第 87 卷 增刊 地 质 学 报 ACTA GEOLOGICA SINICA Vol. 87 Supp.
2013 年 6 月 June 2013

Comparison and modification of methods for estimating evapotranspiration using diurnal groundwater level fluctuations in arid and semiarid regions

YIN Lihe, HOU Guangcai and DANG Xueya
Xi'an Institute of Geology and Mineral Resources, Xi'an, Shaanxi, P.R. China

For sustainable management of groundwater in arid and semiarid regions, a comprehensive understanding of groundwater balance is required. An important component of the groundwater balance is evapotranspiration (ET_G) as the climate in arid environments is characterized by low precipitation and high potential evapotranspiration. Diurnal water-table fluctuations were widely used to estimate ET_G by various methods. This study compares ET_G estimates by different methods for the low-gradient groundwater flow and the high-gradient groundwater flow systems. Groundwater flow modeling was used to create a synthetic water table fluctuation data set under a given ET_G scenario. Modeled water-table fluctuations were used in the White-method, the Hays-method and the-Loheide method to predict the ET_G. Results show that in the low gradient flow system, the White method gives the lowest values; the Loheide-method provides the highest values and closest to the ET_G used in the model; the Hays-method estimates are in between. For the high-gradient groundwater flow, all the three methods produced daily ET_G estimates that are consistent with the actual values. The Loheide-method or the Hays-method is recommended for quantifying the groundwater inflow for log-gradient flow systems and the modified White-method or the Hays-method is recommended for quantifying the groundwater inflow for high-gradient flow systems.

Arid and semiarid regions occupy approximately 30% of the land surface of the Earth. In these regions, vegetation provides a natural protection against desertification and dust storms in these regions. Some vegetation is known as phreatophyte and is groundwater dependent (*Butler et al.*, 2007). Phreatophyte transpiration consumes groundwater and causes diurnal fluctuations of groundwater levels (*Gribovszki et al.*, 2010). On the other hand, surface water is scarce, and groundwater is often the only reliable water resource for the social-economic development in arid regions. Sustainable management of groundwater resources must consider both the water use by human activities and by nature. The starting point to develop a sustainable groundwater use plan is the assessment of groundwater balance. In arid environments, an important component of the groundwater balance is groundwater evapotranspiration (ET_G). The shallower the water table and the drier the climate, the larger the ET_G is and its contribution is to groundwater discharge (*Lubczynski*, 2009).

ET_G is extremely difficult to quantify directly due to its spatial and temporal variability (*Mould et al.*, 2010). In real world, ET_G is driven by incoming solar radiation, therefore, has a strong diurnal signal caused by evapotranspiration of phreatophytic vegetation. In response to water loss, groundwater level fluctuates

Email: ylihe@cgs.cn

diurnally. Groundwater level fluctuations have long been recognized as valuable information for inferring daily groundwater evapotranspiration. There are several practical advantages of using diurnal groundwater level fluctuations to estimate ET_G. Therefore, there is growing number of applications using diurnal groundwater level fluctuations to estimate ET_G (*Gribovszki et al.*, 2010).

White(1932) first proposed the method of estimating ET_G using diurnal groundwater level fluctuations. The original White method has been modified and newly improved methods were developed, such as Hays (2003), and Loheide et al. (2005). These are the three mostly used methods, there are, however, no systematic analysis and comparisons of the methods for estimating ET_G. As it is difficult to assess whether the real-life situations satisfy the basic assumptions of the three methods, it is impossible to select a proper method just based on the assumptions. The objectives of this study are: (1) to compare the accuracy of the different methods used in estimating ET_G, (2) to improve the accuracy of ET_G estimation methods and (3) to give the guidelines for proper method selection.

In this study, a groundwater flow model was used to generate diurnal groundwater level fluctuations by a given evapotranspiration fluxes. The White method, the Hays method and the Loheide method were applied to the model-generated diurnal groundwater level fluctuations to estimate ET_G. The estimated ET_G from the three methods were compared with the actual ET_G of the groundwater flow model.

The hydrogeological conceptual model consists of a phreatophyte-dominated floodplain and an upland region, and is a typical hydrogeological cross-section in many small watersheds. Diurnal fluctuations of groundwater levels across this section were simulated with MODFLOW-2000. The finite difference grid consisted of 25 rows, 50 columns and 1 layer, with a regular cell size of 20 × 20 m. The ET package was used to simulate ET_G. The maximum ET_G rate near the surface varies from 6:00 to 18:00, corresponding to a maximum of 2 mm/h at noon and drops to zero during the night. In the numerical model, a ET package was used and the actual values of ET_G (mm h^{-1}) were calculated using the following equation developed by McDonald and Harbaugh(1988).

Four representative observation wells (Obs1 to Obs4) were located along the cross-section. Obs1 is located in the riparian zone, and the distance to the river is 10 m. Obs2 is at the foot of the hill, Obs3 is in the middle of the hill slope, and Obs4 is near to the water divide. Under the given ET_{Gmax} rate, the model was run on hourly stress periods for 10 days.

For Obs1,the groundwater inflow was calculated using the recovery period of 0:00 to 4:00 for the White method, the whole recovery period for the Hays method, and 0:00 to 5:00 for the Loheide method. The average of the actual daily ET_G was 12.54 mm/d. The average daily ET_G estimated by the White method, the Hays method and the Loheide method were 4.76 mm/d, 6.88 mm/d and 8.33 mm/d, respectively. It is clear that all three methods underestimate severely the actual daily ET_G.

The White method inherently introduces a significant source of error by assuming a constant net groundwater inflow for the 24-h period. As noted by *Troxell* (1936), net groundwater inflow in general is not constant over time and the variable groundwater inflow has been observed in many literatures (*Butler et al.*, 2007;). In this study, Zonebudget (*Harbaugh*, 1990) was used to calculate the inflow and outflow of the model cell where the observation well is located. The net groundwater inflow starts to increase immediately when ET_G occurs, and peaks around 13:00 that is about one hour after ET_G reaches its maximum. During the night time from 18:00 to 06:00, groundwater inflow decreases. In the White method, groundwater inflow from 00:00 to 04:00 is used to calculate the daily groundwater inflow, therefore, groundwater inflow is underestimated because during this period the inflow is small (*Gribovszki et al.*, 2008). *Hays* (2003) applied the hourly rate of water table rise between the minimum water level of the target day and maximum of the following day for the ET_G calculation. The groundwater inflow for the period of

ET_G occurrence was obtained using the formula $S_y(H_2-H_L)T_2/T_1$. The groundwater inflow calculated by the Hays method is 5.98 mm/d that is higher than the White method. However, it is still less than half of the actual groundwater inflow. The Loheide method calculates higher groundwater inflow (8.37 mm/d), but still much less than the actual groundwater inflow. The Loheide method calculates the recovery slope in finer time steps (hourly), it captures better the temporal variations in the recovery limb of the hydrograph.

The average values of ET_G estimates by the White method, the Hays method and the Loheide method were quite close to the average of actual ET_G values for Obs2. The results show that ET_G estimates from the White method and the Hays method are 10.70 mm/d and 10.79 mm/d respectively, about 3% more than the actual value; while the Loheide method estimates is about 5% higher than the actual value. For Obs3, the White method and the Loheide method provide an estimation of 5.05 mm/d and 5.02 mm/d respectively, and they are almost identical to the actual ET_G (5.03 mm/d). For Obs4, the White method gives an estimation of 1.33 mm/d, slightly better than the Loheide method (1.27 mm/d).

Although the Loheide method is relatively better to estimate ET_G for Obs1, there is still some difference from the actual values. As suggested by Loheide (2008), it is preferable to have the longest period to determine theΓ[WTDT]. But, it is not easy to determine the time when ET_G stops. The time when the water table begins to increase may not be the ceasation time of ET_G. In Obs1, water table starts to increase at 16:00 when ET_G is still occurring. Groundwater inflow will contribute to both storage and ET_G when the water table is rising and ET_G is occurring at the same time. Only when ET_G stops, the rise of water table becomes faster. Therefore, the rate of water table change during recovery periods may be used as an indicator of the cease of ET_G. The fastest increase occurred around 18:00 that corresponded to the time when ET_G ended. As a result, $\Gamma[WT_{DT}]$ can be determined using the water table recovery data from 18:00 to 5:00. The best fitting curve was an exponential function for$\Gamma[WT_{DT}]$, rather than a linear equation. Therefore, the Loheide method was modified by using the fitted exponential function to calculate ET_G. The average daily ET_G calculated from the modified Loheide method is 12.31 mm/d, only about 2 % lower than the average of actual daily ET_G. The hourly ET_G estimates with the modified Loheide method is very close to the actual data, much better than the original Loheide method.

This study compared methods of estimating groundwater evapotranspiration (ET_G) using hourly groundwater level hydrographs. The hourly groundwater level hydrographs were generated by a groundwater flow model with diurnal evapotranspiration. A groundwater flow model with diurnal evapotranspiration generated the hourly groundwater level hydrographs. Four representative groundwater observation wells were selected: one observation well was located in the riparian zone near to the river, one well at the foot of the hill, one in the middle of the hill slope, and one near to the water divide. The model simulated hourly groundwater levels at four observation wells for 10 days. The model also calculated the actual ET_G, net groundwater inflow and change of groundwater storage at locations of the four observation wells. The White method, the Hays method and the Loheide method were applied to the four hydrographs to estimate ET_G.

All three methods underestimated severely daily ET_G for Obs1. In Obs1, net groundwater inflow contributes more water to evapotranspiration than the groundwater storage. No methods can accurately account for varying net groundwater flow. The Loheide method is comparatively a better method which because it calculates highest ET_G estimate is the highest. When an exponential equation is used to calculate the rate of water table recovery, the Loheide method can approximate hourly ET_G more accurately.

All of the three methods estimated accurately daily ET_G for the other three wells as groundwater storage contributes more water to evapotranspiration than net groundwater flow. The net groundwater inflow is also almost constant. All the methods can calculate accurately the change of groundwater storage and the constant inflow. The modified White method can also calculate hourly ET_G and is preferably to be used.

The analysis of the pattern of the recovery limb of the groundwater level hydrograph and up and down gradient groundwater level differences can help select a suitable method to estimate ET_G. When the recovery limb of the groundwater level hydrograph is a straight line and the up and down gradient groundwater level differences are parallel and constant, the White methods can be used. Otherwise, the Loheide or modified Loheide methods are recommended.

Key words： Evapotranspiration, Water-table, Diurnal fluctuation, Comparison

Reference

Bulter, J.J., G.J. Kluitenberg, D.O. Whittemore, S.P. Loheide, W. Jin, M.A. Billinger, X. Zhan (2007) A field investigation of phreatophyte-induced fluctuations in the water-table. Water Resources Research 43. Doi:10.1029/2005WR004627.

Gribovszki, Z., J. Sziagyi, P. Kalicz (2010) Diurnal fluctuations in shallow groundwater levels and streamflow rates and their interpretation - A review. Journal of Hydrology 385, 371-383.

Lubczynski, M.W. (2009) The hydrogeological role of trees in water-limited environments. Hydrogeology Journal 17, 247-259.

White, W.N. (1932) A method of estimating ground-water supplies based on discharge by plants and evaporation from soil: results of investigations in Escalante Valley, Utah. US Geological Survey Water Supply Papper 659-A.

Hays, K.B. (2003) Water Use by Saltcedar (Tamarix Sp.) and Associated Vegetation on the Canadian, Colrado and Pecos Rivers in Texas. M.S. thesis. College Station, TX: Texas A&M University. 132p.

Loheide, S.P., J.J. Butler, S.M. Gorelick (2005) Estimation of groundwater consumption by phreatophytes using diurnal water-table fluctuations: A saturated-unsaturated flow assessment. Water Resources Research 41. Doi:10.1029/2005WR003942.

McDonald, M.G., and A.W. Harbaugh (1988) A modular three dimensional finite-difference ground-water flow model. USGS Techniques of Water-Resources Investigations, book 6, chap. A1. Reston, Virginia: USGS.

Troxell, H.C. (1936) The diurnal fluctuation in the ground-water and flow of the Santa Anna River and its meaning. Transactions American Geophysical union 17(4), 496-504.

Harbaugh, A.W. (1990) A computer program for calculating subregional water budgets using results from the U.S. Geological Survey modular three-dimensional ground-water flow model: U.S. Geological Survey Open-File Report 90-392, 46 p.

Loheide, S.P. (2008) A method for estimating subdaily evapotranspiration of shallow groundwater using diurnal water-table fluctuations. Ecohydrology 1, 59–66.