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Evapotranspiration in urban water balance

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ABSTRACT: It is necessary to develop a water balance for urban areas to establish the effect of urbanization. It is used to calculate the daily, monthly, and annual water balance components for an urban catchment in scope of designing and operating an integral urban water management system. The calculation considers both natural and man-induced water sources. In achieving the water balance in the urban area we excluded groundwater. Through this paper we want to show the importance of evapotranspiration to achieve water balance in urban areas and different methods for determining evapotranspiration using physically based equation or by measuring it.

Keywords: urban water balance, urban water cycle, evapotranspiration.

1. INTRODUCTION

The history of the urbanization is the history of humankind in its evolution to the present, in all places on earth. Between humankind evolution and the notion of urbanization is a direct relationship, humankind evolution has led to the development of cities and increasing socio-economic activities. The demand for a more sustainable water system is now growing because of several factors: rising population, urban areas increase, industry development, lack of a water purification system in underdeveloped countries and developing countries, energy costs and climate change. The factors are creating pressures on the management of the available water reserves globally.

Urban water balance is influenced by geographical location, terrain, climate, socio-economic development of the area. There is an interdependence between them. Urban areas are interdependent with the environment, being largely dependent on the ecosystem surrounding it. Urban areas have on the environment (hydrological cycle) a stronger effect than rural areas because of socio-economic activities.

Having a large constructed area, paved areas, the intake of water through water supply network of the city, leads to an increase in the amount of runoff in an urban area. Runoff problem in the urban area is an actual problem that needs to be solved.

Water balance is the balance between the amount of water entering, exiting and accumulated in one place (catchment, soil, etc.) within a given time.

Cleugh et al., (2005) simplified Grimmond's and Oke's (1991) water balance equation for urban areas:

$$P + I = ET + D + \Delta S \qquad (1)$$

where the inputs are rainfall (P), piped water supply(I); the outputs are evapotranspiration (ET), drainage (D) – wastewater and stormwater; and the change in storage (ΔS) in the nature (soil and groundwater aquifers) and build components of the urban system.

In temperate regions, evaporation of water intercepted by the vegetation represents an important part of the evapotranspiration, and sometimes the major part (Calder 1977, 1990; Viville et al. 1993).

2. MODELING THE URBAN WATER BALANCE

2.1. URBAN WATER CYCLE

In daily urban life we can separate land use into three categories: residential area, road and public open space (Cleugh et al., 2005). Residential areas are assumed to have impervious surfaces (roofs, paved areas) and fairly pervious, the roads are impervious and public space are pervious.

Following F.H.M. van de Ven 1990, we made a schematization of urban hydrological system.

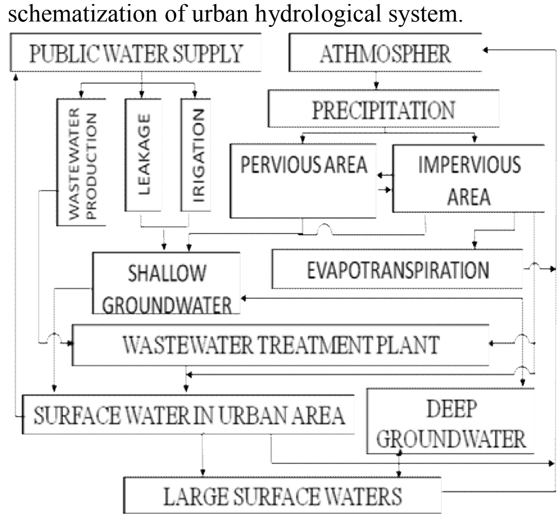

Fig. 1. The urban hydrological system

The total water supply of the world is 1.400.000.000 km^3. Each year, 119.000 km^3 of water

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precipitates on land and 74.200 km^3 evaporates into the atmosphere, by evapotranspiration from soil and vegetation. Of the freshwater on Earth, about 2.200 km^3 flows in the ground, mostly within half a mile from the surface. (http://www.lenntech.com/water-quantity-faq.htm)

2.2. EVAPOTRANSPIRATION

Evapotranspiration is an important part of the urban water cycle. Evapotranspiration (ET) is the sum of evaporation and plant transpiration from the Earth's land surface to atmosphere.

Potential evapotranspiration ***(ET_p):*** The potential evapotranspiration concept was first introduced in the late 1940s and 50s by Penman and it is defined as "the amount of water transpired in a given time by a short green crop, completely shading the ground, of uniform height and with adequate water status in the soil profile" (Suat Irmak and Dorota Z. Haman, 2003). Potential evapotranspiration is usually measured indirectly, from other climatic factors, but also depends on the surface type, such free water (for lakes and oceans), the soil type for bare soil, and the vegetation. Often a value for the potential evapotranspiration is calculated at a nearby climate station on a reference surface, conventionally short grass. This value is called the reference evapotranspiration, and can be converted to a potential evapotranspiration by multiplying with a surface coefficient (www.southamptonweather.co.uk).

There are approximately 50 methods or models available to estimate ET_p, but these methods or models give inconsistent values due to their different assumptions and input data requirements, or because they were often developed for specific climatic regions (Grismer *et al.,* 2002).

Reference evapotranspiration ***(ET_o):*** Reference evapotranspiration is defined as "the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m (4.72 in), a fixed surface resistance of 70 sec m^{-1} (70 sec $3.2ft^{-1}$) and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground" (Suat Irmak and Dorota Z. Haman, 2003).

2.2.1. ESTIMATING EVAPOTRANSPIRATION

1) There are programs designed to calculate reference evapotranspiration (ETo), some of the programs used by UK Cranfield University are:

➢ **AWSET** is a program for calculation of reference evapotranspiration from automatic weather stations. AWSET will read data files generated by an automatic weather station and calculate reference evapotranspiration (ETo) either daily or for each timestep of the data. The minimum required input data are:

- air temperature
- humidity
- solar radiation
- wind speed.

The user can configure the program to accept data in a range of units and formats, thus the software will work with most automatic weather stations as long as they produce an ASCII format output file.

ETo is calculated using one of three methods;

- Penman
- Penman-Monteith
- FAO Modified Penman.

➢ **DAILYET** is a simple 'calculator' for estimating daily reference evapotranspiration (ETo) using data collected from a conventional weather station. The minimum input data required are maximum and minimum air temperature, relative humidity, sunshine duration and wind speed. The program runs under any version of Windows and can accept data in different forms, e.g. wet & dry bulb temperatures in place of relative humidity, sunshine duration in place of solar radiation.

ETo is calculated using one of three methods;

- Penman
- Penman-Monteith
- FAO Modified Penman.

➢ **WaSim ET** is a program for calculating Reference Evapotranspiration (ETo) from data in a text file using the Penman-Monteith, Penman or FAO modified Penman methods.

The program runs under any version of Windows and can accept data in different forms, e.g. wet & dry bulb temperatures in place of relative humidity, sunshine duration in place of solar radiation.

ETo is calculated using one of the following methods;

- Penman-Monteith
- FAO Modified Penman
- Penman
- Penman open water.

2) Expressions for potential evapotranspiration are enumerated by *Jiabiao et. al. 2005.*

➢ *Turc (1961)* developed an evapotranspiration potential formula depending only on average air temperature *t* and global solar radiation R_s, estimated through the sunshine duration:

- for soil with relative moisture RH bigger or equal to 50%

$$PET = 0.013 \cdot \left(\frac{T}{T+15}\right) \cdot (R_s + 50) \qquad (2)$$

where daily potential evapotranspiration (PET) (mm/day), daily mean air temperature (T) (°C), daily solar radiation (R_s) ($cal/cm^2/d$).

-for soil with relative moisture *RH* smaller than 50%

$$PET = 0.013 \cdot \left(\frac{T}{T+15}\right) \cdot (R_s + 50) \cdot \left(1 + \frac{50 - RH}{70}\right) \qquad (3)$$

where daily potential evapotranspiration (PET) (mm/day), daily mean air temperature (T) (°C), daily solar radiation (R_s) ($cal/cm^2/d$), is the daily mean relative humidity (RH) (percent).

➢ *Hamon (1963) Method* (PET=0 when T<0)

$$PET = 0.1651 \times Ld \times RHOSAT \times KPEC \quad (4)$$

$$RHOSAT = 216.7 \times \frac{ESAT}{T + 273.3} \quad (5)$$

$$ESAT = 6.108 \times EXP\left(17.26939 \times \frac{T}{T + 237.3}\right) \quad (6)$$

where daily potential evapotranspiration (PET) (mm/day), daily mean air temperature (T) (°C), the which is time from sunrise to sunset in multiples of 12 hours (Ld), the saturated vapor density (g/m3) at the daily mean air temperature (RHOSAT), saturated vapor pressure (mb) at the given T (ESAT), the calibration coefficient (KPEC).

➢ *Thornthwaite (1948) Method*

$$PET = 1.6L_d\left(\frac{10T}{I}\right)^a \quad (7)$$

where daily potential evapotranspiration (PET) (mm/day), the daytime length which is time from sunrise to sunset in multiples of 12 hours (Ld), monthly mean air temperature (T) (°C), the annual heat index (I), $a = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 0.01791I + 0.49239$;

➢ *Priestley – Taylor (1972) Method*

$$\lambda PET = \alpha\frac{\Delta}{\Delta + \gamma}(R_n - G) \quad (8)$$

where daily potential evapotranspiration (PET) (mm/day), the latent heat of vaporization (λ) (MJ/kg), where λ=2.501-0.002361 T, the daily mean air temperature (T) (°C), the calibration constant (α) (α=026 for wet and humid conditions, the slope of the saturation vapor pressure temperature curve (kPa/°C) (Δ) $\Delta=0.200(0.00738T+0.8072)^7-0.000116$, the psychrometric constant modified by the ratio of canopy resistance to atmospheric resistance (γ) (kPa/°C).

$$\gamma - \frac{c_p p}{0}.622\lambda \quad (9)$$

where the specific heat of moist air at constant pressure (c_p) (kJ/kg/°C) c_p = 1.013 kJ/kg/°C =0.0010 13 MJ/kg/°C; atmospheric pressure (p) (kPa), p = 101.3 − 0.01055 EL; the elevation (EL) (m); the net radiation (Rn) (MJ/m^2/day); the heat flux density to the ground (G) (MJ/m^2/day).

$$G = 4.2\frac{(T_{i+1} - T_{i-1})}{\Delta t} = -4.2\frac{(T_{i-1} - T_{i+1})}{\Delta t} \quad (10)$$

the mean air temperature (T_i) (°C) for the period I; the difference of time (days) between two periods (Δt).

➢ *Makkink (1957) Method*

$$PET = 0.61 \cdot \left(\frac{\Delta}{\Delta + \gamma}\right) \cdot \frac{R_s}{58.5} - 0.12 \quad (11)$$

where daily potential evapotranspiration (PET) (mm/day), the slope of the saturation vapor pressure temperature curve (Δ) (kPa/°C) $\Delta=0.200(0.00738T+0.8072)^7-0.000116$, the psychrometric constant modified by the ratio of canopy resistance to atmospheric resistance (γ) (kPa/°C), daily solar radiation (R_s) (cal/cm^2/d).

➢ *Hargreaues-Samani (1985) Method*

$$\lambda PET = 0.0023 \times R_a \times TD^0.5 \times (T + 17.8) \quad (12)$$

where daily potential evapotranspiration (PET) (mm/day), the daily mean air temperature (T) (°C), the latent heat of vaporization (λ) (MJ/kg), the extraterrestrial solar radiation (R_a) (MJ/m2lday; the daily difference between the maximum and minimum air temperature (°C).

2.2.2. ESTIMATING EVAPORATION

Evaporation (*E*), from the hydrological point of view, is the process in which water from open water surfaces (oceans, seas, lakes and rivers), from uncovered soil and from surfaces covered by snow and glaciers goes into the atmosphere in vapor state. [Musy, 2001]. For evaporation to take place the presence of water inflow is assumed. Water will evaporate from free open surfaces like land, lakes, reservoirs, open streams, but also from soils covered with vegetation, trees, etc. Precipitation that reaches the ground surface returns to the atmosphere in vapor shape (http://echo2.epfl.ch/VICAIRE/).

We can estimate the evaporation using one of the formula below:

➢ *ROHWER Formula:*

$$E = 0.484 \cdot (1 + 0.6 \cdot u) \cdot (e_s - e_a) \quad (13)$$

where evaporation (*E*) (mm), vapor pressure at saturation state at the evaporation surface temperature (e_s) (kPa), vapor pressure during the estimation time interval (e_a) (kPa), wind speed (*u*) (m/s).

➢ *PENMAN Formula:*

$$E = \frac{\Delta + 2\gamma}{\Delta + \gamma} \cdot E_c - \left(\frac{\gamma^{2-\lambda} \cdot E_a}{\Delta + \gamma}\right) \quad (14)$$

$$\gamma = \frac{C_p \cdot P}{\varepsilon \cdot \lambda} = 0.00163 \cdot \frac{P}{\lambda} \quad (15)$$

where evaporation *(E)* (mm), Bowen constant *(γ)* (kPa/°C), slope of the maximum curve tension of the saturated air with vapor depending on temperature *(Δ)*, vaporization constant heat at constant pressure, *(γ)* (*γ* = 2.45 MJ/kg), report vapor molecule *(ε)* (weight /air sec), (*ε*= 0.622), atmospheric pressure *(P)* (kPa), vaporization constant heat at constant pressure *(C_p)*, C_p = 1.013×10-3 (MJ/kg/°C), evaporation calculated by Rohwer formula (E_a) (mm), evaporation measured by Colorado bank (E_c) (mm).

➢ *PRIMAULT formula* for open water surfaces:

$$E = \left(1.03 - \frac{e_a}{e_s}\right) \cdot (N + 2n_d) \qquad (16)$$

where evaporation (E) (mm), vapor pressure at saturation state at the evaporation surface temperature (e_s) (kPa), vapor pressure during the estimation time interval (e_a) (kPa), effective sunstroke duration during the estimation interval (N) (h), total number of days of the estimation interval (n_d).

Among these empirical and semi-empirical formulas the Penman formula is the most used and if the values for the parameters that occur in relation are correctly introduced the result will be reasonably accurate.

2.2.3. EVAPORIMETERS

To determine the soil surface evaporation as well as the extensive use devices called evaporimeters. The evaporation of water from some device can be measured and related to ETo (Hess, 1996).

1) *ATMOMETERS*

Fig.2. Atmometer

An atmometer acts as miniweather station that will provide reference ET (ETr) at a reasonable cost and with little effort. Atmometers have been used since the early 1900's to study plant transpiration, In recent years the ceramic plate has been covered by green canvas or Gore-Tex® to more accurately simulate the transpiration from a plant (Hess, 1996.).

2) *EVAPORATION PANS*

Fig.3 Evaporation pan

With **Pan evaporation** we can measures daily evaporation. The best known of the pans are the "Class A" evaporation pan (fig.3) and the "Sunken Colorado Pan". Knowing daily evaporation we can calculate reference crop evapotranspiration with Doorenbos & Pruitt 1974 formula (S. Mohan 1991):

$$ET_0 = K_{pan} \times E_{pan} \qquad (17)$$

were reference crop evapotranspiration ET_0, pan coefficient K_{pan}, pan evaporation E_{pan}.

3. ROLE OF THE URBAN WATER BALANCE

Role of urban water balance in designing and practicing an integral urban water management was highlighted by F.H.M. van de Ven, (1990). Because in this work we do not refer to effect of urbanization on water quality, we have written urban water balance role in terms of water quantity:

- It is necessary to develop a water balance for urban areas to establish the effect of urbanization.
- The urban water balance is a method for designing and operating an integral urban water management system or an easy way to explain the feasibility of a proposed integral urban water management system.
- We can use infiltration facilities to minimize stormwater runoff from urban areas.
- By interception/evapotranspiration vegetation minimizes stormwater runoff and removes a lot of water from an urban area.

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