**FOUNDATION, ALGEBRAIC, AND ANALYTICAL METHODS IN SOFT COMPUTING**

# An expert method for defining the adaptation conditions of irrigated crops with the ecosystem of Northwestern China

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## Abstract

The uncertain impacts of climate changes on the crop water requirements disarrange the on-farm balance of water supply and demand, thus here needs to adapt a cropping pattern to sustain the Northwestern China Agro-system. Balancing the fluctuations of on-farm available water associated with the uncertainty of crops water requirements could be considered as a complex optimization model. Since the classical optimization models exhibited many problems on the farm studies, e.g., the lack of accurate information, the applied limitations, and short-time accuracy, this study has utilized the fuzzy rule-based system (FRBS). The part of this challenge is back to estimating the sum of water use based on the crops water requirements which resulted from assuming a resilience characteristic to adapt the crops with the water resource capacity under uncertain climatic changes. This study aimed to develop a methodology for operationalizing a coequality approach to balance the crop water requirement with on-farm available water and how selection of the regional suitable crops has been defined. The results of this methodology showed that agriculture sustainability in this region is achieved by planting the irrigated crops whose crop coefficients range from 0.39 to 0.64 which adapted their water demand to the water resources capacity under uncertain conditions. The optimal range of crop coefficients achieved based on this fuzzy-probabilistic approach can be the reference point of water allocation in this irrigation district, since they also are investigated based on the economic factors that are a kind of crop-pattern for sustaining the balance of water supply and demand. This cropping pattern will be a helpful government policy for the sustainability of the Gansu Provinceis the conversion factor, the Agro-system.

**Graphical abstract**
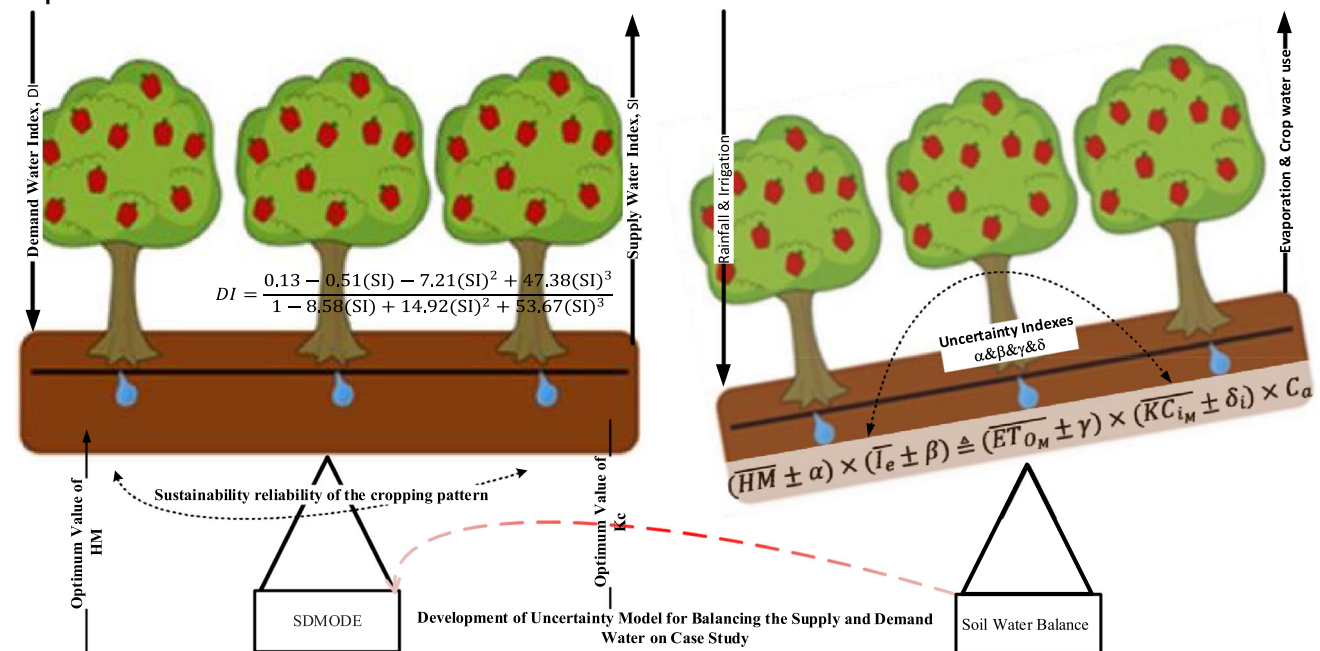
## 1 Introduction

Today, analyzing the direct effects on the water deficit from regional climatic changes has become difficult as the on-farms management upgrade through new technologies. Besides, agricultural production which depends practically on weather changes has strongly been impacted by the policies related to subsidies along with the market prices (Ghahramani et al. 2015). During the last decades, a substantial increase in the crop yield of winter wheat or maize in the arid and semi-arid regions of Northwestern China resulted from the increased water use of irrigation associated with the rapid decline of water resources. The sustainable agro-system especially for grain crops without an immediate reduction of irrigation area has been hazarded. Thus, the research results on crop water demand should be updated due to Northwestern China's climate changes and the drought increase, if they have done or not during the last decades. This lack of study has caused the farmers to tend to use over-irrigation instead of deficit-irrigation that is critically important for reducing evapotranspiration (ET) associated with saving the pumped groundwater in the irrigated area (Wang 2013; Zou et al. 2020; Xiaomin et al. 2017; Tomohiro et al. 2018; Kang et al. 2003; Zhang et al. 2012). Although soil evaporation reduction is a primary way to reduce ET without decreasing the cropped area (Chang et al. 2015; Liu et al. 2015; Yang et al. 2019; Zhang et al. 2004), the level reduction of ET from this agro-system by replacing the suitable with current crops is our study idea. In other words, we think about changes in cropping pattern in this region where the government policy could be the percentage regulation on unit area of different crop system for planting based on total available water.

In the irrigation projects, there have preferred rather the estimation of crop evapotranspiration rate (ETc) than its direct measurement obtained from the balance of flow-water into and out of the plant root zone due to the difficulty in measuring some of the variables in this balance (e.g., deep percolation or the residual amount of water). The evapotranspiration of grass or alfalfa is formally a reference to quantify the water use of irrigated crops which has resulted from it multiplied by the crop coefficient, $K_c$. This evapotranspiration is called the potential, $ET_O$, while there is an ideal condition for the growth, e.g., without stresses in water collected and fertility soil, whereas it is usually utilized to describe evapotranspiration from a certain reference surface along with the measurements of

weather station (Allen 2000). The physiology and morphology of each crop explained in its Kc is an empirical coefficient and is determined by understanding the relation of crops' evapotranspiration rate between the reference and the actual. It practically included all the differences between the crop in question and the $ET_o$. They were reported by Payero et al. (1999) and Hsiao et al. (2012); desertification, groundwater–surface drop along with the quality and quantity of soil–water, and decreasing the vegetation areas by all change factors in crop growth and vitality resulted in reality influencing the day to day values for both $K_c$ and $ET_o$.

To estimate $ET_O$ in the region, the Penman–Monteith, the Hargreaves–Samani, and the Blaney–Criddle are usually the famous methods. As regard, they need an updated weather information database, whereas if they have not, it could result in the high or low estimation of their evapotranspiration rates because of the inaccuracy or incomplete data (Zhang et al. 2008a, b; Allen 2000). In this condition, the $K_C$ and $ET_O$ have often been characterized by the imprecise, vague, inconsistent, incomplete, and subjective information. Thus, their predictions are being limited in the application of conventional methods. Based on the results of Qian et al. (2016), Xiaomin et al. (2017), Tomohiro et al. (2018), and Faybishenko (2011), modeling the crop water requirement has been presenting a great uncertain condition due to the lack of field reliability data, e.g., $K_C$ and $ET_O$. Thus, the present study accomplished predicate and uncertainty analysis using the uncertain input parameters that have been expressed as probability boxes, intervals, and fuzzy numbers.

Several alternative approaches based on fuzzy logic for modeling complex systems with uncertain parameters have been developed. They could be classified based on the fuzzy set and possibility theories, which have resulted from the works of Zadeh (1978, 1986), Dubois and Prade (1994), Yager and Kelman (1996), Qian et al. (2016), Xiaomin et al. (2017), and Tomohiro et al. (2018). The rough sets, imprecise probability, belief functions, the Dempster–Shafer theory of evidence, and fuzzy random variables are another category of this issue (Dempster 1967; Shafer 1976; Smets 1990; Zadeh 1986; Chang et al. 2015; Liu et al. 2015; Yang and Qiang 2019). Some of these approaches include the blending of interval or fuzzy-interval analysis with probabilistic methods (Ferson and Ginzburg 1995; Ferson 2002; Ferson et al. 2003). For example, applying combination methods of a fuzzy framework with probabilistic modeling to hydrological

challenges is a relatively wise direction for hydrological research, risk assessment, and sustainable water resources management under uncertainty (Chang 2005; Wang 2013; Zou et al. 2020; Xiaomin et al. 2017; Tomohiro et al. 2018). These references have formed our motivation for the application potential of this approach for determining the property of irrigated crop plants based on the water-balance calculations, which are created from an inadequacy meteorological information and field data collected on a regional scale.

The demand scenarios in this study were formed based on future climate forecasting during the drought, the normal, and the wet seasons in the Minqin Region aligned and at the same time with its effect on available water resources scenarios. The water-balance model included several steps for analyzing how propagated uncertainty by innovating upon multiple sub-models has differed from the previous research (Zou et al. 2020; Ivezic et al. 2017; Ge et al. 2013; David et al. 2012). This study aimed to find an approach for assessing the uncertainty involved in modeling the crop water requirement by integrating the probability and possibility theories in line with applying the case study data. Here, the main concepts associated with combining the statistical analysis have been illustrated with fuzzy rules based on use in the coequality equation of crop water requirement and on-farm available water. Although this study presents how to select suitable crops for Minqin Region, Gansu, China, it is a way that this equation can balance the soil water, crop evapotranspiration, and water resource system under uncertain conditions in any region.

## 2 Materials and methods

### 2.1 Theory of model

#### 2.1.1 Balance water supply and demand

There are several methods to estimate evapotranspiration, e.g., the calculation of the balance equation of input and output water in the soil layer is given as follows (Hillel 1998; Rahgozar et al. 2012):

$$ET = Pe + I + U - Dp - R - Du \tag{1}$$

The part of rainfall is used by the plant called the effective precipitation, $Pe$ in mm, and can be defined based on the USDA soil conservation services method, i.e., SCS (1972). This amount plus the irrigation, $I$ in mm, and the upward capillary flow, $U$ in mm, have been included as the total input water into the root zone, where the total drain out of root zone is included as the runoff, $R$ in mm, the deep percolation water that estimates with Darcy's law, $Dp$ in mm, and the change of store soil water in the upper soil layer, $Du$ in mm, i.e., 0 to 100 cm. Due to need for identification of maximum crop evapotranspiration utilized in the estimation models of reference evapotranspiration, $ETo$, the sufficient water supplies for the crop growth stages' demand could be calculated using the following equation:

$$ET_H = K_c \times ET_o \tag{2}$$

The crop coefficient, $K_C$, which varies with the growth stages is required to estimate the maximum crop evapotranspiration, $ET_H$ in mm/d, where the $ET_O$ is obtained using the Penman–Monteith equation (Allen et al. 1998), and the actual crop evapotranspiration could thus be calculated as follows (Wang and Sun 2003):

$$ETc = \begin{cases} ET_H & Wr \geq W_C \\ \dfrac{Wr - W_p}{W_C - W_p} ET_H & 0 \leq Wr \leq W_C \end{cases} \tag{3}$$

During the design of the irrigation project, the time of watering is when the soil water in real time ($W_r$) is near to the critical water storage in the root zone ($W_C$), where the actual crop evapotranspiration in mm/d (ETC) is far off the water storage at the wilting point ($W_P$). For water flux at the lower boundary below the root zone as the groundwater–surface is unavailable for the plant demand and generally shallow in the area of saline water irrigation, the lower boundary of the root zone is included in this model and is estimated from the following equation:

$$q = \alpha \left(\frac{Wr}{W_f}\right)^d (Wr - W_c) \tag{4}$$

Based on the results of Wang et al. (1997), Chang et al. (2015), Liu et al. (2015), and Yang et al. (2019), $q$ is the lower boundary of water flux below the root zone soil layer in mm/d; $a$ and $d$ are the coefficients related to soil texture with the value of $a = 0.0508$ and $d = 2.772$, where $Wr$ is the water storage in the root zone soil layer after irrigation or precipitation in mm and $W_f$ is the field water capacity in the root zone soil layer in mm. $W_C$ is an important parameter in estimating $q$, which can indirectly represent the effect of groundwater on q. Zhang et al. (2004, 2008a, b) compared three evapotranspiration models to the Bowen ratio-energy balance method in an arid desert region of Northwest China. This method is the base of Penman–Monteith's FAO method to estimate the reference crop evapotranspiration that was also used for this region by Chang et al. (2015), Hou et al. (2010), and Li et al. (2008). Based on the Penman–Monteith's FAO method, the reference crop evapotranspiration, $ET_o$, can be calculated. It is the rate of evapotranspiration from an assumptive reference crop, in which the crop height is 2 cm with its surface resistance fixed at 70 s/m and albedo at 0.23. Here, it is assumed that a wide surface of green grass cover with

uniform height, actively growing, a complete shadow on the ground and enough water supply is closely resembling the $ET_o$. Thus, $ET_o$ in mm/day can be calculated based on the Penman–Monteith equation and using daily or monthly mean data for 24 h, and simplified as following (Allen et al. 1994):

$$ET_o = \frac{[0.418r(R_n - \mu) + \left(\frac{900\gamma}{T+273}\right)U_2(e_s - e_a)]}{r + \gamma(1 + 0.34U_2)} \tag{5}$$

where 900 is the conversion factor, the net radiation under crop surface, $Rn$, and the soil heat flux, $\mu$ are of MJ m$^{-2}$ per day. The mean air temperature, $T$, is in $^\circ$C, and 2 m height has wind speed, $u$, in m s$^{-1}$. The diminished $ea$ of $es$ is the deficit of vapor pressure in kPa, the vapor pressure curve has the slope of $r$ in kPa $^\circ$C$^{-1}$, and $\gamma$ is the psychrometric constant in kPa $^\circ$C$^{-1}$. The ratio of ETc has evapotranspiration for each crop that is principally computed from multiplying the reference $ET_o$ by the crop coefficient, $K_c$, and is a contract that distinguishes each crop between themselves and the reference $ET_o$ based on their major characteristics and effects integration. These characteristics could be the crop height due to the roughness impacts, the aerodynamic resistance, and albedo of the crop–soil surface, in which they are affected by the age, area, and condition of the leaf, the ground covered fraction with vegetation, and soil surface wetness. In FAO Irrigation and Drainage Paper No. 66 (Hsiao et al. 2012), $K_c$ is defined for pristine conditions having no water or other ET-reducing stresses (Allen 2000).

The irrigation potential evaluation based on the soil and water resources needs simultaneously to assess the irrigation water requirements, IW. Net irrigation water requirement, NI, is the quantity of water necessary for crop growth. It depends on the cropping pattern and the climate and is expressed in mm/year or m$^3$/hm$^2$/year. The used real water called gross irrigation water requirement, GI, is more than the NI. It is obtained based on the information on irrigation efficiency which takes into account the water losses. Multiplying GI by the area that is suitable for irrigation gives the total water requirement for that area. For the crop to thrive, it should be supplied with its evapotranspiration rate called crop water requirement, CWR, and is estimated as follows:

$$\overline{CWR}_i = \sum_{t=0}^{T} \lfloor KC_{i_t} \times ET_{O_i} - P_{e_i} \rfloor \tag{6}$$

where $KC_{i_t}$ is the coefficient of crop $i$ during the growth stages from $t$ to $T$. The effective rainfall, $Pe$, can be computed according to the USDA Soil Conservation Service Method (Allen 2000). In this study, it is assumed that the effective rainfall in the maximum monthly

evapotranspiration can be ignored and the mean of daily evapotranspiration for each crop on this month is as follows:

$$\overline{CWR}_i = \overline{K}_{C_{i_M}} \times \overline{ET}_{O_M} \tag{7}$$

In yearly multiple cropping systems, the crop water requirements are separately computed for any growing period where any crop in a specific schema has the annual water requirements resulted from the sum of its net irrigation water requirements, CWRi. In this way, by dividing the total values of irrigation water demand on the area of the scheme, S in hm$^2$, a value for irrigation water requirements is obtained and is expressed in mm or m$^3$/hm$^2$:

$$NI = \sum_{i=1}^{n} (CWR_i \times S_i)/S \tag{8}$$

where Si is a part of the area of multiple cropping cultivated with the crop $i$ in hm$^2$. The cropping intensity of the scheme can be defined as: $\sum_{i=1}^{n} S_i/S$. In this study, the first step assumes that the area cultivated is similar to each crop and resulting as $NI = \sum_{i=1}^{n} CWR_i/n$. The GI is the water amount to be extracted (by diversion, pumping) and applied to the irrigation scheme. It includes NI plus water losses as $\frac{1}{E_a} \times NIWR$, and $E_a$ is the global efficiency of the irrigation system. Limited objective information on irrigation efficiency is not available and estimates are based on several criteria, e.g., figures found in the literature, type of crops irrigated, and the level of intensification of the irrigation techniques. Finally, GI can be expressed in mm or m$^3$/hm$^2$ and it is as follows:

$$GI = \frac{1}{E_a} \times \frac{1}{n} \times \sum_{i=1}^{n} CWR_i \tag{9}$$

If the GI is given for a period of growing duration such as the mean of daily evapotranspiration for each crop on the maximum month, then it can be explained as "Hydro-Module" and expressed in l/s-hm$^2$ (Halsema et al. 2012; Perry 2011; Finkel 2019). For calculating the hydro-module from GI, it needs the conversion factor as $C_a = 0.116$. Hydro-module reveals what the water demand is supplied by the on-farm water resource and is a key factor to balance water supply and demand for an irrigated crop, and can be computed as follows:

$$HM = C_a \times \frac{1}{E_a} \times \overline{CWR}_i \tag{10}$$

To demonstrate the coequality of this balance, Eq. 10 can be rewritten as follows:

$$HM \times E_a = C_a \times \overline{K}_{C_{i_M}} \times \overline{ET}_{O_M} \tag{11}$$

where HM, $Et_o$, $K_C$, and $Ea$ are the hydro-module (l/s-hm$^2$), reference crop evapotranspiration (mm/day), crop coefficient, and irrigation efficiency (%), respectively.

# 3 Uncertain model for coequality of the water supply and demand balance

The left side of Eq. (11) defined available water resources, and the right side presented the maximum water requirement that should be supplied by the available water resource. This balance created a stable condition between the demand and supply of water, resulting in keeping the sustainability of water resources so long as it is carefully applied in the farms. However, it is sometimes formed based on the unknown values of hydro-module, irrigation efficiency, crop coefficients, and reference crop evapotranspiration, where they are the reasons for trouble in the balance which makes a great challenge for water resources management (Abolpour 2018; Vignola et al. 2015). They are very critical in semi-arid and arid regions as setting this balance is very complex with their imprecise and vague values (Mata et al. 2019; Lima et al. 2018; Dominguez et al. 2013). These factors are created by four reasons: (1) over or lower estimations of reference evapotranspiration, (2) the lack of given values of crop coefficients in the whole crop growth, (3) affecting the adequacy, fluctuation, and on-timing water supply on the estimation of hydro-module, and (4) the lack of real value of irrigation efficiency.

The daily net radiation on the crop surface, soil heat flux, average air temperature, wind speed, vapor pressure deficit, the slope of the vapor pressure curve, and psychrometric constant are the variables which are used for estimating the reference evapotranspiration (*ETo*) based on Eq. (5). They are dependent on local weather conditions and regional climate change, resulting in their accuracy estimates being no easy, and any approach even this equation has the over or lower estimation for *ETo* (Dar et al. 2017). In this study, the average range of *ETo* is used in Eq. (11) developed in uncertain conditions. The crop coefficient (*Kc*) is needed to calculate the real crop evapotranspiration, which is also dependent on the water quantity and quality, soil texture, crop variety, and growth property, the culture system and crop canopy, and the farm management (Allen et al. 1998). It is worth mentioning that any plant is alive and has a reaction to these parameters, and it could thus be adapted with the salinity and/or the water stress in semi-arid and arid regions. This adaptation could be traced in the crop coefficient, resulting in the unknown amount of *Kc* and a range of uncertain variations (Eq. 11).

Planning the shortage of water resources in these regions is a challenge, and supplying on-time enough water is not easy. Therefore, assessing the amount of available water is a rough value, and also the estimated hydro-module has a significant fluctuation via its real values. As a result, a given value of the hydro-module is not, and its mean and range should be defined in Eq. 11. The total water diverted from any source, e.g., river and/or well, maybe not arrived in the root zone which the plant needs to intake water. Due to the water loss across the on-farm irrigation network, the plant could eventually use the remained part stored in the root zone. The irrigation water losses include the evaporation from the soil and water surfaces, the deep percolation across soil layers or sublayers, the water seepage from canals, and runoff. Therefore, to determine their fluctuations caused by their spatial and temporal variabilities, obtaining the mean and range of irrigation efficiency is necessary (*Ea*). Finally, Eq. (2) under uncertain conditions can be rewritten as the following, where $\alpha$, $\beta$, $\gamma$, and $\delta$ are the uncertain ranges of hydro-module, irrigation efficiency, reference evapotranspiration, and crop coefficients, respectively:

$$(\overline{HM} \pm \alpha) \times (\overline{E_a} \pm \beta) \triangleq (\overline{ET_{O_M}} \pm \gamma) \times (\overline{KC_{i_M}} \pm \delta_i) \times C_a \quad (12)$$

## 3.1 Case study

### 3.1.1 Minqin Region

The spread of the Minqin Basin has been located downstream of the Shiyang River in Northwest China at 103020 E–104020 E and 38050 N–39060 N (Fig. 1). The Shiyang River flows into the Minqin Oasis at an altitude of 1000–1400 m and with an arid temperate climate (Ma et al. 2005), and then disappears into the desert. The local farmers had overexploited the groundwater in the Minqin Basin before 2003. Climate change and overuse of water sources in the upper and middle reaches of the Shiyang River were resulting in the rapid reduction of water flowing downstream. The annual runoff flowing into the Minqin Basin was 0.573 mm$^3$ during the 1950s (Zhu et al. 2007) and 0.1 mm$^3$ at present.

According to the development policy of sustainable agriculture, 11,000 wells had been drilled that included 250 deep wells with a depth of 300 m, and the remaining were shallow wells with a depth of 60–150 m (Xue et al. 2016). In 2003, the total consumed water resource in the Minqin Oasis was 0.782 mm$^3$ and around 0.687, 0.076, 0.009, 0.003, and 0.007 mm$^3$ were used for irrigating farmland, forests, and grassland, rural and urban living purposes, and industrial usage, respectively. The average water consumption of irrigated farmland was 5100–6100 m$^3$/hm$^2$.

Since the agricultural water use was not managed in line with the oasis ecosystem's pattern, it harmed the sustainable development of local society, economy, and environment (Mainguet 1991; Li et al. 2006; Zhang et al. 2008a, b; Zheng and Yin 2010).

3161 wells with a depth of over 100 m were closed from 2004 to 2009. The tube irrigation and drip irrigation have gradually been replaced with traditional flood irrigation. The drip and tube irrigation systems had been set up in half of the total irrigated farmland area of this region by the end of 2010. Today, the agricultural infrastructure is changed by an important measure accomplished to save water and improve water use efficiency. For example, fruit trees with high water use efficiency, vegetables in greenhouses, and stable feeding animal husbandry have become popular and replaced the traditional grain crops (Xue et al. 2016; Hu et al. 2009).

## 3.2 Government policies on water resources systems

The effects of regional policies on land and water use are fragile in this arid ecosystem and have been strangely distinguished. The practical policies of effective, sustainable, and environment-friendly are needed for large tracts of unproductive degraded land, aggravating water crisis and food security. The EC policy implemented since the early twenty-first century has brought an evident positive outcome in this region. The actual volume of water flowing into the Minqin Oasis increased from 0.097 mm$^3$ in 2005 to 0.236 mm$^3$ in 2010 and 0.259 mm$^3$ in 2011. The groundwater extraction decreased by 0.24 mm$^3$, while the irrigation area decreased to 41,700 hm$^2$ in 2010. As a result, the

groundwater table has risen 45 cm between 2005 and 2011 in the northern part of this region (Xue et al. 2016; Roger et al. 2009).

There still a need to scientifically evaluate the sustainability of these policies, even though the central government has developed corresponding policies to restore the degraded land since the field surveys reveal that farmers do not welcome many of these new policies, such as drip irrigation, resettlement, and closing wells, and have even been met with passive resistance. A sustainable development that works truly realizing on a social, economic, and environmental level needs a great deal of exploration over time, e.g., developing new technologies to mitigate these environmental problems, and at the same time, planning the adaptation strategies to cope with the farmers' demands (Pinto et al. 2017; Li et al. 2019; Sheibani et al. 2020).

The water-saving practices used in this region showed applying water-saving technology to establish a high efficiency in line with the sustainable artificial oasis ecosystem is an important method, resulting in it could be used to better management of water scarcity and land degradation in arid regions (Xue et al. 2016; Wang et al. 2009). Here are several important problems for the future, which could be a risk for the sustainability of agricultural and water resources in this area. The part of croplands that used water-saving agriculture was not having all its maximum benefits. In this condition, they were changed their cropping pattern to increase their croplands for better economic outcomes. They may be forced on the water resources for supplying their new water demands, while the water shortage would be increased again.

### 3.2.1 Uncertain model for balancing the supply and demand water on case study

Increasing the crop water requirement due to the drought has been another problem in this irrigation district, whereas the farmers have no clear plan to find a certain volume of water demand (Ivezic et al. 2017; Oel et al. 2010). Hence, water is continually withdrawn by high rate pumping from the aquifer, and the government agencies shall indiscriminately monitor groundwater level, resulting in closing of several wells again. In this study, the basic idea found the best balance of crop water requirement across water resources capacity under uncertain conditions by the climatic changes. The first step is the need to select the crops which are better adapted to this condition. In this way, they could be recognized with their Kc that caused the convergence in Eq. 11. Hence, there is a need to detect the state of water supply according to the best amount of hydro-module. The mean of the hydro-module has no fixed value, thus here another decision variable should be added



Fig. 1 Location and landscape map of the Shiyang River Basin

as one of class j in Eq. 11, which can be revealed as follows:

$$(\overline{HM_j} \pm \alpha_j) \times (\overline{E_a} \pm \beta) \triangleq (\overline{ET_{O_M}} \pm \gamma) \times (\overline{KC_{i_M}} \pm \delta_i) \times C_a$$

$$(13)$$

where $\alpha_j$ is the variation range of $j$th class of hydro-module, and $\delta_i$ is the variation range of $i$th class of crop coefficient. They are the expected uncertain ranges of their mean amounts. The $\beta$ and $\gamma$ have expected the uncertain ranges of the mean of irrigation efficiency and reference crop evapotranspiration. It is worth noting that for each class, their values have no significant differences. Finally, this equation can balance the water supply and demand under uncertain conditions and is called uncertain model for balancing the water supply and demand (UMBSDW).

The region has constantly been changing in agents of the water supply and demand, due to farmer resistance with the government policies to conserve water resources. Hence, it was led to the lack of stability in the region's agriculture; thus, any direct field measurement of the state of water supply and demand could not be invoked in a long time. In this study, the basic parameters of water and soil were measured, some data were collected by the completion of field questionnaire forms, and other information were searched by reviewing the literature and historical data on this region (e.g., MWR 2001, 2003, 2006a, b; NBSC 2004, 2005; NDRC 2000; OECD 2015). The part of irrigation districts, i.e., 10,000 hm$^2$, were randomly selected for the collection of observed data, in which anyone had included the several farms near together, resulting they were 30% of total irrigated land; its part was used to collect the farm's information based on the questionnaire forms. Land suitability, irrigation efficiency, water quantity and quality, and crop type with its production were questioned in these areas. The supplied hydro-module for each farm was calculated by dividing the volume of farm's water use by the on-farm area during growth season in l/s-hm$^2$, which was recorded as the amount of available water. The calculated monthly reference evapotranspiration based on the database of Minqin climatic station in line with using the Penman–Monteith approach (Eq. 5) during the recent 20 years was utilized to estimate the maximum monthly crop evapotranspiration, $ET_C$ (Eq. 1); as a result, the crop coefficient $K_C$ from Eq. (2) was obtained. Here, the further amounts of $K_c$ were collected for the usual crops in this region by searching in FAO-56 (Allen et. al. 1998) or other studies such as Yang-Ren et al. (2007), Geo et al. (2010), Benli et al. (2006), Li et al. (2008), Liu and Luo (2010), Hou et al. (2010), and Zhao et al. (2013). They were classified based on the Monte-Carlo method, in which the class of low, normal, or high was defined by each variation

range, resulting in achievement of their mean with uncertain ranges that are shown in Table 1.

## 4 Results and discussion

### 4.1 The infrastructure of the fuzzy inference system

The coequality created in Eq. (13) to on-farm balance between the water resource and the crop requirement in the Minqin Region has included two parts. Its left side variables' function has explained how much water was supplied (SI), and its right side variables' function has demonstrated how much water was required (DI). Therefore, DI and SI are indicators to explain the water demand and the water supply, respectively. SI is a function of uncertain variations of hydro-module and water use efficiency, whereas DI is a function of uncertain variations of reference crop evapotranspiration and crop coefficients. The mean and uncertain range of average hydro-module (l/s-hm$^2$), maximum irrigation efficiency (%), maximum reference evapotranspiration (mm), and average crop coefficient (Table 1) obtained from the primary or reference research or the several experiments studies (Xue et al. 2016; Wang et al. 2009) have been used for the demonstration of uncertainty ranges of the water supply (SI) and demand (DI) in the Minqin cropland (Fig. 2). The fluctuation trend of DI related to the variation domain of SI could lead to five variation classes based on the uncertain ranges of input variables to calculate DI and SI where these input variables do not have any significant fluctuation trend with each other. Although the lack of relationship of input variables by computing DI and SI has formed a certain trend between each other, it is not enough because SI via DI should be distributed around a line 1:1 (Eq. 13). Their point distribution has not only led to line 1:1 but also no linear or nonlinear relationship between together (Fig. 2). Thus, for modeling such behavior, the soft computing approach should be applied (Möller and Beer 2005; Dubrovin et al. 2002; Sasaki and Gen 2003; Harris 2000; Odhiambo 2001; Nguyen and Prasad 1999). In this study, Mamdani's method was used to create a linear relationship according to the variables' uncertain amounts of Eq. (13). The basic concepts and details of this method are described in Zimmermann (1996), Li et al. (2001), Jang et al. (1997), and Oh et al. (2002).

In Mamdani's fuzzy rule based, a membership function is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. Using the classification process from the Monte-Carlo method for defining the membership values of each of the five classes of input (SI) and output (DI)

**Table 1** Variables' characteristics of uncertainty for balancing the water supply and demand in the Minqin Region

| Row | Ave. hydro-module (l/s-hm$^2$) | | Max. irrigation efficiency (%) | | Max. Ref. evapotranspiration (mm) | | Ave. crop coefficient | |
|---|---|---|---|---|---|---|---|---|
| | Mean | Range | Mean | Range | Mean | Range | Mean | Range |
| 1 | 0.23 | ± 0.15 | 37.5 | ± 17.5 | 6.31 | ± 1.22 | 0.33 | ± 0.18 |
| 2 | 0.33 | ± 0.25 | 37.5 | ± 17.5 | 6.31 | ± 1.22 | 0.44 | ± 0.24 |
| 3 | 0.44 | ± 0.28 | 37.5 | ± 17.5 | 6.31 | ± 1.22 | 0.55 | ± 0.30 |
| 4 | 0.55 | ± 0.35 | 37.5 | ± 17.5 | 6.31 | ± 1.22 | 0.70 | ± 0.39 |
| 5 | 0.65 | ± 0.42 | 37.5 | ± 17.5 | 6.31 | ± 1.22 | 0.84 | ± 0.46 |

variables, the mean and range of the possible amounts were recognized for five membership functions for each indicator of SI and DI (Fig. 3). The indexes of membership functions in this figure reveal the uncertain values of SI are less than DI, but they are the same together around the peak. The membership function develops based on the mean and range of the amount variations of the event possibility of each input or output value. The input variable with output values may have more than a one-to-one relationship, resulting in any input membership function related to more than one of the output membership functions.

It seems that the rules are governing under the relationship between input and output variables similar to the principles of this simulation method, in which the input variable once, SI, can be associated by the different possibility amounts with the several uncertain amounts of the output variable, DI. In fact, to achieve such connections between the memberships functions of indicators, the rules formed based on governing their uncertain values have resulted in the design of the inference fuzzy system (FIS) associated with the set of rules over these variables. The general form of Mamdani's method, developing the basic assumptions such as the number and shape of functions, and the rules between them can be carried out by the supervisor or user assessment (Kumar and Schuhmacher 2005; Papadrakakis and Lagaros 2003; Zimmermann 1996; Li et al. 2001). In this study, the best shape of membership functions for input and output variables is triangular (Fig. 3), and the number of functions was 25 rules between input and output indicators. Since the original object of this research is to maintain the balance in Eq. (13) under the uncertain condition, thus the fuzzy rules to establish the balance can be followed as.

If $Mf_{SI} = i$ then $Mf_{DI} = j$ with weighting coefficient $= k$; and or:

If $Mf_{SI} = i + 1$ then $Mf_{DI} = j + 1$ with weighting coefficient $= k + 1$.

where the $Mf_{SI}$ and $Mf_{DI}$ are the membership functions for the $i$th supply index and the $j$th demand index, respectively. They lie on the set of fuzzy rules for having the relationships of "and" or "or" with the weight of $k$. The indexes of $i$ and $j$ are the arrangement numbers of each rule; other information about the rules can be followed in Table 2. The weight factor is from zero to one that shows the role of each rule in the set of rules. The "Or" and "And" operators are also used for determining the role of each rule to create uncertain conditions between the input and output variables.

In this study, the weighted coefficients and the operators build up accordingly to maintain the coequality of two sides of Eq. (13). Rule no. 26 defined the initial conditions on the set of rules. Achieving the membership function properties and rules created a model to analyze the relationships of SI and DI that was called "SDMODEL" in this study, and its results are shown in Fig. 4. The amounts of DI from the model of the output variable via the input amounts, i.e., SI, should be evaluated with the line 1:1. Although the points scatter in this figure is very less than Fig. 2, the model results had not competently distributed upon this line; thus, it is revealed that the model could be detected by the fuzzy behavior on the data set, but it seems that a linear relationship has not been expected by Eq. (13). As a result, such uncertain conditions can be used SDMODEL to review and analyze the balance water supply and demand, instead of Eq. (13), and in the simulation and optimization of this balance, the results of this model should be utilized.

### 4.1.1 Certain amounts of the crop coefficient and the water use efficiency

The increase in DI continues to be high with a constant value of *SI*. This point is a peak value on the variations range of SI and DI, where it has determined the optimum situation for this balance (Fig. 4). Here, a nonlinear function has to be found to display these trends using the curve fitting approach and the SDMODEL results, resulting in the best nonlinear correlation between DI and SI obtained as follows:

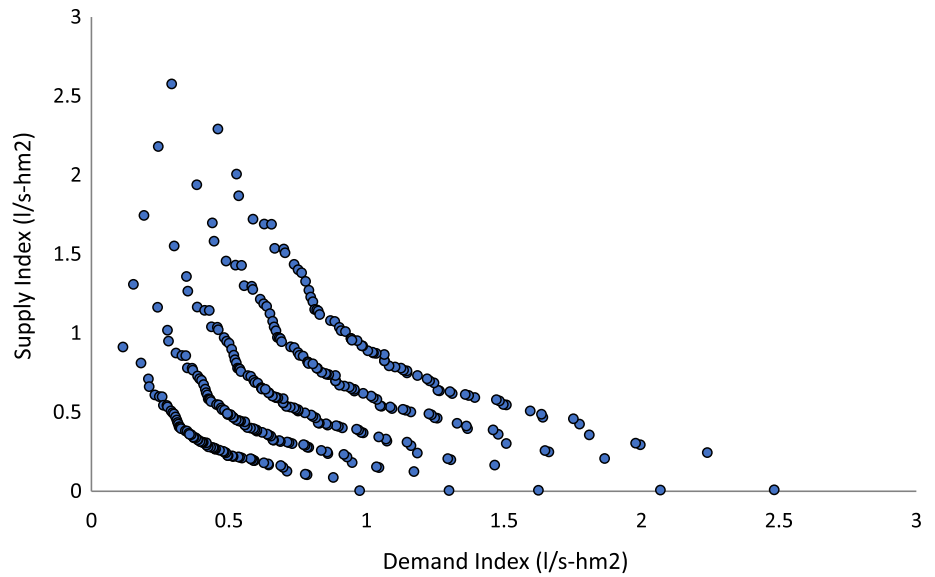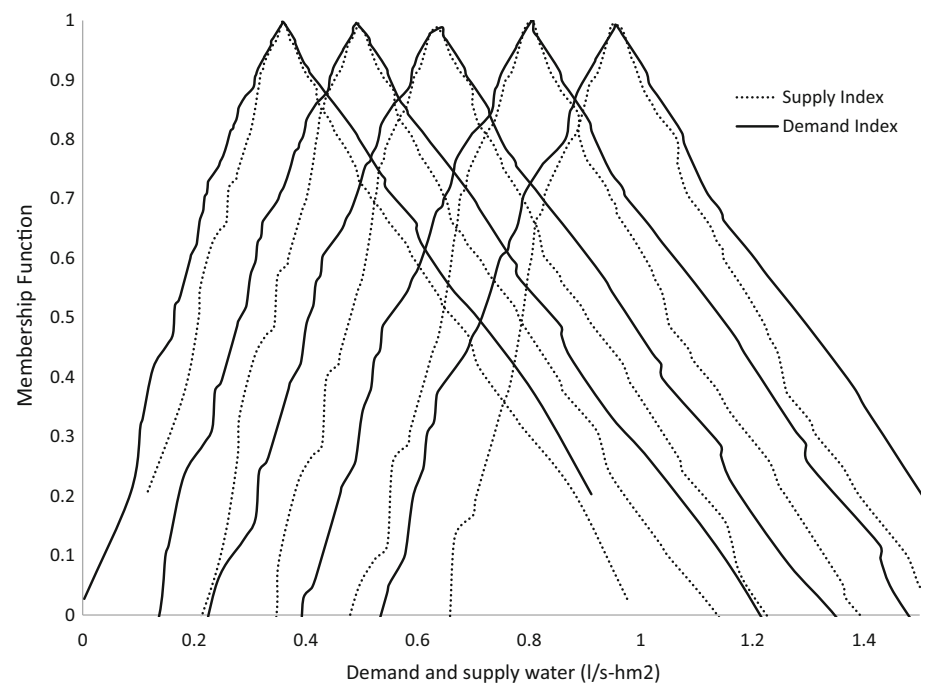**Fig. 2** The uncertainty ranges of the water supply and demand in the Minqin cropland



**Fig. 3** The membership functions for the fuzzy rule-based method to balance the water supply and demand in the Minqin cropland

$$DI = \frac{0.13 - 0.51(SI) - 7.21(SI)^2 + 47.38(SI)^3}{1 - 8.58(SI) + 14.92(SI)^2 + 53.67(SI)^3} \quad (14)$$

Due to any maximum demand that should be supplied by the minimum amounts of water withdrawals, this peak point could not provide the best balance situation of these resources. Thus, the fluctuation of this function needs to be maximized by the least variation of SI. As a result, the objective function in this study can be defined as the following:

$$Max : \frac{\Delta DI}{\Delta SI}$$
$$= \frac{0.13 - 0.51(SI_t) - 7.21(SI_t)^2 + 47.38(SI_t)^3}{1 - 8.58(SI_t) + 14.92(SI_t)^2 + 53.67(SI_t)^3}$$
$$- \frac{0.13 - 0.51(SI_{t-1}) - 7.21(SI_{t-1})^2 + 47.38(SI_{t-1})^3}{1 - 8.58(SI_{t-1}) + 14.92(SI_{t-1})^2 + 53.67(SI_{t-1})^3}$$

subject to

$SI_t$ and $SI_{t-1} > 0$.

where $SI_t$ and $SI_{t-1}$ are the supply index in two demand positions at t and t-1. Using a trial and error approach, the maximum value of objective function was obtained, in

**Table 2** The properties of fuzzy rules on the SI and DI

| Rule | Mf of SI | Mf of DI | Weight | And | Or | Rule | Mf of SI | Mf of DI | Weight | And | Or |
|------|----------|----------|--------|-----|-----|------|----------|----------|--------|-----|-----|
| 1 | 1 | 1 | 1.0 | * | | 14 | 3 | 4 | 0.8 | | * |
| 2 | 1 | 2 | 0.8 | | * | 15 | 3 | 5 | 0.6 | | * |
| 3 | 1 | 3 | 0.6 | | * | 16 | 4 | 1 | 0.4 | | * |
| 4 | 1 | 4 | 0.4 | | * | 17 | 4 | 2 | 0.6 | | * |
| 5 | 1 | 5 | 0.2 | | * | 18 | 4 | 3 | 0.8 | | * |
| 6 | 2 | 1 | 0.8 | | * | 19 | 4 | 4 | 1.0 | * | |
| 7 | 2 | 2 | 1.0 | * | | 20 | 4 | 5 | 0.8 | | * |
| 8 | 2 | 3 | 0.8 | | * | 21 | 5 | 1 | 0.2 | | * |
| 9 | 2 | 4 | 0.6 | | * | 22 | 5 | 2 | 0.4 | | * |
| 10 | 2 | 5 | 0.6 | | * | 23 | 5 | 3 | 0.6 | | * |
| 11 | 3 | 1 | 0.6 | | * | 24 | 5 | 4 | 0.8 | | * |
| 12 | 3 | 2 | 0.8 | | * | 25 | 5 | 5 | 1.0 | * | |
| 13 | 3 | 3 | 1.0 | * | | 26 | 6 | 6 | 1.0 | * | |



**Fig. 4** The results of the fuzzy rule-based method to balance the water supply and demand in the Minqin cropland
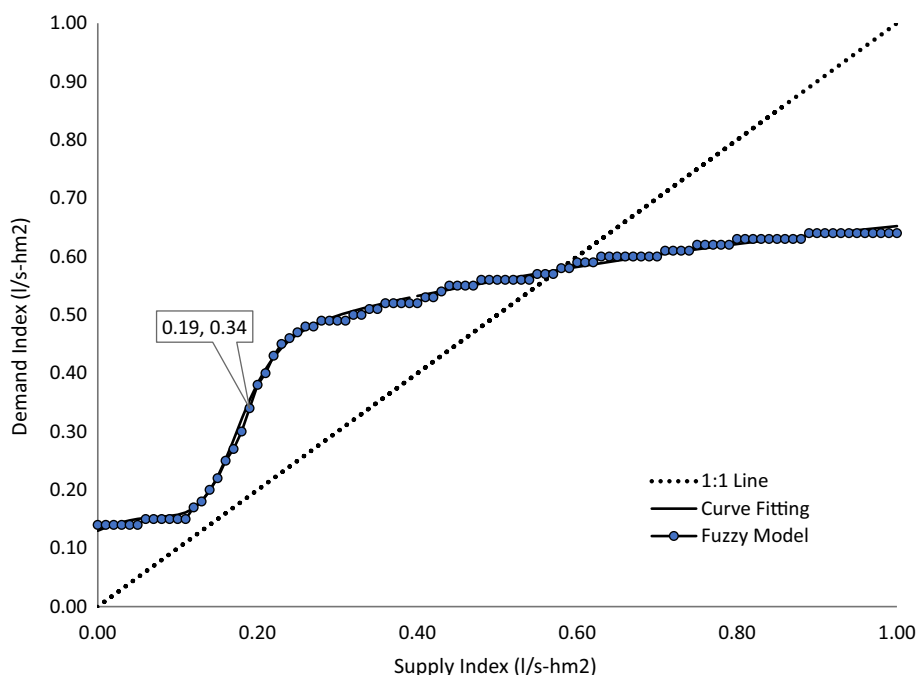
which δDI and δSI were 0.04 and 0.1, respectively. It was the best balance situation in a certain state where SI was 0.19 and could be supplied by the water demand of 0.34 (Fig. 4). As a result, Eq. (13) was in one state of linear equality, where *SI* and *DI* were having values similar to 0.19 and/or 0.34. In this way, if the right side or the left side is of 0.34, the amounts of crop coefficient and/or hydro-module can be calculated. For obtaining the average of potential evapotranspiration, the data of input and output based on the converged results in a certain condition were entered into the SDMODEL. In this condition, ETo was obtained as 6.3 mm/day, and also the optimum crop coefficient was 0.47; $K_c = (0.34)/(0.116 * 6.3)$. Based on the objective function designed to find the maximum crop

water requirement under the minimum water supply, the maximum water use efficiency was obtained at 55%. Thus, the optimal hydro-module was obtained as HM = 0.55 * 0.19 or 0.35 l/s-hm², where it is the least hydro-module that can supply the water requirement for any hectare of each crop, in which the maximum crop coefficient during its growth is 0.47.

The *SI* and *DI* found from SDMODEL and Eq. (14) resulted in the nonlinear correlation that is a kind of the modified form of Eq. (13). Therefore, to estimate the crop coefficient ($K_C$) and hydro-module (HM), Eq. (14) can be utilized, instead of using Eq. (13). In this study, the $K_c$ and HM used to make the observed data set of Eq. (13) are called uncertain values, whereas their values obtained from

**Fig. 5** The certain and uncertain values of HM and Kc in the Minqin Region
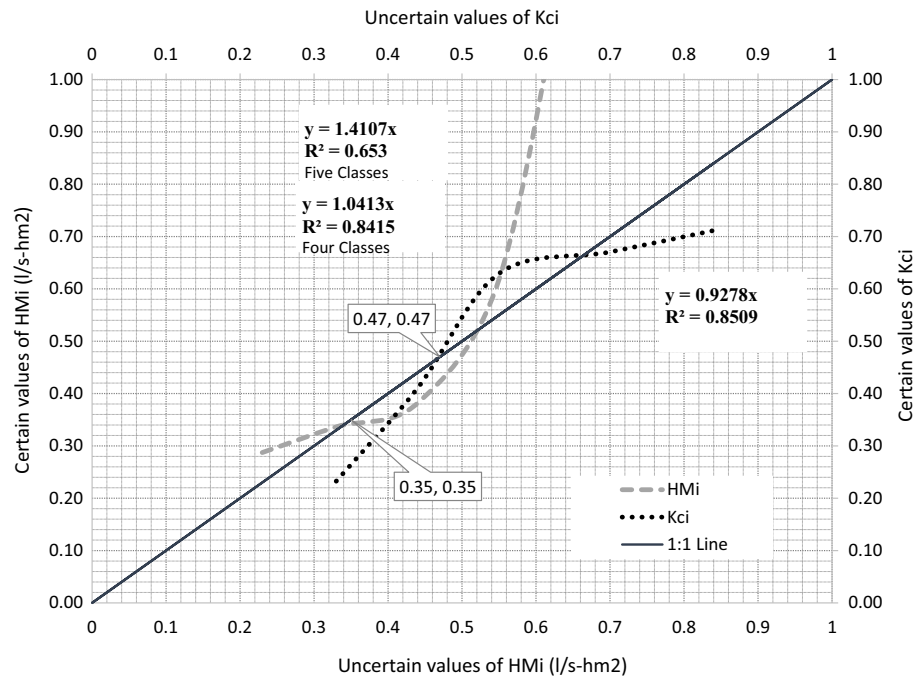


Eq. (14) are called certain values. For example, the left side of Eq. (13), i.e., SI, equals 0.126 according to the water use efficiency of 55% where hydro-module is 0.23, which is the average of its class, e.g., No. 1. Although the left and right sides of Eq. (13) should be equaled as DI = SI = 0.126, DI was 0.170 using Eq. (14), thus 0.126 of DI is the uncertain value via 0.17 of DI which is the certain value in this study. Where DI had uncertain value, i.e., 0.126, 0.230 of HM was the uncertain value obtained by this amount of DI, wherein DI of 0.170, i.e., the right side of Eq. 13, the crop coefficient of 0.230 was achieved using the potential evapotranspiration of 6.3 mm/day which had the average of its class, e.g., No. 1. The $K_C$ of 0.230 obtained from the uncertain value of HM, i.e., 0.230 l/s-hm$^2$, was a certain value, whereas the average of crop coefficient at class No. 1, i.e., 0.330, is its uncertain value (Table 1). As a result, the estimated value 0.230 of $K_C$ by SDMODEL is against its observed value of 0.330, e.g., class No. 1. The certain values of other classes of Kc and HM were similarly estimated that are shown in Fig. 5.

### 4.1.2 The optimum range of the crop coefficient and the water use efficiency

To show the contrast of uncertain and certain amounts of $K_C$ and HM according to the observation data and estimation results, line 1:1 was added in Fig. 5. The correlation coefficient of 0.851 is obtained to relate the calculated values via the average of each class of $K_C$, but here, it is a little different for the hydro-module because it is 0.65 under all HM classes and without the data of class 5 equals

0.841. Having a good correlation between the HM which is indirectly obtained from SDMODEL, the estimation values of KC, and their observation amounts could prove the basic assumptions of this model (Giustiab and Libeli 2015; David et al. 2012; Ge et al. 2013). It needs to mention that this model's basic assumptions are the definitions of fuzzy rules (Table 2) and the number and shape of membership functions for SI and DI. In the regression process between observed and calculated data, the correlation coefficient less hydro-module than the crop coefficient is no reason for the inability to fuzzy model.

The water resources in this region have a very short supply of water for the hydrophilic plants, resulting in the need for this crop water requirement to balance the water supply and demand based on Eq. 13. Hydro-module located in class 5 is more than 1.00 l/s-ha and reveals that water use in this region is very high, and thus it is the critical point in balancing. It was mentioned about the SDMODEL's result, with which increasing the amount of SI from the intersection point of model and line 1:1, the DI is closed to a constant amount (0.640). As a result, balancing the supply and demand for water in this region is having a clear critical point that has been detected by this model. $K_C$ of 0.470 and HM of 0.350 shown in Fig. 5 are the intersection points of their certain and uncertain values, and detected that they are real values in this region, though resulted as the optimum values from the optimization process of Eq. (14). Finally, they are practically answering on achieving the best balance situation of water supply and demand in this region. Therefore, this region needs to have

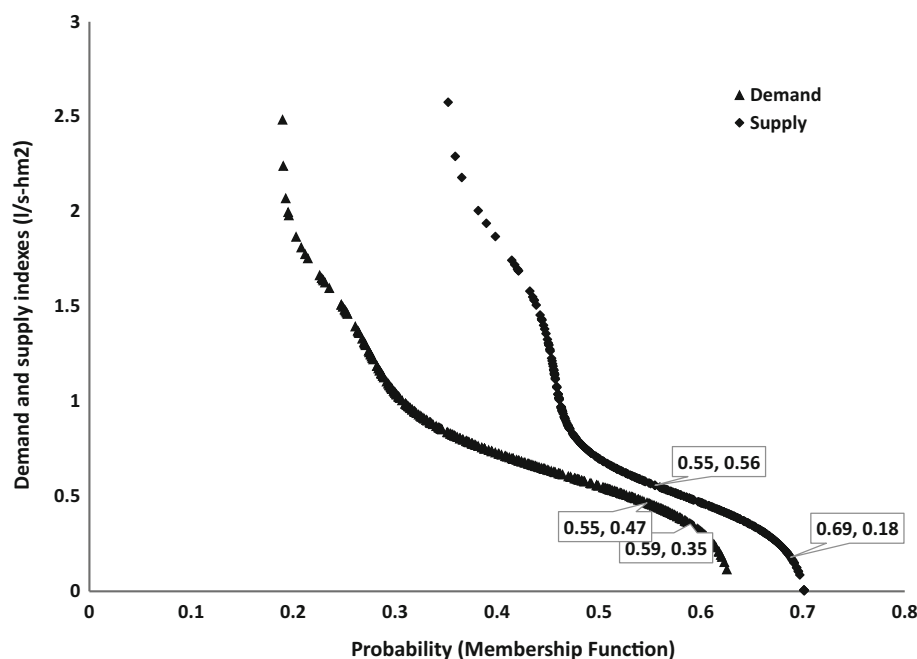**Fig. 6** The event possibility functions of the water supply and demand in the Minqin Region



**Table 3** The optimum values of water consumption parameters under seasons of drought, normal, and wet to suit Minqin irrigated plants; the bold italics and underlined define as the best crop coefficients

| Item | Optimum point No. 1 | Event possibility No. 2 | Drought | Wet year | Normal | Optimum point No. 2 | Event possibility No. 2 | critical years |
|---|---|---|---|---|---|---|---|---|
| $E_a$ | 0.19 | 0.69 | 0.43 | 0.32 | 0.55 | 0.56 | 0.55 | 0.38 |
| $ET_0$ (mm/ d) | 0.34 | 0.59 | 7.59 | 5.01 | 6.300 | 0.47 | 0.55 | 6.30 |
| HM (l/s-hm$^2$) | 0.19 | 0.69 | 0.44 | 0.60 | 0.35 | 0.56 | 0.55 | 1.49 |
| $K_C$ | 0.34 | 0.59 | *0.39* | *0.59* | *0.47* | 0.47 | 0.55 | *0.64* |

these irrigated crops with this property in the normal climatic condition.

According to the climate change effects like the drought and wet years on plant productions in this region, the optimal $K_c$ with its certain value under the normal condition for using as an index of plants' selection cannot yet be considered. The possible values of SI and DI using their membership functions (Fig. 3) and the adaptive neural fuzzy inference systems (ANFIS) were calculated. In this approach, the relationship between input and output variables is determined based on combining the neural networks and fuzzy adaptive system (Kumar and Schuhmacher 2005; Zimmermann 1996; Li et al. 2001). This study has considered the amounts of membership function of any indicator as an input variable and the class representative like their average values as the output variable. In this case, two functions of the event possibility created for SI and DI are shown in Fig. 6.

The possibility functions could be used to calculate the event possible for each variable of any indicator and to determine the possibility of event amounts of any indicator. For example, the optimum values of 0.19 for SI or 0.35 for DI obtained from previous contents have, respectively, 0.69 and 0.59 of event possibility (Fig. 6). The event possibility (i.e., no. 2) of 0.69 for SI reveals the amount of irrigation efficiency is 0.43. The amount of potential evapotranspiration of 7.59 mm/day based on the event possible (i.e., optimum point no. 1) is DI of 0.59 (Table 1). In this case, using 0.19 for SI (i.e., the right side of Eq. 13) and 0.35 for DI (i.e., the left side of that), the amounts of hydro-module and crop coefficient are 0.44 (l/s-hm$^2$) and 0.39, respectively. These calculated values could be used in drought conditions. Although SI of 0.56 and DI of 0.47 are near the event possibility of 0.55, and they have the least difference together at this point (Fig. 6), the try and error method was used for achieving a converge point from the

**Table 4** The proposed cropping pattern for the Minqin Region

| Crop | Reference $K_C$ | | | Realistic $K_C$ | | | Reliability | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Initial | Mid | End | Initial | Mid | End | Initial $K_c^* = 0.39$ | Mid $K_c^* = 0.64$ | End $K_c^* = 0.47$ | Average |
| Sisal | | 0.40–0.70 | 0.40–0.70 | | 0.51 | 0.51 | 1.00 | 0.20 | − 0.09 | 0.4 |
| Sesame | | 1.10 | 0.25 | | 1.02 | 0.23 | 1.00 | − 0.59 | 0.50 | 0.3 |
| Chick pea | | 1.00 | 0.35 | | 0.93 | 0.33 | 1.00 | − 0.45 | 0.31 | 0.3 |
| Barley | | 1.15 | 0.25 | | 1.07 | 0.23 | 1.00 | − 0.66 | 0.50 | 0.3 |
| Oats | | 1.15 | 0.25 | | 1.07 | 0.23 | 1.00 | − 0.66 | 0.50 | 0.3 |
| Wheat | | 1.15 | 0.25 | | 1.07 | 0.23 | 1.00 | − 0.66 | 0.50 | 0.3 |
| Lentil | | 1.10 | 0.30 | | 1.02 | 0.28 | 1.00 | − 0.59 | 0.41 | 0.3 |
| Green gram–cowpeas | | 1.05 | 0.35 | | 0.97 | 0.33 | 1.00 | − 0.52 | 0.31 | 0.3 |
| Pineapple | 0.5 | 0.30 | 0.30 | 0.46 | 0.28 | 0.28 | − 0.19 | 0.56 | 0.41 | 0.3 |
| Sunflower | | 1.00–1.15 | 0.35 | | 1.00 | 0.33 | 1.00 | − 0.56 | 0.31 | 0.3 |
| Peas | | 1.15 | 0.30 | | 1.07 | 0.28 | 1.00 | − 0.66 | 0.41 | 0.2 |
| Maize | | 1.20 | 0.35 | | 1.11 | 0.33 | 1.00 | − 0.74 | 0.31 | 0.2 |
| Potato | | 1.15 | 0.40 | | 1.07 | 0.37 | 1.00 | − 0.66 | 0.21 | 0.2 |
| Grapes (wine) | 0.3 | 0.70 | 0.45 | 0.28 | 0.65 | 0.42 | 0.28 | − 0.01 | 0.11 | 0.1 |
| Alfalfa | 0.4 | 0.50 | 0.50 | 0.37 | 0.46 | 0.46 | 0.05 | 0.27 | 0.01 | 0.1 |
| Cotton | | 1.15–1.20 | 0.70–0.50 | | 1.09 | 0.56 | 1.00 | − 0.70 | − 0.18 | 0.0 |
| Onions | | 1.05 | 0.75 | | 0.97 | 0.70 | 1.00 | − 0.52 | − 0.48 | 0.0 |
| Beans dry | 0.4 | 1.15 | 0.35 | 0.37 | 1.07 | 0.33 | 0.05 | − 0.66 | 0.31 | − 0.1 |
| Faba bean | 0.5 | 1.15 | 0.30 | 0.46 | 1.07 | 0.28 | − 0.19 | − 0.66 | 0.41 | − 0.1 |
| Melons | 0.4 | 1.00 | 0.75 | 0.37 | 0.93 | 0.70 | 0.05 | − 0.45 | − 0.48 | − 0.3 |
| **Walnuts** | **0.5** | **1.10** | **0.65** | **0.46** | **1.02** | **0.60** | **-0.19** | **-0.59** | **-0.28** | **-0.4** |

least difference of two functions. The event possibility for two sides of Eq. (13) almost closes to this point. This equation could thus be expressed as a linear relationship, and balancing the water supply and demand closes to a reliable status. In fact, this point can be as the intersection point of SDMODEL and line 1:1 in Fig. 4, in which both sides of Eq. (13) were equal to this amount, e.g., 0.58. Similar to Chen and Paydar 2012, our study has enough accuracy in both methods for selecting a certain range of decision variables in this region.

### 4.1.3 Reliability of proposed crops

The event possibility of 0.55 is not sure for supplying the highest water requirement with the least water resources and results in a lack of suitable balance of water supply and demand in this region. Thus, 0.375 of water use efficiency and 6.3 mm/day of potential evapotranspiration obtained from this unstable point are their normal values (Table 1). Hence, based on 0.56 of SI and 0.47 of DI (i.e., optimum point no. 2) in Table 3, the hydro-module of 1.49 l/s-ha and the crop coefficient of 0.64 can be achieved. As a result, this point is represented as the beginning of the crisis state in this balance, which

explained the critical supply situation for the maximum water requirement. This region has no very wet years, but the farmers cultivate yet plants that need the highest water use along with the lowest efficiency. For example, they have been planting watermelon that was being a good job in some years.

The best crop coefficients during drought, normal and wet years are 0.39, 0.47, and 0.59, respectively. As a result, the range from 0.39 to 0.64 can be utilized to select the appropriate plants in the region (Table 3). The crops have lied on this optimal range extracted based on the list of FAO No. 66 represented by Finkel (2019) and Allen et al. (2000) and is shown in Table 4. They have reported the crop coefficients under different growth stages such as beginning, middle, and end, but are not competent to be covered the crops conditions in this region. Therefore, the $K_C$ symmetric value of the selected crops calculated using the correlation results is shown in Fig. 5, and added "Realistic $K_C$" in the middle part of Table 4. The cultivation historical information of some selected crops showed some of them have no acceptable yield in some years, e.g., watermelon. Although they were good in some years, they may be incompatible crops with these local weather conditions, and/or the farmers were not satisfied

with their cultivation due to the economic factors. Thus, planting these crops has different credibility at each year, resulting in for the need of an index of production reliability that could explain the economic factors and climatic conditions.

The primary optimization models that have been used to the suitable crop selection in each region sometimes have several problems, e.g., their requirement of adequate information, the practical limitations, and reducing the accuracy of their results in a long time. The optimal range is the output of this study as same as the results of these models, and it is a way, which could thus be defined as the practical information for the crop production infrastructure in these issues. According to these differences, adapting the basic factors of crop water requirement with the water resources capacity under uncertain conditions was the main purpose of this study. Therefore, the next step detected how to adapt the selected crops under this region's condition, and this adaptation was how reliable. Hence, the following equation is used to calculate the reliability of any selected crop in this study (Duckstein and Plate 1987; Hashimoto et al. 1982):

$$R = \frac{V_E - V_A}{V_E} \qquad (15)$$

where $VE$ and $VA$ are the expected and actual values of any variable (e.g., $K_C$). The reliability of selected crops listed in Table 4 should be examined by two viewpoints such as the economic situations and climate changes. Due to a mismatch in some crop coefficients for selected crops in some of the various growth stages with the optimal range of this study, the overlap reliability should initially be computed. The climatic condition may change this difference between $KC$ for any crop with the optimal range. Thus, the crop coefficient in various stages of growth for any crop ($VA$) and the optimum crop coefficient under different climatic conditions ($VE$) were used in the process of reliability calculation based on the climatic conditions. Due to the fluctuation of rainfall under the initial periods of growth during dry years, it is assumed to select each crop in the region, the difference between the reference and optimum of $K_C$ can have a key role. Thus, for calculating the reliable value during drought, the optimal value has been assumed as the expected value of $K_C$ (e.g., 0.39). On the other hand, the maximum crop production is usually affected by the water resources situation to supply the water demand during the middle periods of growth, so assumed that the coefficient of the critical crop is the expected value (i.e., 0.64). Finally, concerning the limitations of water resources to supply the water requirements, the last irrigation for irrigated land, the optimum of $K_C$ during normal years can be assumed as the expected value (e.g., 0.47). In this case,

the reliability coefficients were calculated for the selected crops and are shown in Table 4.

The range of this coefficient is from − 1 to 1, which is greater than zero, which defines how much is adapted the crop with the climatic conditions, and whatever it is less than zero to reveal the non-adaptive. Besides, to display the crop sensitivity to the climatic conditions, this coefficient can be used. It is also utilized to arrange the priority of each selected crop for the region. Although the solving process in this study may be a simple form of the complex optimization models, the model outputs are alike. It would simply utilize for solving a complex topic like determining the cropping pattern (Ganoulis 2010; Abolpour and Javan 2007; Abolpour et al. 2007, 2008). Perhaps, one of the reasons for creating this doubt is that there were not reviewing the economic factors. Therefore, using the information about crop production in line with their prices in the region, another reliability coefficient for some of the selected crops could annually be calculated.

### 4.1.4 Economic factors on proposed crops

Figure 7 shows the price via the yield for some of the selected crops that have the largest cultivation area since 1990. Using the regression analysis, i.e., three orders of a nonlinear function, the relationship between the price in USD and yield in ton/hm$^2$ was evaluated. The highest correlation coefficient has occurred for sunflower, whereas cotton has no good correlation. The fluctuation of price via production is no fixed trend for all the crops. For example, the cotton yield has annually had a significant difference but no change in its price. It is reversed in the onion, its yield has almost been constant, but its price has a significant difference in any year.

The fluctuation of yield via price in sunflower has been no significant difference before the last decade. But they have intensively increased in recent years. Not only the yield and price for watermelons and barley have always been changing, but also they have practically the peak point for their trend. It should be concluded the effects of climate change along with economic factors on each crop are different. The expected values of yield should be calculated for each crop again according to the reliability coefficient computed based on the economic viewpoint. The onion's price had no change as its market risk has been an important economic factor for its price, thus its yield mean was the expected value for determining the reliability. On the other hand, a little change in cotton's price during this period revealed that the yield is not a function of climate change and not the increase of cultivated areas. Thus, the yield means could be considered the expected value as the peak point has no clear trend. Since the price via yield in recent years has been a positive trend without
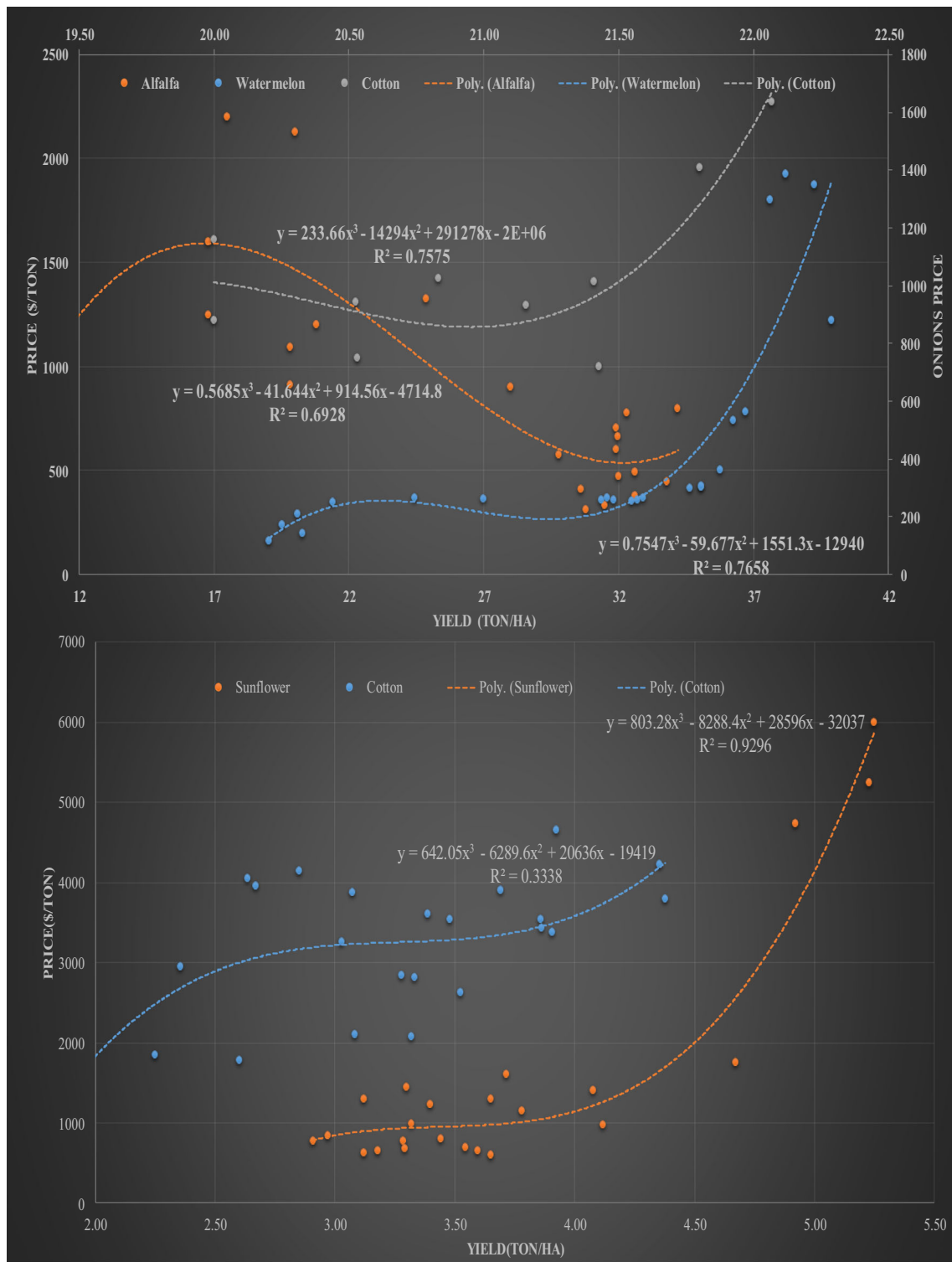
**Fig. 7** The price and yield of Minqin's usual crops since 1990

the peak point, the maximum yield of sunflower could be used as the expected value.

The changing trend of price to yield for watermelon or barley has clear extreme points that can consider as the expected values. Here, watermelon yield is 31 or 23 tons/ hm² which are the max or min values, in which the price has almost been constant across these two points. The yield between these two peaks is a function of the effectiveness of the climatic changes. Else, it is a function of the increase of cultivated areas (i.e., economic factors). As a result, the

**Table 5** The reliability of crop production in the Minqin Region from two models of price and plant suitability

| Years | Sunflower $Y_{Max} = 5.25$ | Alfalfa $Y_{OPT} = 32.25$ | Cotton $Y_{Mean} = 3.25$ | Onions $Y_{Mean} = 21$ | Melons $Y_{OPT} = 23.25$ |
|---|---|---|---|---|---|
| 1991 | 0.31 | − 0.03 | − 0.65 | | 0.14 |
| 1992 | 0.30 | − 0.05 | − 1.27 | | 0.09 |
| 1993 | 0.32 | − 0.09 | − 1.00 | − 1.00 | 0.12 |
| 1994 | 0.35 | − 0.02 | − 0.89 | 0.41 | 0.10 |
| 1995 | 0.41 | − 0.06 | − 0.61 | 0.80 | 0.04 |
| 1996 | 0.22 | 0.01 | − 0.58 | 1.07 | − 0.10 |
| 1997 | 0.37 | − 0.07 | − 0.18 | − 1.00 | − 0.48 |
| 1998 | 0.37 | − 0.09 | − 0.22 | − 0.47 | − 0.21 |
| 1999 | 0.41 | − 0.07 | − 0.17 | − 0.47 | − 0.46 |
| 2000 | 0.39 | − 0.13 | 0.03 | 0.16 | − 0.43 |
| 2001 | 0.45 | − 0.06 | 0.07 | − 0.17 | − 0.41 |
| 2002 | 0.34 | − 0.08 | 0.27 | 0.43 | − 0.47 |
| 2003 | 0.43 | − 0.14 | − 0.40 | | − 0.42 |
| 2004 | 0.37 | 0.07 | 0.08 | | − 0.56 |
| 2005 | 0.28 | 0.34 | 0.14 | | − 0.58 |
| 2006 | 0.30 | 0.66 | 0.23 | | − 0.58 |
| 2007 | 0.37 | 0.34 | 0.61 | | − 0.61 |
| 2008 | 0.29 | 0.44 | 0.66 | | − 0.63 |
| 2009 | 0.22 | 0.44 | 0.61 | | − 0.65 |
| 2010 | 0.11 | 0.42 | 0.44 | | − 0.69 |
| 2011 | 0.06 | 0.33 | 0.67 | | − 0.72 |
| 2012 | 0.00 | 0.17 | 1.13 | | − 0.76 |
| 2013 | 0.00 | 0.31 | 1.11 | | − 0.79 |
| Average | 0.29 | 0.11 | 0.00 | − 0.02 | − 0.39 |
| $K_c$ Model | 0.30 | 0.10 | 0.00 | 0.00 | − 0.40 |

expected value is chosen 23 tons/hm$^2$. Since the impact of economic factors and climatic condition is reversed in a manner, the expected value could be considered 31 tons/hm$^2$. The method of trial and error is used to determine these peak points. Finally, using Eq. 15 and determine the expected values for any crop, their production reliability coefficients were calculated and are shows in Table 5. The plant's production reliability coefficient represents the reliable amount of annual yield per its expected amount during a long-time period. Here, it is assumed that any selected crop along with having the crop coefficient extracted among the regional optimum crop coefficients would be planted. It needs to keep its reliability amount in future conditions as if the same period of the last 24 years. The last two rows in Table 5 present the results of two different approaches for computing the reliability coefficients. It can be seen that there is a perfect correlation between them, and the above assumption is true by comparing their results.

Proving this hypothesis resulted in the range of selected crops of Table 4, where they could be used for this region. The expected yield of any crop should be determined based on calculating the production reliability due to the economic factors affecting yield and price. It seems this way that not only ranking the selected crops by the crop reliability coefficient that has been obtained from the balance of supply and demand along with the crop characteristics but also the role of economic factors has been considered. Finally, the presented study approach could be used as the simple optimization method to replace building the complex optimization models for such issues (McCarhy et al. 2014; Merot and Bergez 2010).

# 5 Conclusion

Because of the knowledge lack of necessary calculations to manage the on-farm water use under uncertain conditions, the farmers could not be cultured their favorite crops (Abolpour 2018). Therefore, there needs to a suitable pattern as reference points for their croplands with a clear plan for water use. This idea formed the research framework of this study to balance the on-farm water supply with the crop water demand that has resulted in the development of

a new approach; it is a way that could be used as the selection methodology of these non-physical points for any irrigation districts. The establishment of this balance depended on the certain prediction of the climate change effects on crop water requirements that has formed the basic concepts of our study to select the optimum cropping pattern. The optimum range of crop coefficient adapted to the climate changes achieved from the fuzzy-probabilistic approach is the reference point of water allocation on irrigation districts. Thus, it is a way which could be defining the crop-pattern by the balance of water supply and demand in line with the plant's characteristics and the effectiveness of the economic factors.

There have been combined approaches of fuzzy logic methods with models of multi-criteria decision-making or classic stochastic to balance demand and supply water for determining sustainable agricultural water management in the current research (Radmehr et al. 2022; Li and Huang 2011; Zou et al. 2020; Ivezic et al. 2017; Ge et al. 2013; David et al. 2012). However, in this study, balancing the water demand and supply to sustain agricultural water resources have formed from a process that step by step developed models to adapt the crops with the water resource capacity under uncertain climatic changes.

The crop coefficients from 0.39 to 0.64 obtained on the best state of the balance of water supply and demand have been proposed for this region where the plant properties matched the economical hydro-module. Adapted this optimal range to the uncertain condition of water resource capacity is a reference point to show how sustaining the agro-system of Gansu Province according to the government policies on water resources management. This range resulted in ranking the region's famous crops in Table 4 that is a kind of proposed crop-pattern since the expected yield of selected crops has been defined as the production reliability coefficient obtained from the crop prices which resulted from the effects of economic factors on yield. This approach study could be used as a simple optimization method to replace building the complex optimization models for such issues.

**Availability of data and materials** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Conflict of interest** The authors declare that they have no competing interests.

**Ethical approval** Not applicable.

**Consent to participate** Not applicable.

**Consent to publish** Not applicable.

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