ARTICLE IN PRESS

Resources, Conservation & Recycling xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

# Assessing crop virtual water content under non-standard growing conditions using Budyko framework

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ARTICLE INFO

*Keywords:*
Virtual water content
Budyko framework
Non-standard conditions
Crop evapotranspiration

ABSTRACT

One of the most challenging steps in implementing analysis of virtual water content (VWC) of agricultural crops is how to properly assess the volume of consumptive water use (CWU) for crop production. In practice, CWU is usually considered equivalent to the crop evapotranspiration ($ET_c$). Following the crop coefficient method, the $ET_c$ from crops grown under standard or non-standard conditions can be estimated by multiplying the reference evapotranspiration ($ET_0$) by one or a few coefficients. However, when current crop growing conditions deviate from standard conditions, accurately determining the coefficients under non-standard conditions will be a complicated process and requires lots of field experimental data. Based on regional surface water-energy balance, this research integrates the Budyko framework into the traditional crop coefficient approach to simplify the coefficients determination. This new method enables us to assess the volume of agricultural VWC only based on some hydrometeorological data and agricultural statistic data in regional scale. To demonstrate the new method, we apply it to the Shijiazhuang Plain, which is an agricultural irrigation area in the North China Plain. The VWC of winter wheat and summer maize is calculated and we further subdivide VWC into blue and green water components. Compared with previous studies in this study area, VWC calculated by the Budyko-based crop coefficient approach uses less data and agrees well with some of the previous research. It shows that this new method may serve as a more convenient tool for assessing VWC.

## 1. Introduction

Analysis of the virtual water flow associated with the international food trade provides a global perspective for the effective water resource management (Chapagain et al., 2006; Aldaya et al., 2010; Giljum et al., 2011; Antonelli and Greco, 2015; Antonelli and Sartori, 2015; Chen et al., 2017). A most important prerequisite for this kind of analysis is the reliable calculation of crop virtual water content (VWC). VWC is mathematically calculated as the ratio of consumptive water use (CWU) to crop yield (Chapagain and Hoekstra, 2004). The crop yield information can be obtained from statistical data, and we can easily guarantee its accuracy. However, as another key variable for VWC assessment, the volume of CWU in agriculture is difficult to measure and directly estimate (Yuan and Shen, 2013; Wang et al., 2014). Since CWU of crops is eventually transformed into crop transpiration and soil evaporation, people tend to use the term crop evapotranspiration ($ET_c$) interchangeably with actual CWU by crop, and indirectly estimate CWU in practical calculation through deriving $ET_c$ from reference evapotranspiration ($ET_0$) (Rajan and Maas, 2014).

The most classic formula for indirectly calculating CWU for VWC is the crop coefficient approach listed in the FAO Irrigation and Drainage Paper No 56 on Crop Evapotranspiration (Allen et al., 1998). This simple quantification method generally assumes the standard conditions under which irrigation water is always readily available when crops need it. In the crop coefficient approach, CWU is determined by multiplying $ET_0$ by crop coefficient ($k_c$) during the growth period. $k_c$ is an experimentally determined ratio between measured $ET_c$ and $ET_0$. This approach uses the $k_c$ to represent the crop characteristic and soil evaporation that distinguish a specific crop from the reference crop. It is easy to determine the value of $k_c$ under standard conditions since it can be obtained from literatures. However, the calculated result of CWU from this approach does not often match the actual crop water consumption, since the assumption of standard conditions is viable only if irrigation water is sufficient and used rationally. Under some non-standard conditions, such as in some areas undergoing water scarcity, irrigation water can hardly be guaranteed, leaving the calculated results larger than the actual CWU and VWC (Papadaskalopoulou et al., 2015; González Perea et al., 2016). Or in some areas with poor irrigation

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http://dx.doi.org/10.1016/j.resconrec.2017.08.009
Received 30 April 2017; Received in revised form 11 August 2017; Accepted 11 August 2017
0921-3449/ 

practices, irrigation water could be wasted through long-time flood irrigation, making the calculated results smaller than the actual CWU and VWC (Hu et al., 2010; Lazzara and Rana, 2010). Consequently, to some degree, the results of virtual water calculation under standard conditions are in the nature of a theoretical crop water requirement rather than the actual CWU.

To calculate actual CWU and VWC under non-standard conditions, people tend to adjust the $k_c$ by adding more coefficients in the calculation formula, such as water stress coefficient ($K_s$), yield response factor ($K_y$), resistance correction factor ($F_r$), the fraction of the ground covered by the crop ($f_c$), density coefficient ($K_d$) and so on (Allen et al., 1998; Allen and Pereira, 2009; de Miguel et al., 2015). For example, a widely-known improvement is to add a water stress coefficient $K_s$, which is used to represent the effect of water stress on crop transpiration. These added coefficients can improve the accuracy of estimating crop evapotranspiration under non-standard conditions (Allen et al., 2005; Shukla et al., 2013; Pereira et al., 2015). However, the values of these coefficients mainly depend on several factors, such as local agro-climatic conditions and various management practices (Allen et al., 1998). These factors vary during the growing period, as well as with different locations. It makes the coefficients difficult to be determined accurately. In addition, none of the existing literatures provides the uniform reference values for all of these coefficients. Researchers need to determine these values by field experiments. Thus, when the crop coefficient approach is chosen to quantify crop VWC under non-standard conditions, one big challenge is that the determination of the coefficients is complicated and requires large amounts of observation data. A more convenient approach is urgently needed to determine the coefficients for crops under non-standard conditions.

In agriculture-dominated regions, a large volume of water from rainfall and irrigation is consumed for crop evapotranspiration (Lei and Yang, 2010). This part of water plays an important role in regional climate system and links with the regional water and energy supply–-demand dynamics (Zhao et al., 2013). In addition to field experiments, the crop coefficients used to adjust $k_c$ can be alternatively estimated based on the regional water and energy supply–demand dynamics. The Budyko framework, a widely used and well-established hydrological model, offers us an effective tool for characterizing regional water-energy balance (Yao et al., 2016). With the aid of the Budyko framework, we can explore the relationship between crop evapotranspiration and regional total evapotranspiration, and then adjust $k_c$ for crops in non-standard conditions. Because only a few easily accessible parameters appear in the model, the Budyko framework is simple and convenient to be used.

The objective of this study is to extend the traditional crop coefficient approach with the aid of Budyko framework for assessing regional VWC of crops under non-standard conditions. The method is applied to assess the VWC of major crops (winter wheat and summer maize) in Shijiazhuang Plain, which is an important agricultural area with intensive irrigation in North China. Considering water storage changes caused by over-exploitation of groundwater in the study area, we apply a non-steady state Budyko equation to determine the crop coefficients. The Budyko framework enables us to estimate CWU of crops in the study area at regional level, and benchmarked with long-term series of agricultural statistic data, to further explore temporal variations of VWC.

## 2. Methodology

The methodology consists of four parts: (1) a brief introduction of Budyko frameworks under steady-state and unsteady-state conditions; (2) the crop coefficient approach used to calculate the $ET_c$ under non-standard conditions; (3) the procedure of using Budyko framework to determine coefficients in the crop coefficient approach; (4) the outline of crop VWC calculation and its subdivision into blue and green water.

### 2.1. A brief introduction of the Budyko framework

The Budyko framework, also refers to Budyko's hypotheses, has a proven ability to estimate and examine the water-energy balances and inter-annual evapotranspiration variations under a variety of landscapes and climate conditions (Budyko, 1958; Budyko, 1974; Gentine et al., 2012).

From the perspective of application, the various forms of Budyko equations can be divided into two categories: Budyko frameworks under steady-state and unsteady-state conditions.

The steady-state conditions have two indispensable prerequisites: (1) storage change is negligible at regional scale and long-term timescale, and (2) the studied system is closed and natural. One of the most popular forms to steady-state conditions is the Fu's Equation, which is also commonly served as the reference formula to unsteady-state conditions (Fu, 1981). It is a single parameter conceptual model derived from dimensional analysis and mathematical reasoning (Zhang et al., 2004). The form of Fu's Equation can be expressed as:

$$\frac{\mathrm{AET}}{\mathrm{P}} = 1 + \frac{\mathrm{PET}}{\mathrm{P}} - \left[1 + \left(\frac{\mathrm{PET}}{\mathrm{P}}\right)^{\omega}\right]^{1/\omega} \tag{1}$$

where AET is actual evapotranspiration across the region, P is precipitation and PET is potential evapotranspiration. In this equation, all the three fluxes (AET, PET and P) are expressed in millimetres (mm) per year. ω is a model parameter related to the landscape characteristics of catchments, such as vegetation cover, soil properties, and topography. The range of the parameter ω is from 1 to infinity. Setting $\omega = 2.6$ in Fu's Equation, we will get the original formulation and curves introduced by Budyko (Fig. 1). PET is potential evapotranspiration of the reference grass crop and calculated according to the FAO Penman-Monteith equation (Allen et al., 1998):

$$\mathrm{PET} = \frac{0.408\Delta(R_n - G) + \gamma \times \frac{900}{T+273} \times u_2 \times (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{2}$$

where Δ is the slope of the vapor pressure curve, kPa °$C^{-1}$; $R_n$ the net radiation, MJ $m^{-2}d^{-1}$; G is the soil heat flux density, MJ $m^{-2}d^{-1}$; γ is the psychrometric constant, kPa °$C^{-1}$; T is the average air temperature, °C; $u_2$ is the wind speed measured at 2 m height, m/s; $e_s$ is the saturation vapor pressure, kPa; and $e_a$ is the actual vapor pressure, kPa.

However, the assumptions of steady state restricted the further application of the Budyko framework, since parts of watersheds in the world are not under steady state. In irrigated croplands like

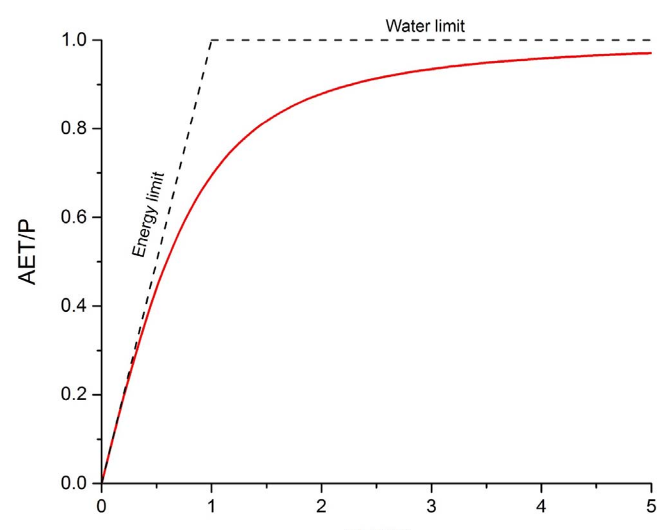


**Fig. 1.** Plots of evaporation index (AET/P) vs aridity index (PET/P) showing origin Budyko curve (Fu's equation) under steady-state conditions.