bou-Zeid E. Contribution of impervious surfaces to urban evaporation[J]. Water Resources Research, 2014, 50(4):2889-2902.

[5] Krüger E L, Pearlmutter D. The effect of urban evaporation on building energy demand in an arid environment[J]. Energy & Buildings, 2008, 40(11):2090-2098.

[6] Lei Y, Wei W, Chen L. How does imperviousness impact the urban rainfall-runoff process under various storm cases?[J]. Ecological Indicators, 2016, 60:893-905.

[7] Grimmond, C.S.B., Oke, T.R., 1986. Urban water balance 2: results from a suburb of Vancouver, British Columbia. Water Resour. Res. 22, 1404–1412.

[8] Zhang S, Guo Y. Analytical Probabilistic Model for Evaluating the Hydrologic Performance of Green Roofs[J]. Journal of Hydrologic Engineering - ASCE,2013,18(l):19-28.

[9] Gash J H C . An analytical model of rainfall interception by forests[J]. QJRMS, 1979, 105(443).

[10] Shuguang Liu. Canopy Interception Model[M]. China Meteorological Press, Beijing, 1997, 252-254.(in Chineses)

[11] Ershadi A , Mccabe M F , et al. Impact of model structure and parameterization on Penman–Monteith type evaporation models[J]. Journal of Hydrology, 2015, 525:521-535.

[12] Manzi A O , Planton S , Noilhan J . Implementation of a Soil-Vegetation Transfer Scheme in an Atmospheric General Circulation Model[M]// Responses of Forest Ecosystems to Environmental Changes. Springer Netherlands, 1992.

[13] Rui Xiaofang. Principles of Hydrology[M]. China Water&Power Press,2004.(in Chinese)

[14] Oke, T.R., 1987. Boundary Layer Climates. Routledge, London, UK

[15]Kang Shaozhong, Liu Xiaoming, Xiong Yunzhang. Water transport theory of soil-plant-atmosphere continuum and its application [M]. Water Resources and Electric Power Press, 1994,122-150.

[16]Ranhao Sun,Yening Wang, Liding Chen. 2018. A distributed model for quantifying temporal-spatial patterns of anthropogenic heat based on energy consumption. Journal of Cleaner Production,170(1):601-609.

[17] Yap D , Oke T R . Sensible Heat Fluxes over an Urban Area-Vancouver, B.C.[J]. Journal of Applied Meteorology, 2010, 13(8):880-890.

[18] JRvi L , Grimmond C S B , Christen A . The Surface Urban Energy and Water Balance Scheme (SUEWS): Evaluation in Los Angeles and Vancouver[J]. Journal of Hydrology (Amsterdam), 2011, 411(3-4):219-237.