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Basin Irrigation Design with Multi-Criteria Analysis Focusing on Water Saving and Economic Returns: Application to Wheat in Hetao, Yellow River Basin

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Abstract: The sustainability of the Hetao Irrigation System, located in the water scarce upper Yellow River basin, is a priority considering the need for water saving, increased water productivity, and higher farmers' incomes. The upgrading of basin irrigation, the main irrigation method, is essential and includes the adoption of precise land levelling, cut-off management, improved water distribution uniformity, and adequate irrigation scheduling. With this objective, the current study focuses on upgrading wheat basin irrigation through improved design using a decision support system (DSS) model, which considers land parcels characteristics, crop irrigation scheduling, soil infiltration, hydraulic simulation, and environmental and economic impacts. Its use includes outlining water saving scenarios and ranking alternative designs through multi-criteria analysis considering the priorities of stakeholders. The best alternatives concern flat level basins with a 100 and 200 m length and inflow rates between 2 and 4 L s^{-1} m^{-1}. The total irrigation cost of designed projects, including the cost of the autumn irrigation, varies between 2400 and 3300 Yuan ha^{-1}; the major cost component is land levelling, corresponding to 33–46% of total irrigation costs. The economic land productivity is about 18,000 Yuan ha^{-1}. The DSS modelling defined guidelines to be applied by an extension service aimed at implementing better performing irrigation practices, and encouraged a good interaction between farmers and the Water Users Association, thus making easier the implementation of appropriate irrigation management programs.

Keywords: surface irrigation modelling; precise land levelling; irrigation systems design; beneficial water use; decision support systems (DSS); inflow rates; cut-off time

1. Introduction

The Yellow River basin is a water scarce region, with low water availability; about 500 m^3 per capita per year [1]. Agricultural irrigation corresponds to close to 90% of the total water use in the basin [2], and is particularly important in the Hetao Irrigation District. Climate change is likely a main cause for a decrease of water availability during the last decades [3–5], while increased water abstractions for industrial and domestic uses highly exacerbate water scarcity [2]. Forecasted scenarios on water resources allocation and use in the Yellow River basin point out the need to reduce irrigation water use [6].

The reduction of water resources allocation for irrigation due to the increased demand by non-agricultural sectors has unbalanced traditional irrigation management [6–9] and resulted in heavy challenges for the future use of water for irrigation. Thus, major priorities in the upper Yellow River basin refer to developing and implementing appropriate technologies aimed at water saving, improved water productivity, and increased farmer's incomes [7]. Since basin irrigation is the most used irrigation method in the 570,000 ha of irrigated land of Hetao, there is a requirement to focus on improving basin irrigation, which implies precise land levelling, appropriate inflow discharges and cut-off times, and adopting improved crop irrigation schedules [10–14], as well as improved supply management, namely modernizing canal conveyance and the distribution service aimed at upgrading water delivery and reducing runoff and seepage wastages [12,15–17]. When soils are saline [18], basin irrigation modernization also needs to consider salinity control practices [12,17,19], mainly adopting improved out of season autumn irrigation to appropriately leach the salts out of the soil's root zone. In addition, because water-saving practices impact groundwater dynamics [9,20], it is required that mutual influences of groundwater-irrigation are assessed and target groundwater depths are defined [21].

It is known that the performance of surface irrigation systems highly depends upon design and management [17,22–25]. Thus, appropriate design procedures and modelling are required because surface irrigation design based on simulation models produces results more easily, provides a better description of runoff and infiltration processes and the assessment of expected system performance, and results in the improved quality of design solutions [23–25]. In fact, there are a variety of factors that influence surface irrigation performance and shall be considered in the design: soil infiltration rates, hydraulic roughness, inflow discharge and duration, field length and slope, land shape, and surface micro-topography, as well as irrigation scheduling and control of salinity [17,22–29]. In addition, design must consider the negative impacts of irrigation, such as operational water losses by deep percolation and runoff out of the fields, water erosion due to surface flow, or relative to the control of fertilizer and chemical pollution and/or to control health impacts of irrigation with treated wastewater [29].

Decision support systems (DSS) aimed at the design of surface irrigation [30–32] may be the most adequate design tools because they may integrate data, models, and other calculation tools that focus on the various factors and impacts referred to above and, therefore, can be utilised for the easy creation of design alternatives. In addition, DSS integrate computational facilities that rank the considered design solutions, thus supporting design decision making. Ranking may be performed with multi-criteria analysis (MCA) [33], which identifies the compatibility among contradictory design criteria such as those relative to water saving and economic viability [34,35].

The application of DSS models for irrigation design easily associates issues relative to the hydraulics of the system with factors determining the irrigation performance and the environmental and economic results [30,36–39]. They are appropriate to be used in Hetao to assess solutions for water saving and economic returns for farmers because related design solutions depend upon numerous factors. However, design solutions cannot be field validated and model generated design alternatives have to be assessed and ranked to support the selection of the "best" solution, i.e., the alternative that better satisfies the design criteria. Thus, models and computational tools used by the DSS to create the design alternatives need to be parameterized using field data and validated models. Considering that good results were previously obtained with the DSS SADREG in surface irrigation design applied to wheat and cotton in Syria and Central Asia [31,34], this DSS model was selected for the current application to wheat in the Dengkou area of Hetao.

The objective of the present study was to assess and rank several design alternatives developed for basin irrigation applied to wheat in the experimental area of Dengkou, in the south-eastern part of Hetao. With this objective, the DSS model SADREG was used to create and rank various design alternatives. Ranking was performed with MCA considering two groups of design criteria, one relative to water saving and the other to economic returns. To appropriately parameterize SADREG, previous studies were developed during three years in the Dengkou area, one relative to basin irrigation [13], and the other to crop irrigation management [14], which provided field data for validating the simulation tools integrated in SADREG. Further objectives refer to preparing for extending the use of the DSS model for surface irrigation design to other areas of Hetao as a base for implementing irrigation water saving and modernization at the farm level.

2. Materials and Methods

2.1. The Study Area

The Hetao irrigation district is located in the upper reaches of the Yellow River and is one of the three largest irrigation districts of China, with 570,000 ha of irrigated land, and is 250 km long and 50 km wide (Figure 1). Hetao has an arid continental monsoon climate, with an average annual rainfall of 200 mm. According to the Köppen classification [40], the climate is BWk, with hot and dry summers and long, dry, and severely cold winters, which extend from November to March. Agriculture is only feasible during the spring-summer crop season and when irrigated.

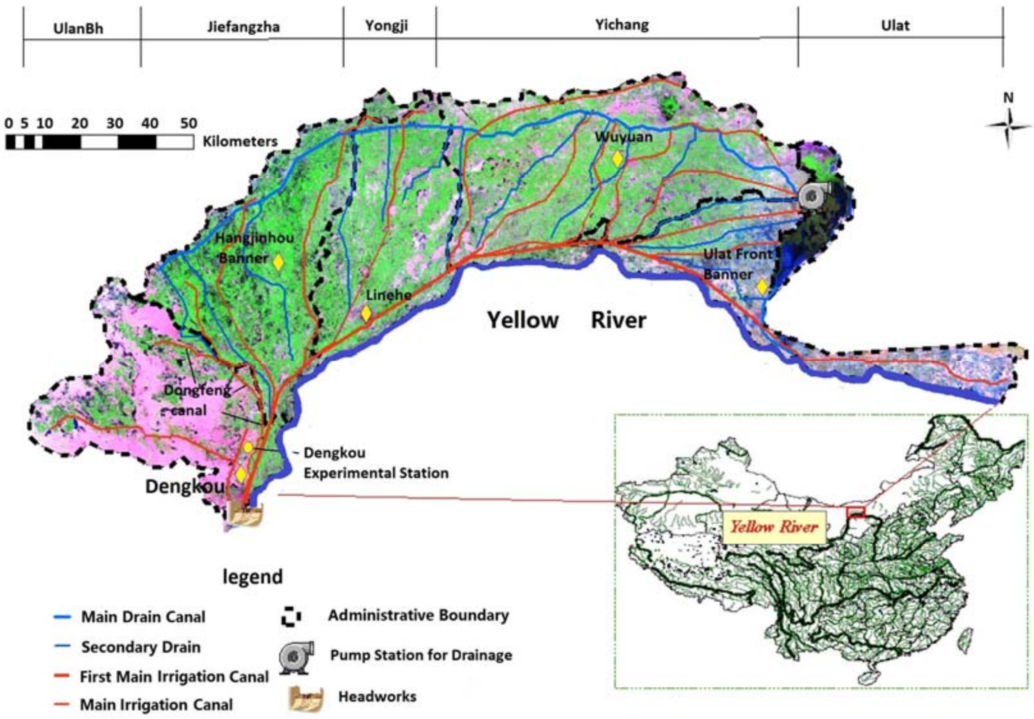

Figure 1. Map of the Hetao Irrigation District with representation of: (**a**) main irrigation drainage canals, (**b**) cropped areas, in green; (**c**) location of the Dengkou experimental area (Wu et al. [18]).

Water diverted from the Yellow River for irrigation totals about 5.2 billion m^3 $year^{-1}$ [41,42]. To address water scarcity and the demand of non-irrigation water user' sectors, the Yellow River Water Conservancy Commission decided that diversions for irrigation in Hetao should be reduced to nearly 4.0 billion m^3 $year^{-1}$. However, a heavy reduction of water available for agriculture may have very important social impacts and a more flexible water allocation policy is advocated [43], limiting restrictions to irrigation water use to 10% in dry years. In addition, there are limitations in using groundwater due to salinity [18,44] and the presence of arsenic [45]. Only a small area is irrigated with groundwater and uses drip irrigation. Xu et al. [9,20] provided descriptions of the Hetao surface and groundwater systems and respective interactions as influenced by irrigation. Recent analysis of water use in Hetao includes a study on the water footprint of crop production [46] and an assessment of crop evapotranspiration dynamics [47].

The conveyance and distribution system of Hetao consists of seven levels of irrigation canals. The first main canal is gravity-fed from the Yellow River, with head-works located nearby Dengkou city and along the river (Figure 1). This first main canal supplies the main canals that flow South to North. Secondary drains also flow in the same direction into a main drain that flows West to East into a great lake. There are 61 areas served by the main and sub-main irrigation canals, named divisions, averaging ca. 9300 ha each. Branch and lower order canals of each division are managed by Water Users Associations (WUA), namely to deliver water to farms and to clean canals from deposited sediments carried by the irrigation water. Main and sub-main canals and drains, as well as the head-works and the drainage pumping station, are managed by the Hetao Administration, which is in charge of water allocation policies, water measurements, water fees, and the modernization of hydraulic structures.

An experimental area has been installed in Dengkou, in the upstream part of Hetao and where irrigation water is supplied by the Dongfeng canal (Figure 1). It is a main canal, 63 km long, designed for a discharge of 25 $m^3\ s^{-1}$, and that supplies a division comprising 480 irrigation sectors and a total irrigated area of 16,300 ha. The branch and distributor canals that deliver water to the farms are currently being upgraded. A rotation delivery scheme is applied by the WUA, with fields supplied with a nearly constant discharge during each irrigation event. The application time is defined by the WUA depending upon the farmer's demand and the available water. The experimental area of Dengkou consists of a sector with 33.4 ha, with 394 land parcels and 210 farmers. The most common crops are maize, wheat, and sunflower, sometimes intercropped [14]. Experimentation is performed in the farmers' fields and respective irrigation management is agreed with the WUA.

2.2. Weather and Soils Data

Daily weather data, including precipitation, maximum and minimum air temperature (°C), maximum and minimum relative humidity (%), wind speed ($m\ s^{-1}$), and sunshine duration (h) were recorded in an automatic weather station (40°13′ N, 107°05′ E, and 1048 m elevation) located within the experimental area. Precipitation and grass reference evapotranspiration (ET_o) computed with the FAO-PM method [48] are shown in Figure 2, relative to the period of experimentation, 2010–2012. It may be noticed that rainfall is much smaller than ET_o and highly varies with time. Differently, ET_o varies little and its variability relates to the occurrence of rainfall in Summer.

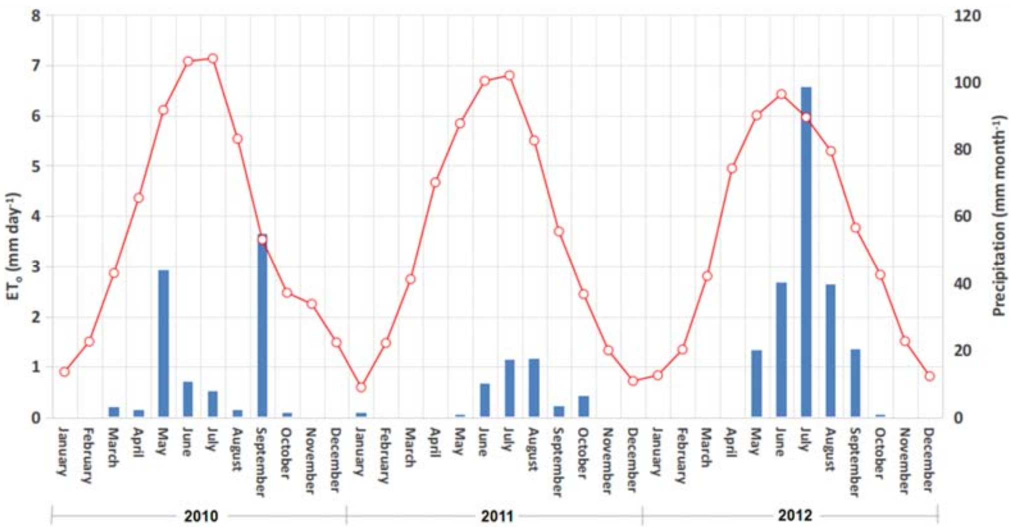

Figure 2. Monthly precipitation (▮) and daily reference evapotranspiration (-○-) observed in the Dengkou experimental area during the three years of experimentation, 2010–2012.

The soil in the experimental area is a siltic irragric Anthrosol [49] originated from sediments deposited by the Yellow River. Main soil textural and hydraulic properties were obtained from sampling in various locations within the study area. The texture of Dengkou soils is generally silt loamy in the upper layers, until a 0.60 m depth, and silt clay can be found below that depth. Soil textural and hydraulic properties were measured in a laboratory: texture was determined using a dry particle size analyser (HELOS RODOS, Sympatec, Clausthal-Zellerfeld, Germany); and the soil water retention curve was measured using a pressure plate extractor (model 1500F1, Soil Moisture Equipment Corp., Santa Barbara, CA, USA). Main soil physical characteristics are shown in Table 1. The total available soil water (TAW) ranges from 200 to 260 mm m^{-1}. Despite salinity occurring in large areas of Hetao, in the Dengkou area, the electrical conductivity of the saturation extract of the soil, EC_e, ranges from 0.11 to 1.58 dSm^{-1}. These values are smaller than the EC_e threshold relative to the referred main crops [48]. Moreover, such low salinity levels do not affect infiltration.

Table 1. Main soil textural and hydraulic properties of the soil in Dengkou (from [14]).

Depth (m)	Particle Size Distribution (%)			Soil Water Content (cm^3 cm^{-3})		
	Clay	Silt	Sand	At Saturation	At Field Capacity	At Wilting Point
0–0.20	23.0	76.7	0.3	0.47 ± 0.01	0.36 ± 0.01	0.16 ± 0.01
0.20–0.40	12.1	81.6	6.3	0.48 ± 0.01	0.37 ± 0.01	0.16 ± 0.01
0.40–0.60	14.6	84.2	1.2	0.49 ± 0.01	0.37 ± 0.01	0.16 ± 0.01
0.60–0.80	35.1	64.9	0.0	0.50 ± 0.02	0.39 ± 0.02	0.17 ± 0.02
0.80–1.00	42.5	57.5	0.0	0.52 ± 0.02	0.41 ± 0.02	0.18 ± 0.02

Following previous studies [13], infiltration is described by the Kostiakov equation [50]:

$$Z = K \cdot \tau^a \tag{1}$$

where Z is the cumulative infiltration depth (m), τ is the infiltration time (min), and K (m min^{-a}) and a (dimensionless) are empirically adjusted parameters. Because the duration of the water application in basin irrigation is small, the intake rate derived from Equation (1) does not significantly under-estimate infiltration at the end of irrigation [50]; thus, a third parameter representing the basic infiltration rate was not considered.

A large number of field measurements of irrigation events in Dengkou determined six standard infiltration curves [13]. Field basin infiltrometer tests [28] were performed, which provided a first estimation of the parameters K and a (Equation (1)). Later, these parameters were optimized using field advance and recession observations through the application of the inverse method [51,52] with the model SIRMOD [53]. This is a mechanistic surface irrigation simulation model aimed at the numerical solution of the Saint-Venant Equations for the conservation of mass and momentum [28].

Results of the infiltration tests performed have shown that the cumulative infiltration in silty soils increases with the precision of the adopted land levelling. Tests have also shown that infiltration rates decreased from the first to the following irrigation events, particularly for the precision levelled basins [13]. This behaviour was also observed in the nearby Huinong area [11] and by Bai et al. [26] in the North China Plain. It is likely due to the deposition of detached soil particles by the flowing water, which reduces infiltration due to the clogging of surface soil pores.

Six standard infiltration curves (SC-I to SC-VI) were obtained for the Dengkou silty soils from field observations [13]. For operational purposes, following the approach by Walker et al. [50], infiltration curves were clustered into three infiltration families (Figure 3) characterized by:

(i) High infiltration rates, when the first irrigation event is described by the observed curve SC-I, the second event to the curve SC-II, and the third and following events to the SC-III curve;
(ii) Medium infiltration rates, with the first event described by the curve SC-III, the second event by the curve SC-IV, and the third and following events by the curve SC-V; and
(iii) Low infiltration rates, where the first irrigation event is described by the curve SC-IV, the second event by the curve SC-V, and the third and later events by the curve SC-VI.

The K and a parameters relative to the infiltration curves are given in Figure 3. The distribution of high, medium, and low infiltration soils in the study area corresponds to 7–9%, 70–72%, and 20–22%, respectively. Further information on the methodologies applied is provided in Miao et al. [13,14].

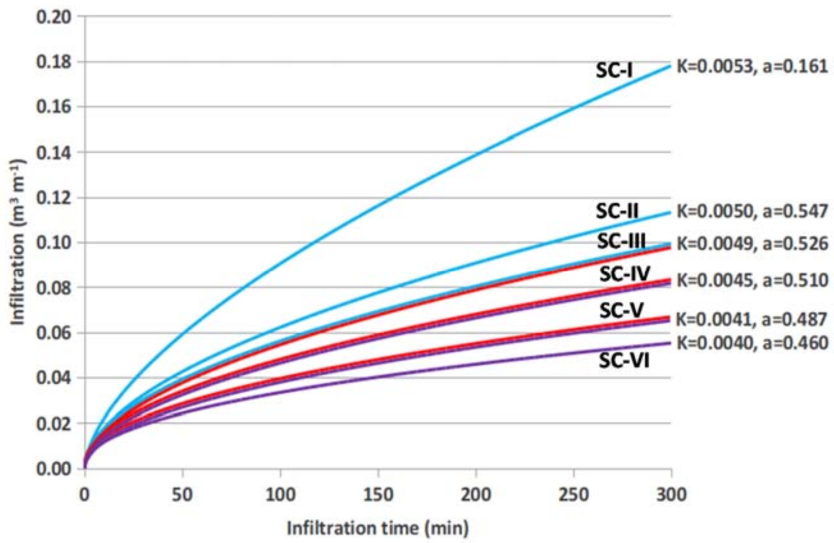

Figure 3. Cumulative infiltration curves SC-I to SC-VI characterizing the infiltration families relative to high, medium, and low infiltration rates represented with blue, red, and violet lines, respectively.

2.3. Irrigation and Yield Data

A survey on basin irrigation has been performed in the Dengkou experimental area [13] and the results have been used in the current design study. The typical sizes of field parcels and respective inflow discharges are summarized in Table 2. Irrigation basins commonly have a length of 50 m and widths ranging from 7 to 50 m. The wider fields often have more than one inlet. The field topography is flat but micro-topography is uneven.

Table 2. Field sizes and inflow discharges observed in Dengkou.

Field Sizes Length × Width (m)	Field Area (ha)	Inflow Discharge (Ls^{-1})	Field Sizes Occurrence in the Area (%)
50 × 10	0.05	10 ± 2	10
50 × 30	0.15	15 ± 3	30
65 × 20	0.30	20 ± 4	20
65 × 40	0.60	25 ± 5	10
100 × 25	0.25	15 ± 3	10
100 × 50	0.50	25 ± 5	20

A land levelling survey was also performed in several field parcels [13] with traditional and precise land levelling using the methodology described by Dedrick et al. [54]. The traditional land levelling (TL) consists of land smoothing using rudimentary equipment and practices and is performed by farmers without the support of topography surveys, hence resulting in a poor micro-topography and an uneven land surface. Differently, precise land levelling (PL) is performed with modern laser controlled levelling equipment, which provides a very regular soil surface with the target slopes. Precise land levelling is already well known in North China, including relative to its impacts on irrigation performance [25,26,55]. The latter were studied in Dengkou [13]. This study recognized the effects of inflow discharge control and irrigation scheduling on performance when aiming at water saving and higher crop yields.

The survey collected field data provided for calculating cut and fill volumes, and operation time and costs. Basin slopes were selected using terrain elevation data obtained by performing a field topography survey. It resulted in the following target slopes: zero cross slope for all cases, zero longitudinal slope (S_o) for level basins (LB), and S_o of 0.5‰ and 1.0‰ for graded basins (GB). The land levelling survey determined the following economic and technical parameters to be used in basin irrigation design:

(i) Operation time for maintenance: 3–4 and 4–5 h ha^{-1} for TL and PL basins, respectively, depending upon the distances between cut and fill sites, the power of the levelling equipment, the experience of the operator, and the soil conditions;
(ii) Hourly operation costs: 80 to 120 Yuan h^{-1} for TL basins and 200 to 240 Yuan h^{-1} for PL basins, with prices depending upon the equipment power and size;
(iii) Quality of land forming as expressed by the root mean of squared deviations between observed and target land elevations: 6 to 10 cm for TL basins and less than 4 cm for PL;
(iv) Frequency of land levelling maintenance: annual for both TL and PL basins.

According to observations [56], the spring wheat yield of 6000 kg ha^{-1} can be assumed for non-stressed conditions, i.e., full irrigation in a low salinity soil. The previous field and simulation study on the wheat crop irrigation scheduling [14] was used herein. The improved full irrigation scheduling implies a seasonal net irrigation depth of 300 mm with three irrigation events of 100 mm each. The irrigation practice includes, in addition to summer irrigation, out of season autumn irrigation, which is performed after the crop season and applies a high irrigation depth, usually close to 250 mm or larger, particularly when the soil salinity is high. The main objectives of autumn irrigation consist of: (a) controlling soil salinity through leaching the salts out of the root zone; (b) to improve soil structure, porosity, and permeability, due to the effect of successive soil water freezing and melting during winter; and (c) to store water in the soil to be available for cropping in early spring. Related processes are well known [57–59]. Following Li et al. [59,60], an irrigation depth of 230 mm was assumed adequate to leach the salts out of the root zone. Crop season and autumn irrigation data are summarized in Table 3.

Table 3. Water use components relative to current and improved wheat irrigation schedules (from [16]).

Irrigation Schedules	**Number Irrigation Events**	**Net Target Irrigation Depth (mm)**	**Season Net Irrigation (mm)**	**Autumn Irrigation (mm)**	**Effective Rainfall (mm)**	**$ET_{c\ act}$ (mm)**	**$T_{c\ act}$ (mm)**	**Yield (kg ha^{-1})**
Present	3	95	285	250	60	629	568	5880
Improved	3	100	300	230	60	644	574	6000

Notes: $ET_{c\ act}$—actual crop evapotranspiration; $T_{c\ act}$—actual crop transpiration.

To estimate the yield impacts of the various irrigation alternatives, the yield response curve proposed by Solomon [61] was adopted:

$$Y_a/Y_{max} = f(W_a/W_{max}) \tag{2}$$

where Y_a and Y_{max} are the actual and the maximum yield (kg ha^{-1}), respectively; W_a is the actual net irrigation water applied (mm); and W_{max} is the net water required to achieve Y_{max}. The respective parameterization is performed with the data in Table 4, which applies to Dengkou soils with low salinity and is based upon regionally observed data [56,62].

Table 4. Parameters used in the water-yield function.

W_a/W_{max}	0.5	0.75	1.0	1.5	2.0
Y_a/Y_{max}	0.40	0.70	1.0	0.95	0.90

2.4. Irrigation Performance

The irrigation performance indicators used consist of the distribution uniformity (DU, %) and the beneficial water use fraction (BWUF, %) [63]. DU is defined as:

$$DU = \frac{Z_{lq}}{Z_{avg}} \times 100 \quad (3)$$

where Z_{lq} is the average low quarter depth of water infiltrated (mm) and Z_{avg} is the average depth of water infiltrated in the whole irrigated field (mm). Two equations are used for BWUF to distinguish the cases of over-irrigation ($Z_{lq} > Z_{req}$) and under-irrigation ($Z_{lq} < Z_{req}$):

$$BWUF = \begin{cases} \frac{Z_{req}}{D} \times 100 & Z_{lq} > Z_{req} \\ \frac{Z_{lq}}{D} \times 100 & Z_{lq} < Z_{req} \end{cases} \quad (4)$$

where Z_{req} is the average depth (mm) required to refill the root zone in the quarter of the field having a higher soil water deficit, and D is the average water depth (mm) applied to the field. Z_{req} is estimated from measurements or using a soil water balance model. Z_{lq} and Z_{avg} are estimated from computing the depth of water infiltrated during the irrigation process with SIRMOD [53]. D is given by the product of the cut-off time (t_{co}) and the average inflow rate (Q_{in}).

The previous field basin irrigation evaluations [13] estimated DU and BWUF for both TL and PL basins. The results in Table 5 clearly show that traditional irrigation is not able to achieve water saving and salinity control since DU and BWUF indicators are far behind the potential values. Contrarily, precise levelling provides a high DU in modernized basins. However, BWUF values show a large gap between observed and potential values when irrigations follow traditional scheduling. High BWUF values are only attainable when adopting well-adjusted t_{co} and Q_{in}. Alternative values for t_{co} and Q_{in} were therefore used in model design simulations.

Table 5. DU and BWUF obtained from observations in traditional and precise levelled basins for various irrigation events and their potential values (from Miao et al. [13]).

Irrigation Event	DU (%)			BWUF (%)		
	Traditional	Improved Observed	Improved Potential	Traditional	Improved Observed	Improved Potential
1st	60	92	94	58	69	92
2nd	67	90	90	54	53	86
3rd	64	91	91	59	74	89

2.5. The DSS Model SADREG and Multi-Criteria Analysis

SADREG is a decision support system developed to assist the process of designing and planning improvements in farm surface irrigation systems as described by Gonçalves and Pereira [30]. Applications include those by Gonçalves et al. [31] to Fergana, Central Asia, and by Darouich et al. [34,64] to eastern Syria. The design component applies database information and produces a set of alternatives in agreement with the user options and field conditions. The hydraulic simulations are performed with the simulation model SIRMOD [53], which is incorporated in SADREG. The procedure for creating the required design alternatives and for their evaluation and ranking, follows various steps:

(i) Creating the "workspace" with main field data relative to soil water retention and soil infiltration rate characteristics, Manning's roughness coefficient, field length and width, longitudinal and cross slopes of the field, and land surface unevenness conditions;

(ii) Creating a "project" for selected combinations of workspace data, which characterizes the irrigation method, land levelling, crop data, field water supply, economic data, and number of units and outlets;
(iii) Grouping various projects to constitute a set of alternatives having different in-farm distribution systems and inflow rates Q_{in};
(iv) Application of associated model tools for land levelling design and for computing irrigation requirements, Z_{req} (mm);
(v) Performing the design simulation applying the SIRMOD model to every alternative, thus computing advance, wetting, and recession times, and infiltration depths, namely the average and the low quarter depths, Z_{avg} and Z_{lq} (mm), respectively;
(vi) Calculation of performance indicators for every alternative using the respective design data;
(vii) Application of multi-criteria analysis for ranking the alternatives according to the defined design criteria and user's priorities, based on the respective performance attributes.

The economic and labour input data reported for 2010 are presented in Table 6. At present, the farmer's irrigation fees in Hetao are not computed in terms of water use but just depend on the irrigated area. Fees vary from 600 to 800 Yuan ha^{-1} and cover WUA operation and maintenance (O&M) costs. The water price established by the Yellow River Commission for the water derived at the sector level ranges from 0.04 to 0.06 Yuan m^{-3}. In the current study, an irrigation cost averaging 700 Yuan ha^{-1} is considered, which is partitioned into a fixed cost of 420 Yuan ha^{-1} for O&M, and a variable cost for the gross water use was assumed with a water price of 0.05 Yuan m^{-3}.

Table 6. Economic and labour input data for wheat basin irrigation.

Type	Description	Value	Units
Distribution equipment	Non-lined canal cost (with field gate)	7 ± 1	Yuan m^{-1}
Irrigation water	Volumetric water cost	0.05 ± 0.01	Yuan m^{-3}
	Fixed cost per unit area	700 ± 100	Yuan ha^{-1}
Spring wheat crop	Yield price	3.0 ± 0.5	Yuan kg^{-1}
	Maximum yield	6000	kg ha^{-1}
	Production cost (excluding irrigation costs)	7.25 ± 0.2	10^3 Yuan ha^{-1}
Labour	Labour cost	11 ± 3	Yuan h^{-1}
Life-time	Building a non-lined distribution canal	1	year
Labour requirements	Operation of the non-lined canal	$t = t_{co}$	min
	Installing the non-lined canal	40	min 100 m^{-1}

The Manning's hydraulic roughness coefficient n = 0.20 $m^{-1/3}$ s was used for hydraulic simulations of basin irrigation when fields were cropped with wheat. That n value was obtained from a former field study in the same area [65]. Other studies [11,25,66] support the assumption that the parameter n essentially depends upon tillage and plants density, but not upon the land slope or land levelling precision. Pereira et al. [11] reported that n values slightly increase from the first to the last irrigation due to crop development. However, because impacts of n values on simulated basin irrigation performances are reported to be small [25,67], the constant value n = 0.20 $m^{-1/3}$ s was assumed in the current study.

The irrigation methods considered are the flat level basin (LB) and the flat graded basin (GB). Precise land levelling (PL) with a null cross slope was considered with three options for the longitudinal slope (S_o): zero level, 0.5‰, and 1.0‰.

The inflow rates (Q_{in}, L s^{-1} m^{-1} width) were defined in relation to the land parcel sizes (Table 7), i.e., the combination length-width, with a larger Q_{in} for longer basins.

Table 7. Basin sizes and related unit inflow rates for modernized design alternatives.

Inflow Rate Identifier	Length 50 m		Length 100 m		Length 200 m	
	Width (m)	Inflow Rate (L s^{-1} m^{-1})	Width (m)	Inflow Rate (L s^{-1} m^{-1})	Width (m)	Inflow Rate (L s^{-1} m^{-1})
(S)mall	30	0.5	30	1.0	30	2.0
(M)edium	15	1.0	15	2.0	15	3.0
(L)arge	7.5	2.0	7.5	3.0	7.5	4.0

The modernization scenarios are represented by projects and groups of alternatives as indicated in Figure 4. Projects refer to precision levelling (PL) and level basins (LB) and graded basins (GB) with S_o values of 0.5‰ and 1.0‰ slope. Groups refer to basin lengths, and alternatives are discriminated according to inflow rates S, M, and L, defined in Table 7 in combination with basin widths.

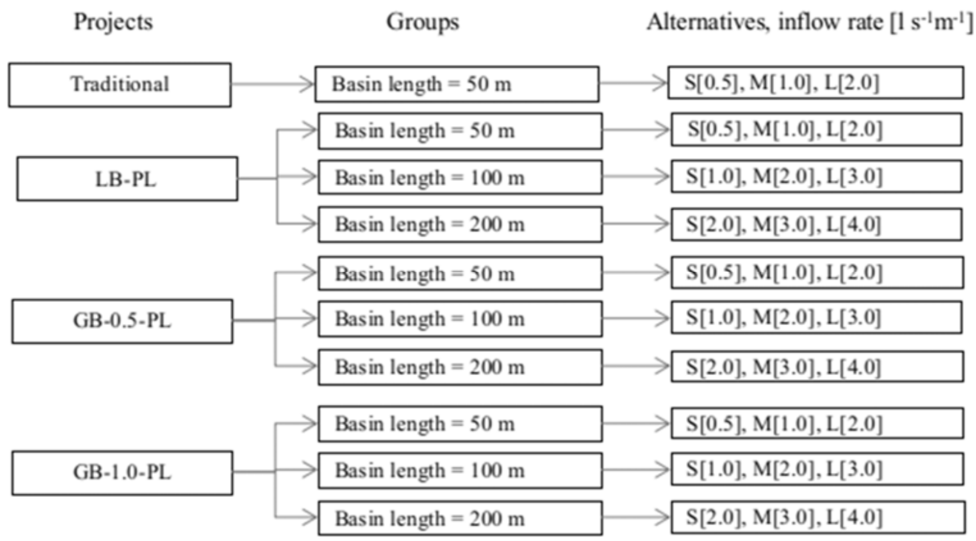

Figure 4. Structure of setting alternatives: projects (traditional, level basin LB and graded basins GB with slopes of 0.5‰ and 1.0‰), grouped for field lengths of 50, 100, and 200 m, and alternatives having different inflow rates and field widths.

The evaluation and selection of the design alternatives is the last task in the design decision making process. That selection is a multiple objective problem, for which a rational solution often requires multi-criteria analysis (MCA) to integrate different types of design attributes in a trade-off process, thus comparing adversative objectives or criteria [68,69]. In irrigation, adversative objectives generally refer to environmental, water saving, and economic criteria.

Linear utility functions were used for each criterion j:

$$U_j = \alpha_j x_j + \beta_j \tag{5}$$

which are normalized in the [0,1] interval, with zero for the most adverse and 1 for the most advantageous result. The slope parameter α is negative for criteria whose highest values are the worse, e.g., costs and water use, and is positive for criteria whose higher values are the best, e.g., water productivity. For each alternative, the linear weighted summation method [70,71] calculated the global utility that represents the integrated score performance of the considered alternative:

$$U_{glob} = \sum_{j=1}^{Nc} \lambda_j U_j \tag{6}$$

where U_{glob} is the global utility, scaled in the [0,1] interval; N_c is the number of criteria (N_c = 7 in this application); λ_j is the weight assigned to criterion j; and U_j is the utility relative to criterion j (Equation (5)). The decision criteria attributes, the respective weights, and the parameters of their linear utility functions (Equation (5)) are presented in Table 8. Overlapping or redundancy of criteria was checked and avoided.

Table 8. Criteria attributes, utility functions, and weights.

Decision Criteria Attributes	Symbol	Units	Weights (λ_j)	Utility Parameters (Equation (5))	
				α	β
Economic Productivity and Costs					
Economic land productivity	ELP	Yuan ha^{-1}	0.20	1.25×10^{-4}	−1.25
Fixed irrigation costs	FIC	Yuan ha^{-1}	0.10	-2.50×10^{-4}	1
Variable irrigation costs	VIC	Yuan ha^{-1}	0.10	-2.50×10^{-4}	1
Economic water productivity ratio	EWPR	ratio	0.10	0.25	1
Water Saving and Environment					
Total irrigation water use	IWU	m^3 ha^{-1}	0.20	-3.17×10^{-4}	1.95
Beneficial water use fraction	BWUF		0.15	1.818	−0.727
Irrigation water productivity	IWP	kg m^{-3}	0.15	-3.17×10^{-4}	1.95

The attributes relative to economic criteria are:

(i) Economic land productivity (ELP, €·ha^{-1}), the monetary yield value per unit of land;
(ii) Fixed irrigation costs (FIC, €·ha^{-1}), corresponding to investment costs per unit of land;
(iii) Variable irrigation costs (VIC, €·ha^{-1}), corresponding to the operation and maintenance costs per unit of land; and
(iv) Economic water productivity ratio (EWPR, dimensionless), defined as the ratio of total yield value to the total irrigation costs [63].

The attributes relative to water saving criteria consist of:

(i) Total irrigation water use (IWU, mm), corresponding to the seasonal gross irrigation depth (or irrigation volume, m^3);
(ii) Beneficial water use fraction (BWUF, dimensionless), defined with Equation (4); and
(iii) Irrigation water productivity (IWP, kg m^{-3}), ratio of total yield to IWU (in m^3).

Criteria are grouped into economic and water saving issues (Table 8); thus an economic utility (U_{EC}) and a water saving utility (U_{WS}) were defined:

$$U_{EC} = \sum_{i=1}^{Nc(EC)} \lambda_{ECi} U_{ECi} / \lambda_{EC} \tag{7}$$

$$U_{WS} = \sum_{i=1}^{Nc(WS)} \lambda_{WSi} U_{WSi} / \lambda_{WS} \tag{8}$$

where λ_{EC} and λ_{WS} are the sums of the weights relative to the economic and water saving criteria, respectively, with $\lambda_{EC} + \lambda_{WS}$ = 1.0. The global utility corresponds to the sum of U_{EC} and U_{WS}:

$$U_{glob} = \sum_{j=1}^{Nc} \lambda_j U_j = \lambda_{EC} U_{EC} + \lambda_{WS} U_{WS}. \tag{9}$$

Solving Equation (9) in relation to U_{WS} results in

$$U_{WS} = \frac{U_{glob}}{\lambda_{WS}} - \frac{\lambda_{EC}}{\lambda_{WS}} U_{EC} \tag{10}$$

that allows a Cartesian representation of U_{glob} in the U_{EC}-U_{WS} Plane, and where the U_{glob} isolines are straight lines with slopes depending upon the values of λ_{EC} and λ_{WS}. That representation provides a better understanding of the impacts of water saving and economic results on the global utility.

To provide a sensitivity analysis of changes in the decision making priorities, several combinations of weights were used, starting when 20% of weights were assigned to farm economic results and 80% to water saving, and after considering pairs λ_{EC}-λ_{WS} of 40%-60%, 60%-40%, and 80%-20%. The weights λ_j used for the criteria attributes were consequently modified proportionally to those in Table 8, representing a balance between economic and water saving criteria (50% for each group).

3. Results and Discussion

3.1. Irrigation Water Use and Performance

Beneficial and non-beneficial water use (BWU and NBWU, $m^3\ ha^{-1}$) are compared in Figure 5 for 27 design alternatives. A smaller NBWU is achieved in level basin projects with a length of up to 200 m and for GB with 0.5‰ slopes when the length does not exceed 100 m. Naturally, a smaller NBWU corresponds to projects whose BWUF is higher and water productivity IWP is also higher (Table 9).

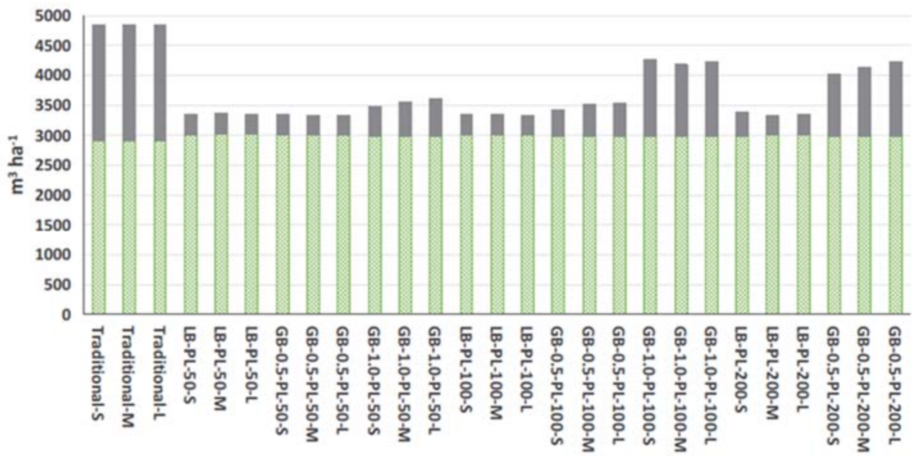

Figure 5. Beneficial and non-beneficial water use (BWU and NBWU , $m^3\ ha^{-1}$) relative to summer irrigation in a medium infiltration soil and considering level basins (LB) and graded basins (GB) with slopes of 1.0‰ and 0.5‰, with precise land levelling (PL); lengths of 50, 100, and 200 m; and inflow rates S, M, and L (defined in Table 7).

Main irrigation performance indicators relative to design alternatives for medium infiltration soils, the third irrigation event, and adopting an improved irrigation schedule, are presented in Table 9. These results indicate that:

(i) Modernization projects may achieve a BWUF of up to 90% when deep percolation (DP) is well controlled, thus when basin irrigation is highly improved relative to traditional systems, which have an average BWUF of 60% and DP of 40%.
(ii) Graded basin alternatives with a 200 m length and 1.0‰ slope are non-satisfactory (BWUF < 60% and DP > 40%), and hence were not considered further in the selection analysis.
(iii) The relationship between inflow rates (Q_{in}) and DU have been shown to be very weak, thus indicating that the magnitude of Q_{in} has small impacts on DU. However, as formerly observed for medium and low infiltration silty soils in China, inflow rates $Q_{in} \geq 2\ L\ s^{-1}\ m^{-1}$ are required [11,26,27]. This result also indicates that a high irrigation performance may be obtained with a flexible, varied inflow discharge. Differently, the cut-off time plays a crucial role in adjusting the applied depth to its target to avoid over-irrigation.

(iv) It was observed that S_o only slightly influences DU and that S_o = 0‰ (level basins) generally leads to a higher DU and BWUF. Poor results for long graded borders (L = 200 m) are likely due to the fact that S_o > 0‰ simultaneously favours advance and a long recession time resulting in high infiltration downstream, thus in a high DP and low DU.

(v) Irrigation water productivity is high (>1.8 kg m^{-3}) for LB and GB with S_o = 0.5‰ with a 50 m length, and for LB with a 100 m or 200 m length.

(vi) Relationships of field length (L) with DU are also quite weak, which may indicate that long basins are feasible but their performance depends on the combination S_o-Q_{in}.

Table 9. Irrigation performance and management indicators for various basin lengths, longitudinal slopes, and unit inflow rates in the case of medium infiltration soils.

Length (m)	Slope (‰)	Inflow Rate (1)	Project Alternatives	BWUF (%)	DU (%)	D (mm)	DP (mm)	t_{adv} (min)	t_{co} (min)	IWP (2) (kg m^{-3})
50	uneven	Small	Traditional-S	60.3	61.1	157	62	88	268	1.12
		Medium	Traditional-M	60.3	63.4	157	62	68	134	1.12
		Large	Traditional-L	60.2	67.0	157	62	48	67	1.12
	0	Small	LB-PL-50-S	90.1	90.0	111	11	96	186	1.80
		Medium	LB-PL-50-M	90.1	91.5	111	11	52	93	1.79
		Large	LB-PL-50-L	90.0	93.1	111	11	31	47	1.79
	0.5	Small	GB-0.5-PL-50-S	90.1	93.4	111	11	88	185	1.80
		Medium	GB-0.5-PL-50-M	90.0	92.7	111	11	48	93	1.80
		Large	GB-0.5-PL-50-L	89.9	92.5	111	11	29	46	1.80
	1.0	Small	GB-1.0-PL-50-S	84.4	85.8	118	18	83	197	1.72
		Medium	GB-1.0-PL-50-M	83.6	85.6	119	20	45	100	1.69
		Large	GB-1.0-PL-50-L	83.1	85.3	120	20	28	50	1.66
100	0	Small	LB-PL-100-S	90.1	93.3	111	11	136	186	1.79
		Medium	LB-PL-100-M	90.0	92.9	111	11	77	93	1.79
		Large	LB-PL-100-L	90.1	92.7	111	11	60	62	1.94
	0.5	Small	GB-0.5-PL-100-S	85.1	87.0	117	17	121	195	1.75
		Medium	GB-0.5-PL-100-M	83.9	86.1	119	19	71	99	1.70
		Large	GB-0.5-PL-100-L	84.0	85.5	119	19	54	66	1.69
	1.0	Small	GB-1.0-PL-100-S	65.1	70.5	153	53	111	255	1.35
		Medium	GB-1.0-PL-100-M	70.7	75.1	141	41	66	118	1.39
		Large	GB-1.0-PL-100-L	70.1	75.1	142	43	50	79	1.37
200	0	Small	LB-PL-200-S	90.1	93.0	111	11	198	186	1.77
		Medium	LB-PL-200-M	90.1	93.0	111	11	198	124	1.80
		Large	LB-PL-200-L	90.0	93.9	111	11	118	93	1.80
	0.5	Small	GB-0.05-PL-200-S	72.3	76.4	138	38	171	230	1.47
		Medium	GB-0.05-PL-200-M	71.7	75.8	139	39	128	154	1.42
		Large	GB0.05-PL-200-L	70.7	75.6	141	41	105	118	1.38
	1.0	Small	GB-0.10-PL-200-S	58.3	58.3	171	72	156	285	1.15
		Medium	GB-0.10-PL-200-M	46.5	55.3	214	115	117	238	0.77
		Large	GB-0.10-PL-200-L	51.1	59.7	195	95	97	163	0.83

Notes: BWUF—beneficial water use fraction; DU—distribution uniformity, gross irrigation depths; DP—deep percolation; t_{adv}—advance time; t_{co}—cut-off time; IWP—irrigation water productivity; LB and GB—level and graded basins; PL—precision land levelling; (1) inflow rates defined in Table 7; (2) IWP computed for irrigation water use during the crop season.

To assess the effects of soil infiltration on the irrigation performance, particularly on irrigation water use (IWU), the results relative to several alternatives applied to soils with high, medium, and low infiltration (Figure 3) are compared in Table 10. In general, IWU values for low and medium infiltration soils are similar, with differences not exceeding 8%. Differently, the IWU values of high infiltration soils are different of those for medium infiltration soils, particularly for basin lengths larger than 100 m. No feasible solutions were found for long basins in high infiltration soils due to excessive infiltration and very high percolation.

Table 10. Gross irrigation water use (IWU, m^3 ha^{-1}) during the crop season for several projects with medium inflow rates as influenced by soil infiltration—high, medium, and low (defined in Figure 3).

Projects	IWU (m^3 ha^{-1}) for Various Infiltration Rate Families		
	High	Medium	Low
LB-PL-50-M	3430	3360	3360
GB-0.5-PL-50-M	3410	3340	3330
GB-1.0-PL-50-M	3440	3550	3580
LB-PL-100-M	3530	3350	3350
GB-0.5-PL-100-M	3700	3520	3560
GB-1.0-PL-100-M	4010	4180	4160
LB-PL-200-M	4560	3330	3340
GB-0.5-PL-200-M	4670	4130	4160

Water saving, defined as the difference between the IWU of traditional irrigation (7350 m^3 ha^{-1}) and IWU relative to the retained alternatives, was estimated for the various design alternatives (Figure 6). IWU includes both the summer season and the autumn irrigation. The results in Figure 6 show that projects LB and GB with S_o = 0.5‰ provide annual water savings ranging from 1520 to 1740 m^3 ha^{-1}, i.e., 21% to 24% of IWU. LB perform slightly better than GB when the same basin length and inflow rate are considered. Water saving benefits of improved basin irrigation were reported in several studies carried out in China [7,11,13,27], Egypt [72], Portugal [30], Spain [73], and USA [74], supporting the assumption that water use decreases when the irrigation performance is improved.

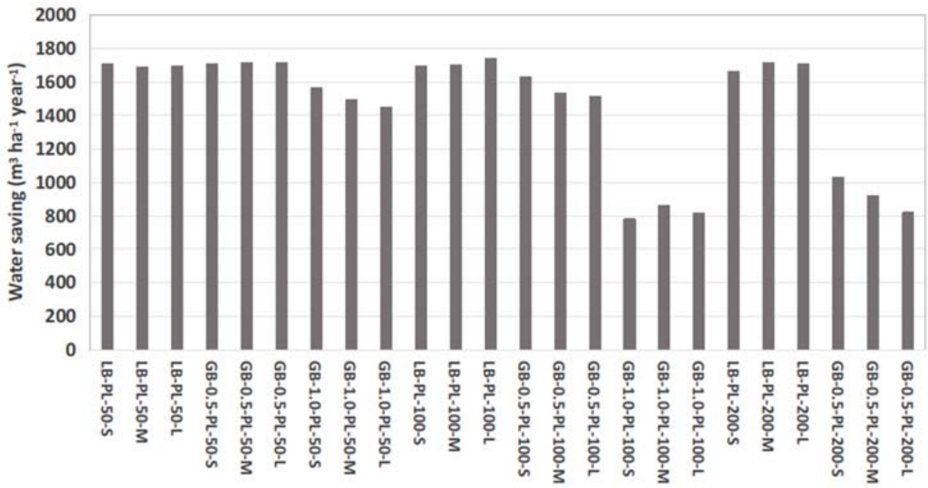

Figure 6. Water saving achievable by various design alternatives for level basins (LB) and graded basins (GB) with slopes of 1.0‰ and 0.5‰, with precise land levelling (PL); lengths of 50, 100, and 200 m; and inflow rates S, M, and L (as defined in Table 7) for a medium infiltration soil.

3.2. Economic Performance

The economic attributes relative to various design alternatives adopting a medium inflow rate are presented in Table 11. The total irrigation costs (TIC), relative to both the summer season and the autumn irrigation, vary between 2408 and 3292 Yuan ha^{-1}.Precision land levelling costs (1100 Yuan ha^{-1}) consist of the main component of TIC (33–46%). Considering that fixed water costs are 700 Yuan ha^{-1} (21–29% of TIC) and that variable water costs range from 269 to 328 Yuan ha^{-1} , i.e., only 8.8 to 13% of TIC, it can be inferred that the water operative costs are low and cannot play a large enough role as an incentive for water saving. Labour costs in traditional irrigation average 1330 Yuan ha^{-1}, about 45% of TIC, while for modernized systems, the labour costs are smaller, varying from 276 to 997 Yuan ha^{-1} (12–29% of TIC) because basin sizes are improved and processes of irrigation water supply require less manpower, and labour costs are lesser for level basins with a 200 m length. Nevertheless, further tests are required for long basins.

Table 11. Irrigation costs of various design alternatives and their cost components compared with yields, economic land productivity (ELP), and economic water productivity ratio (EWPR) of several projects for a medium infiltration soil and assuming medium inflow rates.

Design Alternatives	Components of the Irrigation Costs (Yuan ha^{-1})					Yield (kg ha^{-1})	ELP (Yuan ha^{-1})	EWPR
	Land Levelling	Supply System	Water	Labour	Total			
Traditional-M	350	200	1067	1335	2952	5447	16,342	5.54
LB-PL-50-M	1100	200	983	932	3215	6000	18,000	5.60
GB-0.5-PL-50-M	1100	200	982	925	3207	6000	18,000	5.61
GB-1.0-PL-50-M	1100	200	993	984	3277	5985	17,956	5.48
LB-PL-100-M	1100	100	982	555	2737	6000	18,000	6.58
GB-0.5-PL-100-M	1100	100	991	583	2774	5989	17,967	6.48
GB-1.0-PL-100-M	1100	100	1024	691	2915	5820	17,461	5.99
LB-PL-200-M	1100	50	982	276	2408	6000	18,000	7.47
GB-0.5-PL-200-M	1100	50	1021	341	2512	5850	17,549	6.99
GB-1.0-PL-200-M	1100	50	1106	479	2734	4494	13,483	4.93

Note: water and labour costs include summer and autumn irrigation.

The economic land productivity (ELP) and the economic water productivity ratio (EWPR) vary, as expected, from one project to another (Table 11). The minimal value for ELP refers to a 200 m long graded basin with S_o = 1.0‰ (GB-1.0-PL-200-M) because its irrigation performance is less good due to high percolation by downstream. The next poor performing alternative is the traditional one, with a low ELP value because yields are also less good. However, since the current ELP value is not much lower than for improved designs, it may be difficult to convince farmers to invest in modernization. Relative to EWPR, the best values (6.48 to 7.47) refer to basins of 100 or 200 m, both LB and GB, whose performance are good, yields are high, and total costs are low. It may be observed that issues relative to water saving (Figure 6) and to economic results (Table 12) are contradictory, so requiring the use of MCA to search for the best alternative designs, namely for other crops and different areas.

To evaluate the effects of increasing the irrigation costs, MCA was applied to rank the various projects under three scenarios of irrigation costs: (a) current costs; (b) the current costs increased by 20%; and (c) the current costs increased by 50%. The ranking of the alternatives was determined by the global utilities, U_{glob}. Results for the first 15 design alternatives for scenario (a) are presented in Table 12. It shows that the ranking based on U_{glob} values is different to the one that could result if considering economic results only, U_{EC}, due to the impact of water saving issues on U_{glob}, which evidences the need for associating U_{EC} and U_{WS} in the analysis. It is important to note that an increase of 20% of the irrigation costs does not produce a change of the ranking; contrarily, an increase of 50% produces a great change in ranking. For the current prices, the first six alternatives refer to level basins with lengths of 200 or 100 m without a great impact of the inflow rates. That ranking results from the fact that long basins have lower costs than the most common basins, with lengths of 50 m, which rank 8 to 14. However, adopting longer basins would lead to great changes in the structure of the irrigated fields when replacing the 50 m lengths with the 100 or 200 m long basins. The graded basins with a small slope (S_o = 0.5‰) rank 7 to 10; longer ones, of 200 m, are not included in the first 15 ranked projects.

Table 12. Impacts of increasing the total irrigation cost on the ranking of design alternatives determined by the global utilities U_{glob} considering an application to medium infiltration soils.

Design Alternatives	Current Total Irrigation Cost			Current Total Irrigation Cost Increased by 20%			Current Total Irrigation Cost Increased by 50%		
	U_{EC}	U_{glob}	Rank	U_{EC}	U_{glob}	Rank	U_{EC}	U_{glob}	Rank
LB-PL-200-M	0.86	0.87	1	0.83	0.85	1	0.64	0.76	9
LB-PL-200-L	0.86	0.87	2	0.83	0.85	2	0.64	0.75	10
LB-PL-200-S	0.86	0.85	3	0.83	0.84	3	0.64	0.76	8
LB-PL-100-L	0.81	0.85	4	0.77	0.83	4	0.72	0.81	5
LB-PL-100-M	0.80	0.84	5	0.76	0.82	5	0.71	0.75	12
LB-PL-100-S	0.80	0.83	6	0.76	0.81	6	0.71	0.75	15
GB-0.5-PL-100-S	0.80	0.82	7	0.76	0.80	7	0.73	0.84	1
GB-0.5-PL-50-L	0.74	0.80	8	0.69	0.78	8	0.79	0.82	4
GB-0.5-PL-50-M	0.74	0.80	9	0.69	0.78	9	0.79	0.83	2
GB-0.5-PL-50-S	0.74	0.80	10	0.69	0.78	10	0.79	0.83	3
LB-PL-50-S	0.74	0.80	11	0.69	0.78	11	0.73	0.63	21
LB-PL-50-L	0.74	0.80	12	0.69	0.78	12	0.75	0.68	19
LB-PL-50-M	0.74	0.80	13	0.69	0.78	13	0.74	0.65	20
GB-0.5-PL-100-M	0.80	0.79	14	0.76	0.77	14	0.72	0.80	6
GB-0.5-PL-100-L	0.80	0.79	15	0.75	0.77	15	0.72	0.79	7

It is interesting to note that level basins consist of the most commonly considered highly performing systems worldwide [17,23,25,29,75] and in China [7,11,13,26,27,56]. This common behaviour justifies why studies referring to graded basins are rare and point to solutions having small slopes [76].

Ranking is greatly modified if irrigation costs increase by 50%. The first six ranked projects are now graded basins with S_o of 0.5‰ and lengths of 50 m and 100 m. Level basins become low ranked and all basins 200 m long also fall in their ranking. The explanation for this is found when looking at the costs and the benefits, namely the economic land productivity (ELP) and the economic water productivity ratio (EWPR). These results indicate that the design approaches used may not be appropriate if large changes in irrigation costs occur, particularly if those increases are not well balanced with the economic benefits.

3.3. Ranking of Design Alternatives

The global utility, the economic utilities relative to the criteria attributes ELP, FIC, VIC, and EWPR, and the water saving utilities referring to the criteria attributes IWU, BWUF, and IWP are compared in Figure 7 for the best alternative of each project when applied to a medium infiltration soil. The results show that U_{glob} values relative to all design alternatives are significantly higher than U_{glob} characterizing the traditional systems. Nevertheless, the U values relative to costs FIC and VIC are similar for traditional and modernization systems, and the same occurs for ELP, particularly for short basin lengths (50 m). Differently, the U values referring to water use and saving, attributes IWU and BWUF, are much smaller than the corresponding U values for the modernization projects. These results evidence that modernization projects respond well to the need for adopting water saving irrigation but, simultaneously, make it clear that economic results are not advantageous enough for farmers to invest in modernization and water saving. These results show the need for economic incentives for farmers if the common attitude of "business as usual" is to be overcome.

Comparing the U_{glob} of the best modernization design alternatives, it can be observed that higher U_{glob} values are seen for level basins with a 100 and 200 m length. These high U_{glob} values result from high ELP and EWPR values and low costs, FIC and VIC, as indicated by the high U scores for these criteria attributes, particularly for the 200 m long basins. High U scores are also observed for criteria attributes IWU, BWUF, and IWP; the highest scores are for the 100 m length basins. The next ranking alternatives are for level and small slope (0.5‰) graded basins with 100 m lengths, whose utilities relative to the referred criteria are quite similar to those previously referred to. LB and GB basins of 50 m rank next because U scores relative to economic criteria are lower than the former. The last ranked alternative is GB with 1.0‰ slope, whose performance is affected by low U scores relative to IWU, BWUF, and IWP, i.e., to water saving.

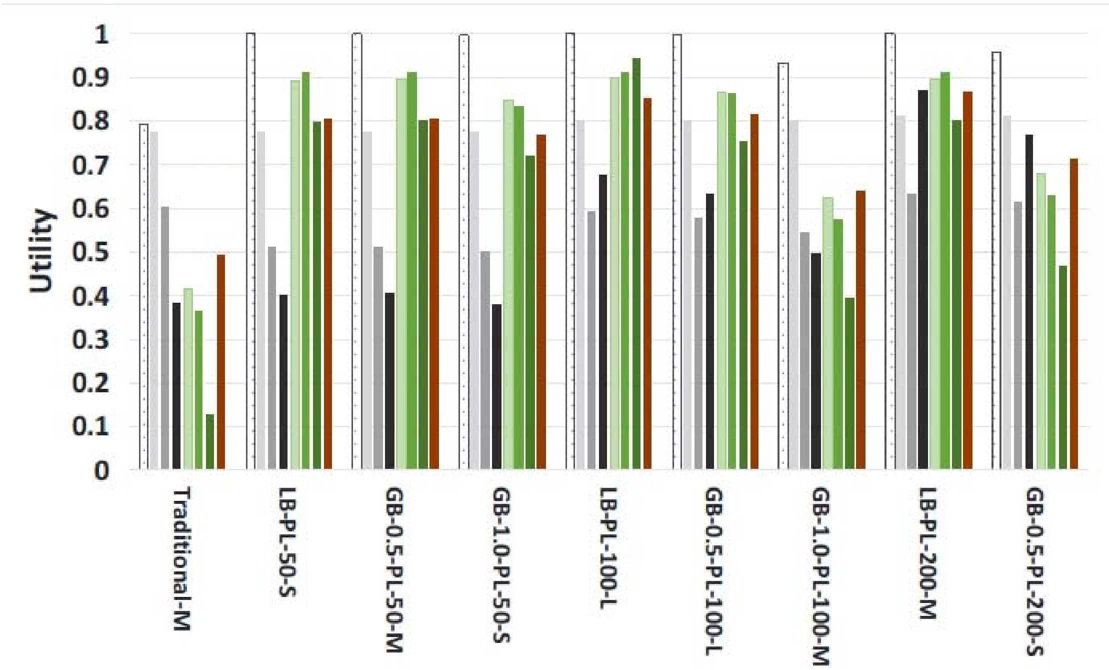

Figure 7. Comparison of the utilities relative to the considered criteria attributes ELP ( ), FIC ( ), VIC ( ), EWPR ( ), IWU ( ), BWUF ( ), IWP ( ), and of the global utilities ( ) for the best project alternatives and the traditional one when applied to a medium infiltration soil.

A graphical evaluation of the best alternatives relative to a medium infiltration soil and adopting a medium inflow rate is presented in Figure 8. Using the representation of U_{glob} in the U_{EC}-U_{WS} Plane (Equation (10)), it is easy to understand through observing the contribution of the economic utilities (U_{EC}) and water saving utilities (U_{WS}) to the global utility (U_{glob}) of the considered design alternatives. The 0.60, 0.80, and 0.90 U_{glob} isolines were computed with Equation (10) for $\lambda_{EC} = \lambda_{WS} = 0.50$. The results in Figure 8 show that the best four ranked design alternatives have about the same U_{WS}, close to 0.87 (level basins with lengths of 50, 100, and 200 m, and a graded basin with S_o = 0.5‰ and length of 50 m), but have quite different U_{EC}, ranging from 0.75 to 0.87. Hence, the economic results dictated the ranking of those four design alternatives, with the 200 m long basins ranking first and the 50 m basins ranking fourth due to irrigation costs. It may also be observed that GB with S_o = 1.0‰ are the last ranked in terms of economic results, but the GB-1.0‰ for L = 50 m ranks high in terms of water saving, with a U_{WS} value of 0.78. These results indicate that using the Cartesian representation as in Figure 8 provides a good explanation on ranking, thus making easier the selection of alternatives by a decision maker.

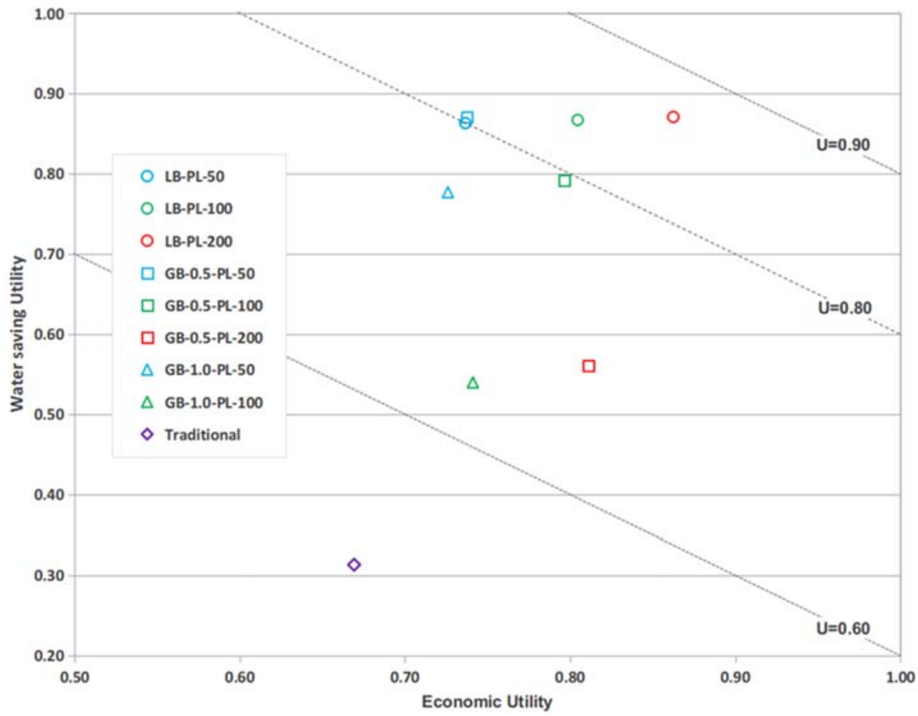

Figure 8. Evaluation of alternatives considering the joint effects of the economic and water saving utilities on the global utility of the best project alternatives for a medium infiltration soil and for medium inflow rates. Isolines of the global utility 0.60, 0.80, and 0.90 are included.

The results in Figures 7 and 8 make it evident that water saving and farm economics are contradictory, particularly when observing that the best rankings for U_{WS} are affected by the economic results when U_{glob} values are considered. This was also observed in former studies using MCA [31,34]. To better shed light on this behaviour, the rankings of the best 15 project alternatives were determined adopting weights attributed to economic issues and water saving different from 50%, which were adopted in the previous analysis. Various combinations of weights were therefore used (Table 13), starting when 20% of weights were assigned to farm economic results and 80% to water saving, and later considering different pairs λ_{EC}-λ_{WS} of 40%-60%, 60%-40%, and 80%-20%. The results clearly show that level basins have the best rankings for all priority combinations for basins with L = 100 m or 200 m. The length L = 100 m has a slight advantage when the priority is assigned to water saving and the length L = 200 m is more advantageous when prioritizing economic results. The graded border with a slope S_o = 0.5‰ and length L = 50 m is the following design alternative in the ranking when a higher priority is for water saving, followed by the LB projects of 50 m. If the priorities relative to farm economics increase, then longer GB are selected, always with the small slope of 0.5‰. A few cases are highlighted in Table 13 to give better visibility to changes in the ranking of selected project alternatives when the assigned priority weights change. These results indicate that the level basin is in general the best choice, that graded borders with S_o = 0.5‰ are feasible, and that basin lengths of 50 m, as at present, are also feasible, but have lower ranks than the 100 m long basins.

Table 13. Changes in ranking of the first 15 ranked design alternatives for a medium infiltration soil when priority scenarios relative to water saving and to farm economic results are modified. Some LB and GB alternatives are highlighted for easily observing changes in ranking when priorities are modified.

Rank	Large Priority for Water Saving	Small Priority for Water Saving	Small Priority for Economic Issues	Large Priority for Economic Issues
	Weights 20%-80%	**Weights 40%-60%**	**Weights 60%-40%**	**Weights 80%-20%**
1	LB-PL-100-L	LB-PL-200-M	LB-PL-200-M	LB-PL-200-M
2	LB-PL-200-M	LB-PL-200-L	LB-PL-200-L	LB-PL-200-L
3	LB-PL-200-L	LB-PL-100-L	LB-PL-200-S	LB-PL-200-S
4	LB-PL-100-M	LB-PL-200-S	LB-PL-100-L	LB-PL-100-L
5	LB-PL-100-S	LB-PL-100-M	LB-PL-100-M	LB-PL-100-M
6	LB-PL-200-S	LB-PL-100-S	LB-PL-100-S	LB-PL-100-S
7	GB-0.5-PL-50-L	GB-0.5-PL-100-S	GB-0.5-PL-100-S	GB-0.5-PL-100-S
8	GB-0.5-PL-50-M	GB-0.5-PL-50-L	GB-0.5-PL-100-M	GB-0.5-PL-100-M
9	GB-0.5-PL-50-S	GB-0.5-PL-50-M	GB-0.5-PL-100-L	GB-0.5-PL-100-L
10	LB-PL-50-S	GB-0.5-PL-50-S	GB-0.5-PL-50-L	GB-0.5-PL-200-S
11	LB-PL-50-L	LB-PL-50-S	GB-0.5-PL-50-M	GB-0.5-PL-50-L
12	LB-PL-50-M	LB-PL-50-L	GB-0.5-PL-50-S	GB-0.5-PL-50-M
13	GB-0.5-PL-100-S	LB-PL-50-M	LB-PL-50-S	GB-0.5-PL-50-S
14	GB-0.5-PL-100-M	GB-0.5-PL-100-M	LB-PL-50-L	LB-PL-50-S
15	GB-1.0-PL-50-S	GB-0.5-PL-100-L	LB-PL-50-M	LB-PL-50-L

4. Conclusions

This study aimed at the application of a DSS with multi-criteria analysis to design and rank alternative design solutions for water-saving basin irrigation of spring wheat in Hetao, currently focusing on its upstream area represented by the Dengkou experimental area. The DSS SADREG was successfully used, thus providing appropriate design information for implementing the modernization of basin irrigation in the area. It was able to generate and rank multiple design alternatives with a consideration of both water saving and economic returns. The adoption of a linear weighted sum MCA, where criteria weights can be changed to modify the priorities attributed to the criteria, was revealed to be appropriate for involving stakeholders in the decision process relative to the future implementation of best design alternatives. To support that implementation throughout Hetao, irrigation design alternatives must be assessed considering different crops and environmental conditions occurring in Hetao, namely relative to salinity.

The results of the study have shown a clear preference for level basins with a 100 m and 50 m length, particularly when priorities are assigned to water saving criteria because less water is then used and yields are high. Differently, project alternatives for longer basins, of 200 m, are highly ranked if the priorities are assigned to economic criteria because costs of modernized irrigation are reduced for long basins. It was evidenced that ranking for water saving or for farm economic results is contradictory, but MCA was able to rank project alternatives with a consideration of and associating both types of criteria, i.e., preferring one or another type of criteria does not imply that the other has to be excluded. Apparently, the best decision is to adopt level basins with a 50 m length, or graded basins with the same length and a small slope of 0.5‰ because these sizes would not require changes in the structure of the fields contrarily to adopt lengths of 100 or 200 m. In addition, selecting 50 m lengths agrees with the experience of the irrigators. Despite the fact that inflow rates do not play a major role, the results indicate that medium to large Q_{in} values should be selected taking into consideration the size of the irrigated fields.

This study provides an insight on the adequacy of modern basin irrigation in Hetao aimed at reducing/controlling the demand for irrigation water, which is a major requirement for the sustainability of irrigated agriculture. However, in addition to improving farm irrigation systems, it is definitely required to improve irrigation management, mainly irrigation scheduling. Yields and water use considered in the current study were determined for conditions of modern, rational irrigation scheduling; otherwise, results considered herein are not achievable. It is also required that the canal system operation is modernized to provide adequate delivery scheduling, i.e., that matches the irrigation demand of modernized irrigation scheduling. Considering the great pressure by the drip irrigation market, future studies are also required to appropriately compare surface and drip irrigation considering both water saving and economic criteria; otherwise, directions for change may be unclear.

The implementation of modern basin irrigation in Hetao, which implies a combination of surface irrigation design and management, definitely requires appropriate extension and training services for farmers and local irrigation canal operators, as well as institutional and economic incentives for farmers to invest in upgrading their irrigation systems. To support that implementation, irrigation design alternatives must be assessed considering different cropping systems and environmental conditions occurring in Hetao, namely relative to salinity.

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References

1. Wang, H.; Yang, Z.; Saito, Y.; Liu, J.P.; Sun, X. Interannual and seasonal variation of the Huanghe (Yellow River) water discharge over the past 50 years: Connections to impacts from ENSO events and dams. *Glob. Planet. Chang.* **2006**, *50*, 212–225. [CrossRef]
2. Liu, C.M.; Xia, J. Water problems and hydrological research in the Yellow River and the Huai and Hai River basins of China. *Hydrol. Process* **2004**, *18*, 2197–2210. [CrossRef]
3. Fu, G.; Chen, S.; Liu, C.; Shepard, D. Hydro-climatic trends of the Yellow River Basin for the last 50 years. *Clim. Chang.* **2004**, *65*, 149–178. [CrossRef]
4. Yang, D.; Li, C.; Hu, H.; Lei, Z.; Yang, S.; Kusuda, T.; Koike, T.; Musiake, K. Analysis of water resources variability in the Yellow River of China during the last half century using historical data. *Water Resour. Res.* **2004**, *40*. [CrossRef]
5. Zhang, Q.; Peng, J.; Singh, V.P.; Li, J.; Chen, Y.D. Spatio-temporal variations of precipitation in arid and semiarid regions of China: The Yellow River basin as a case study. *Glob. Planet. Chang.* **2014**, *114*, 38–49. [CrossRef]
6. Yu, L. The Huanghe (Yellow) River: Recent changes and its countermeasures. *Cont. Shelf Res.* **2006**, *26*, 2281–2298. [CrossRef]
7. Pereira, L.S.; Cai, L.G.; Musy, A.; Minhas, P.S. (Eds.) *Water Savings in the Yellow River Basin. Issues and Decision Support Tools in Irrigation*; China Agriculture Press: Beijing, China, 2003; 290p.
8. Qu, Z.; Yang, X.; Huang, Y. Analysis and assessment of water-saving project of Hetao Irrigation District in Inner Mongolia. *Trans. Chin. Soc. Agric. Mach.* **2015**, *46*, 70–76. (In Chinese)
9. Xu, X.; Huang, G.H.; Qu, Z.Y.; Pereira, L.S. Assessing the groundwater dynamics and predicting impacts of water saving in the Hetao Irrigation District, Yellow River basin. *Agric. Water Manag.* **2010**, *98*, 301–313. [CrossRef]
10. Deng, X.-P.; Shan, L.; Zhang, H.; Turner, N.C. Improving agricultural water use efficiency in arid and semiarid areas of China. *Agric. Water Manag.* **2006**, *80*, 23–40. [CrossRef]

11. Pereira, L.S.; Gonçalves, J.M.; Dong, B.; Mao, Z.; Fang, S.X. Assessing basin irrigation and scheduling strategies for saving irrigation water and controlling salinity in the Upper Yellow River Basin, China. *Agric. Water Manag.* **2007**, *93*, 109–122. [CrossRef]
12. Pereira, L.S.; Cordery, I.; Iacovides, I. *Coping with Water Scarcity. Addressing the Challenges*; Springer: Dordrecht, The Netherlands, 2009; p. 382.
13. Miao, Q.; Shi, H.; Gonçalves, J.M.; Pereira, L.S. Field assessment of basin irrigation performance and water saving in Hetao, Yellow River basin: Issues to support irrigation systems modernisation. *Biosyst. Eng.* **2015**, *136*, 102–116. [CrossRef]
14. Miao, Q.; Rosa, R.D.; Shi, H.; Paredes, P.; Zhu, L.; Dai, J.; Gonçalves, J.M.; Pereira, L.S. Modeling water use, transpiration and soil evaporation of spring wheat-maize and spring wheat-sunflower relay intercropping using the dual crop coefficient approach. *Agric. Water Manag.* **2016**, *165*, 211–229. [CrossRef]
15. Roost, N.; Cui, Y.L.; Xie, C.B.; Huang, B. Water supply simulation for improved allocation and management. In *Water Savings in the Yellow River Basin. Issues and Decision Support Tools in Irrigation*; Pereira, L.S., Cai, L.G., Musy, A., Minhas, P.S., Eds.; China Agriculture Press: Beijing, China, 2003; pp. 275–290.
16. Gonçalves, J.M.; Pereira, L.S.; Fang, S.X.; Dong, B. Modelling and multicriteria analysis of water saving scenarios for an irrigation district in the Upper Yellow River Basin. *Agric. Water Manag.* **2007**, *94*, 93–108. [CrossRef]
17. Pereira, L.S.; Oweis, T.; Zairi, A. Irrigation management under water scarcity. *Agric. Water Manag.* **2002**, *57*, 175–206. [CrossRef]
18. Wu, J.W.; Vincent, B.; Yang, J.Z.; Bouarfa, S.; Vidal, A. Remote sensing monitoring of changes in soil salinity: A case study in Inner Mongolia, China. *Sensors* **2008**, *8*, 7035–7049. [CrossRef] [PubMed]
19. Hoffman, G.J.; Shalhevet, J. Controlling salinity. In *Design and Operation of Farm Irrigation Systems*, 2nd ed.; Hoffman, G.J., Evans, R.G., Jensen, M.E., Martin, D.L., Elliot, R.L., Eds.; American Society of Agricultural and Biosystems Engineers: St. Joseph, MI, USA, 2007; pp. 160–207.
20. Xu, X.; Huang, G.H.; Qu, Z.Y.; Pereira, L.S. Using MODFLOW and GIS to assess changes in groundwater dynamics in response to water saving measures in irrigation districts of the upper Yellow River basin. *Water Resour. Manag.* **2011**, *25*, 2035–2059. [CrossRef]
21. Xu, X.; Huang, G.H.; Sun, C.; Pereira, L.S.; Ramos, T.B.; Huang, Q.Z.; Hao, Y.Y. Assessing the effects of water table depth on water use, soil salinity and wheat yield: Searching for a target depth for irrigated areas in the upper Yellow River basin. *Agric. Water Manag.* **2013**, *125*, 46–60. [CrossRef]
22. Pereira, L.S. Higher performances through combined improvements in irrigation methods and scheduling: A discussion. *Agric. Water Manag.* **1999**, *40*, 153–169. [CrossRef]
23. Clemmens, A.J.; Walker, W.R.; Fangmeier, D.D.; Hardy, L.A. Design of surface systems. In *Design and Operation of Farm Irrigation Systems*, 2nd ed.; Hoffman, G.J., Evans, R.G., Jensen, M.E., Martin, D.L., Elliot, R.L., Eds.; American Society of Agricultural and Biosystems Engineers: St. Joseph, MI, USA, 2007; pp. 499–531.
24. Strelkoff, T.; Clemmens, A.J. Hydraulics of surface systems. In *Design and Operation of Farm Irrigation Systems*, 2nd ed.; Hoffman, G.J., Evans, R.G., Jensen, M.E., Martin, D.L., Elliot, R.L., Eds.; American Society of Agricultural and Biosystems Engineers: St. Joseph, MI, USA, 2007; pp. 436–498.
25. Reddy, J.M. Design of level basin irrigation systems for robust performance. *J. Irrig. Drain. Eng.* **2013**, *139*, 254–260. [CrossRef]
26. Bai, M.; Xu, D.; Li, Y.; Pereira, L.S. Stochastic modeling of basins microtopography: Analysis of spatial variability and model testing. *Irrig. Sci.* **2010**, *28*, 157–172. [CrossRef]
27. Bai, M.J.; Xu, D.; Li, Y.N.; Pereira, L.S. Impacts of spatial variability of basins microtopography on irrigation performance. *Irrig. Sci.* **2011**, *29*, 359–368. [CrossRef]
28. Walker, W.R.; Skogerboe, G.V. *Surface Irrigation. Theory and Practice*; Prentice-Hall: Englewood Cliffs, NJ, USA, 1987.
29. Pereira, L.S.; Gonçalves, J.M. Surface irrigation. In *Oxford Encyclopaedia of Agriculture and the Environment*; Oxford University Press: Oxford, UK, 2017.
30. Gonçalves, J.M.; Pereira, L.S. Decision support system for surface irrigation design. *J. Irrig. Drain. Eng.* **2009**, *135*, 343–356. [CrossRef]
31. Gonçalves, J.M.; Muga, A.P.; Horst, M.G.; Pereira, L.S. Furrow irrigation design with multicriteria analysis. *Biosyst. Eng.* **2011**, *109*, 266–275. [CrossRef]

32. Bazzani, G.M. An integrated decision support system for irrigation and water policy design: DSIRR. *Environ. Model. Softw.* **2005**, *20*, 153–163. [CrossRef]
33. Roy, B.; Bouyssou, D. *Aide Multicritère: Méthodes et Cas*; Economica: Paris, France, 1993.
34. Darouich, H.; Gonçalves, J.M.; Muga, A.; Pereira, L.S. Water saving vs. farm economics in cotton surface irrigation: An application of multicriteria analysis. *Agric. Water Manag.* **2012**, *115*, 223–231. [CrossRef]
35. Darouich, H.; Pedras, C.M.G.; Gonçalves, J.M.; Pereira, L.S. Drip vs. surface irrigation: A comparison focusing water saving and economic returns using multicriteria analysis applied to cotton. *Biosyst. Eng.* **2014**, *122*, 74–90. [CrossRef]
36. Oad, R.; Garcia, L.; Kinzli, K.-D.; Patterson, D.; Shafike, N. Decision support systems for efficient irrigation in the Middle Rio Grande Valley. *J. Irrig. Drain. Eng.* **2009**, *135*, 177–185. [CrossRef]
37. Pedras, C.M.G.; Pereira, L.S. Multicriteria analysis for design of microirrigation systems. Application and sensitivity analysis. *Agric. Water Manag.* **2009**, *96*, 702–710. [CrossRef]
38. Khadra, R.; Lamaddalena, N. Development of a decision support system for irrigation systems analysis. *Water Resour. Manag.* **2010**, *24*, 3279–3297. [CrossRef]
39. Barradas, J.M.M.; Matula, S.; Dolezal, F. A Decision Support System-Fertigation Simulator (DSS-FS) for design and optimization of sprinkler and drip irrigation systems. *Comput. Electron. Agric.* **2012**, *86*, 111–119. [CrossRef]
40. Kottek, M.; Grieser, J.; Beck, C.; Rudolf, B.; Rubel, F. World Map of the Köppen-Geiger climate classification updated. *Meteorol. Z.* **2006**, *15*, 259–263. [CrossRef]
41. IWC-IM. *Construction and Rehabilitation Planning Project for Water-Saving in Hetao Irrigation District of the Yellow River Basin, Inner Mongolia*; Institute of Water Conservancy and Hydropower of Inner Mongolia: Hohhot, China, 1999. (In Chinese)
42. Hetao Administration. *The Datasets of Evaluation of Irrigation Water Use Efficiency in Hetao Irrigation District of Inner Mongolia*; Hetao Irrigation Administration Bureau: Hohhot, China, 2003. (In Chinese)
43. Shao, W.W.; Yang, D.W.; Hu, H.P.; Sanbongi, K. Water resources allocation considering the water use flexible limit to water shortage—A case study in the Yellow River Basin of China. *Water Resour. Manag.* **2009**, *23*, 869–880. [CrossRef]
44. Yu, R.; Liu, T.; Xu, Y.; Zhu, C.; Zhang, Q.; Qu, Z.; Liu, X.; Li, C. Analysis of salinization dynamics by remote sensing in Hetao Irrigation District of North China. *Agric. Water Manag.* **2010**, *97*, 1952–1960. [CrossRef]
45. Guo, H.; Zhang, Y.; Jia, Y.; Zhao, K.; Li, Y.; Tang, X. Dynamic behaviors of water levels and arsenic concentration in shallow groundwater from the Hetao Basin, Inner Mongolia. *J. Geochem. Explor.* **2013**, *135*, 130–140. [CrossRef]
46. Sun, S.; Wu, P.; Wang, Y.; Zhao, X.; Liu, J.; Zhang, X. The impacts of interannual climate variability and agricultural inputs on water footprint of crop production in an irrigation district of China. *Sci. Total Environ.* **2013**, *444*, 498–507. [CrossRef] [PubMed]
47. Bai, L.; Cai, J.; Liu, Y.; Chen, H.; Zhang, B.; Huang, L. Responses of field evapotranspiration to the changes of cropping pattern and groundwater depth in large irrigation district of Yellow River basin. *Agric. Water Manag.* **2017**, *188*, 1–11. [CrossRef]
48. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements*; Paper 56; FAO: Rome, Italy, 1998; p. 300.
49. IUSS Working Group WRB. *World Reference Base for Soil Resources 2014, Update 2015. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*; World Soil Resources Reports No. 106; FAO: Rome, Italy, 2015.
50. Walker, W.R.; Prestwich, C.; Spofford, T. Development of the revised USDA–NRCS intake families for surface irrigation. *Agric. Water Manag.* **2006**, *85*, 157–164. [CrossRef]
51. Katopodes, N.D.; Tang, J.H.; Clemmens, A.J. Estimation of surface irrigation parameters. *J. Irrig. Drain. Eng.* **1990**, *116*, 676–696. [CrossRef]
52. Horst, M.G.; Shamutalov, S.S.; Pereira, L.S.; Gonçalves, J.M. Field assessment of the water saving potential with furrow irrigation in Fergana, Aral Sea Basin. *Agric. Water Manag.* **2005**, *77*, 210–231. [CrossRef]
53. Walker, W.R. *SIRMOD—Surface Irrigation Modeling Software*; Utah State University: Logan, UT, USA, 1998.
54. Dedrick, A.R.; Gaddis, R.J.; Clark, A.W.; Moore, A.W. Land forming for irrigation. In *Design and Operation of Farm Irrigation Systems*, 2nd ed.; Hoffman, G.J., Evans, R.G., Jensen, M.E., Martin, D.L., Elliot, R.L., Eds.; American Society of Agricultural and Biosystems Engineers: St. Joseph, MI, USA, 2007; pp. 320–346.

55. Zheng, H.X.; Shi, H.; Guo, K.Z.; Hao, W.L. Study on influence of field surface slope on irrigation efficiency in combination with different irrigation parameters. *Agric. Res. Arid Areas* **2011**, *29*, 43–48. (In Chinese)
56. Bai, G.; Du, S.; Yu, J.; Zhang, P. Laser land leveling improve distribution of soil moisture and soil salinity and enhance spring wheat yield. *Trans. Chin. Soc. Agric. Eng.* **2013**, *29*, 125–134. (In Chinese)
57. Chamberlain, E.J.; Gow, A.J. Effect of freezing and thawing on the permeability and structure of soils. *Eng. Geol.* **1979**, *13*, 73–92. [CrossRef]
58. Wang, L.P.; Akae, T. Analysis of ground freezing process by unfrozen water content obtained from TDR data in Hetao Irrigation District of China. *J. Jpn. Soc. Soil Phys.* **2004**, *98*, 11–19. [CrossRef]
59. Li, R.; Shi, H.; Flerchinger, G.N.; Zou, C.; Li, Z. Modeling the effect of antecedent soil water storage on water and heat status in seasonally freezing and thawing agricultural soils. *Geoderma* **2013**, *206*, 70–74. [CrossRef]
60. Li, R.; Shi, H.; Akae, T.; Zhang, Y.; Zhang, X.; Flerchinger, G.N. Scheme of water saving irrigation in autumn based on SHAW model in Inner Mongolia Hetao irrigation district. *Trans. Chin. Soc. Agric. Eng.* **2010**, *26*, 31–36. (In Chinese)
61. Solomon, K.H. Yield related interpretations of irrigation uniformity and efficiency measures. *Irrig. Sci.* **1984**, *5*, 161–172. [CrossRef]
62. Tong, W.J.; Liu, Q.; Chen, F.; Wen, X.Y.; Li, Z.H.; Gao, H.Y. Salt tolerance of wheat in Hetao irrigation district and its ecological adaptable region. *Acta Agron. Sin.* **2012**, *38*, 909–913. (In Chinese) [CrossRef]
63. Pereira, L.S.; Cordery, I.; Iacovides, I. Improved indicators of water use performance and productivity for sustainable water conservation and saving. *Agric. Water Manag.* **2012**, *108*, 39–51. [CrossRef]
64. Darouich, H.; Cameira, M.R.; Gonçalves, J.M.; Paredes, P.; Pereira, L.S. Comparing sprinkler and surface irrigation for wheat using multi-criteria analysis: Water saving vs. economic returns. *Water* **2017**, *9*, 50. [CrossRef]
65. Zheng, H.; Shi, H.; Zhu, M.; Liu, H.; Gonçalves, J.M. Estimation of infiltration parameters for border irrigation based on SIRMOD method and modelling of border irrigation. *Trans. Chin. Soc. Agric. Eng.* **2009**, *25*, 29–34. (In Chinese)
66. Strelkoff, T.S.; Clemmens, A.J.; Bautista, E. Estimation of soil and crop hydraulic properties. *J. Irrig. Drain. Eng.* **2009**, *135*, 537–555. [CrossRef]
67. Nie, W.; Fei, L.; Ma, X. Estimated infiltration parameters and Manning roughness in border irrigation. *Irrig. Drain.* **2012**, *61*, 231–239.
68. Pomerol, J.C.; Barba-Romero, S. *Multicriterion Decision in Management: Principles and Practice*; Springer Science and Business Media: Berlin, Germany, 2000; Volume 25.
69. Ishizaka, A.; Nemery, P. *Multi-Criteria Decision Analysis: Methods and Software*; Wiley: Chichester, UK, 2013.
70. Stanimirovic, I.P.; Zlatanovic, M.L.; Petkovic, M.D. On the linear weighted sum method for multi-objective optimization. *Facta Acta Univ.* **2011**, *26*, 49–63.
71. Yan, H.B.; Huynh, V.N.; Nakamori, Y.; Murai, T. On prioritized weighted aggregation in multi-criteria decision making. *Expert Syst. Appl.* **2011**, *38*, 812–823. [CrossRef]
72. Clemmens, A.J.; El-Haddad, Z.; Strelkoff, T.S. Assessing the potential for modern surface irrigation in Egypt. *Trans. ASAE* **1999**, *42*, 995–1008. [CrossRef]
73. Playán, E.; Mateos, L. Modernization and optimization of irrigation systems to increase water productivity. *Agric. Water Manag.* **2006**, *80*, 100–116. [CrossRef]
74. Clemmens, A.J.; Allen, R.G.; Burt, C.M. Technical concepts related to conservation of irrigation and rainwater in agricultural systems. *Water Resour. Res.* **2008**, *44*, W00E03. [CrossRef]
75. Playán, E.; Faci, J.M.; Serreta, A. Modeling microtopography in basin irrigation. *J. Irrig. Drain Eng.* **1996**, *122*, 339–347. [CrossRef]
76. González, C.; Cervera, L.; Moret-Fernández, D. Basin irrigation design with longitudinal slope. *Agric. Water Manag.* **2011**, *98*, 1516–1522. [CrossRef]