Irrigation evaluation based on performance analysis and water accounting at the Bear River Irrigation Project (U.S.A.)

by

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Abstract

The purpose of this work is to contribute to the development of a combined approach to evaluate irrigated areas based on: 1) irrigation performance analysis intended to assess the productive impacts of irrigation practices and infrastructures, and 2) water accounting focused on the hydrological impacts of water use. Ador-Simulation, a combined model that simulates irrigation, water delivery, and crop growth and production was applied in a surface irrigated area (1213 ha) located in the Bear River Irrigation Project, Utah (U.S.A.). A soil survey, a campaign of on-farm irrigation evaluations and an analysis of the database from the Bear River Canal Company and other resources were performed in order to obtain the data required to simulate the water flows of the study area in 2008. Net land productivity (581 US\$ ha⁻¹) was 20% lower than the potential value, whereas on-farm irrigation efficiency (IE) averaged only 60%. According to the water accounting, water use amounted to 14.24 Mm³, 86% of which was consumed through evapotranspiration or otherwise non-recoverable. Gross water productivity over depleted water reached 0.132 US\$ m⁻³. In addition, two strategies for increasing farm productivity were analyzed. These strategies intended to improve water management and infrastructures raised on-farm IE to 90% reducing the gap between current and potential productivities by about 50%. Water diverted to the project was reduced by 2.64 Mm³. An analysis based on IE could lead to think that this volume would be saved. However, the water accounting showed that actually only 0.91 Mm³ would be available for alternative uses. These results provide insights to support the decision-making processes of farmers, water user associations, river basin authorities and policy makers. Water accounting overcomes the limitations and hydrological misunderstandings of traditional analysis based on irrigation

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efficiency to assess irrigated areas in the context of water scarcity and competitive agricultural markets.

Keywords: land productivity, surface irrigation, water accounting, water balance, water consumption, water depletion, water management, water productivity.

Introduction

Utah is the second driest state in the U.S.A. By 2050, Utah's population is expected to double to nearly five million people (GOPB, 2000). According to the U.S. Census Bureau (2000), Utah is the fourth fastest growing state in the nation. About 82% of the population is located in urban areas. Although agricultural irrigation will continue to be the main water use, municipal and industrial (M&I) uses will sustain the greatest increases over the next four decades. Assuming the current rates of per capita use (Kenny *et al.*, 2009), the population growth will lead to an increase of about 1,200 Mm³ in M&I water diversions. This volume represents a 20% increase in total water demand compared to 2000, mainly for residential outdoor uses (UDWR, 2001).

Higher water demand that exceeds supply will lead to social conflicts over water resources and higher vulnerability to the impact of the frequent drought events in Utah (UDWR, 2008). Two large water development projects are being planned to meet water demand and mitigate drought impacts. These projects are aimed at transferring water from the Bear River (in the North) and the Colorado River (in the South) to the most populated areas in Utah. These projects require considerable capital investment to construct new water storage and transport infrastructures (UDWR, 2001).

Water demand management is being prioritized to lessen the projected increase in water use and delay investments in water development. M&I water conservation programs are being promoted to reduce per capita water use by about 25% (UDWR, 2001). Water audits, xeric-landscaping or water-pricing are some of the measures implemented for such purposes (Endter-Wada *et al.*, 2008). Moreover, increasingly competence for water resources is expected to result in economic incentives that will lead to water transfers from agriculture to M&I users and encourage water

management strategies that maximize the benefits of water use (Flake *et al.*, 2010). Increased agricultural water use efficiency is one such strategy (UDWR, 2001).

Globally, food demand is predicted to increase by 70-90% by 2050 (FAO, 2003). Half of the additional food demand could be met by decreasing 80% of the gap between actual and potential productivity (de Fraiture *et al.*, 2007). Molden *et al.* (2010) pointed out that the increase in water productivity will require strategies based on biophysical and socioeconomic factors.

The evaluation of irrigated areas will become more and more important in diagnosing and improving the performance of irrigation schemes in order to achieve optimal productivity in the context of increasing food demand, open global markets and competition for limited freshwater resources (Burt *et al.*, 1997; Molden *et al.*, 1998). Such assessments should analyze the productive and hydrological impacts of internal irrigation processes to assist agents involved in crop production, water management and water policy to improve the performance of irrigated areas (Perry *et al.*, 2009; Molden *et al.*, 2010).

Water management is linked to crop production and farmers' profits (Clemmens *et al.*, 2008). Assessment of irrigation performance is required in order to improve water management on farms and irrigation districts (Clemmens and Dedrick, 1994; Burt *et al.*, 1997). Irrigation evaluations are conducted to quantify the gap between potential and actual performance of irrigation systems (Merriam and Keller, 1978). Irrigation simulation models can extend our understanding of irrigation district performance and ways to improve it by means of both managerial and infrastructure interventions (Walker and Skogerboe, 1987).

Several authors have combined these techniques to assess the performance of irrigated areas through external indicators (Molden *et al.*, 1998) such as efficiencies or productivities and have analyzed the internal irrigation processes related to timing, duration or water flows to diagnose the described performance (Playán *et al.*, 2000; Dechmi *et al.*, 2003; Lorite *et al.*, 2004a; Bos *et al.*, 2005; Lecina *et al.*, 2005; Lecina and Playán, 2006a; Mateos *et al.*, 2010).

Water management is also linked to hydrology in a basin. The irrigation sector is usually the major water user in many semi-arid regions, so modifications in the way

89 irrigation water is used imply sensible hydrological impacts (Seckler, 1996; Seckler *et al.*,
90 2003; Lecina *et al.*, 2010a). Efficiencies used to describe the performance of irrigated areas
91 are not appropriate for assessing the hydrological impacts of irrigation water use in a
92 basin (Willardson *et al.*, 1994; Perry, 1999; Jensen, 2007; Perry, 2007). Efficiency does not
93 take into account issues such as water reuse, the distinction between water use and
94 water consumption, the influence of location of use within the basin, and water quality.
95 For these reasons, on-farm irrigation efficiency improvements do not necessarily imply
96 water savings and can lead to higher water consumption at basin scale (Huffaker, 2008;
97 Ward and Pulido-Velázquez, 2008; Lecina *et al.*, 2010b). Understanding what the
98 destinations of water are is essential to assess the hydrological impact of irrigation.
99 Water accounting has been proposed for this purpose (Molden and Sakthivadivel, 1999;
100 Clemmens *et al.*, 2008; Perry *et al.*, 2009; Foster and Perry, 2010). This methodology applies the
101 law of conservation of mass through water balances. Balances identify the destinations
102 of the water used and distinguish between consumptive and non-consumptive uses.

103 A number of authors have performed water balances in irrigated areas. Most of them
104 have focused on the environmental impact of irrigation on water quality (Cavero *et al.*,
105 2003; Isidoro *et al.*, 2006a; Isidoro *et al.*, 2006b; Causapé, 2009a). Others have assessed
106 the performance of irrigated areas based on external indicators derived from water
107 balance components (Droogers and Bastiaanssen, 2002; Isidoro *et al.*, 2004; Akbari *et al.*,
108 2007; Causapé, 2009b). However, these studies do not relate the external performance
109 indicators and water balance to the internal irrigation processes that influence them.

110 Models for the simulation of irrigated areas reproduce the interaction between
111 irrigation water, conveyance network and agricultural production (Yamashita and
112 Walker, 1994; Prajamwong *et al.*, 1997; Lorite *et al.*, 2004b). These models relate the
113 internal processes derived from management of water and infrastructures to the
114 performance of the analyzed irrigated areas. Ador-Simulation is a model included in
115 this category that simulates water flows in irrigation districts (Lecina and Playán,
116 2006b). This model has been successfully applied to assess and diagnose the irrigation
117 performance reproducing a preliminary water balance in irrigation districts (Lecina
118 and Playán, 2006a). These capabilities are also useful to evaluate the hydrological
119 impacts of internal irrigation processes in addition to irrigation performance.

120 The objective of this work is to contribute to develop a combined approach in the
121 evaluation of irrigated areas based on both irrigation performance analysis and

preliminary water accounting. Irrigation performance analysis is intended to assess the productive impacts of irrigation practices and is mainly addressed to agricultural entrepreneurs and water user associations. Water accounting is focused on the hydrological impacts of irrigation water use and is mainly addressed to river basin authorities. Both analyses are also of interest to policy makers, particularly in water scarcity contexts when changes in water management and infrastructures are planned to increase farm profitability and reduce water use. This approach has been applied to a Utah irrigated area using Ador-Simulation. The irrigated area is representative of the old surface irrigated areas in the Western United States. The evaluation of this area to determine its potential to increase its productivity and the hydrological impacts of the strategies adopted to this end constitutes a secondary objective of this work.

The Bear River irrigation project

The Bear River Irrigation Project (BRIP) is located in North Utah, in the lower Bear River Basin, close to the mouth of the river in the Great Salt Lake (Figure 1). This project was developed by a sugar beet company at the beginning of the twentieth century, and is currently managed by the Bear River Canal Company (BRCC). The command area is 26856 ha, of which 1213 ha were selected as a study area for this work.

The climatic characterization of the study area was carried out using the 1980-2009 thermopluviometric data series from a National Weather Service station located at Tremonton, within the boundaries of the irrigated area. According to such data, the climate in this region is continental and semi-arid. The annual average temperature is 10 °C, with a wide thermal oscillation between seasons. The annual average precipitation is 413 mm, unevenly distributed throughout the year. The mean precipitation during summer is 69 mm, mainly as thunderstorms, with mean precipitation in the other seasons ranging from 107 mm to 125 mm. The mean annual reference evapotranspiration (ET_0) (Allen *et al.*, 1998) is 1368 mm. Spring and summer accounts for 1094 mm of ET_0 . Average recurrence intervals of moderate and severe drought conditions are 4.4 and 8.5 years respectively (UDWR, 2001). The last one was in 2004 when water availability fell by 25% with regard to an average year (Watterson, 2005).

According to the SSS-NRCS (2008), two main soil units are distinguished in the study area, located in a terrace about 25 m above the Malad River (Figure 1), a tributary of the Bear River. The first unit corresponds to Parleys soils (PdA). These soils are deep, stone-free, and have a loam texture with no salinity problems. This unit occupies 530 ha in the study area. The second unit covers the remaining area and corresponds to Fielding soils (Fd), with similar characteristics, but with a silt-loam texture.

Field crops are predominant in the study area. Generally, the cropping pattern is based on a rotation of alfalfa and other forages (50%), corn (25%) and other winter/spring cereals (25%), although the area devoted to each crop may vary from year to year. The main destination of agricultural production is the livestock industry in the region.

The Bear Lake is the only irrigation water reservoir in the Lower Bear River Basin. The storage capacity of this infrastructure is 1754 Mm³ and its use is shared with a power company and other irrigation projects upstream in the basin, which amount to 195000 ha. Irrigation water used in the BRIP is diverted from the Bear River in the Cutler Dam. This irrigation water comes from the natural water flow of the Bear River, the water releases from the Bear Lake and the return flows from irrigation projects and other upstream water users. The unlined West Side Canal transports the water to the study area. Water conveyance structures consist of a network of unlined ditches, starting at 25 headgates at the West Side Canal, which deliver water to the plots. The on-farm irrigation systems are, almost exclusively, blocked-end borders. Farmers usually use siphons to manage the water at the field level.

Water delivery is performed applying a varied frequency rotation system, according to the classification system proposed by Clemmens (1987). The daily irrigation period is 24 h. Water volumes delivered to each farmer are not measured or estimated. A fixed pricing structure (a specified fee per unit of area) is applied for operational and maintenance services billing. This water delivery system and pricing structure are usual in the old surface irrigated areas in the Western United States (Burt and Styles, 2000).

Percolation from plots and seepage from the water conveyance network produce a shallow water table that drains into the Malad River with a response time in the order of days (SSS-NRCS, 2008). In some areas there are buried drains to prevent the water table from reaching the root zone. Spills from the network of ditches discharge directly into the Malad River. This river is the natural drainage system of the study area flowing into the Bear River and the Great Salt Lake 25 km downstream.

The Bear River Migratory Bird Refuge is the last water user in the Bear River Basin, located between the BRIP and the Great Salt Lake. Its water rights amount to 525 Mm³ per year (UDWR, 2004). Preserving the environment of the Bear River delta and mitigating outbreaks of botulism in the bird population are the purposes of this water allocation. The water required for such uses represents committed water in the basin, following the terminology proposed by Molden and Sakthivadivel (1999). However, the flow of the Bear River is inadequate to meet the Bird Refuge's needs during the summer months, so new water development projects are being planned to meet

196 summer needs at the mouth of the river (UDWR, 2004). For these reasons, the Bear
197 River Basin is classified as a closing basin, according to the definition proposed by
198 Seckler et al. (2003).

199

Materials and Methods

Ador-Simulation was used to simulate the water flows in the study area. Its version aimed at surface irrigated areas is composed of five modules covering on-farm surface irrigation, crop growth, open channel distribution networks, irrigation decision-making and hydrosaline balance. These modules are executed in parallel and are connected by a series of variables. The surface irrigation module is based on a numerical hydrodynamic one-dimensional routine. The simulation of water conveyance is performed on the basis of the capacity of the elements of the conveyance network. Crop growth is simulated using a scheme derived from the CropWat model (Smith, 1992). The irrigation decision-making module satisfies water orders considering water stress, yield sensitivity to stress, multiple water sources and the network capacity. The hydrosaline module is based on a steady state approach, and provides estimations for the volume and salinity of the irrigation return flows for the whole irrigation season (Aragüés *et al.*, 1990). A more detailed description of Ador-Simulation can be found in Lecina and Playán (2006b).

Ador-Simulation was applied to simulate the irrigation campaign of 2008 on a daily basis (hourly for water delivery). Two additional simulations were performed considering different strategies to improve the surface irrigation performance. The characterization of the study area was the step required prior to carrying out these simulations.

Characterization of the study area

A characterization of weather, soils, plots, crops, infrastructures and water management is required to simulate the water flows with Ador-Simulation. A soil survey and an on-farm irrigation evaluation campaign were performed to collect soil and irrigation parameters in the study area. At the same time, interviews were conducted with farmers, BRCC managers and ditch riders, as proposed by Burt and Styles (2004), to obtain other required parameters concerning the infrastructures, water management and agronomy practices in the study area. The BRCC management database and satellite images as well as other resources were also analyzed to characterize the study area during 2008.

Soil survey

A soil survey was performed to obtain the total available water (TAW) and the soil water content before irrigation. Soil sampling was carried out just before irrigation in the same plots where the on-farm irrigation was evaluated (Figure 1). A soil sample was obtained using an auger in two pits in each plot for the top 0.15 m and 0.30 m and each subsequent 0.30 m until a depth of 1.20 m was reached. Field capacity and wilting point were determined using pressures of 0.033 MPa and 1.5 MPa respectively, in addition to the gravimetric water content (Soil Survey Laboratory, 2004). Bulk density was also determined at the same sampling points from which undisturbed soil cores were extracted (Soil Survey Laboratory, 2004).

The results of these determinations were used to estimate the TAW (mm) in each soil profile (Allen *et al.*, 1998). Soil water content just before irrigation was expressed as a percentage of the TAW and soil water depletion as a value complementary to this percentage.

On-farm irrigation evaluation

The purposes of on-farm irrigation evaluations were to characterize soil infiltration and on-farm irrigation management in the study area. A total of 13 evaluations were performed during the summer season in 2008. Seven of them were carried out on PdA soils while the remaining six were carried out on Fd soils. The methodology proposed by Merriam and Keller (1978) to evaluate surface irrigation was adopted in all cases.

Rectangular borders distributed in each soil unit were chosen to perform the evaluations (Figure 1). During the irrigation evaluations the farmers carried out their normal irrigation practices. A measuring wheel and a topographic level were used to determine the border dimensions, the slope and the standard deviation of elevation.

The inflow irrigation discharge was measured at the beginning of the irrigation event using a mini-propeller meter according to the USBR (2001). Frequent water depth measurements were performed in the ditch after the inflow discharge was determined to check that it remained constant throughout the evaluation. The advance phase was determined by recording the water advance times at reference points located every 10-30 m along the border. The flow depth was measured shortly before cutoff at the upstream end of the border. A number of flow depth measurements were performed

across the border every 3-4 m. The average of these measurements was considered to represent flow depth at this cross section and time.

Infiltration and roughness were determined from the irrigation advance times and the flow depth using SIRMOD, a hydrodynamic one-dimensional surface irrigation model (Walker, 1993). Tentative values of the coefficient k and exponent a from the Kostiakov infiltration equation (Kostiakov, 1932), and Manning's coefficient n were used to iteratively execute the model. These parameters were adjusted until the model satisfactorily reproduced the experimental values of irrigation advance times and flow depth (Playán *et al.*, 2000). The location of each evaluation, its infiltration equation and a soil map implemented in a geographic information system (GIS) (SSS-NRCS, 2008) were used to identify an infiltration class in each soil unit. The curve corresponding to each infiltration class was obtained by applying a regression analysis on the infiltration curves represented by the class.

Irrigation performance indexes were obtained using an *ad hoc* hydrodynamic one-dimensional surface irrigation model (Lecina *et al.*, 2005). These indexes included the application efficiency (AE, %) and the low-quarter distribution uniformity (DU_{lq} , %). According to Burt *et al.* (1997), such indexes are defined as follow:

$$AE = \frac{\text{Average depth of irrigation water contributing to target depth}}{\text{Average depth of irrigation water applied}} \times 100 \quad [1]$$

$$DU_{lq} = \frac{\text{Average low quarter water depth}}{\text{Average water depth}} \times 100 \quad [2]$$

Soil water depletion determined just before the irrigations as described above was considered the target irrigation depth (Z_r , mm) of the evaluated irrigations.

Other simulation data sources and processing

In Ador-Simulation, the plot is the basic geographical unit. A typical irrigation unit (a border in this case) is characterized in each plot. Irrigation simulation is performed in the irrigation unit and extended to the whole plot area (Lecina and Playán, 2006b). The study area was divided in 25 sub-command areas corresponding to the areas irrigated with the same irrigation module and from the same headgate located in West Side Canal (Figure 2). The number and area of the plots present in each sub-command area

were obtained from the management database of the BRCC. The cartographic representation of the sub-command areas, implemented in a GIS, was obtained from a combination of cadastral cartography provided by the Utah Government and the local knowledge of the BRCC ditch riders.

A cartographical restitution of an aerial photograph provided by the Utah Government was used to measure the average border length and width of each typical border. The average slopes were extrapolated from the irrigation evaluations. A GIS spatial analysis tool was applied to identify the area corresponding to each soil unit within each plot and to assign the corresponding soil physical properties. The initial soil water depletion at the onset of the simulation period was estimated from the meteorological conditions prevailing during the weeks preceding sowing.

The crops present in the plots were obtained from eight Landsat 5 TM images provided by the U.S. Geological Survey, which were taken on May 10, May 17, June 2, June 18, June 27, July 13, July 29 and August 21. These images were used to estimate the crop coefficient curves according to the methodology originally proposed by Bausch and Neale (1987) based on the correlation between spectral vegetation indexes and crop phenology. Crop identification was performed comparing the crop coefficient curve obtained in each pixel with the theoretical local curves (Allen and Robison, 2007). A GIS spatial analysis tool was applied to localize the crops within the area of each plot.

The sowing date for each crop and plot was assigned following the statistical distribution obtained from interviewing the farmers in the study area. The duration of the phenological phases, the values of the thermal integral and the related temperature threshold, plus the crop coefficients, were derived from local experiences (Hill, 1994; Allen and Robison, 2007).

Crop evapotranspiration was estimated following the guidelines proposed by Allen *et al.* (1998). Daily weather data were obtained from the Agricultural Weather Station of the Utah State University Cooperative Extension located at Tremonton, close to the study area. The allowable soil water depletion was computed according to Allen *et al.* (1998). Soil water depletion above allowable water depletion entails crop water stress. The crop water stress sensitivity was obtained from the Stewart coefficients determined by Doorenbos and Kassam (1979).

The layouts of the water networks were drawn over a cadastral cartography in a GIS according to the maps provided by the BRCC, the ditch riders' interviews and field work. Each ditch was characterized by a service and a conveyance discharge, which were obtained from the management database of the BRCC. Each plot was related to a water conveyance network element. The water delivery capacity (WDC, %) at each sub-command area was characterized for a monthly period as follows (Molden *et al.*, 1998):

$$WDC = \frac{\text{Ditch capacity to deliver water at subcommand area head}}{\text{Peak crop irrigation requirements expressed as flow rate}} \times 100 \quad [3]$$

Seepage, direct evaporation and weed evapotranspiration from ditches were considered to be about 10% of total water flow according to the inflow-outflow measurements carried out by the BRCC (Davidson, personal communication; Watterson, 2009). Similar figures were obtained in other surface irrigated areas in the Western United States (USBR, 1963; Worstell, 1976). According to Lecina and Playán (2006b), operational water spills were estimated considering the time period between the end of the irrigation in one plot of a ditch and the beginning of the next one observed in the study area.

Common water delivery and irrigation practices were gathered from the BRCC management database and interviews with farmers and ditch riders. Related agronomy practices such as pre-sowing irrigations or time delay for irrigation after alfalfa harvest were characterized in the same way. All these data were used to simulate the water flows in the study area.

Simulation of water flows

The simulation of the water flows allowed the irrigation performance and the water balance of the study area to be analyzed. Previously, the model was calibrated and validated in the conditions of the BRIP following the methodology proposed by Lecina and Playán (2006a). The monthly volume of water demand from West Side Canal provided by the BRCC was the contrasted data source for this purpose. The calibration parameters were operational due to the fact that irrigation decision-making is dictated by factors not related to water balance (Lamacq, 1997; Labbé *et al.*, 2000), which were not modeled in Ador-Simulation. These operational parameters were the following:

1) The varied frequency rotation system; and 2) the farmers' decisions regarding the duration of the irrigation.

In addition to analyzing the current situation in 2008, two strategies were addressed from the farmers' preference for improving their surface irrigation practices:

- Strategy 1: improving both on-farm irrigation management and water delivery.
- Strategy 2: partial improvement of the infrastructures in addition to the managerial improvements proposed in Strategy 1.

Irrigation performance analysis

The aim of the irrigation performance analysis was to estimate the potential increase of farm income through the improvement of water management and/or infrastructures proposed in the strategies. The analysis was based on the study of the internal irrigation processes and their consequences on irrigation performance at on-farm level.

Internal irrigation processes were characterized by a number of indexes related to irrigation duration and depths, irrigation frequency and time periods in which crops are water stressed, at least at 25% of the border areas.

Irrigation performance was characterized by irrigation efficiency (IE), in addition to DU_{iq} [3] and productivities. IE covers the entire irrigation season and then considers the influence of irrigation scheduling, and hence infrastructures and water management, on irrigation performance. No other beneficial uses of water were considered in addition to crop evapotranspiration. According to Burt *et al.* (1997), IE (%) is defined as follows:

$$IE = \frac{\text{Volume of irrigation water beneficially used}}{\text{Volume of irrigation water} - \Delta \text{ storage of irrigation water}} \times 100 \quad [4]$$

Productivities were determined to estimate the impact of irrigation practices on farm income. Crop yields obtained as a function of crop evapotranspiration from the crop growth module in Ador-Simulation were used to estimate productivities following the guidelines set out by Molden *et al.* (1998), Molden *et al.* (2003), Playán and Mateos (2006) and Hussain *et al.* (2007). Gross land productivity was obtained as the ratio between gross value of production and cropped area. The gross value was computed as crop yield multiplied by price. Net land productivity was obtained as the ratio

between net margin of production and cropped area. The net margin was calculated as gross value minus direct costs and amortizations. Potential yields, prices and costs were obtained from the Utah State University Cooperative Extension (2008). Gross and net water productivities were computed in the same way, using the irrigation water demand. These water productivities are important for farmers during drought years.

Hydrologic analysis

A water balance was estimated for the preliminary assessment of the impacts of the irrigation performance on the hydrology of the Bear River Basin. This analysis was based on the definition of a temporal and spatial domain of the water balance, the quantification of its components from Ador-Simulation and the computation of a number of indexes to characterize the hydrological impacts of the study area.

The temporal domain of the water balance was 2008. The spatial domain was the boundaries of the study area from the headgates of the West Side Canal, considering the root zone and the underlying groundwater. The study area is limited in the North and the West by the West Side Canal, in the East by the Malad River and in the South by a drainage collector (Figure 1).

The water balance components were adapted to the principles of water accounting indicated by Molden and Sakthivadivel (1999) and Perry *et al.* (2009). These principles define gross inflow (GI) as the total amount of water flowing into the domain while net inflow (NI) adds any change in soil water and groundwater storage in the domain in order to ensure compliance with the law of conservation of mass. In this study, groundwater storage change between the beginning and the end of the temporal domain was assumed to be negligible.

Net inflow is divided into four water balance components or outflows: 1. Beneficial evapotranspiration (ET_B), referred to crop evapotranspiration; 2. Non-beneficial evapotranspiration (ET_{NB}) made up by evapotranspiration from non-productive vegetation and direct evaporation from water bodies such as ditches; 3. Non-recoverable runoff/percolation (RP_{NR}), relative to irrigation return flows (including seepage and operational spills from ditches) not available for further use because its destination is not economically exploitable sinks, such as saline water bodies and deep aquifers, or its quality prevents its reuse; and 4. Recoverable runoff/percolation (RP_R).

411 The hydrological impact of the irrigation performance was estimated through a
412 number of indexes in addition to the water balance components. These indexes are
413 defined as follow (Willardson *et al.*, 1994; Molden and Sakthivadivel, 1999; Perry *et al.*,
414 2009).

415 The two water balance components relating to evapotranspiration constitute the
416 consumed fraction (CF) over net inflow:

$$417 \quad CF = \frac{ET_B + ET_{NB}}{NI} \quad [5]$$

418 Total evapotranspiration and non-recoverable runoff/percolation represent the
419 fraction of total net inflow that is depleted in a basin (DF), meaning that the water is
420 not available for further use:

$$421 \quad DF = \frac{ET_B + ET_{NB} + RP_{NR}}{NI} \quad [6]$$

422 Beneficial evapotranspiration over the depleted water constitutes the depleted
423 beneficial fraction (DBF):

$$424 \quad DBF = \frac{ET_B}{ET_B + ET_{NB} + RP_{NR}} \quad [7]$$

425 Moreover, gross water productivity was computed over water depletion. This
426 productivity represents the economic return for society from the water physically
427 removed from the basin.

Results and Discussion

Characterization of the study area

Soil survey

The total available water was high and uniform in both soil units. Parleys soils presented an average TAW of 204 mm and Fielding soils of 228 mm (Table 1). The coefficient of variation (CV) was 6% and 4% respectively. The soil depth in all pits was higher than 1.2 m and no stones were found in any of the soil samples.

Soil moisture just before the irrigation events averaged 41% of TAW in Parleys soils and 49% in Fielding soils. The CV was 28% and 30% respectively. Average soil water depletion represented about 55% of the crop water requirements computed during the irrigation interval that ranged from 21 to 30 days. Alfalfa and winter/spring cereals were the crops grown in the surveyed plots.

The long irrigation intervals, the low soil water depletion relative to crop evapotranspiration and the seemingly healthy appearance of the crops entailed that a water flux fed the root zone from the shallow water table by capillary rise. According to the SSS-NRCS (2008), on average the water table was located about 1.4 m deep. This secondary water source contributed to meet the crop water requirements in addition to irrigation and precipitation.

On-farm irrigation evaluation

Table 1 presents the aggregated results of the on-farm irrigation evaluations by soil unit. The size of the evaluated borders was about 1.5 ha, with moderate variability. Borders were larger in Fielding soils. The field slope presented a wide range of variation. On average, the slope was similar in both soil units (about 0.0017 m m⁻¹). The maximum value of the standard deviation of soil surface elevation was 22 mm, with the average value being 15 mm. These figures indicate that laser leveling is often practiced in the study area.

Two infiltration classes were derived from the infiltration equations obtained in each evaluation (Figure 2). Infiltration in Fielding soils is larger than in Parleys soils. However, the average irrigation discharge was similar in both soil units (91 l s⁻¹,

2.6 l s⁻¹ m⁻¹), ranging from 50 to 120 l s⁻¹. These similar figures of unitary discharges and slopes by soil units suggest that infiltration differences were not considered in the design of the borders. The high spatial variability of the distribution of the soils in the study area (Figure 1) could explain this fact. Only 9 out of 25 headgates present a predominant soil occupying more than 85% of the sub-command area.

The cutoff time was long and very variable as a function of the unitary irrigation discharges. Farmers applied longer times of irrigation in Fielding soils (7.2 h ha⁻¹) than in Parleys soils (5.7 h ha⁻¹) due to the higher infiltration and larger borders of Fielding soils, and similar discharges and slopes. Therefore, irrigation depths were also larger in Fielding soils than in Parleys soils, averaging 230 mm and 144 mm respectively.

On average, AE was 51% in Fielding soils and 65% in Parleys soils, varying in a range of 18% in both soil units. These values indicate that applied irrigation depths were notably larger than required in both soil units. The excess of water was mainly accumulated at the end of the blocked-end borders, so DU_{iq} was low, particularly in Parleys soils, where infiltration is lower (66% compared to 74% in Fielding soils).

Other characteristics of the study area during the irrigated season

The meteorological conditions during the 2008 irrigation season were characterized by an average reference evapotranspiration and a slightly dry campaign, particularly during the spring. The return probabilities of reference evapotranspiration (1172 mm) and precipitation (117 mm) from April to October were 55% and 65% respectively, according to the abovementioned 1980-2009 weather data set.

Alfalfa was the predominant crop, occupying 45.8% of the study area. Corn and other winter/spring cereals were cultivated in 22.6% and 29.0% of the area respectively, and other forages in 2.3%, while fallow plots were only present in 0.3%. The spatial distribution of this cropping pattern was heterogeneous. Predominant areas of one crop were not identified.

A total of 130 plots and 79 farms formed the study area, according to the management database of the BRCC. The average plot size was 9.3 ha although 50% of them presented an area smaller than 7.3 ha. Only 19% of the farmers cultivated an area

larger than 20 ha and another 19% between 20 ha and 10 ha. About 78% of the farmers cultivated their land in a single plot.

The analysis of the network of ditches showed that irrigation discharge averaged 85 l s⁻¹, ranging from 50 l s⁻¹ to 120 l s⁻¹. The size of the 25 sub-command areas of each headgate was very irregular, ranging from 3.0 ha to 127.6 ha (Figure 1). The spatial variability of the water delivery capacity was very large, mainly as a function of the size of the sub-command areas. The largest sub-command areas presented a WDC lower than 100%. These amounted to 55% of the study area. The remaining sub-command areas presented a WDC that was higher than 125%.

Simulation of water flows: current situation

According to the rotation delivery scheme adopted by the BRCC and the agronomic and irrigation practices carried out by the farmers, the seasonal number of irrigations averaged five for alfalfa and other forages, six for corn and three for winter/spring cereals. The minimum irrigation interval averaged 26 days for forages, 14 days for corn and 21 days for other winter/spring cereals during the peak of the season. Similar irrigation depths were applied in each irrigation event at the same border during the season, following common behaviour in surface irrigated areas due to the low flexibility of these systems (Clemmens and Molden, 2007). In order to calibrate the model, this water delivery scheme was considered in addition to the extrapolated cutoff time from the on-farm irrigation evaluations.

The validation of the model showed that the simulated water demand compares well with the BRCC data. The seasonal cumulative difference was 1% and on a monthly basis the difference ranged from 1% to 8% in absolute values (Figure 3). The error rate was only higher in April (34%). Agronomic practices of the farmers during sowing, which are difficult to establish and model, plus differentiated soil infiltration during the first irrigation, might be the reasons for such error. However, water demand during this month only represented 1% of seasonal water demand.

Irrigation performance analysis

Table 2 presents the irrigation indicators obtained through the simulation of water flows in the study area. Average irrigation time of 6.5 h ha⁻¹ involved large irrigation

depths (194 mm as an average) and an excess of water that percolated mostly at the end of the blocked-end borders. As a result, the DU_{Iq} averaged 65% and the on-farm IE was 60%, ranging from 50% to 68% among the 25 sub-command areas. There was no spatial distribution pattern of this indicator due to the heterogeneity of the distribution of soils, unitary irrigation discharges and crops (Figure 4). The average irrigation water demand was $10392 \text{ m}^3 \text{ ha}^{-1}$. Seasonal percolation was generally larger in corn and other winter/spring cereal plots because their root systems were still shallow during early irrigations.

The average irrigation interval was 28 days. However, crops were water stressed the last 11 days of this interval. Water stress was not severe owing to the fact that capillary rise prevented the soil water content from plunging during this interval. The long irrigation interval scheduled by the BRCC was based on this effect of capillary rise, among other factors. Nevertheless, soil water depletion just before irrigation averaged 56% of TAW while allowable water depletion averaged 42% of TAW. Consequently, actual crop evapotranspiration decreased 7% relative to potential crop evapotranspiration, similar to other surface irrigated areas in the Western United States (Allen *et al.*, 2005), involving an average yield reduction of 11%. Yield reduction was higher in the larger sub-command areas where the WDC was lower than 100% (Figure 5).

Net productivities were about 20% lower than potential as a consequence of the crop yield reduction. Crop yields averaged 49 t ha^{-1} for silage corn, 6 t ha^{-1} for winter/spring cereals and 12 t ha^{-1} for forages, according to the potential yields reported by the Utah State University Cooperative Extension (2008). The net land productivity averaged $581 \text{ US\$ ha}^{-1}$ while the net water productivity computed over irrigation water demand averaged $0.056 \text{ US\$ m}^{-3}$. These productivities implied a reduction of $143 \text{ US\$ ha}^{-1}$ and $0.014 \text{ US\$ m}^{-3}$ relative to those computed with maximum crop yields. This gap represents a loss of net income for the farmers and a higher sensitivity of such income to water scarcity during drought periods. The high variability of the prices of agricultural commodities (OECD-FAO, 2010) must be taken into consideration for an appropriate assessment of these figures.

Higher irrigation frequency is required to decrease the current crop water stress period between irrigation events and hence the gap between potential and actual crop yields

and productivities. Increasing flexibility of water delivery is essential for this purpose (Cross, 2000; Clemmens, 2006; Merriam *et al.*, 2007; Zaccaria *et al.*, 2010). In the case of the study area, one main factor to increase the flexibility of water delivery is to decrease irrigation times, particularly in those sub-command areas where the WDC is lower.

The long cutoff time suggests that farmers only consider the large irrigation interval to adjust the irrigation time but not soil water depletion. Farmers respond in this way due to the fact that they do not have a quantitative estimation of soil water depletion but they know the rotation system scheduled by the BRCC. This trend to overirrigate under uncertainty conditions has also been described by other authors (English, 2002; Wichelns, 2004).

Water accounting

Table 2 presents the results of the water balance performed in the study area in 2008. A schematic representation of the water flows based on the template proposed by Perry (1996) is shown in Figure 6. Inflows were 13.77 Mm³ while net inflow was 14.24 Mm³. Irrigation water was 89% (12.61 Mm³) of net inflow. Precipitation and soil water variation represented 8% (1.17 Mm³) and 3% (0.46 Mm³) respectively.

Most of the net inflow was consumed. The consumed fraction was 0.72 mainly due to crop evapotranspiration (10.01 Mm³). Irrigation was the main source of water for crop evapotranspiration (84%), followed by precipitation (11%) and soil water (5%). A total of 0.25 Mm³ of consumed water was estimated as non-beneficial evapotranspiration because of direct evaporation and weed evapotranspiration from unlined ditches. Considering only irrigation water, 67% was evapotranspired by crops. Almost all rainfall was evapotranspired (98%), as a consequence of low precipitation distributed in light rainfall events during the irrigation campaign and large TAW of the soils.

The non-consumed water was 28% (3.99 Mm³) of outflows. Total flow from the root zone and ditches to the water table was 5.83 Mm³. About 82% of this percolation flow came from plots and 18% from ditches because of seepage. A total of 1.84 Mm³ (32% of percolation, 13% of net inflow) were reused by capillary rise from the water table. Hence, the remaining percolation and the spills from ditches totalized the returns (3.99 Mm³) that flowed to the Malad River from the domain of the study area.

Return flows were partially used by the Bear River Migratory Bird Refuge, the last water user in the Bear River Basin, located between the BRIP and the Great Salt Lake. During the summer months, river flow did not meet the water right allotment to the Bird Refuge, so the runoff/percolation from the BRIP augmented the river flow and was reused by the refuge. According to the flow data recorded by the USGS (2009) in the Bear River Basin, about 49% (1.96 Mm³) of runoff/percolation was used between July and September by the Bird Refuge in 2008 considering the quantitative and qualitative water requirements of this protected area (UDWR, 2004). The balance of the runoff/percolation (2.03 Mm³, 51%) flowed directly into the Great Salt Lake during the remaining months.

Water depletion was 86% (12.29 Mm³) of net inflow considering consumed water and non-recoverable return flows. The depleted beneficial fraction was 0.81 as a consequence of low non-recoverable returns and non-beneficial evapotranspiration. The complementary value to this fraction (0.19, 2.28 Mm³, 16% of net inflow) represents the potential water saving of the study area in 2008. The gross water productivity computed over water depletion was 0.132 US\$ m⁻³. This figure represents 79% of potential productivity (0.167 US\$ m⁻³) computed as the ratio between maximum gross value of production (maximum crop yield) and potential crop evapotranspiration. Considering this gross water productivity, the potential water saving is equivalent to a value of US\$ 0.301 million.

Simulation of water flows: strategies to increase farm income

Irrigation performance analysis

Table 2 presents the results of the simulation of the two strategies considered with a view to increasing farm income. The first strategy focused on improving both the on-farm irrigation management and the water delivery scheme. The aim of this strategy was to reduce the irrigation interval increasing the number of seasonal irrigation events in order to decrease crop water stress and yield reduction.

A reduced irrigation time is needed to obtain more flexible water delivery. A number of simulations of the irrigation season were performed gradually decreasing the cutoff time in each border of the study area. An optimum cutoff time was defined as the time that provided maximum net productivities. Simulations started at the irrigation time in

the current situation and ended at the minimum time required to complete the irrigation in each border.

Figure 7 shows the effects of the progressive reduction of the average cutoff time over productivities, crop yield reduction, IE and other variables. Productivities gradually increase as cutoff time decreases. Lower irrigation times allow the number of seasonal irrigations to increase, irrigation intervals and duration of crop water stress periods to decrease, and evapotranspiration, yields and productivities to rise.

Maximum net land productivity was reached at an irrigation time of 3.4 h ha⁻¹. Such productivity hardly varied below this time. Most of the border-irrigated fields had already reached the minimum time to complete irrigation at this time and the gaps to increase evapotranspiration and yields were small in the remaining borders. In contrast, water productivities continued to increase for irrigation times below 3.4 h ha⁻¹ because the gap to reduce water demand remained large in these border-irrigated fields until the minimum irrigation time was attained.

The minimum irrigation time averaged 3.1 h ha⁻¹ (52% lower than the current situation). At this time, the average irrigation depth dropped to 91 mm, diminishing percolation and water accumulation at the end of the blocked-end border. DU_{lq} and IE rose to 83% and 91% respectively. This last variable ranged from 70% to 95% (Figure 4). Irrigation water demand decreased from 10392 m³ ha⁻¹ to 8220 m³ ha⁻¹ despite the higher irrigation frequency because of the plunge in the irrigation depth.

The average irrigation interval fell from 28 days to 16 days, whereas the average number of seasonal irrigations increased from five to nine. Consequently, the water stress period between irrigation events plunged to 4 days. Soil water depletion just before irrigation (50% of TAW) was closer to allowable soil water depletion (41% of TAW). Therefore, crop evapotranspiration increased 4% (97% of the potential value) and yield reduction dropped from 11% to 5%. Equity between farmers was slightly improved by the increased flexibility of the water delivery scheme. The standard deviation of yield reduction among sub-command areas decreased from 3% to 2% (Figure 5).

Maximum net land productivity was 638 US\$ ha⁻¹. This figure included an additional cost in irrigation tasks as a consequence of higher irrigation frequency. The gap

between current and potential productivities decreased 40% (52% without additional irrigation costs). Maximum net land productivity of Strategy 1 represented 91% of potential value. Net water productivity computed over irrigation water demand amounted to 0.078 US\$ m⁻³. These figures are an estimation of the potential increases in productivities than can be obtained at low cost merely by improving water management. Further increases would require improvements in infrastructures and larger investments.

The second strategy involved a partial improvement of existing infrastructures in addition to the managerial improvements proposed in Strategy 1. The goal was to increase crop yields in those sub-command areas where water delivery was more constrained. Conveyance capacity was doubled for the upper half of the main ditch in the sub-command areas where WDC was lower than 100%. These sub-command areas represented 69% of the total net value reduction for the whole study area.

Crop evapotranspiration and yields increased with respect to the previous strategy owing to the shorter irrigation intervals and water stress periods in the improved sub-command areas. These variables averaged 15 days and 2 days respectively for the entire study area. The higher irrigation frequency resulted in higher irrigation water demand (8745 m³ ha⁻¹) than in Strategy 1 despite the fact that irrigation efficiencies were comparable, since irrigation times and depths were not modified.

Consequently, the net land productivity reached 663 US\$ ha⁻¹ (94% of the potential value). The gap between the current and potential values decreased a further 27%, so the total fall was 67%. However, there was hardly any variation in the net water productivity computed over irrigation water demand, owing to the fact that crop yields and water demand increased proportionally. Therefore, the sensitivity of the farms to water scarcity did not diminish. The amortization of the investment to increase conveyance capacity should be deducted from these productivities in order to obtain the net benefit of this strategy.

An alternative strategy focusing on raising the capacity of the ditches to increase the irrigation discharge (up to at least 120 l s⁻¹ in all plots) was disregarded because the area with infrastructures that needed to be upgraded (84%) was higher than that of Strategy 2 (55%) while productivity and water demand were similar (results not shown).

These results highlight the potential to reduce current irrigation water demands and increase farm productivities through the improvement of water management and surface irrigation infrastructures. This study is useful for farmers and BRCC managers to assess such potential values and to identify the strategies required to achieve them, thereby lessening the degree of uncertainty in their respective decision-making processes. Technical assistance, farmers training and an advanced database program for water management are required to validate and to apply these strategies at field level (Burt and Styles, 2000; Playán *et al.*, 2007; Clemmens, 2009; Batt and Merkley, 2010).

Water accounting

Figure 8 shows a graphical comparison between the two strategies and the current situation, in addition to Table 2. The first strategy involved a progressive reduction of net inflow as irrigation time decreased. The improvement in water management considered in this strategy lowered excess water and met the crop water requirements better. Consequently, the consumed fraction rose from 0.72 to 0.90 considering the irrigation time that provided the highest productivities. Net inflow was 17% lower (2.47 Mm³) than the current situation while crop evapotranspiration rose 4% (0.40 Mm³) and non-consumed water fell 71% (2.83 Mm³).

Shorter irrigation intervals and crop water stress periods contributed to decrease more than half the volume of water reuse from the water table (0.76 Mm³). This volume made up 45% of percolation from the root zone and ditches and 6% of net inflow.

The remaining percolation in addition to operational spills from ditches amounted to 1.16 Mm³. Distinction between recoverable and non-recoverable returns was estimated according to the downstream flow data in the Bear River during 2008 (USGS, 2009) and the water requirements of the Bird Refuge (UDWR, 2004). A total of 0.39 Mm³ (34% of return flows) were estimated as the recovered volume of runoff/percolation.

Water depletion decreased 7% (0.91 Mm³), mainly due to the reduction of non-recoverable runoff/percolation. The impact of this reduction on depletion was partially offset by the increase in crop evapotranspiration. The decrease in water depletion represented the theoretical water savings provided by this strategy. It accounted for 40% of estimated potential water savings relative to the current situation. Additionally,

the proportion of water beneficially depleted increased because of both the decrease in non-recoverable runoff/percolation and the increase in crop evapotranspiration. Therefore, the depleted beneficial fraction rose from 0.81 to 0.91.

It is important to note that not all irrigation water conservation (reduction in irrigation water demand) resulted in water savings (reduction in non-beneficial water depletion). The water depletion reduction made up 34% of the decrease in irrigation water demand. Only water that cannot be recovered by other users can be saved. In addition, real water savings also depend on other issues beyond the study area. Among others, these include the capacity to store the saved volume in a reservoir, or the proportion of irrigation water used in the study area that actually comes from return flows of upstream irrigation schemes. These issues should be analyzed in a broader study for the whole irrigated area in the basin.

Net inflow was almost totally depleted by evapotranspiration and non-recoverable runoff/percolation. The depleted fraction rose from 0.86 to 0.96. The decrease in net inflow was higher than the decrease in water depletion because the drop in runoff/percolation was split between recoverable and non-recoverable return flows.

The gross water productivity computed over water depletion increased 14% (from 0.132 US\$ m⁻³ to 0.151 US\$ m⁻³), reaching 90% of potential productivity, as a consequence of both the decreased water depletion and the increased gross value. Such an increase suggests that there will be a higher economic return for society from the depletion of water resources in the study area. An additional benefit of Strategy 1 for society is the improvement in water quality of the water bodies downstream in the study area. The reduction in runoff/percolation contributes to decrease the export of pollutants from the irrigated area and achievement of the total maximum daily loads (U.S. Congress, 2002) assigned to the mouth of the Bear River (UDWR, 2004). Further studies are required to quantify the impact of this strategy on the ecological status of the rivers and the Bird Refuge.

The second strategy involved a 13% reduction in net inflow (1.86 Mm³). This decrease was lower than that of Strategy 1. A higher irrigation frequency and the same minimum irrigation depths as Strategy 1 in those sub-command areas where conveyance capacity was increased weakened the reduction of net inflow. Total runoff/percolation was 1.64 Mm³, 59% lower than the current situation. In contrast,

better crop water supply raised crop evapotranspiration to 10.54 Mm³, 5% higher than the current situation. Consequently, the consumed fraction was 0.87.

Water reuse from the water table was slightly lower with respect to Strategy 1 due to the higher irrigation frequency. This water reuse represented 31% of percolation from the root zone and seepage from ditches, and 5% of net inflow. The recoverable volume from total return flows increased relative to the previous strategy as a consequence of the higher runoff/percolation. This volume was estimated as 44% of total returns (0.72 Mm³).

Water depletion was 5% (0.62 Mm³) lower than the current situation. This decrease was slightly lower than that of Strategy 1 for the abovementioned reasons. It represented 27% of potential water savings and 31% of the reduction in irrigation water demand. The depleted fraction and the total beneficial depleted fraction also decreased slightly relative to Strategy 1 (0.94 and 0.90 respectively), along with the gross water productivity computed over water depletion (0.150 US\$ m⁻³). The higher gross value was offset by higher water depletion.

These results show the relationship between water depletion and productivities considering the current cropping pattern in the study area. This analysis is useful to enable river basin authorities and policy makers to obtain an overview that can support decision-making processes on water planning. Preliminary identification of the general strategies to follow and the areas where investment should be prioritized can be based on comparing the results obtained in different irrigation projects in one basin. More detailed analyses are required to design specific strategies in these areas. Precise water accounting should be performed for such purposes.

Conclusions

The irrigation performance of the study area can be improved in order to increase farm productivity. The gap between current and potential net land productivity can be reduced 40% at low cost, thereby improving water management. Better on-farm irrigation practices that decrease the cutoff time and increase the flexibility of water delivery are required to meet this goal. Further increases in net land productivity require greater investment as a higher capacity of water delivery is needed. Doubling the capacity of those sub-command areas where water delivery capacity is lower than 100% will reduce the gap between current and potential net land productivity by 67%. The importance of these improvements on the farms' profits will depend on the amortization of the investment required to carry them out, plus the uncertain agricultural and energy prices. These results are also subjected to the spatial and temporal domain of this work.

Water depletion decreases in the study area as a consequence of better irrigation performance. The application of the minimum cutoff time required to complete the irrigation in the borders involves a reduction in runoff/percolation that can decrease water depletion by 7%. Return flows are only partially recoverable downstream from the study area because of its location, close to the Great Salt Lake. This reduction in water depletion would be lower (5%) if infrastructures are upgraded in addition to improved water management. Higher water delivery capacity also increases irrigation frequency but decreases the reduction in runoff/percolation because larger decreases in irrigation times and depths are not possible. These reductions in water depletion should be analyzed at basin scale in order to determine the water savings that can actually be obtained in the Bear River Basin.

Irrigation evaluations based on the estimation of irrigation efficiencies can lead to misleading conclusions about the hydrological impacts on the performance of the evaluated areas. Decreases in water depletion only represented between 34% and 31% of the reduction in irrigation water use obtained in the study area as a result of improved irrigation efficiency. This difference is due to the fact that a fraction of the runoff/percolation is recoverable.

Irrigation evaluations based on irrigation performance analysis and water accounting as proposed in this work are useful for improving water use in irrigated areas and to provide a general overview that supports decision-making processes on water planning at basin scale. The level of detail and scope of this methodology provide insights about the relationship between internal irrigation processes and both productivities and water depletion, overcoming the limitations and misconceptions of the evaluations based exclusively on irrigation efficiencies. Irrigation efficiencies alone do not give the whole picture, while water accounting methods do not offer enough insights to indicate what should be done. Thus, a combination is preferable for developing and testing strategies.

This methodology can help to identify those irrigated areas in a basin and those general strategies that provide the highest returns relative to the required investment and water depletion. Precise water accounting should subsequently be performed to design specific strategies in these areas. Additionally, further studies relative to water storage and transport infrastructures, hydrogeology, water rights or variability of energy and crop prices, among others, are required in order to obtain a comprehensive understanding of the impacts of irrigation water use at basin scale.

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1310 **Table 1.** *Results of the 13 irrigation evaluations performed in the study area.*

		Parleys soils	Fielding soils
Area (m ²)	Average	12,589	17,569
	CV (%)	47	21
Width (m)	Average	37	49
	CV (%)	17	20
Slope (m m ⁻¹)	Average	0.00189	0.00148
	CV (%)	31	58
Standard deviation of soil surface elevation (mm)	Average	13	16
	CV (%)	38	22
Discharge (m ³ s ⁻¹)	Average	0.091	0.091
	CV (%)	53	14
Irrigation time (h ha ⁻¹)	Average	5.7	7.2
	CV (%)	49	22
Irrigation depth (mm)	Average	144	230
	CV (%)	22	19
Manning n	Average	0.18	0.23
	CV (%)	20	13
Kostiakov k (m min ⁻¹)	Average	0.0145	0.0173
	CV (%)	15	18
Kostiakov a	Average	0.318	0.376
	CV (%)	4	5
Total Available Water (mm)	Average	204	228
	CV (%)	6	4
Application Efficiency (%)	Average	65	51
	CV (%)	18	18
Low Quarter Distribution Uniformity (%)	Average	66	74
	CV (%)	18	13

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1319 **Table 2.** *Estimated water balances, irrigation, hydrological and economic indicators in the*
1320 *study area for the current situation and Strategies 1 and 2.*

	Current situation	Strategy 1	Strategy 2
Water balance			
Inflows (Mm ³)	13.77	11.14	11.77
Irrigation	12.61	9.97	10.61
Precipitation	1.17	1.17	1.17
Net inflow -water use- (Mm ³)	14.24	11.77	12.38
Soil water variation (Mm ³)	-0.46	-0.63	-0.60
Outflows (Mm ³)	14.25	11.77	12.39
Consumed volume	10.26	10.61	10.75
Beneficial evapotranspiration	10.01	10.41	10.54
Non-beneficial evapotranspiration	0.25	0.20	0.21
Non-consumed volume	3.99	1.16	1.64
Non-recoverable Runoff/Percolation	2.03	0.77	0.92
Recoverable Runoff/Percolation	1.96	0.39	0.72
Hydrological indicators			
Depleted volume (Mm ³)	12.29	11.38	11.67
Depleted fraction (m ³ m ⁻³)	0.86	0.97	0.94
Depleted beneficial fraction (m ³ m ⁻³)	0.81	0.91	0.90
Consumed fraction (m ³ m ⁻³)	0.72	0.90	0.87
Water reuse -capillary rise- (Mm ³)	1.84	0.76	0.62
Irrigation indicators			
Average irrigation time (h ha ⁻¹)	6.5	3.1	3.1
Average water depth (mm)	194	91	91
Average on-farm irrigation efficiency (%)	60	91	88
Average low-quarter distribution uniformity (%)	65	83	73
Average irrigation interval (d)	28	16	15
Average crop water stress period during irrigation interval (d)	11	4	2
Average soil water depletion just before irrigation (% TAW)	56	50	47
Average allowable soil water depletion (% TAW)	42	41	41
Crop evapotranspiration reduction (%)	7	3	2
Economic indicators			
Yield reduction (%)	11	5	3
Net production value reduction (%)	20	9	6
Net production value (M US\$)	0.704	0.773	0.805
Net land productivity (US\$ ha ⁻¹)	581	638	663
Net water productivity -irrigation water- (US\$ m ⁻³)	0.056	0.078	0.076
Gross production value reduction (%)	10	4	3
Gross production value (M US\$)	1.625	1.719	1.750
Gross land productivity (US\$ ha ⁻¹)	1340	1417	1443
Gross water productivity –water depletion- (US\$ m ⁻³)	0.132	0.151	0.150