Water Consumption under Advective Conditions in Irrigated Fields under an Arid Climate

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Abstract

In arid regions, evapotranspiration at the edge of irrigated fields sometimes shows a high value. When planning irrigation, spatial differences of water consumption in the field have to be taken into account. A two dimensional numerical model which simulates the formation of boundaries on vapor pressure and temperature was used to estimate evaporation along the fetch. The estimated results of the model were compared with the data obtained from a wind tunnel. The effects of upwind surface temperature on evaporation on the downwind field were clarified.

The data observed in one of the deserts in China were applied in the calculation to discuss the distribution pattern of water consumption along the fetch. The applicability of Bowen ratio method is also discussed and the calculated results show it takes over 200 m from the leading edge to achieve a good estimation.

Key words: advection, evapotranspiration, irrigation, fetch

1. Introduction

In the advective condition, a one dimensionally derived evapotranspiration estimating method cannot be applied. This is shown in some reports on mass and heat transfer under advective conditions affected by irrigation. Analyses of large scale advection on irrigated field were proposed by de Vries(1959), Philip(1959), Rider et al.(1963) and Mcnaughton(1976). The evaluation of advection effects on water consumption were reported by Dyer and Pruitt(1962), Dyer and Crawford(1965) and Lang(1973).

In this report, the advection phenomena were examined using a two dimensional numerical model and a wind tunnel experiment. The results were applied to estimate the water demand of an irrigated field in an arid climate.

2. Evaporative conditions in the desert

The experimental station is on North–East of Lanzhou city in China. A vast desert named Tengkoli spreads along the north side of the Yellow River. The longitude, latitude and altitude are 105 degrees, 37 degrees and 1300 m, respectively. In August, surface temperature increases to 60 degrees, and air temperature at 2 m sometimes exceeds 35 degrees, while relative humidity decreases to less than 20 %.

The Yellow River flowing in the desert is considered to show resembled phenomena with irrigated field. Fig. 1 show diurnal changes of temperature and humidity near the river on August 13. In the midday, temperature at the river side was 3 to 4 degrees lower than a point separated 600 m from the River. On

the other hand, relative humidity at the River side was 10 % higher than at the 600 m point. The same observations were pursued along the river, but the data showed no differences.

Fig. 1 Temperature and humidity distribution around Yellow River.

3. Model to estimate evapotranspiration affected by advection

The heat and water flows in the surface layer can be described with the next equations

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} = \frac{\partial}{\partial z} (K_a \frac{\partial T}{\partial z}), \quad \frac{\partial e}{\partial t} + u \frac{\partial e}{\partial x} = \frac{\partial}{\partial z} (K_a \frac{\partial e}{\partial z}) \quad (1)$$

where, u is the wind speed, T is the temperature, t is the time, e is the humidity, x is the fetch, z is the height. The eddy exchange coefficient K_a can be given as

$$K_a = \kappa(z-d)u_*/\phi(z/L) \quad (2)$$

where, κ is the von Karman constant, d is the zero plane displacement, u_* is the friction velocity, $\phi(z/L)$ is the stability function and L is the Monin-Obkov length.

Stability function is expressed as

$$\phi(z/L) = (1 + nz/|L|)^m \quad (3)$$

where, n, m are constants.

In the area above the soil surface, a viscous sub-layer was assumed following Owen and Thomson (1962) and Chamberlain (1968). Surface resistance of the layer was assumed as,

$$r_g = u_{*g} \ln(z/z_{0g})/\kappa + a(\xi/\nu)^b (\nu/D_a)^c \quad (4)$$

where, r_g is the surface diffusivity resistance, u_{*g} is the friction velocity, z_{0g} is the roughness length, a, b, c are constants. ξ is the effective roughness, ν is the kinematic viscosity coefficient, D_a is the molecular diffusivity of vapor in air.

Moisture and heat flow in the soil layer can be expressed as

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} (D_w \frac{\partial \theta}{\partial z}) + \frac{\partial}{\partial z} (D_t \frac{\partial T_g}{\partial z}) + \frac{\partial K_g}{\partial z} \quad (5)$$

$$c_v \frac{\partial T_g}{\partial t} = \frac{\partial}{\partial z} (\lambda \frac{\partial T_g}{\partial z}) + l \rho \frac{\partial}{\partial z} (D_v \frac{\partial \theta}{\partial z}) \quad (6)$$

where, θ is the volumetric moisture content, T_g is the soil temperature, D_w is the diffusivity of soil water, D_t is the soil water thermal diffusivity, D_v is the diffusivity of vapor, λ is the thermal conductivity, c_v is the volumetric heat capacity, K_g is the hydraulic conductivity, l is the latent heat of vaporization, ρ is the density of liquid water.

4. Wind tunnel experiment

To clarify the advection effects on water consumption, a wind tunnel shown in Fig. 2 was used. The floor can be heated up to 70 degrees to simulate the hot soil surface in the desert. At the end of floor, 9

boxes filled with wetted soil columns were set to measure the evaporation rate along the fetch. Air temperature, humidity and wind speed profiles were measured at each 1 cm height up to 20 cm.

Fig. 2 Schematic view of the wind tunnel

Fig. 3 shows the difference of evaporation between heated and non-heated conditions. Big differences were observed in the heated conditions. At the leading edge, evaporation rate was 2.5 larger than that downstream. The calculated results agreed well with the observations.

Fig. 3 Changes of evaporation along the fetch.

5. Discussion

The meteorological data observed in Tengkoli desert were used to estimate evapotranspiration from an irrigated field in the desert. In the calculation, the length of the irrigated field was assumed to be 1000 m. Upper and lower boundaries were 100 m and -1 m, respectively.

Calculation began at 7 a.m. with a time step of 1 min. For estimating upwind boundary conditions, the following equations were applied.

$$\frac{\partial}{\partial z}(K_a \frac{\partial T}{\partial z}) = 0, \quad \frac{\partial}{\partial z}(K_a \frac{\partial e}{\partial z}) = 0 \quad (7)$$

Fig. 4 shows one of the examples of the energy balance components at noon along the fetch. The upwind surface temperature, air temperature, humidity and wind speed at 2 m were 60 degrees, 35 degrees, 20 % and 2 m/s, respectively. The evaporation at the leading edge was 20 % larger than the downwind. Ground heat flux increased gradually and sensible heat flux decreased gradually along the fetch. Soil surface temperature increased up to 43 degrees. Latent heat flux calculated by Bowen ratio method using the temperature and the humidity at 1.5 m and 2.0 m height, were shown with dotted line. It takes about 200m to have a good estimation.

Fig. 4 Energy balance along the fetch and the evaporation by Bowen ratio method

6. Conclusion

Evaporation under the condition of advection was successfully estimated with a numerical technique. Applying the model to an irrigated bare field, using the meteorological data observed in the China desert, energy balance components along fetch were clarified. The evaporation at the fetch within 200 m is always affected by advection in normal conditions. When planning irrigation, additional water has to be prepared to keep crops in a no moisture stress condition.

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