Water Losses Calculation Model of Irrigation Channel

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Abstract
A considerable part of losses to farmland irrigation water invalid losses is in the channel water delivery process, in order to calculate the truly water losses in the channel water delivery process accurately, the author takes irrigation water channel in Hebei piedmont plain as the research object, from the perspective of regional water resources, put forward that the real losses of irrigation channel can be divided into supply of vadose zone water shortage, water surface evaporation loss, capillary rising amount and soil evaporation loss in the groundwater deep buried area. According to the generation mechanism of the four part losses, the calculation methods are discussed and the mathematical models are built to calculate the losses respectively. The research can provides technical supports to the further study of the regional rational development and utilization of water resources, the development of water-saving irrigation and improve the using efficiency of irrigation water and other relevant contents in the irrigation area, etc.
Key words: WATER RESOURCES, IRRIGATION CHANNEL, REAL WATER LOSS, INFILTRATION RATE.

1. Introduction

The existing cultivated land of Hebei piedmont plain area is 1812800 hm^2, accounting for the total land area of 64%, among them, the effective irrigation area is 1592100 hm^2, accounting for 87.82% of the farmland, which is the major grain producing area. The major irrigation methods in this area is traditional ground irrigation, the open channel water irrigation area accounts for more than 80% of the total irrigated area, and nearly 60% of the irrigation channels are not lining, and the water use coefficient of the canal system is low, water resources waste seriously. However, with the continuous development of the social economy, industrial water and living water demand is sustained growth, which makes the regional water use in agricultural and other departments of industrial and living water is getting more and more outstanding. Therefore, analysis on farmland irrigation canal water loss has a very important significance on regional water resources rational development and utilization, the development of agricultural water saving and alleviate the tense situation of other department of water.

Since 1960's, many domestic and foreign experts and scholars began to study the channel loss problem. In foreign countries, Ernst deduced the calculation formula of steady infiltration channels by analytical method in 1963[1]. In 1980's Rantz analyzed and studied how to use the dynamic water method for measuring water channel seepage quantity [2]. In 1992 Rastogi solved the seepage calculation model using the finite element method, and then accurate calculation of canal seepage is discussed [3]. In 2001 and 2003, Soneneshein and Luo using the finite difference method presented the groundwater calculation model which be used in the canal infiltration loss quantity[4, 5]. In 2002, Osman classified the canal seepage into all penetrate the aquifer and not fully penetrate the aquifer two categories, and then the calculation formulae are deduced [6].

In China, Zhang Yuzhen deduced the calculating formula of the flow between two adjacent groove at any time in any section considering the linear correlation between groundwater level and evaporation based on the basic equation of unsteady groundwater flow in 1963[7]. In 1995, Wang Shaoli analyzed the relationship between free seepage channel's seepage quantity and water depth of the channel by the hydrostatic test method [8]. In 2001, two-dimensional mathematical calculation model is established by Guo Weidong, Li Baofa, Ji Zhijun according to the theory of unsaturated soil water movement, and verified the result of numerical simulation research through the test [9]. In 2005, Yang Hongjuan, Ni Guangheng, Hu Heping by using Richards equation, considering the joint solution of saturated and unsaturated flow, has established the two-dimensional numerical calculation of canal seepage simulation model[10]. In 2010, Li Hongxing, Fan Guisheng combined with experimental data, established the three stages pressure infiltration model of soil channel [11], which accurately calculates the seepage quantity of canal. No matter which kind of methods of analysis and calculation, the main calculation is the seepage quantity of the irrigation channel. While the research considering the evaporation loss and the capillary rise water loss of lateral seepage boundary line of infiltration is relatively small. As the long time supply water to channel, the infiltration rate will reaches stabilize, then infiltration leakage loss will be fully recharge of groundwater. From a regional perspective of water resources (especially well and canal combined irrigation), this part of water is return flow, while is not invalid water loss and can be reused.

Thus, we take irrigation water channel in Hebei piedmont plain as the research object, analyze the calculation methods of the truly water loss in the channel water delivery process based on the consideration of section size of channel, water depth of channel and soil characteristics from the perspective of regional water resources, which can provide technical support to the further study of the regional rational development and utilization of water resources, the development of water-saving irrigation and improve the using efficiency of irrigation water and other relevant contents in the irrigation area, etc.

2. Analysis of water delivery loss of channel

The total losses include infiltration loss and evaporation loss two part in the process of water delivery of channel. Infiltration refers to the process of water seep into the soil form the soil water through the infiltrate control boundary. It’s an important link in the transformation of surface water, soil water and groundwater. Although the process of infiltration of channel water and field irrigation water are all refer to the water seep into the soil vertically, there are more differences between them, which mainly exist in the difference of infiltration boundary conditions in the soil and the difference of water movement driving force due to the certain water depth in the channel. The evaporation loss of irrigation canal in the process of delivery water mainly include water surface evaporation loss and soil evaporation loss in the soil under the effect of capillary force rising close to the ground which through channel side seepage into the soil.

According to the relationship between the channel water and underground water level, the analysis of channel seepage loss calculation is generally divided into 4 situations: the underground water level is higher than the channel water, aquifer recharge channels; groundwater level between the channel water and the channel bottom elevation, channel water recharge aquifer; underground water level is lower than the channel bottom elevation, and the aquifer water with backwater effect to canal seepage, channel water supply aquifer; underground water level is lower than the channel bottom elevation, and aquifer water level had no effect on canal seepage, channel water recharge aquifer. Taking into account the groundwater buried deeply in piedmont plain area in Hebei Province, the paper focuses on the fourth case, namely water loss calculation in free leakage conditions of irrigation channels, as shown in figure 1.

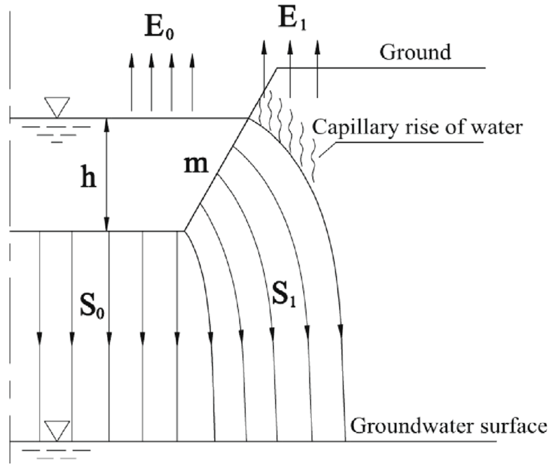

Figure 1. Irrigation channel freedom leakage schematic

In order to facilitate research, we assume that the soil homogeneous and isotropic between channel bed and underground water, and the underground water level has no influence on channel seepage. From the perspective of the analysis of regional water resources, irrigation canal water losses mainly include 4 parts: infiltration recharge the canal bottom and sides of a certain range of vadose zone water shortage S, the capillary rise water MS outside the boundary saturation line on both sides of the channel after reached a stable infiltration, the amount of evaporation loss of soil E_1 produced from the infiltration water both sides of the channel which close to the ground under the action of capillary forces, water surface evaporation E_0 of channel.

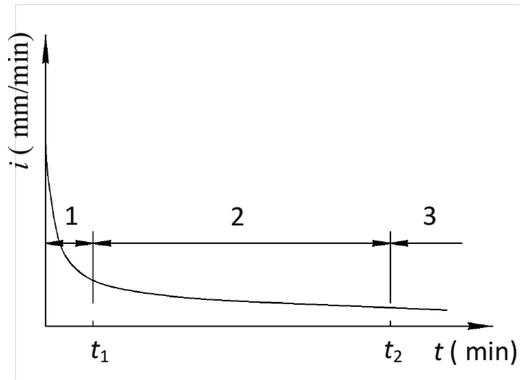

Figure 2. The relationship curve of infiltration rate and time

Considering infiltration trend rate, by the homogeneous soil infiltration curve under adequate water supply as shown in Figure 2, the infiltration process is divided into three stages: the infiltration rate rapidly decline stage, the infiltration rate decreasing linear stage and the stable infiltration stage. In the first stage, the initial infiltration rate is larger, then the infiltration rate decreased rapidly, until the moment of t_1 the infiltration rate began to linearly decreases, thus the first stage ended and entered the second stage; If water delivery time of channel is long enough, with the change of time, the channel bottom infiltration water promote wetting front moved down gradually, but the channel side infiltration volume partly to promote the wetting front moving down, another is used to satisfy the development of phreatic line boundary to the outside in the horizontal, until the vadose seepage reached saturation in the canal bottom and sides of a certain range (over the water table), then the infiltration rate began to keep stable, the corresponding time is t_2, then the infiltration into the beginning of the third stage; since the t_2 moment, canal water seepages are all recharged the groundwater, on both sides of the channels the infiltration boundary line reached the limit position, infiltration volume partially consumed by boundary saturation line outside the capillary rise of water, partially consumed by soil evaporation near the ground. From the analysis of regional water resources point of view, among the channel infiltration to the soil and underground water, the recharge of underground water in the third stage is the return of water, which can be repeated use, this is not calculated to the channel loss, except that the infiltration water are all water loss due to channel infiltration. Water surface evaporation loss of channel is the amount of water vapor evaporate from the water surface escaping to the atmosphere, in this part of the loss, the water can not reuse for irrigation, which is the real loss. Water surface evaporation loss of the channel is related to the surface scale and channel area, the location of the channel, season, climate and other conditions. In general, it can be estimated by the local measured evaporator evaporation and evaporator reduction coefficient.

3. Water losses calculation formula

3.1 Calculation of supply of vadose water deficit S

Infiltration which recharge vadose water deficit S in canal bottom and sides within a certain range is the loss of water in the process of the first and second infiltration stage, this paper combined with Kostiakov, Kostiakov - Lewis infiltration model and using empirical formula proposed by hongxing li and guisheng fan calculate this part of water, the infiltration experience formula in the first and second stage are:

$$i(t)=\begin{cases}k_0 t^{-a_0} & t\le t_1\\ i(t_1)+b(t-t_1) & t_1<t\le t_2\end{cases} \qquad (1)$$

Where k_0 is infiltration coefficient, t_1 is infiltration index, t_1 is the first stage over time, b is the second stage over time, b is the slope of infiltration curve in second stage. For symmetric trapezoidal canal, loss accumulation in each stage can be decomposed into channels on both sides of the slope infiltration and channel infiltration two parts. Considering the effect of channel water pressure, the infiltration rate in each canal bottom point in the same moment are the same, but the water pressure in the channel slope is gradually reduced as the water depth decreases, therefore, the slope infiltration rate should be considered the influence of time and depth two factors at the same time.

Considering the above factors, the cumulative infiltration volume in each stage can be calculated by integration for (1) formula's two stages respectively. The cumulative infiltration volume in first stage is:

$$S_{t1}=2S_1^1+S_1^0 = 2\sqrt{1+m^2}\int_0^h kt^a dx + k(h)t^{a(h)}B \qquad (2)$$

The cumulative infiltration volume in second stage is:

$$S_{t2}=2S_2^1+S_2^0$$

$$(3)\quad =2\int_0^h\left[(i(t_1)-bt_1)t+bt^2/2\right]_{t_1}^{t}dx+\int_{t_1}^{t}((i(t_1)+bt)B)dt$$

Water deficit S in the vadose zone recharged by channel infiltration is:

$$S=S_{t1}+S_{t2} \qquad (4)$$

Where the superscript "0" of m indicates channel bottom , "1" indicates the slope, the subscript "1" represents the cumulative infiltration of the corresponding region in first phase; "2" represents the cumulative infiltration of the corresponding region in second phase; m is the trapezoidal channels slope coefficient; h is the channel bottom width (m); h is the channel depth (m); x is a change of variable depth, $0 \le x \le h$; a is the infiltration index, $a = 1 - a_0$; k is the infiltration coefficient, $k = k_0(1 - a_0)$; infiltration parameters k ,*a,b* are all linear function; in formula (4) t is the channel leakage per meter in the drainage channels from the start of delivery water after t time, $0 < t \le t_2$, when $t = t_2$, then $t = t_2$.

3.2 Calculation of water surface evaporation loss E0

Irrigation canal water surface evaporation loss E_0 can be measured by evaporator to estimate the amount, calculated as:

$$E_0 = 0.001t(B + 2mh)LKE' \quad (5)$$

Where 0.001 is the conversion factor; t is the time from the beginning of delivery water to the end (d); L is the prismatic channel length (m); E' is the conversion factor of the evaporator, this coefficient is effected by the evaporator size, season and climatic zones and hydrothermal conditions, wind and other factors, coefficient can be measured or local authorities to provide; E' is the measured channel water evaporation by evaporator in unit time period (mm/d).

3.3 Calculation of capillary rise of water MS

MS capillary rise of water refers to the water immersed in the soil pore after channel lateral leakage reached stabilize, which is effected by the capillary force outer the limit boundary saturation line. MS is related to the initial soil moisture, soil properties, porosity, the linear and length of the infiltration limit boundary line and so on. The style of the infiltration limit boundary line also influenced by soil properties, soil stickiness is greater, the movement range of the saturation line is greater in the lateral. Where MS equal to per unit time of side channel leakage multiplied empirical coefficient in stable infiltration stage, the estimate formula is:

$$MS = \gamma \cdot 2\sqrt{1+m^2}\int_0^h f_0 dx \quad (6)$$

Where f_0 is the stable infiltration rate, the value of this parameter changed with the water depth, for both sides of the channel side slope seepage f_0 can be approximated as one dollar function of x; γ is the experience factor, $\gamma = 0.1 \sim 0.4$, when capillary action is strong, γ should use the higher value.

3.4 Calculation of soil evaporation loss E1

Soil evaporation loss E_1 refers to the loss of evaporation produced from the infiltration water both sides of the channel which close to the ground under the action of capillary forces. E_1 is affected mainly by the largest rising height of the capillary, soil properties, porosity, local weather conditions and other factors. We use side channel leakage amount of per unit of time in stable infiltration stage multiplied by the water time and use empirical coefficients to estimate E_1:

$$E_1 = \beta \cdot 2t\sqrt{1+m^2}\int_0^h f_0 dx \quad (7)$$

Where t is the water delivery time(d); β is the empirical coefficient.

3.5 Calculation of water loss

Take a branch irrigation canal in Hebei province piedmont plain to calculate the water loss, the canal with bed for loam, bottom width B=0.8m, the slope coefficient m=1.0, water depth h=1.5m, the design flow Q=2.25m^3/s, the channel length L=14.5km, water conveyance time T=11d, t_1=240min, t_2=1250min, steady infiltration rate of channel bottom f_0(h)=0.096mm/min. Channel real amount of water loss in 120min, 220min, 1000min, 4000min and 11d is calculated separately by equation (2)-(7), and the results are shown in Table 1.

Thus, before the steady infiltration stage, the channel water loss is composed of the supplementary of vadose water shortage and water surface evaporation, among which the supplementary of vadose water shortage accounted for the 99% of the total loss. After enters the stable infiltration stage, vadose saturated, the infiltration recharge of vadose zone water shortage reaches the maximum, and it no longer increases with the time, in this stage the infiltration boundary on both sides of the channel is no longer expand outward, and the capillary rise water reaches a steady state. But the water surface evaporation loss and soil evaporation loss are increased with the time.

From the data in the table, during the period of farmland irrigation, infiltration supplement of vadose zone water shortage accounts for a maximum proportion to the total water losses, up to 88.8%; evaporation of water surface accounts for 5.5% of the total losses amount; capillary rise of water accounts for the total losses amount of 3.8%, soil evaporation only accounts for 1.9% of the total losses.

4. Conclusions

The study takes the irrigation water channel in Hebei piedmont plain zone as the research object, from the angle of regional water resources, the leakage recharge to the underground water is separated from the canal seepage quantity, which is not the invalid loss, and establish the mathematical model of each part of the real loss to analyses and calculates them, in theory, which is more practical.

In addition, the capillary rise of water outside the infiltration limit boundary line on both sides of the canal and the soil evaporation of the capillary rise of water close to the surface on both sides of the channel included in the channel water losses, so that the channel loss calculation result is more accurate. The

Table 1. The calculated results of channel real water loss

Water delivery time	S (m^3)	E_0 (m^3)	MS (m^3)	E_1 (m^3)	Total water loss (m^3)
120min	6921	21	–	–	6942
220min	8895	39	–	–	8934
1000min	41503	176	–	61	41740
4000min	45362	704	1958	217	48241
11d	45362	2788	1958	985	51093

results of the research will be the real loss in channel process, which shall be used for the region (or irrigation) rational exploitation of water resources and water-saving irrigation and other related research, thus the calculated data will be more reasonable, and has more practical significance.

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