AN IRRIGATION WATER DISTRIBUTION MODEL FOR AREA OF MIXED CULTIVATION

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ABSTRACT

A water distribution model is presented which is capable of satisfying water demand in an area with large-scale mixed cultivation during the water-shortage periods. The proposed model is based on a new parameter called modified *K*-factor in which farm areas, canal and ditch lengths, and crop types are considered. Actual applications show that the proposed model has advantages over the model based on the original *K*-factor. The proposed model can deliver appropriate amounts of irrigation water to specific blocks at the right time, fairly and rationally. The model can be applied to either a main or to a lateral canal system. It is found that the water distribution of the main canal system is to be preferred for severe water shortages.

Key Words: water distribution; field irrigation requirements; mixed cultivation.

I. INTRODUCTION

The common practice of irrigation water distribution has been constructed based on single crops over large areas. Typical examples are paddy rice agriculture in Japan and Taiwan (Pereira *et al*., 1993; Masakazu, 1999; Chang *et al*., 2001) and upland crop agriculture in American and European countries (Droogers *et al*., 1999). Since there is only one crop in the irrigation service area, the water distribution practice can achieve accuracy to a certain extent. However, as crop diversity has become a trend in maintaining the competitiveness of agricultural productivity (Masayoshi, 1999), the mixing of paddy rice and upland crops in an irrigation service area will be more common in Taiwan. Since various crops have to be considered and their growth periods are different, the irrigation practice will become more difficult. The water demands of upland crops are often ignored or estimated by using only a representative crop in the whole irrigation service area. Although using such simplified methods may reduce the cost of irrigation management, the growth of crops is affected. Hence, it is justified to establish an irrigation water distribution model that accounts for the actual situation of mixed cultivation.

Regarding irrigation water distribution during water shortage periods, Pasandaran *et al*. (1989) proposed the *K*-factor method for solving the water distri-bution problem. However, this method is applicable only for minor shortage conditions. In addition, the calculation of system conveyance loss is inadequate. The *K*-factor method considers the total conveyance loss for the whole irrigation service area. However, in actual practice of rotational irrigation, only parts of the whole irrigation service areas are irrigated. For systematic water distribution in large paddy areas, Kan and Hsu (1984) proposed an adjusted irrigation plan by lengthening the rotational irrigation periods. Nevertheless, the distribution efficiency and amounts of water distributed under various shortage conditions were not discussed. Lin (1992) attempted to estimate the water distribution efficiency based on the weighting of canal lengths and rotational farm units. Kan *et al*. (1997a) and Chen *et al*. (1997) respectively modified the calculation of system conveyance loss in the *K*-factor method according to farm areas and canal lengths. However, they did not consider the water distribution in laterals and farm units in a mixed-cultivation situation. Therefore, there is a need to establish a water distribution model according to the farm areas, canal and ditch lengths, crop types and canal systems in order to satisfy the water requirements for various crops.

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This paper is organized as follows. Factors affecting water distribution are investigated in Section II. In Section III, a water distribution model is established which is capable of satisfying water demand in large-scale mixed cultivation irrigation areas during water shortage periods. Application of the proposed model and the corresponding discussions of the simulated results are presented in Section IV. Finally, conclusions are given in Section V.

II. FACTORS AFFECTING WATER DISTRIBUTION

The irrigation water distribution requires overall consideration of crop types, growing stages, crop water requirements, percolation, conveyance loss, and effective rainfall, etc. These factors vary with time and locations. Consequently, how to convey an adequate amount of water to specific blocks at the right time in large areas requires sophisticated professional skill. The corresponding factors are discussed as follows.

1. Crop Water Requirement

The crop water requirement (CWR) can be determined by direct measurement or through indirect estimation. Although direct measurement can yield an actual water requirement, it requires more money and labor due to morphological constraints. Instead, the indirect estimation is generally used. The estimation equation is expressed as

$$q_{jk}^{\mathrm{CWR}} = \mathrm{CC}_{jk} \times \mathrm{ET}_k^{\mathrm{refer}} \tag{1}$$

where q_{jk}^{CWR} is the crop water requirement for the jth crop during the kth irrigation period per hectare of irrigation area, CC_{jk} is the dimensionless crop coefficient for the jth crop during the kth irrigation period, and $\mathrm{ET}_k^{\mathrm{refer}}$ is the reference evapotranspiration of standard crop canopy during the kth irrigation period per hectare of irrigation area. The $\mathrm{ET}_k^{\mathrm{refer}}$ is often estimated using the Penmen-Monteith method (Monteith, 1994; Kan *et al.*, 1996). As to the crop coefficients, one can use the values recommended by the Food and Agriculture Organization (Doorenbos and Pruitt, 1977). Then, according to the growing seasons of all crops (paddy rice and upland crops), one can determine the total crop water requirement for any period.

2. Percolation in Paddy Fields

The percolation process in paddy fields is very complicated and varies with soil texture, ponding depth, water temperature, groundwater level, extension of root system, etc. In Taiwan the percolation in paddy fields is estimated using an empirical formula from the Taiwan Water Conservancy Bureau (Kan, 1978).

3. Effective Rainfall

Effective rainfall is the amount of rainfall that can be utilized by crops. From the viewpoint of irrigation managers, the amount of rainfall helpful to reduce the irrigation water supply is considered as effective rainfall. Because rainfall itself is uncontrollable, there are yet no accepted criteria for the estimation of effective rainfall. For areas with mixed cultivation of paddy rice and upland crops, one used to consider only the effective rainfall for paddy rice. However, for the ideal management of irrigation water, one needs to estimate the effective rainfalls for the paddy rice and upland crops separately.

Regarding the estimation of the effective rainfall for paddy rice, each irrigation association in Taiwan generally adopts its own experimental result that does not exceed 60% of mean precipitation or 50% of field water requirement, whichever is least. As to the estimation of the effective rainfall for upland crops, daily precipitation within 50 mm can be regarded as effective rainfall according to the experimental results of the Taiwan Water Conservancy Bureau (Kan, 1978).

4. Conveyance Loss in Canals and Ditches

Conveyance loss is the water lost during the conveyance process from source to fields, including evaporation, seepage, operation loss, etc. The conveyance path consists of a main canal (from the main intake to a lateral intake), a lateral canal (from the lateral intake to a farm intake), and ditches (from the farm intake to fields). In the past practice of irrigation, the conveyance losses in canals and ditches were generally considered as constant, which is inadequate. In this paper, methods for estimating the conveyance losses in canals and ditches are proposed in Sections III.1.(i) and III.1.(ii).

5. Water Requirement for Land Preparation

During land preparation, the field is ploughed and a considerable amount of water is applied so that soil is saturated and is ready for the transplantation of paddy. Theoretically, the water requirement for land preparation is composed of irrigation for paddy rice and the water needed to saturate the soil. The amount of water required for land preparation generally ranges from 120 to 200 mm (Cheng, 1980).

III. WATER DISTRIBUTION MODEL

1. Development of Model

The model to be developed can convey the appropriate amount of water to specific blocks at the right time under various circumstances, while agricultural production is not affected. For irrigation water distribution in an area of mixed cultivation during water shortage periods, Pasandaran *et al.* (1989) proposed the K-factor

$$K = \frac{\text{Available water}}{\text{Gross water demand}} \tag{2}$$

For the kth irrigation period, the K-factor is expressed as K_k herein. The K-factor is applicable during minor water shortage periods in which uniform reduction of water distributed is used. For rotational irrigation, the calculation of system conveyance loss is inadequate. The K-factor considers the total conveyance loss for the whole irrigation service area, although only a part of the area is actually irrigated. The K-factor cannot consider only the actual irrigation area and the conveyance path from the water source to the farm units to be irrigated. Hence, the water is wasted due to inadequate calculation of conveyance loss. In this paper, a procedure called modified K-factor is proposed in which farm areas, canal and ditch lengths, and crop types are considered. The modified K-factor is written as

$$\tilde{K}_k = \frac{Q_k^{\text{actual}} - Q_k^{\text{loss}}}{Q_k^{\text{project}} - Q_k^{\text{loss}}} \tag{3}$$

where $\tilde{K}_k$ is the K-factor for the kth irrigation period, Q_k^{actual} is the actual amount of water delivered to the system during the kth irrigation period, Q_k^{project} is the projected water demand of the system during the kth irrigation period, and Q_k^{loss} is the conveyance loss of the system during the kth irrigation period. The system herein refers to a main or lateral canal water distribution system.

(i) Conveyance Loss Coefficient for Ditches in a Farm Unit

When water is delivered from the intake of the rotational irrigation block (referred to as the farm intake herein) to fields through ditches, some water is lost in ditches. Hence, to obtain the projected water demand at the farm intake, a correction coefficient should be applied to the amount of water as calculated from the field irrigation requirement (see Eq. (8)). The correction coefficient is referred to as the conveyance loss coefficient (CLC) herein. In the past practice of irrigation, the CLC for any farm unit was taken as

$$\text{CLC}^{\text{farm}} = 1 + S \tag{4}$$

where S is the water loss in decimals and an empirical value of 0.2 or 0.25 is often used. In this paper the conveyance loss in ditches of a farm is regarded as a variable. Hence, the CLC for the ith farm is expressed as

$$\text{CLC}_i^{\text{farm}} = 1 + S_i \tag{5}$$

where

$$S_i = S_{\text{exp}}(A_i/A_{\text{exp}})\left(\sum_{i=1}^{n} S_i/n\right)\left(\sum_{i=1}^{n} A_i S_i / \sum_{i=1}^{n} A_i\right)^{-1} \tag{6}$$

where S_{exp} is the experimental water loss of a farm with an area of A_{exp}, A_i is the area of the ith farm, and n is the total number of farm units. The (A_i/A_{exp}) is introduced to consider the effect of the farm size on the water loss, which yields a larger value of water loss for a larger area of farm. The $\sum_{i=1}^{n} S_i/n$ is the average water loss and $\sum_{i=1}^{n} A_i S_i / \sum_{i=1}^{n} A_i$ is the area-weighted average water loss for all farms. They are introduced to yield a more rational estimate of the water loss in ditches of the ith farm (Kan *et al.*, 1997b; Lin, 1992).

(ii) Conveyance Loss Coefficient for Main and Lateral Canals

The same considerations apply to the calculation of the projected water demand at the lateral intake and main intake as the water losses in lateral and main canals are considered (see Eqs. (10) and (11)). In the past practice of irrigation, the conveyance loss in canals was regarded as a constant no matter for how long the water was delivered. That is $\text{CLC}^{\text{canal}} = 1 + C$ where C is the water loss in canals in decimals. In fact, the shorter the distance from the intake to the farm unit is, the smaller the conveyance loss is. Hence, the conveyance loss from the canal intake to a farm intake is regarded as a variable in this paper. Furthermore, the CLC is expressed as

$$\text{CLC}_i^{\text{canal}} = 1 + C_{\text{exp}} L_i \left(\sum_{i=1}^{n} L_i/n\right)^{-1} \tag{7}$$

where C_{exp} is the experimental water loss in decimals, L_i is the canal length from the canal intake to the ith farm unit, and $\sum_{i=1}^{n} L_i/n$ is the average canal length. The $L_i(\sum_{i=1}^{n} L_i/n)^{-1}$ is introduced to give a rational estimate of the water loss in canals (Kan *et al.*, 1997b; Lin, 1992), which can reflect the influence of the canal length on the water loss.

(iii) Projected Water Demand at the Farm Intake

For an area of mixed cultivation of paddy rice and upland crops, previous irrigation water distribution practices usually considered only the water demand for the paddy rice. As to the upland crops, their water demands were often neglected or estimated from a representative crop. In this paper, the actual situation of mixed cultivation is considered.

The projected water demand at the farm intake for the jth crop in the ith farm unit during the kth irrigation period is

$$Q_{ijk}^{\text{project, farm}} = q_{jk}^{\text{FIR}} \times A_{ij} \times \text{CLC}_i^{\text{farm}} \tag{8}$$

where q_{jk}^{FIR} is the field irrigation requirement (FIR) for the jth crop during the kth irrigation period per hectare of irrigation area, and A_{ij} is the area for the jth crop in the ith farm unit. The q_{jk}^{FIR} can be computed from

$$q_{jk}^{\text{FIR}} = q_{jk}^{\text{CWR}} + q_j^{\text{p}} - q_{jk}^{\text{ER}} \tag{9}$$

where q_{jk}^{CWR} is the crop water requirement (CWR) for the jth crop during the kth irrigation period per hectare of irrigation area as defined in Eq. (1), and q_{jk}^{ER} is the effective rainfall (ER) for the jth crop during the kth irrigation period per hectare of irrigation area, and q_j^{p} is the percolation in paddy fields for the jth crop per hectare of irrigation area. It should be noted that q_j^{p} is zero for upland crops.

(iv) Projected Water Demand at Lateral and Main Canal Intakes

Once the projected water demand at the farm intake for the jth crop in the ith farm unit during the kth irrigation period, $Q_{ijk}^{\text{project, farm}}$, is determined, the corresponding projected water demand at a lateral canal intake can then be calculated from

$$Q_{ijk}^{\text{project, lateral}} = Q_{ijk}^{\text{project, farm}} \times \text{CLC}_i^{\text{lateral}} \tag{10}$$

where $\text{CLC}_i^{\text{lateral}}$ is the conveyance loss coefficient for the lateral canal which delivers water to the ith farm intake.

From Eq. (10), one can obtain the projected water demand for a certain lateral canal intake. Then taking into account the conveyance loss between this lateral canal intake and the main canal intake, one can obtain the corresponding projected water demand at the main canal intake as

$$Q_{ijk}^{\text{project, main}} = Q_{ijk}^{\text{project, lateral}} \times \text{CLC}_i^{\text{main}} \tag{11}$$

where $\text{CLC}_i^{\text{main}}$ is the conveyance loss coefficient for main canal between the lateral and main canal intakes.

For areas with mixed cultivation of crops, for example paddy rice and upland crops, the projected water demand at a lateral canal intake during the kth irrigation period can be calculated from

$$Q_k^{\text{project, lateral}} = \sum_{i=1}^{n} \sum_{j=1}^{r} Q_{ijk}^{\text{project, lateral}} \tag{12}$$

where n is the number of farm units, and$r$ is the number of crop types. In a like manner, one can obtain the projected water demand at the main canal intake during the kth irrigation period

$$Q_k^{\text{project, main}} = \sum_{i=1}^{n} \sum_{j=1}^{r} Q_{ijk}^{\text{project, main}} \tag{13}$$

Subsequently, the water loss of a lateral canal during the kth irrigation period is

$$Q_k^{\text{loss, lateral}} = Q_k^{\text{project, lateral}} - Q_k^{\text{project, farm}} \tag{14}$$

Likewise, the water loss of a main canal during the kth irrigation period is written as

$$Q_k^{\text{loss, main}} = Q_k^{\text{project, main}} - Q_k^{\text{project, lateral}} \tag{15}$$

(v) Modified Farm Water Demand

In this paper, the modified K-factor of Eq. (3) is used to distribute the water to meet the farm water demand during the kth irrigation period, Q_k^{project}, during a water shortage (i.e., under a given actual water supply Q_k^{actual}). Eq. (3) can be applied to a main or lateral canal. For example, for the water distribution of a lateral canal, the Q_k^{project}, Q_k^{loss}, and Q_k^{actual} in Eq. (3) refer to $Q_k^{\text{project, lateral}}$, $Q_k^{\text{loss, lateral}}$, and $Q_k^{\text{actual, lateral}}$, respectively. The $Q_k^{\text{project, lateral}}$ and $Q_k^{\text{loss, lateral}}$ are obtained from Eqs. (12) and (14). Once the modified K-factor, $\tilde{K}_k$, is determined, one can find the modified projected farm water demand for the ith farm unit during the kth irrigation period as

$$\tilde{Q}_{ik}^{\text{project, farm}} = \tilde{K}_k \times Q_{ik}^{\text{project, farm}} \tag{16}$$

2. Water Distribution Schemes during Water Shortages

(i) Uniform Water Reduction

When there is no water shortage during the kth irrigation period ($K_k \geq 1.0$), one can implement the normal irrigation plan. If the water supply is slightly deficient ($0.75 < K_k < 1.0$), one can use a plan called uniform reduction method (Pasandaran *et al.*, 1989; Kan *et al.*, 1997a). This method reduces, by the same amount, the water allocated to each farm unit, while the whole irrigation service area is still irrigated simultaneously.

(ii) Rotation among Irrigation Groups

When the water supply is further deficient during the kth irrigation period ($K_k < 0.75$), the water source is not capable of providing enough water head (i.e., the water depths in canals from lateral intakes to farm intakes are not deep enough) to deliver water to the whole irrigation service area. Hence, the rotation among irrigation groups method should be implemented. This method divides the whole irrigation service area into several groups. Each group contains several farm units. It should be noted that the farm unit is the basic unit in the rotation among irrigation groups method. When this method is implemented, the water is only delivered to certain groups at any one time (Chen *et al*., 1998).

The rotation intervals and the number of rotation groups depend on the total readily available moisture of soils and the drought tolerance of crops in the irrigation service area. Once the rotation intervals and the number of rotation groups are confirmed, the mode of rotation is dependent on the water available for irrigation. The following rotation modes are adopted. When K_k=0.75, three out of four groups are irrigated at a time; when 0.5<K_k<0.75, two out of three; when K_k=0.5, one out of two; when 0.25≤K_k <0.5, one out of three. When the water is in extreme deficiency (K_k<0.25), one can deliver water only to part of the irrigation service area (Chen *et al*., 1998).

IV. APPLICATION AND DISCUSSIONS

Actual application of the proposed model is presented to demonstrate the applicability of the model. An irrigation area with a considerable scale of mixed-cultivation in southern Taiwan is selected herein for application of the model.

1. Study Area

The study area, with a size of 65,195 ha, belongs to the Chia-Nan Irrigation Association. There are 2 main canals (South Main 10,073 m long, and North Main 47, 251m long), 44 laterals, and 2,022 farm units in the study area. A schematic diagram of mains, laterals and farm units for the study area is shown in Fig. 1. It should be noted that the length of canal in Fig. 1 refers to the canal length between the main and lateral intakes or between the lateral and farm intakes. The study area lies in a subtropical climate. According to the meteorological records (from 1951 to 1999), the lowest, mean, and highest annual temperatures are 13, 24, and 33 degrees Celsius, and the mean daily evaporation is 3.5 mm/day. The wet season is from May to September, and the dry season is from October to April. The soil is mainly composed of loam (17.11% clay, 47.95% silt, and 34.94% sand) and silt loam (13.05% clay, 50.26% silt, and 36.69% sand). Crops are paddy rice, sugar cane, corn, peanuts, and vegetables. The first-season paddy rice begins in late January and ends in mid-May, while the second-season paddy rice begins in early June and ends in early November. The sugar cane begins in early January and ends in early December. The other upland crops only grow in spring and summer.

2. Assessment of Model Performance

For easy comparison and clear demonstration of the model performance using the original and the modified *K*-factor methods, a criterion named the coefficient of efficiency is used herein. The coefficient of efficiency (CE) is defined as

$$\mathrm{CE}_k = 1 - \frac{\sum_{i=1}^{n}[Q_{ik} - Q_{ik}^{\mathrm{actual}}]^2}{\sum_{i=1}^{n}[Q_{ik} - \overline{Q}_k]^2} \qquad (17)$$

where $\overline{Q}_k = (\sum_{i=1}^{n} Q_{ik})/n$ is the average farm water demand during the *k*th irrigation period, Q_{ik} is the projected farm water demand for the *k*th irrigation period in the *i*th farm unit, Q_{ik}^{actual} is the actual amount of water delivered to the *i*th farm unit during the *k*th irrigation period, and *n* is the number of farm units. The suitability is higher when CE is closer to 1 as the amount of water actually distributed matches the projected water demand better.

3. Field Irrigation Requirement

Using Eq. (9), one can calculate the field irrigation requirement for the *j*th crop during the *k*th irrigation period per hectare of irrigation area. Fig. 2 shows the field irrigation requirements per hectare of irrigation area for various crops, namely, paddy rice, vegetable, sugar cane, peanuts and corn. As shown in Fig. 2, the field irrigation requirement of paddy rice is higher than that of the upland crops, and its peaks occur during land-preparation periods. In addition, the field irrigation requirements of all crops in the study area show a trend of multiple peaks during their growing stages. This phenomenon results from the influence of climate and precipitation. Such a unique trend of field irrigation requirement in Taiwan prompts the application of water distribution.

Fig. 3 gives the estimates of total field irrigation requirements of the study area for different treatments of upland crops. As shown in Fig. 3, the case that considers all the upland crops in the estimation yields the highest field irrigation requirement. The case that ignores upland crops and the case that considers only the sugar cane as the single upland crop underestimate the field irrigation requirement. Hence, to assure the normal growth of paddy rice and all upland crops, one should use the field irrigation requirement, which accounts for the actual situation of mixed cultivation for mobile water distribution.

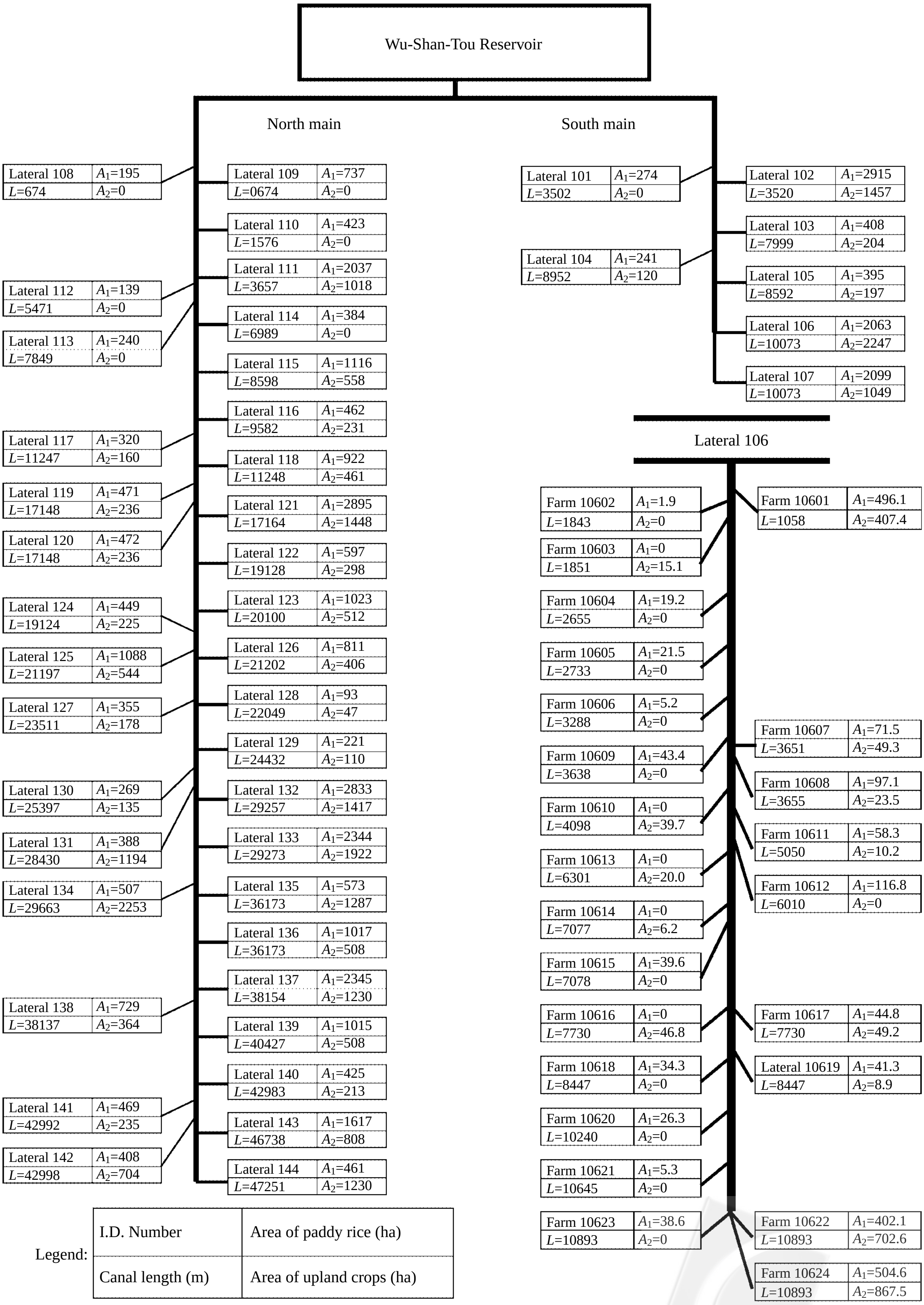


Fig. 1 Schematic diagram of mains, laterals and farms in the Chia-Nan irrigation district

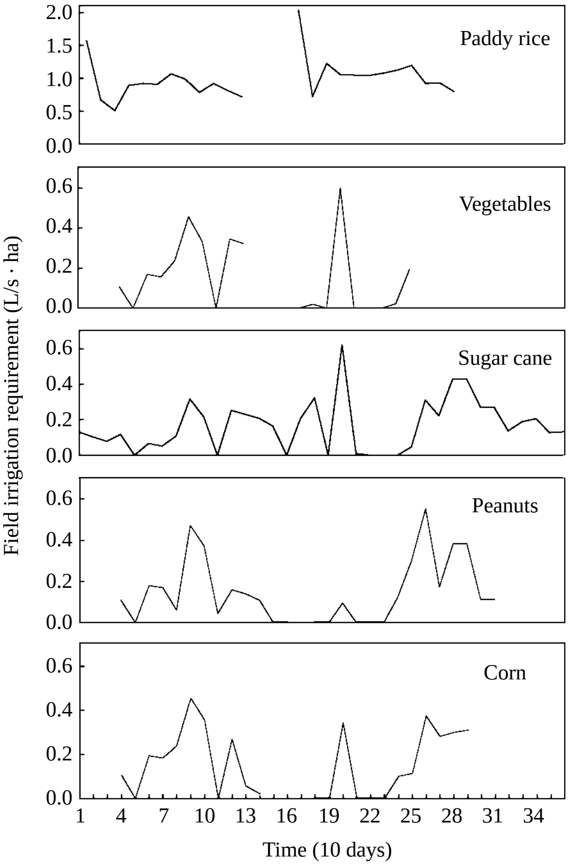


Fig. 2 Field irrigation requirements per hectare of irrigation area for various crops

4. Conveyance Loss and Projected Water Demand

The conveyance loss coefficients for a farm unit and a canal can be estimated using Eqs. (5) and (7), respectively. The conveyance loss coefficients related to Lateral 106 are given in Table 1. As shown in Table 1, the mean conveyance loss coefficient for farm units is 1.126, and that for canals is 1.150. Once the conveyance loss coefficient of a farm unit is obtained, the corresponding projected farm water demand can be computed using Eq. (8). Furthermore, the projected water demand at the lateral intake can be obtained from Eq. (10). For the system of Lateral 106, these two types of water demands during the period of August 1 to 10 are given in Table 1. As shown in Table 1, the projected farm water demand is 3,658 L/sec, and the projected water demand at the later intake is 4,501 L/sec. The difference between these two values, 843 L/sec, is the water loss of Later 106 as defined in Eq. (14).

In a like manner, one can apply the methodology to the whole irrigation district. The mean conveyance loss coefficients are 1.105, 1.097 and 1.10 for farm units, laterals, and mains, respectively (see Table 2). The corresponding projected water demands at the intakes of farms, laterals and mains are 50,824, 58,303, and 64,199 L/sec, respectively (see Table 2). Furthermore, according to Eqs. (14) and (15), the water loss of lateral canals is 7,499 L/sec and that for main canals is 5,896 L/sec.

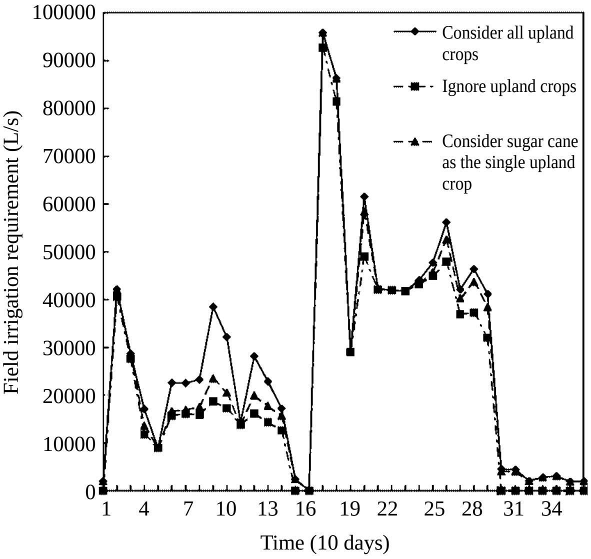


Fig. 3 Estimates of field irrigation requirements for different treatments of upland crops

5. Water Distribution for Mixed Cultivation

The aforementioned water distribution schemes during water shortages (see Section III.2) are applied to the study area (see Fig. 1). The performances of schemes based on the original and modified *K*-factor methods are compared. As a water shortage may occur in any growing stage, the results during the period of August 1 to 10 are presented as an example.

(i) Water Distribution in Main Canals

Five water deficits, namely 801, 1,401, 1,901, 20,501, and 29,501 L/s (referred to as S_1, S_2, S_3, S_4 and S_5 in Table 3), are considered. Table 3 presents the amounts of water delivered to each lateral intake under various water shortages using the original and the modified *K*-factor methods. According to the methodology presented in Section III.2, the uniform reduction method is adopted for cases with water shortages of S_1 (K_k=0.99), S_2 (K_k=0.98) and S_3 (K_k= 0.97), while the rotation among irrigation groups method should be implemented for cases with water shortages of S_4 (K_k=0.65) and S_5 (K_k=0.5). For Case S_4, two out of three groups are irrigated at a time, and the three groups are G_1 (Laterals 101 to 115), G_2 (Laterals 116 to 132), and G_3 (Laterals 133 to 144). As to Case S_5, one out of two groups is irrigated at a

Table 1 Water demand at farm and lateral intakes for each farm unit of Lateral 106

Farm number	Area (ha)					Conveyance loss coefficient		Water demand (L/s)	
	Rice	Sugar cane	Corn	Peanuts	Vegetables	Farm	Lateral	Farm intake	Lateral intake
10601	496.1	180.0	100.0	73.0	54.4	1.637	1.023	908	929
10602	1.9	0.0	0.0	0.0	0.0	1.001	1.041	2	2
10603	0.0	0.0	0.0	0.0	15.1	1.011	1.041	0	0
10604	19.2	0.0	0.0	0.0	0.0	1.013	1.059	21	22
10605	21.5	0.0	0.0	0.0	0.0	1.015	1.061	23	25
10606	5.2	0.0	0.0	0.0	0.0	1.004	1.073	6	6
10607	71.5	20.0	15.0	10.0	4.3	1.085	1.081	87	94
10608	97.1	10.0	5.0	4.0	4.5	1.085	1.081	115	124
10609	43.4	0.0	0.0	0.0	0.0	1.031	1.091	48	53
10610	0.0	20.0	8.0	7.0	4.7	1.028	1.112	2	2
10611	53.3	8.0	2.2	0.0	0.0	1.045	1.133	60	68
10612	116.8	0.0	0.0	0.0	0.0	1.082	1.140	136	155
10613	0.0	10.0	5.0	0.0	5.3	1.014	1.157	1	1
10614	0.0	0.0	0.0	0.0	6.2	1.004	1.157	0	0
10615	39.6	0.0	0.0	0.0	0.0	1.028	1.171	44	51
10616	0.0	20.0	10.0	13.0	3.8	1.033	1.171	3	3
10617	44.8	30.0	5.0	10.0	4.2	1.066	1.187	53	63
10618	34.3	0.0	0.0	0.0	0.0	1.024	1.187	38	45
10619	41.3	0.0	0.0	8.9	0.0	1.035	1.227	47	58
10620	26.3	0.0	0.0	0.0	0.0	1.019	1.236	29	36
10621	5.3	0.0	0.0	0.0	0.0	1.004	1.242	6	7
10622	402.1	362.0	138.0	134.0	68.6	1.763	1.242	827	1027
10623	38.6	0.0	0.0	0.0	0.0	1.027	1.242	43	53
10624	504.6	390.0	216.0	178.0	83.5	1.973	1.446	1158	1675
Total	2063	1050	504	438	255	27.035	27.600	3658	4501
Mean	–	–	–	–	–	1.126	1.150	–	–

time, and the two groups are G_a (Laterals 101 to 122) and G_b (Laterals 123 to 144). As mentioned earlier, the coefficient of efficiency (CE) is used to compare the model performance. When CE is equal to 1, the amount of water actually distributed matches the projected water demand. For Cases S_1, S_2 and S_3 (minor water deficient conditions), the corresponding CE's are 1.0, 0.999 and 0.998, respectively. It should be noted that the modified and the original *K*-factor methods yield the same results for Cases S_1, S_2 and S_3. For Case S_4, a comparison of the CE's shows that the modified *K*-factor method proposed in this paper is better than the original *K*-factor method. The advantage of the modified *K*-factor method over the original *K*-factor method can also be shown from *K*-factor values. When K_k or $\tilde{K}_k$ is less than 1, the water actually delivered to lateral intakes cannot meet the project demand. For Case S_4, the modified *K*-factor method results in *K*-factors of 1.00, 1.03 and 1.04, while the original *K*-factor method yields *K*-factors of 0.92, 1.01 and 0.99. Based on these two criteria, CE and *K*-factor, one can conclude that the modified *K*-factor method is to be preferred. Hence, only the modified *K*-factor method is applied to the severest water shortage case (Case S_5). The resulting values of $\tilde{K}_k$ are 1.10 and 1.08, and the value of CE is 0.983. It is shown that the proposed modified *K*-factor has very good performance even for the severest case.

Figure 4 presents the schematic diagram of the irrigation system of Case S_4. In Case S_4, two out of three groups (i.e., G_1+G_2, G_2+G_3, G_3+G_1) are irrigated at a time. Using the G_1+G_2 in Case S_4 as an example (see Table 3), the water available at the main intake is 43,698 L/s. The modified *K*-factor method can deliver 41,017 L/s to the lateral intakes. However, the *K*-factor method can only deliver 37,802 L/s to the lateral intakes. The difference is 3,215 L/s. This amount of water is not received by the lateral intakes. Water remains in the main canal and flows further downstream. Such a waste of water is due to the fact that the *K*-factor did not exclude the conveyance loss of the non-irrigated group.

Table 2 Water demand at farm, lateral and main intakes for each lateral

Lateral number	Area (ha)					Conveyance loss coefficient			Water demand (L/s)		
	Rice	Sugar cane	Corn	Peanuts	Vege-t tables	Farm	Lateral	Main	Farm intake	Lateral intake	Main intake
101	274	0	0	0	0	1.062	1.035	1.017	314	325	330
102	2915	884	243	243	88	1.285	1.210	1.017	4110	4973	5060
103	408	102	34	34	34	1.082	1.058	1.039	485	513	533
104	241	60	20	20	20	1.051	1.052	1.044	278	292	305
105	395	99	33	33	33	1.072	1.055	1.042	465	490	511
106	2063	1050	504	438	255	1.126	1.150	1.050	3658	4501	4725
107	2099	554	245	175	75	1.124	1.145	1.050	2597	2973	3121
108	195	0	0	0	0	1.046	1.021	1.003	220	225	225
109	737	0	0	0	0	1.052	1.085	1.003	836	907	910
110	423	0	0	0	0	1.048	1.036	1.008	478	495	499
111	2037	534	230	170	85	1.123	1.142	1.018	2517	2875	2927
112	139	0	0	0	0	1.020	1.022	1.027	153	156	160
113	240	0	0	0	0	1.045	1.032	1.034	270	279	289
114	384	0	0	0	0	1.087	1.035	1.039	450	466	484
115	1116	279	93	93	93	1.118	1.112	1.042	1371	1524	1589
116	462	116	39	39	39	1.089	1.068	1.047	553	590	618
117	320	80	27	27	27	1.068	1.051	1.055	375	395	416
118	922	231	77	77	77	1.121	1.103	1.055	1135	1252	1322
119	471	118	39	39	39	1.085	1.085	1.085	562	610	661
120	472	118	39	39	39	1.092	1.085	1.085	566	614	666
121	2895	880	241	241	85	1.281	1.221	1.085	4070	4969	5390
122	597	197	50	50	2	1.101	1.092	1.094	721	787	861
123	1023	341	85	85	0	1.120	1.121	1.094	1257	1409	1542
124	449	112	37	37	37	1.087	1.065	1.099	537	571	628
125	1088	318	91	91	45	1.122	1.128	1.104	1340	1511	1669
126	811	203	68	68	68	1.116	1.109	1.105	995	1103	1218
127	355	89	30	30	30	1.072	1.061	1.109	418	444	492
128	93	23	8	8	8	1.032	1.020	1.116	106	108	120
129	221	55	18	18	18	1.048	1.032	1.120	254	262	294
130	269	67	22	22	22	1.052	1.035	1.125	311	322	362
131	388	777	199	119	99	1.118	1.115	1.125	509	567	638
132	2833	959	236	136	86	1.218	1.182	1.140	3772	4459	5084
133	2344	1362	320	120	120	1.258	1.210	1.144	3242	3923	4489
134	507	1385	376	317	176	1.121	1.143	1.146	702	803	920
135	573	744	214	214	114	1.120	1.138	1.178	748	852	1004
136	1017	339	85	85	0	1.118	1.135	1.178	1247	1415	1667
137	2345	715	205	205	105	1.125	1.147	1.188	2898	3324	3950
138	729	182	61	61	61	1.116	1.102	1.188	893	984	1170
139	1015	254	85	85	85	1.114	1.118	1.199	1243	1389	1666
140	425	142	35	35	0	1.068	1.063	1.212	498	530	642
141	469	156	39	39	0	1.075	1.072	1.212	553	593	719
142	408	469	117	117	0	1.110	1.115	1.212	517	577	699
143	1617	404	135	135	135	1.121	1.135	1.230	1991	2260	2780
144	461	715	205	205	105	1.117	1.125	1.233	608	684	844
Total	39245	15112	4585	3949	2303	48.626	48.266	48.400	50824	58303	64199
Mean	–	–	–	–	–	1.105	1.097	1.100	–	–	–

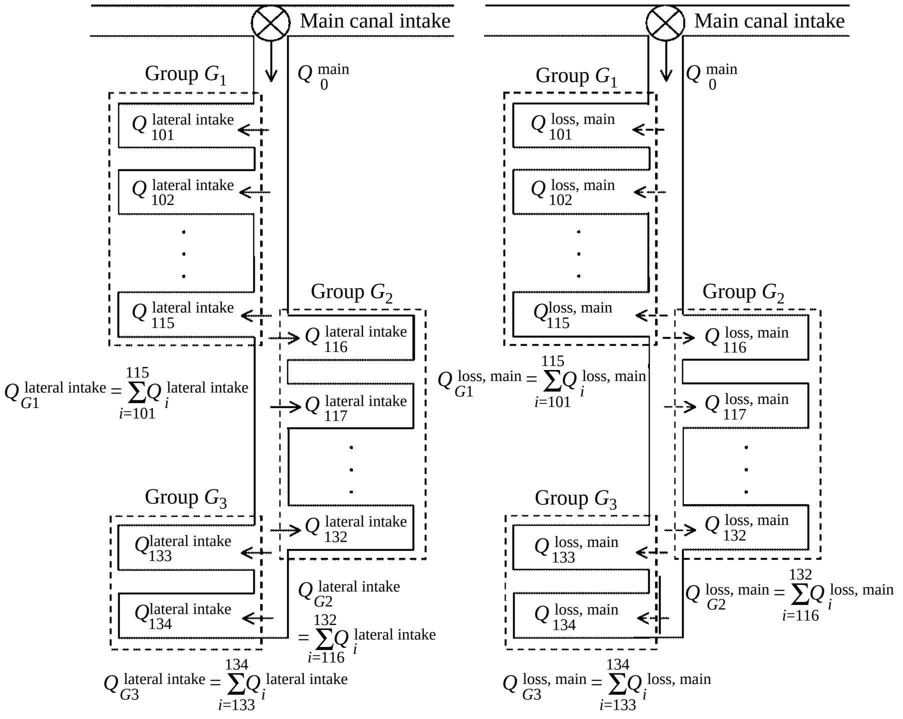
Table 3 Water distribution for each lateral under various water shortages using the original and the modified *K*-factor methods

Lateral number	Water demand at the lateral intake (L/s)	Amount of water delivered to the lateral intake (L/s)										
		S_1	S_2	S_3	S_4 Modified *K*-factor method			S_4 *K*-factor method			S_5 Modified *K*-factor method	
					G_1+G_2	G_2+G_3	G_3+G_1	G_1+G_2	G_2+G_3	G_3+G_1	G_a	G_b
101	325	320	317	314	325	0	337	299	0	320	358	0
102	4973	4905	4854	4811	4979	0	5166	4589	0	4905	5483	0
103	513	506	501	496	514	0	533	473	0	506	566	0
104	292	288	285	283	293	0	304	270	0	288	322	0
105	490	484	479	474	491	0	509	452	0	484	541	0
106	4501	4439	4393	4354	4506	0	4675	4153	0	4439	4962	0
107	2973	2933	2902	2877	2977	0	3088	2744	0	2933	3278	0
108	225	221	219	217	225	0	233	207	0	221	248	0
109	907	895	885	878	908	0	942	837	0	895	1000	0
110	495	488	483	479	496	0	514	457	0	488	546	0
111	2875	2835	2806	2781	2878	0	2986	2653	0	2835	3169	0
112	156	154	152	151	156	0	162	144	0	154	172	0
113	279	275	272	270	279	0	290	258	0	275	308	0
114	466	460	455	451	466	0	484	430	0	460	514	0
115	1524	1503	1488	1474	1526	0	1583	1406	0	1503	1680	0
116	590	582	576	571	591	609	0	545	598	0	651	0
117	395	389	385	382	395	407	0	364	400	0	435	0
118	1252	1235	1222	1212	1254	1292	0	1156	1269	0	1381	0
119	610	601	595	590	610	629	0	562	618	0	672	0
120	614	606	600	594	615	634	0	567	622	0	677	0
121	4969	4901	4850	4807	4975	5124	0	4585	5035	0	5478	0
122	787	776	768	761	788	811	0	726	797	0	867	0
123	1409	1390	1375	1363	1411	1453	0	1300	1428	0	0	1520
124	571	564	558	553	572	589	0	527	579	0	0	616
125	1511	1491	1475	1462	1513	1559	0	1395	1531	0	0	1630
126	1103	1088	1077	1067	1104	1138	0	1018	1118	0	0	1190
127	444	438	433	430	444	458	0	410	450	0	0	479
128	108	106	105	104	108	111	0	100	109	0	0	116
129	262	259	256	254	262	270	0	242	266	0	0	283
130	322	318	314	312	323	332	0	297	326	0	0	348
131	567	559	554	549	568	585	0	523	575	0	0	612
132	4459	4398	4352	4314	4464	4599	0	4114	4518	0	0	4810
133	3923	3869	3828	3795	0	4045	4074	0	3974	3869	0	4231
134	803	791	783	776	0	828	834	0	813	791	0	866
135	852	840	831	824	0	878	885	0	863	840	0	919
136	1415	1395	1381	1369	0	1459	1470	0	1434	1395	0	1526
137	3324	3279	3244	3216	0	3428	3453	0	3368	3279	0	3586
138	984	971	961	952	0	1015	1023	0	997	971	0	1062
139	1389	1370	1356	1344	0	1433	1443	0	1408	1370	0	1499
140	530	522	517	512	0	546	550	0	537	522	0	571
141	593	585	579	574	0	612	616	0	601	585	0	640
142	577	569	563	558	0	595	599	0	584	569	0	622
143	2260	2229	2205	2186	0	2330	2347	0	2290	2229	0	2438
144	684	675	668	662	0	706	711	0	693	675	0	738
Total	58303	57502	56902	56402	41017	38474	39810	37802	37802	37802	33308	30303

Table 3 Water distribution for each lateral under various water shortages using the original and the modified *K*-factor methods (Continue)

Lateral number	Water demand at the lateral intake (L/s)	Amount of water delivered to the lateral intake (L/s)										
		S_1	S_2	S_3	S_4						S_5	
					Modified *K*-factor method			*K*-factor method			Modified *K*-factor method	
					G_1+G_2	G_2+G_3	G_3+G_1	G_1+G_2	G_2+G_3	G_3+G_1	G_a	G_b
	Water supply at the main intake (L/s)											
	64199	63398	62798	62298	43698	43698	43698	43698	43698	43698	34698	34698
		The original or modified *K*-factor (K_k or $\tilde{K}_k$)										
		0.99	0.98	0.97	1.00	1.03	1.04	0.92	1.01	0.99	1.10	1.08
		Coefficient of efficiency CE										
		1.00	0.999	0.998	0.992			0.985			0.983	

Note:
S_1, S_2, S_3, S_4, and S_5 refer to water shortages of 801, 1401, 1901, 20501, and 29501 L/s, respectively.
G_1, G_2, and G_3 refer to Laterals 101 to 115, 116 to 132, and 133 to 144, respectively.
G_a and G_b refer to Laterals101 to 122 and123 to 144, respectively.



(a) (b)

Fig. 4 A three-group irrigation system illustrating the water distribution in the main canal: (a) water delivered to lateral intakes, and (b) water lost between the main and lateral intakes

(ii) Water Distribution in Lateral Canals

In a like manner, water distribution schemes can be applied to a lateral system. Lateral 106 is presented herein as an example. Three water deficits, namely 801, 1401 and 1901 (referred to as S_1, S_2 and S_3 in Table 4), are considered. Table 4 presents the amounts of water delivered to each farm unit under various water shortages using the original and the modified *K*-factor methods. According to the

Table 4 Water distribution for each farm unit of Lateral 106 under various water shortages using the original and the modified *K*-factor methods

Farm number	Water demand at the farm intake (L/s)	Amount of water delivered to the farm intake (L/s)								
		S_1	S_2						S_3	
			Modified *K*-factor method			*K*-factor method method			Modified *K*-factor method	
			T_1+T_2	T_2+T_3	T_3+T_1	T_1+T_2	T_2+T_3	T_3+T_1	T_a	T_b
10601	908	709	1008	0	887	820	0	798	1384	0
10602	2	2	2	0	2	2	0	2	3	0
10603	0	0	0	0	0	0	0	0	0	0
10604	21	16	23	0	20	19	0	18	32	0
10605	23	18	26	0	23	21	0	21	36	0
10606	6	4	6	0	6	5	0	5	9	0
10607	87	68	96	0	85	78	0	76	132	0
10608	115	90	127	0	112	104	0	101	175	0
10609	48	38	54	0	47	44	0	42	74	0
10610	2	1	2	0	2	2	0	2	3	0
10611	60	47	67	0	59	54	0	53	92	0
10612	136	107	151	0	133	123	0	120	208	0
10613	1	0	1	1	0	1	1	0	1	0
10614	0	0	0	0	0	0	0	0	0	0
10615	44	34	49	45	0	40	44	0	67	0
10616	3	2	3	3	0	2	3	0	4	0
10617	53	42	59	55	0	48	54	0	81	0
10618	38	30	42	39	0	34	38	0	58	0
10619	47	37	52	49	0	43	47	0	72	0
10620	29	23	32	30	0	26	29	0	44	0
10621	6	4	6	6	0	5	6	0	9	0
10622	827	646	918	854	0	747	830	0	0	597
10623	43	33	47	44	0	39	43	0	0	31
10624	1158	905	0	1197	1131	0	1163	1018	0	836
Total	3658	2944	2708	2323	2507	2257	2257	2257	2483	1464
	Water supply at the lateral intake (L/s)									
	4501	3700	3100	3100	3100	3100	3100	3100	2600	2600
		The original or modified *K*-factor (K_k or $\tilde{K}_k$)								
		0.78	1.11	1.03	0.98	0.90	1.00	0.88	1.52	0.92
		Coefficient of efficiency CE								
		0.941		0.991			0.980		0.83	

Note:

S_1, S_2, and S_3 refer to water shortages of 801, 1401, and 1901 L/s, respectively.

T_1, T_2, and T_3 refer to farm units 10601 to 10612, 10613 to 10623, and 10624, respectively.

T_a and T_b refer to farm units 10601 to 10621 and10622 to 10624, respectively.

methodology presented in Section III.2, the uniform reduction method is adopted for Case S_1 (K_k=0.78), and the rotation among irrigation groups method are employed for Cases S_2 (K_k=0.62) and S_3 (K_k=0.48). For Case S_2, two out of three groups are irrigated at a time, and the three groups are T_1 (Farm units 10601 to 10612), T_2, (Farm units 10613 to 10623), and T_3 (Farm unit 10624). As to Case S_3, one out of two groups is irrigated at a time, and the two groups are T_a (Farm units 10601 to 10621) and T_b (Farm units 10622 to 10624). For Case S_2, the modified *K*-factor method results in *K*-factors of 1.11, 1.03 and 0.98 and a CE of 0.991, while the original *K*-factor method yields *K*-factors of 0.90, 1.00 and 0.88 and a CE of

0.98. Table 4 also shows that the modified *K*-factor method is to be preferred. However, as shown in Case S_3, the resulting values of $\tilde{K}_k$ are 1.52 and 0.92 for the first and second rotation groups, respectively. This results from the fact that areas of farm units are not uniform and each farm unit cannot be further divided.

(iii) Comparison of Water Distribution in Main and Lateral Canals

For Case S_1, the uniform reduction method is implemented for both the main and lateral canal systems. However, the main canal system has a CE of 1.0 and the lateral system has a CE of 0.941. For Case S_2, the uniform reduction method is implemented for the main canal system, while the (two out of three groups) rotation among irrigation groups method has to be used for the lateral canal system. For Case S_3, one can still apply the uniform reduction method to the main canal system, while one has to employ the (one out of two groups) rotation among irrigation groups method for the lateral canal system. When the shortage reaches up to 20,501 L/sec (Case S_4), the lateral canal system is incapable of handling the water distribution practice. However, the (two out of three groups) rotation among irrigation groups method can still be applied to the main canal system.

For minor water deficits, the water distribution in the lateral canal system can be applied using considerations of management and operation cost. However, for severe water shortages, the ratio of water shortage to the lateral's projected water demand is high. Hence, water distribution from the main canal system has to be employed.

V. CONCLUSIONS

In this paper, a water distribution model is proposed which is capable of satisfying water demand in large-scale mixed cultivation irrigation areas during water shortage periods. The proposed model is based on a new parameter called the modified *K*-factor. Actual applications of the model are performed. It is found that the proposed model is better than the model based on the original *K*-factor. The model can be applied to either a main or to a lateral canal system. According to the simulated results, it is suggested to employ water distribution in the lateral canal system for minor water-shortage conditions. However, for severe water shortages, the practice of water distribution from the main canal system is recommended. The proposed model can deliver appropriate amounts of irrigation water to specific blocks at the right time, fairly and rationally, under various circumstances, while agricultural production is not affected.

NOMENCLATURE

A_{exp}	area of an experimental farm
A_i	area of the *i*th farm unit
A_{ij}	area for the *j*th crop in the *i*th farm unit
C	water loss in canals (in decimals)
C_{exp}	experimental water loss in canals (in decimals)
CC_{jk}	crop coefficient for the *j*th crop during the *k*th irrigation period
CE_k	coefficient of efficiency during the *k*th irrigation period
CLC	conveyance loss coefficient
CLC^{farm}	conveyance loss coefficient for farm units
$\text{CLC}_i^{\text{lateral}}$	conveyance loss coefficient for the lateral canal which delivers water to the *i*th farm intake
$\text{CLC}_i^{\text{main}}$	conveyance loss coefficient for main canal between the main intake and the lateral intake from which water is delivered to the *i*th farm intake
$\text{ET}_k^{\text{refer}}$	reference evapotranspiration of standard crop canopy during the *k*th irrigation period per hectare of irrigation area
i	index corresponding to the farm unit
j	index corresponding to the crop type
k	index corresponding to the irrigation period
K_k	*K*-factor for the *k*th irrigation period
$\tilde{K}_k$	modified *K*-factor for the *k*th irrigation period
L_i	canal length from the canal intake to the *i*th farm unit
n	number of farm units
q_j^{p}	percolation in paddy fields for the *j*th crop per hectare of irrigation area
q_{jk}^{CWR}	crop water requirement for the *j*th crop during the *k*th irrigation period per hectare of irrigation area
q_{jk}^{ER}	effective rainfall for the *j*th crop during the *k*th irrigation period per hectare of irrigation area
q_{jk}^{FIR}	field irrigation requirement for the *j*th crop during the *k*th irrigation period per hectare of irrigation area
Q_{ik}	projected farm water demand for the *k*th irrigation period in the *i*th farm unit
Q_{ik}^{actual}	actual amount of water delivered to the *i*th farm unit during the *k*th irrigation period
$\overline{Q}_k$	average farm water demand during the *k*th irrigation period
Q_k^{actual}	actual amount of water delivered to the system during the *k*th irrigation period
Q_k^{loss}	conveyance loss of the system during the *k*th irrigation period

Q_k^{project}	projected water demand of the system during the kth irrigation period
$Q_{ijk}^{\text{project, farm}}$	projected water demand at the farm intake for the jth crop in the ith farm unit during the kth irrigation period
$Q_{ijk}^{\text{project, main}}$	projected water demand at the main canal intake for the jth crop in the ith farm unit during the kth irrigation period
$\tilde{Q}_{ik}^{\text{project, farm}}$	modified projected farm water demand for the ith farm unit during the kth Irrigation period
$Q_k^{\text{loss, lateral}}$	water loss of a lateral canal during the kth irrigation period
$Q_k^{\text{loss, main}}$	water loss of a main canal during the kth irrigation period
$Q_k^{\text{project, lateral}}$	projected water demand at a lateral canal intake during the kth irrigation period
$Q_k^{\text{project, main}}$	projected water demand at a main canal intake during the kth irrigation period
r	number of crop types
S	water loss in ditches of a farm (in decimals)
S_{exp}	the experimental water loss of a farm with an area of A_{exp} (in decimals)

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