Long-term water balances in La Violada Irrigation District (Spain): I. Sequential assessment and minimization of closing errors

R. Barros[1], D. Isidoro[1] and R. Aragüés[1]

[1] Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA)-Diputación General de Aragón (DGA), Unidad de Suelos y Riegos (Unidad Asociada EEAD-*CS*IC), Avenida Montañana 930, 50059 Zaragoza, España.

*Corresponding author. Tel.:+34 976716393; fax: +34 976716335. E-mail address: disidoro@aragon.es (D. Isidoro).

Abstract

Long-term analysis of hydrologic series in irrigated areas allows identifying the main water balance components, minimizing closing errors and assessing changes in the hydrologic regime. The main water inputs [irrigation (I) and precipitation (P)] and outputs [outflow (Q) and potential (ET_c) crop evapotranspiration] in the 4000-ha La Violada irrigation district (VID) (Ebro River Basin, Spain) were measured or estimated from 1995 to 2008. A first-step, simplified water balance assuming steady state conditions (with error $\varepsilon = I + P - Q - ET_c$) showed that inputs were much lower than outputs in all years (average ε = -577 mm/yr or -33% closing error). A second-step, improved water balance with the inclusion of other inputs (municipal waste waters, canal releases and lateral surface runoff) and the estimation of crop's actual evapotranspiration (ET_a) through a daily soil water balance reduced the average closing error to -13%. Since errors were always higher during the irrigated periods, when canals are full of water, a third-step, final water balance considered canal seepage (CS) as an additional input. The change in water storage in the system (ΔW) was also included in this step. CS and ΔW were estimated through a monthly soil-aquifer water balance, showing that *CS* was a significant component in VID. With the inclusion of *CS* and ΔW in the water balance equation, the 1998-2008 annual closing errors were within ±10% of total water outputs. This long-term, sequential water balance analysis in VID was an appropriate approach to accurately identify and quantify the most important water balance components while minimizing water balance closing errors.

Keywords: Canal seepage, closing error, evapotranspiration, irrigation, soil-aquifer balance, water balance analysis.

Objective: Sequential estimation of the unknown terms of water balances at the irrigation district level and minimization of closing errors using long time series.

1. **Introduction**

Irrigated agriculture in arid and semi-arid areas increases land productivity and enhances crop diversification (FAO, 2005), but may have a significant negative impact on water quantity and quality at irrigation district and catchment scales (Tanji and Kielen, 2002; Wriedt et al., 2009). Irrigated agriculture is the major water consumer in the world, accounting for more than 60% of total abstraction (OECD/Eurostat, 2000), as well as in the Ebro River basin (Spain) with a demand of 6310 hm^3/yr (86% of diverted water) (CHE, 1996). Climate change is expected to intensify problems of water scarcity in the Mediterranean region (IPPC, 2007), pointing to the need for an improved analysis of available water resources. The agricultural analysis should focus on determining the actual water consumption and the magnitude of the main flow-paths, and on identifying the components of irrigated agriculture where efficiency could be improved. To these aims, the performance of water balances at the irrigation district scale is a required approach.

The European Water Framework Directive (WFD, 2000/60/EC) seeks to ensure a sustainable use of water resources in terms of quantity and quality. Since irrigated agriculture is a major water consumer and water polluter (Aragüés and Tanji, 2003) improved procedures are needed to quantify water balances and pollutant loads at the irrigation district scale. As pointed out by Thayalakumaran et al., (2007) “the management of the water balance is likely to be more effective in managing productivity and the off-site impacts of irrigation than managing a farm or regional salt balance”. Hence, the quantification and management of water balances at the irrigation district scale is a sound approach for minimizing pollutant loads and the deleterious effects of irrigation return flows on the quality of receiving water bodies.

A water balance at the irrigation district scale consists in determining its water inputs and outputs for a given period of time (Ridder and Boonstra, 1994). The definition of the hydrological boundaries is extremely important and difficult to delineate accurately. For example, groundwater systems in irrigated areas with recharge-discharge flows should be included within the boundaries of the system (Clemmens and Burt, 1997). However, it is unlikely that the hydrological boundaries of the groundwater system, local storage and flow mechanisms are well understood, especially if groundwater is not exploited. The Thornthwaite and Mather (1955, 1957) water balance model is valid as a water accounting procedure when only reduced information about hydrologic inputs and aquifer characteristics is available, as applied by Peranginangin et al. (2004).

Once the hydrological boundaries are properly defined, the water balance components must be identified and quantified. Some components as irrigation, precipitation and surface drainage can be measured directly in most cases. In contrast, other components as evapotranspiration and groundwater inflows and outflows are difficult to measure and are generally estimated (Molden, 1997). As the actual evapotranspiration is the largest outflow in most irrigated areas, substantial efforts have been addressed to its estimation under different approaches and methodologies (Allen et al., 1998; Pastor and Post, 1984; Thornthwaite and Mather, 1957), including remote sensing techniques combined with traditional methods (Karatas et al. 2009). In some instances, other input flows such as operational releases and seepage from canals may be significant (Ahmed and Umar, 2008; Arumí et al., 2009) and should be determined separately or inferred from the water balance.

The estimation of water losses from canals is a challenging enterprise. A large number of studies have assessed canal seepage losses using different methodologies [ponding test (Bakry and Awad, 1997), inflow-outflow method (Arshad et al., 2009), or electrical resistivity (Hotchkiss et al., 2001), among others]. Most of these works have been performed in unlined canals, whereas seepage from lined canals has not been widely analyzed because it is assumed that they are practically impervious as compared to unlined canals (Katibeh, 2004; Rastogi and Prasad, 1992). However, lining materials are not completely impervious or may deteriorate over time, as concrete materials in gypsiferous soils (UPIRI, 1984), resulting in water losses and low conveyance efficiencies. These losses must be estimated and minimized for water conservation and correct exploitation and management of groundwater and surface reservoirs.

The water balance method is a sensible approach only if its main inputs and outputs can be measured or estimated with sufficient accuracy at the irrigation district scale. Water balances with low closing errors allow quantifying irrigation quality parameters, assessing potential water savings, and estimating irrigation-induced return flows. By measuring pollutant concentrations in irrigation return flows, pollutant loads and off-site irrigation-induced pollution can then be properly quantified.

Studies aimed at identifying and quantifying irrigation-induced environmental problems have been generally undertaken for short periods of time (Gilfedder et al., 2000; Oosterveld and Carefoot, 1979) and limited surface areas, preventing the analysis of temporal, climatic, agronomic, and spatial variability (Qassim et al., 2008; Silva et al., 2006). Irrigation districts with long-term records are particularly interesting since they provide information of distinct hydrological years, crop patterns and irrigation and management systems (Abtew and Khanal, 1994; He et al., 2006; Sato et al., 2008). This information allows proper identification and quantification of the effects of these variables on the hydrologic patterns, to evaluate the present and potential future uses of irrigation water (Peranginangin et al., 2004), and to analyze water balance trends (Marc and Robinson, 2007).

The present study in La Violada irrigation district (VID, Ebro River basin, Spain), consists of two parts. Part I involves performing VID water balances along fourteen hydrological years (1995 to 2008) with the following objectives: (1) the sequential identification and assessment of main water inputs and outputs, and (2) the sequential minimization of water balance closing errors.

This sequential approach allowed illustrating how the systematic closing errors, along with an appropriate knowledge of the system, directed the incorporation of the new and most important water balance components in our study area. To that end, the VID water balance is presented in three steps of increasing complexity: (1) a first, simple water balance that includes only readily measurable or easy to estimate components, (2) a second, more complex water balance that incorporates new components guided by the closing errors found in the first step, with special emphasis on estimation of actual crop evapotranspiration, and (3) a final water balance where some components are estimated through a monthly balance including the water content in the system and where canal seepage losses are incorporated as a significant input in VID.

Following the attainment of consistent water balances, part II will present the evolution of several irrigation performance indices along years 1995 to 2008 as affected by irrigation improvements that have taken place in this irrigation district (Barros et al., 2011).

2. Description of La Violada irrigation district (VID)

VID is located in the middle Ebro River basin in the lower reaches of the 19637-ha La Violada Gully watershed (north-east Spain; latitude: 41°59' – 42°04' N; longitude: 0°32' – 0°40' W) and is integrated in the Monegros I irrigation scheme (Fig. 1). The altitude ranges between 414 m in the north and 345 m in the south-west. The whole district (irrigable and non irrigable area) occupies an area of 5282 ha delimited by the Monegros, Violada and Santa Quiteria canals (Fig. 1), and has about 4000 ha of irrigable land. These canals supply irrigation water with excellent quality (EC < 0.4 dS/m) from the Gállego River, tributary of the Ebro River. The Monegros and, especially, the Violada canals showed infiltration problems right after construction (year 1934), due to the presence of gypsum in the soils and the deleterious effect of sulphate on concrete (Llamas, 1962).

The climate of the area is Mediterranean, dry, subhumid and mesothermic, with precipitations concentrated in spring and autumn. Mean annual values for the period 1986-2008 were 438 mm (precipitation), 13.8°C (air temperature) and 1166 mm (Penman-Monteith reference evapotranspiration, ET_0).

VID is underlain by a Tertiary impervious clay layer (ITGE, 1995) that prevents deep percolation, so that all or most of the return flows are intercepted by La Violada Gully. Thus, La Violada Gully watershed forms a closed hydrological system appropriate for performing water balances. The gypsum-rich alluvial soils over this impervious layer have favoured the development of a perched, shallow, unconfined aquifer at a mean depth of about 2.6 m (SEIASA, 2005). Coarse-textured soils are present in the glacis in the NE of VID, whereas silt deposits occur in the valley fills along the Valsalada and Artasona ditches (Fig. 1) (ITGE, 1995), where most ground waters flow towards La Violada Gully (SEIASA, 2005). A dense, open-ditch drainage network has been implemented in VID since the 1940's to alleviate waterlogging problems, although groundwater levels remain relatively high in some areas of the district (Sayah, 2008). Three natural gullies (Las Pilas, Azud and Valdepozos; Fig. 1) drain the upper dryland area of La Violada watershed and flow under the Monegros Canal into the drainage network (Isidoro et al., 2004).

Until 2008, 94% of VID was flood irrigated (5% sprinkle and 1% drip irrigation), generally with blocked-end plots. During the study period (1995 to 2008) some structural and management improvements have taken place in VID: (i) Construction of the elevated La Violada Canal that replaced the old concrete-lined La Violada Canal, seriously affected by seepage losses. The new Canal rendered service just before the 2003 irrigation season, reducing or eliminating its seepage losses; (ii) Intense reuse of drainage waters from the gully in the water-scarce 1999, 2005 and 2006 years; (iii) Better control of tail-waters from irrigation ditches due to new rules enforced by Confederación Hidrográfica del Ebro (CHE); (iv) Irrigation modernization through the construction of five internal reservoirs; and (v) Starting in 2008, transformation of flood irrigation into solid set sprinkler irrigation systems. Other factors in recent years influencing the VID hydrologic regime were the changes in crop patterns (from corn and alfalfa as dominant crops in the 1990's, to alfalfa and winter cereals in the 2000's), and irrigation restrictions in years 1999 and 2005 due to severe water limitations following winter seasonal droughts.

3. Materials and Methods

The study area comprises the irrigable area of VID (around 4000 ha; Table 1; Fig. 1) including the soil (root zone) and the shallow aquifer associated to La Violada Gully. The lower boundary is the impervious layer under VID (ITGE, 1995) and the lateral boundaries are the three irrigation canals surrounding VID and the location of the D-14 gauging station in la Violada Gully (Fig. 1). The return flows from VID discharge into the Gállego River through this gully.

3.1. First step, simplified water balance

A simple water balance was performed for the hydrological years (October 1 to September 30) of the study period (1995-2008). Only the main flow paths (easy to measure or estimate) were taken into account at this step, while other secondary flows and complex processes were not considered. Furthermore, the water volume storage in the system was assumed to be equal at the beginning of each hydrological year. The main water inputs considered were irrigation, I, and precipitation, P, and the main outputs were surface outflow, Q, and crop evapotranspiration, ET_c (assuming no water or salinity stress). The inputs and outputs were measured or estimated daily for the 1995 to 2008 hydrological years. For simplicity purposes, only the monthly or yearly aggregated values are reported.

The error (ε) of the simplified water balance is given by eq. 1:

$$\varepsilon = I + P - Q - ET_c \quad (1)$$

considering that the change in water storage in the system (ΔW) was equal to 0 for the hydrologic year. The units chosen for this balance and the following steps are mm (water height), with some terms (ET_c and P) directly measured in mm and others (I and Q) converted from volumetric values by dividing by the irrigable area and the appropriate unit conversion factor.

Daily irrigation volume (I) was taken from the records of water billed to the farmers provided by the VID Water User Association (Comunidad de Regantes de Almudevar; CRA) as measured at the head of the 42 irrigation intakes distributed along the three main canals (11 in Monegros, 16 in Violada and 19 in Quiteria) that supply water to VID. Daily surface outflow (Q) at the D-14 gauging station in La Violada Gully (Fig. 1) was provided by CHE. Daily precipitation (P) was measured at the Almudévar meteorological station (no.489; CHE) (Fig. 1).

Reference evapotranspiration (ET_0) was calculated with the FAO Penman-Monteith method (Allen et al., 1998), the most reliable procedure for this region (Martínez-Cob et al., 1998). The meteorological data needed to calculate ET_0 were taken daily from the Almudévar meteorological station. Crop evapotranspiration was calculated as $ET_c = K_c \cdot ET_0$ for each crop, where K_c is the crop coefficient. ET_c was estimated on a daily basis for the total irrigable area: irrigated crops (corn, alfalfa, sunflower, rice, wheat, barley, pepper, olive trees, and ray-grass) and not cultivated land, following the methodology described by Allen et al., (1998). The acquisition of data on the area of each crop was facilitated by CRA. Evapotranspiration by natural vegetation was considered unimportant for the level of approximation and the scale of this work.

The results obtained with the simplified water balance (eq. 1) show that the error was negative (i.e., outputs > inputs) in all the hydrological years (Table 1). Assuming steady-state conditions for water storage, these results suggest that other water inputs were missing, or that inputs were underestimated and/or outputs were overestimated.

3.2. Second step, improved water balance

Based on the results of the simplified water balance and on our previous knowledge of the study area (Faci et al., 2000; Isidoro et al., 2006), the analysis of potentially significant new components was carried out. The output ET_a (real or actual crop evapotranspiration, instead of ET_c) and other inputs (*OI*) as canal releases (*CR*), surface runoff (*SR*), municipal waste waters (*MW*), and lateral groundwater inflows (*GI*) were next considered. The improved water balance error (assuming $\Delta W = 0$ along the hydrological year, i.e., that the water stored in the system at the beginning of each hydrological year is similar) is given by eq. 2:

$$\varepsilon = I + P + CR + SR + MW + GI - Q - ET_a \quad (2)$$

Groundwater outflows from the district were considered negligible due to the narrow outlet of the basin at D-14 (Fig. 1) and the presence of an impervious stratum underlying the district. Spills and seepages from secondary irrigation ditches were not considered as additional inputs to the system because they are already included in the volume delivered for irrigation (*I*).

3.2.1 Actual Evapotranspiration (ET_a)

VID has inadequate irrigation distribution and delivery systems, and irrigation management is poor (large irrigation intervals, large delay times in water delivery, and marginal areas with deficit irrigation) (Faci et al., 2000). Hence, crop water-stress occurs widespread in VID and crop yields are lower than optimum, so that the real or actual crop evapotranspiration (ET_a) may be significantly lower than ET_c. In contrast, salinity stress in VID is negligible because of the low presence of salts in the irrigation water and soils and the low irrigation efficiencies (high leaching).

ET_a was calculated daily as $ET_a = K_s \cdot ET_c$, where K_s is a stress coefficient estimated for the growing season (except for the initial stage of crop development) by a daily soil-water balance performed for the most important irrigated crops. The actual crop areal distribution for each year in VID was not available preventing to perform soil water balances for the different crops actually present on each soil type. For the initial stage of crop development, for the non-growing season and for the non-cultivated land, the daily soil-water balance was performed only for the upper 20 cm soil following the methodology described for bare soils by Allen et al., (1998).

The daily soil-water balance depends on soil and crop characteristics. The average soil hydraulic properties were calculated for the 92 soil units determined by Playán et al., (2000) for the whole district area with the following mean values: field capacity (FC = 21% weight), wilting point (WP = 14% weight), average crop's rooting depth (Z_r = 0.927 m) and percentage of coarse fragments (S = 11.4%). The total available soil water (TAW) in mm was estimated from these values and the bulk density taken as 1.4 g/cm^3. The readily available soil water (RAW) was calculated as $RAW = p \cdot TAW$, where the evapotranspiration depletion factor (p) is the average fraction of TAW that can be depleted from the root zone before the crop experiences water stress. The p values, different for each crop, were taken from Allen et al., (1998).

To start the soil-water balance, the initial soil water content ($W_{s\,0}$) was set at FC at the beginning of the study period (1 October 1994). The equation for the daily soil water balance was defined as:

$$W_{s\,final} = W_{s\,initial} + P + I_s - ET_a - D \quad (3)$$

Where $W_{s\,initial}$ = soil water content at the beginning of the day, $W_{s\,final}$ = soil water content at the end of the day (and the $W_{s\,initial}$ for the next day), P = daily precipitation, and I_s and ET_a are irrigation and actual evapotranspiration for each crop in that day. When the actual $W_{s\,final}$ computed at the end of each day was above FC, the excess water was assigned to vertical drainage (D) below the root zone. D was set equal to 0 if $W_{s\,final} < FC$.

The stress coefficient (K_s) was calculated from the daily soil water content after P and I_s had been added to $W_{s\,initial}$:

$$K_s = \begin{cases} 1 & if \quad W_{s\,initial} + P + I_s \geq FC - RAW \\ \dfrac{(W_{s\,initial} + P + I_s) - WP}{(1-p)\cdot TAW} & if \quad W_{s\,initial} + P + I_s < FC - RAW \end{cases} \quad (4)$$

Since the daily irrigation volumes applied to each crop were not available, they were estimated by an average irrigation schedule (I_s) defined from surveys to local farmers. These interviews and the information gathered in CRA (Faci et al., 2000; Isidoro et al., 2004) allowed to establish (i) the approximate annual number of irrigations (9 for corn, 10 for alfalfa and 2 for winter crops), (ii) the average depth of each irrigation (110 mm for corn and alfalfa and 150 mm for winter crops), (iii) the time interval between irrigations (average of 13 days for corn and alfalfa), and (iv) the date of the first irrigation.

The number and volume of irrigations in each year were adjusted to the annual irrigation volumes applied in VID plus the approximate volumes of reused water [around 2 hm^3 per year (approximately 10% of I) of drainage water reuse in the dry years 1999, 2005 and 2006 through a new internal reservoir that collects the drainage waters from the Artasona ditch; data facilitated by CRA).

An average calendar was selected for each crop maintaining the approximate irrigation intervals established through the interviews to farmers of VID and maximizing crop water use (ET_a). It was assumed that the actual irrigations would take place around that average calendar date. The water balance was repeated for each crop moving the irrigation calendar from five days before to five days after the average calendar date defined from the survey. The results of the 11 soil-water balances performed for each crop were averaged assigning a higher weight (6) to the central calendar and decreasing weights (from 5 to 1) as the calendars departed form the central one. In this way, the inability of all farmers to irrigate in the best available date was taken into account.

This soil-water balance implicitly assumes that there is no upward flow from the water table, and does not account for preferential flows and irrigation uniformities within the plots. Although these factors could affect the estimations of ET_a and D, this approach provided ET_a values that were more realistic than the ET_c estimates.

3.2.2. Canal releases (CR)

For operational reasons, direct water spills from the Monegros Canal to the drainage network (Las Pilas, Azud and Valdepozos gullies) are endorsed occasionally through three gates (DT-3, DT-13 and DT-15; Fig. 1). These *CR* take place through gates different from the gates used to divert irrigation water, and thus *CR* are not included in the irrigation volumes provided by CRA (the term *I* in the balance) and have to be estimated independently.

Canal releases (*CR*) for DT-3 and DT-13 gates were calculated from daily records of the water level in the canal, the opening dates and heights of the gates, and the width of the gates provided by CHE. For gate DT-15, CHE only provided information on its opening dates. The rises in the hydrograph at D-14 in some of these days without precipitation and irrigation events were assumed to be *CR* through DT-15. The volumes of these *CR* were estimated by subtracting the flow above the hydrograph levels before and after the rise.

3.2.3. Surface Runoff (SR)

SR may originate from precipitation runoff in the dry land area located within La Violada gully watershed (especially the land north of Los Monegros Canal) and may flow into VID through three natural gullies (Fig. 1). The daily *SR* volumes were identified in the D-14 hydrograph as flow peaks in the same day or following days after a precipitation event. These volumes were estimated by subtracting from the hydrograph the volumes measured on the days before the hydrograph rise and the maximum-curvature point in the falling limb of the hydrograph, which was assumed to be the end of the superficial flow due to precipitation (Aparicio, 1994). The volumes subtracted for each rain period were aggregated to calculate the monthly *SR*. This *SR* includes the runoff originating from the non-irrigable land within the district and in the irrigable land itself, as it is calculated at the outlet of the system (D-14). The latter should not be included as an input to the system, but it is deemed much lower than the *SR* from dryland.

3.2.4. Municipal Waste Waters (MW)

The daily volumes of water supplied from the main canals to municipal and industrial users within VID were obtained from CRA, and their wastewater returns (*MW*) were taken as 80% of the supply water (Isidoro et al., 1999).

The three terms *CR*, *SR*, and *MW* flow directly into La Violada Gully and have to be subtracted from the outflow *Q* to isolate the actual outflow originating from the irrigated system ($Q^* = Q - CR - SR - MW$).

3.2.5. Groundwater inflows (GI)

Lateral groundwater inflows were estimated in 1995, 1996, 2007 and 2008 through chemical hydrograph separation (Caissie et al., 1996) assuming complete mixing of waters in the gully (sample at D-14). A three end-member mixing analysis (EMMA) was performed following the methodology given by Isidoro et al. (2006) and Isidoro et al. (2010) given the different EC and Cl^- for canal irrigation waters (Q_0: EC = 0.41 ± 0.03; Cl^- = 0.95 ± 0.22) (mean ± standard deviation), drainage waters originated in VID (Q_d: EC = 2.64 ± 0.09; Cl^- = 2.10 ± 0.41) and groundwater inflows (Q_g: EC = 3.10 ± 0.13; Cl^- = 7.00 ± 0.38).

3.3. Third step, final water balance

The results obtained with the improved water balance (eq. 2) (assuming $\Delta W = 0$ for the hydrological year) showed that the error was still negative (i.e., outputs > inputs) in all the hydrological years (Table 1). This unbalance was tentatively attributed to canal seepages (*CS*), and this new input was incorporated into the final water balance. Also, the change in water storage in the system was considered (ΔW different to cero), defined as the sum of the storage in the soil (ΔW_s) and in the aquifer (ΔW_{ph}) calculated separately in both sub-systems. Therefore, the equation for the final water balance error was (eq. 5):

$$\varepsilon = I + P + CR + SR + MW + GI + CS - Q - ET_a - \Delta W \quad (5)$$

Thus, this third step includes two innovations in relation to Step 2: the incorporation of *CS* as a new input and the accounting for changes in the water stored in the system (ΔW). Both terms are calculated together through an iterative selection process of the best aquifer parameters and canal seepage rates minimizing the monthly closing errors of the balance, as explained in the following sections.

The reasons to include *CS* as a significant input in VID were: (1) the long-term CRA knowledge on important seepage losses in the excavated, concrete-lined, old Violada canal, (2) the water balance closing errors (ε) estimated by eq. 2, that were more negative (i.e., higher undetermined inputs as *CS*) before 2003 (mean 1995-2002 ΔW = -263 mm), with the old Violada canal in operation, than after 2003 (mean 2003-2008 ΔW = -119 mm), with the new elevated Violada canal in operation (i.e., low or non existent seepage losses), (3) the higher monthly ε from June to September when *I* is highest (Fig. 2), pointing to the presence of unaccounted inflows especially during the irrigation season, when canals are full of water and seepage losses would be higher, and (4) the hydrograph in the D-14 gauging station showing that flows were higher than zero in periods without water inputs (*I*, *CR*, *SR*, *MW* or *P*) but with the canals full of water (data not presented).

Furthermore, the relationships between the monthly irrigation volumes applied in VID (*I*) and the net monthly surface outflow (Q^*) originating from the irrigable land ($Q^* = Q - CR - SR - MW$; outflow water minus surface inflows previously defined that go directly to La Violada Gully) were analyzed for the April to September irrigation months, when the canals are full of water (Fig. 3). The linear regression ($Q^* = a + b \cdot I$) performed showed significant differences (P<0.001) for the 1998-2002 and 2003-2008 periods, with identical slopes and significantly different intercepts (P<0.005).

Neglecting ΔW and GI, the water balance (eq. 5) can be written as $I + P = Q^* + ET_a - CS$. Transforming this equation into $Q^* = CS + [1 - (ET_a - P)/I] \cdot I$ (Isidoro et al., 2004), these intercepts could be assumed to be the monthly CS volume estimates. As hypothesized, CS was much higher with the old (1995-2002 period) than with the new (2003-2008 period) Violada Canal in operation.

Since direct measurements of CS could not be made in VID, it was estimated through a soil-aquifer water balance analysis with the concurrent measurement of the wetted areas in the irrigation canals (for the 1998 to 2008 period with available data of canal wetted areas). Also, this methodology allowed the estimation of the change in the water storage in the system ($\Delta W = \Delta W_s + \Delta W_{ph}$). For simplicity purposes, the soil and aquifer water balance and its terms were estimated in hm^3 and the CS and ΔW estimates were then transformed into mm (dividing by the irrigable area, around 4000 ha depending on years, and the appropriate unit conversion factor) to incorporate them in equation 5 and thus evaluate the water balance closing errors.

3.3.1. Canal Seepage (CS)

Since two periods (1998-2002 with potential CS from Violada, Monegros and Santa Quiteria lined canals and 2003-2008 without CS from the new elevated Violada canal) were previously identified with potentially different CS values, canal seepages were estimated monthly for each period as a function of their aggregated wetted areas (A_c) in m^2 and their mean areal seepage rates (s; $hm^3 \cdot month^{-1} \cdot m^{-2}$) (eqs. 6 and 7):

$$CS_1 = s_1 \cdot A_{c1} \text{ (1998-2002 period)} \quad (6)$$

$$CS_2 = s_2 \cdot A_{c2} \text{ (2003-2008 period)} \quad (7)$$

A_{c1} is the total wetted area of Violada canal (A_v) and Monegros and Quiteria canals (A_{mq}) ($A_{c1} = A_v + A_{mq}$); A_{c2} is the wetted area of Monegros and Quiteria canals

($A_{c2} = A_{mq}$); s_1 is the mean seepage rate for Violada, Monegros and Quiteria canals from 1998 to 2002 and s_2 the mean seepage rate for Monegros and Quiteria canals from 2003 to 2008, respectively. The wetted areas of these canals were obtained by multiplying their lengths by their cross-sectional wet perimeters calculated from their shapes and the daily records of water level (*H*) provided by CHE. These lengths were 10.4 km for Violada, 14.7 km for Monegros and 5.4 km for the non-elevated section of Quiteria. Thus, the three canals were taken into account in the 1998-2002 period, whereas Violada was not included in the 2003-2008 period, after its rebuild as an elevated canal.

For each period, the seepage rates were selected that minimized the sum of the absolute value of the mean error (ε_m) and the standard deviation [$S(\varepsilon)$] of the error (ε) of the monthly water balance defined by the equation 5; [$|\varepsilon_m| + S(\varepsilon)$]. This condition provided *CS* estimates that minimized both the overall and the monthly water balance closing errors for the period 1998-2008 with available data on canal's wetted area.

3.3.2. Soil-aquifer water balance

In order to calculate the monthly error (eq. 5), it was necessary to estimate the change in the soil ($\Delta W_s = W_{s\,t+1} - W_{s\,t}$) and in the aquifer water storage ($\Delta W_{ph} = W_{ph\,t+1} - W_{ph\,t}$) in each month (t). To this end, the system was divided into two sub-systems (Fig. 4): the soil (the unsaturated zone from the soil surface to the water table surface), and the aquifer (the saturated zone from the water table surface to the bottom of La Violada Gully, or depth of the aquifer contributing to the gully flow).

First, a water balance for the soil sub-system was performed. The terms of the daily soil-water balance performed to estimate ET_a (section 3.2) were aggregated monthly and multiplied by the annual crop surfaces in VID to obtain the monthly values of *D* and ET_a for the irrigable area.

The soil water content at the end of month "t" or the beginning of month "$t+1$" ($W_{s\,t+1}$) was obtained from eq. 8:

$$W_{s\,t+1} = W_{s\,t} + I_{s\,t} + P_t - ET_{a\,t} - D_t \quad (8)$$

where $W_{s\,t}$ is the volume of water stored in the soil at the beginning of month t, $I_{s\,t}$ is the irrigation established by the average irrigation calendar, P_t is precipitation, $ET_{a\,t}$ is actual crop evapotranspiration, and D_t is the vertical drainage from the soil to the aquifer (Fig. 4) (all values in month t aggregated from the daily soil water balance). The initial soil water content ($W_{s\,0}$) for this balance was the average soil water content in October 1997 calculated by the daily soil water balance used to estimate ET_a.

Second, a water balance for the aquifer sub-system was performed. The volume of drainable water stored in the aquifer at the beginning of month "$t+1$" ($W_{ph\,t+1}$) was obtained from eq. 9:

$$W_{ph\,t+1} = W_{ph\,t} + D_t + CS_t - Q_{b\,t} \quad (9)$$

where $W_{ph\,t}$ is the volume of drainable water stored in the aquifer at the beginning of month t, $Q_{b\,t}$ is the discharge from the aquifer to La Violada Gully in month t and CS_t is the canal seepage recharging the aquifer in month t. $Q_{b\,t}$ was assumed to be proportional to $W_{ph\,t}$ (Chow et al., 1994) (eq. 10):

$$Q_{b\,t} = k \cdot W_{ph\,t} \quad (10)$$

where k is the discharge coefficient of the aquifer.

Since CS_t is different in the 1998-2002 and 2003-2008 periods (eqs. 6 and 7), equation 9 was subdivided into eqs. 11 and 12 for each period:

$$W_{ph\,t+1} = W_{ph\,t} + D_t + s_1 \cdot A_{c1\,t} - k \cdot W_{ph\,t} \quad \text{(1998-2002 period)} \quad (11)$$

$$W_{ph\,t+1} = W_{ph\,t} + D_t + s_2 \cdot A_{c2\,t} - k \cdot W_{ph\,t} \quad \text{(2003-2008 period)} \quad (12)$$

The initial (October 1997) water stored in the aquifer ($W_{ph\,0}$, in ·1000 m^3) that can be drained naturally towards La Violada Gully is related to the height of the water table (Z_0, in m) above the level of the gully bottom (eq. 13):

$$W_{ph\,0} = 10 \cdot Z_0 \cdot a \cdot \mu \tag{13}$$

where a is the area of the aquifer (actually unknown, but the irrigable area can be taken as a rough estimate, ~4000 ha) and μ is the drainable pore space (Ridder, 1994) that was taken as 0.125, the average difference between total porosity and field capacity for the VID soils (Playán et al., 2000; Sayah, 2008).

3.3.3. Joint estimation of canal seepage and soil-aquifer water storage

As a first approximation, the monthly aquifer water balance was calculated by eqs. 11 (1998-2002 period) and 12 (2003-2008 period) for all the $W_{ph\,0}$ values corresponding to Z_0 values ranging from 0.2 m to 3.0 m in intervals of 0.1 m and all the k values ranging from 0.2 month^{-1} to 0.9 month^{-1} in intervals of 0.1 month^{-1}. For each $Z_0 - k$ combination, the $s_1 - s_2$ combinations minimizing $|\varepsilon_m| + S(\varepsilon)$ were selected. Once the range of $W_{ph\,0}$ and k values with minimum $|\varepsilon_m| + S(\varepsilon)$ were obtained, two subsequent finer approximations allowed for estimating Z_0 (i.e., $W_{ph\,0}$) and k within a narrower range and obtaining the final s_1 and s_2 estimates leading to the minimum sum of $|\varepsilon_m| + S(\varepsilon)$ for both periods.

The seepage rates for Violada canal (s_v) and Monegros and Quiteria canals (s_{mq}) were estimated from s_1 and s_2 as (eqs. 14 and 15):

$$s_v = s_1 \cdot \frac{A_v + A_{mq}}{A_v} - s_2 \frac{A_{mq}}{A_v} \tag{14}$$

$$s_{mq} = s_2 \tag{15}$$

where A_v and A_{mq} are the mean wetted areas of Violada and Monegros + Quiteria canals, respectively, for the 1998-2002 period assuming that seepage from the elevated Violada canal was negligible in the 2003-2008 period.

For comparison purposes with the revised literature, the annual seepage volumes (CS) are reported in terms of canal unit length ($hm^3\ km^{-1}\ yr^{-1}$) and in L/s·100 m of canal length.

4. Results and Discussion

Table 1 summarizes the 1995-2008 water balances performed in VID for the 4000-ha irrigable land. The mean irrigated area (3565 ha) was relatively similar along the study period (coefficient of variation CV = 13%), with a minimum value of 3081 ha in the driest year 2005. The lowest value of 2198 ha in 2008 was not representative of normal irrigation practices since it was due to irrigation modernization works in VID.

Annual mean irrigation (I) was 732 ± 219 mm/yr (mean ± standard deviation; CV = 30%), with a significant decrease following year 2004 (mean 2005 to 2008 I = 445 ± 128 mm/yr) due to water restrictions in 2005 and the on-going irrigation modernization that caused a shift in crop patterns from summer to winter crops. Annual mean precipitation (P) was 446 ± 111 mm/yr (CV = 25%), with a lowest value of 297 mm in the driest 2005 year. Annual mean surface outflow (Q) was 805 ± 320 mm/yr, with a high annual variability (CV = 40%). In agreement with the lower volumes of irrigation in 2005-2008, Q was much lower in this period (Q = 391 ± 108 mm/yr) than in the 1995-2004 period (Q = 970 ± 194 mm/yr). Annual mean reference evapotranspiration was uniform along the study period (ET_0 = 1166 ± 39 mm/yr; CV = 3%), and annual mean potential crop evapotranspiration (ET_c = 950 ± 60 mm/yr) was also very stable (CV = 6%).

4.1. First step, simplified water balance

Independently of the variability of water inputs and outputs in VID, the simplified water balance (eq. 1) was systematically negative in all years (i.e., outputs > inputs) (Table 1). The mean annual water balance closing error (ε) was -577 ± 117 mm/yr, equivalent to a -33% error over the sum of outputs ($Q + ET_c$) (Fig. 5). Errors varied among years, with absolute values below 30% in four years and above 40% in two years (Fig. 5).

These consistently negative annual water balances suggest that water inputs were underestimated, and/or water outputs overestimated. Whereas I, P and Q were confidently measured, it was anticipated that ET_c did not reliably represented the actual crop evapotranspiration (ET_a) because of the poor irrigation management in VID. Thus, it was hypothesized that, due to crop water stress, ET_a could be significantly lower than ET_c. Hence, a second step, improved water balance was performed substituting ET_c by ET_a. Other potential inputs (*OI*) were also considered in the improved water balance.

4.2. Second step, improved water balance

The new terms in the improved water balance equation (eq. 2) were the output ET_a and the inputs canal releases (*CR*), surface runoff (*SR*), municipal wastewaters (*MW*) and groundwater inflows (*GI*).

4.2.1. Actual Evapotranspiration (ET_a)

The calculated mean I_s (irrigation established by an average calendar, including water reuse) for the study period was 778 mm/yr, only 6% higher than the measured mean I (732 mm), giving confidence to the performed soil-water balance and the resulting estimates. The mean annual ET_a for the study period was 655 ± 84 mm/yr, with a minimum of 510 mm in the driest 2005 year (the lowest ET_a of 482 mm in 2008 was due to other reasons given above) (Table 1). This mean ET_a was 31% lower than the mean ET_c (950 ± 60 mm/yr), with a maximum difference of 44% in the driest year 2005. Faci et al., (2000) and Isidoro et al., (2004) detailed the poor irrigation management in VID (large irrigation intervals, large delay times in water delivery, and marginal areas with deficit irrigation). These intervals and doses were also well established by local interviews and by the information facilitated by CRA, and have not changed along the study period as they depend on the irrigation distribution system that has been unchanged until 2008. Therefore, crops were affected by water stress due to improper irrigation infrastructures and irrigation management in VID. However, the actual crops yields in VID obtained from interviews were reasonable and for some crops as corn and alfalfa not far to the optimum yields for flood-irrigated crops. The differences between ET_c and ET_a for each crop's growing season were lower than for the whole hydrological year and the values obtained were comparable with the actual yields obtained from interviews.

Isidoro et al., (2004) performed a somewhat similar soil water balance in VID for the hydrological years 1995 and 1996 for every crop upon five soil classes (different in their water properties) established from the data of Playán et al., (2000) and using only one irrigation calendar for each crop on each soil type. Their results (738 mm in the hydrologic year 1995 and 759 mm in 1996) were very similar to the annual ET_a's obtained with a single average soil in this work (696 mm and 761 mm respectively, Table 1). These results show that including the different soil properties in the balance did not affected greatly the calculated ET_a.

The substitution of ET_c by ET_a in eq. 1 reduced the average water balance closing error to ε = -283 ± 141 mm/yr, equivalent to -18% of the sum of outputs (eq. 2a, Fig. 5). This error was much lower than the original -33% average error obtained with ET_c (eq. 1, Fig. 5). Even so, Fig. 5 shows that errors were still negative in all years.

Thus, other inputs (*OI*) were considered next in the improved water balance equation (eq. 2).

4.2.2. Other inputs (OI): canal releases (CR), surface runoff (SR), municipal waste waters (MW) and groundwater inflows (GI)

Annual mean *CR* for the study period was 39 ± 23 mm/yr, with a maximum of 100 mm in 1995 and a minimum of 11 mm in 1997 (Table 1). This mean *CR* was only 5% of the mean *I*, and lower than 3% of total outputs, indicating that this input was unimportant in VID.

Annual mean *SR* for the study period was 34 ± 24 mm/yr, with a maximum of 90 mm in 2001 and a minimum of 7 mm in the driest 2005 year (Table 1). This input was therefore considered minor in VID.

The yearly *MW* volumes were stable (between 12 and 5 mm/yr; Table 1) and very low (mean of 9 ± 2 mm/yr for the study period) in VID.

The end-member mixing analysis (EMMA) shows that the average *GI* (Q_g in Table 2), given in percentage of *Q*, was 3.5% in the 1995, 1996, 2007 and 2008 irrigation seasons, 1.4% in the 2007 and 2008 non-irrigation seasons, and 2.0% in the 2007 and 2008 hydrological years (Table 2). Since these Q_g values were very low and the analysis was not performed in the rest of years (due to the lack of required chemical data), *GI* was considered irrelevant and, therefore, was not included in eqs. 2 and 5.

Based on the annual mean *CR*, *SR* and *MW* volumes for the study period (Table 1), the term other inputs ($OI = CR + SR + MW$) was 82 mm/yr, equivalent to 7% of total water inputs (*I*, *P*, *OI*). These surface inputs that flow directly into La Violada Gully were discounted from the mean outflow measured at D-14 (Q = 805 mm/yr) to obtain the mean net outflow ($Q^* = Q - OI$ = 723 mm) originating from the VID irrigated area. This Q^* for the 1995-2008 period (equivalent to 90% of *Q*) was higher than the mean

Q_d estimated through EMMA in 2007-2008 (78.5% of Q, Table 2), pointing to the presence of some additional diluted flows.

The improved water balance (eq. 2) closed with an average error of ε = -201 mm ± 122 mm/yr (Table 1), equivalent to -13% of the sum of outputs (eq. 2, Fig. 5). All the yearly errors were lower than those obtained with the simplified water balance, varying in absolute terms between a maximum of about 21% (years 1995 and 2001) and a minimum below 2% (year 2006) (Fig. 5). Nevertheless, all the yearly closing errors were still negative (Fig. 5), so that the potential existence of other undetermined inputs was next considered in the third step, final water balance.

4.3. Third step, final water balance

The monthly water balance errors obtained with the improved water balance (eq. 2) were higher in the summer months, when irrigation took place and the three main canals were permanently full of water (Fig. 2). The mean 1995-2002 annual error (ε = -263 mm) obtained with the old Violada canal in operation was significantly higher (P<0.05) than the mean 2003-2008 annual error (ε = -119 mm) obtained with the new elevated Violada canal in operation (i.e., negligible seepage losses). Furthermore, the I-Q^* linear regressions for the 1998-2002 and 2003-2008 periods were significantly different (P<0.05), and the CS estimates (i.e., the intercepts of the regressions) were higher in 1998-2002 (CS = 39 mm/month) than in 2003-2008 (CS = 17 mm/month) (Fig 3). Hence, a final water balance was performed incorporating canal seepages (CS) as an additional input and taking into account the change in water storage (eq. 5).

The water balances previously performed assumed no changes in the water stored in the system (i.e., ΔW = 0) along a hydrological year. However, water balances performed on a monthly basis showed that a fraction of the irrigation applied in April replenished the soil and aquifer pools (decreasing the expected Q) and was released in

May (increasing the expected Q) (Fig. 2). Thus, monthly estimates of the water stored in the soil (ΔW_s) and in the aquifer (ΔW_{ph}) were obtained and the corresponding soil drainage or aquifer recharge (D), and aquifer discharge to La Violada Gully (Q_b) were calculated (Fig. 4). Although the monthly soil water contents were fairly constant (W_s = 235 ± 23 mm; CV = 11%), they were somewhat higher during the October to March non irrigation season due to lower winter ET_a values (Fig. 2). The 1998-2008 annual average D was 537 ± 135 mm/yr (CV = 25%), varying from a low mean monthly value of 16 mm/month during the non irrigation season to a high mean monthly value of 73 mm/month during the irrigation season. The 1998-2008 average W_{ph} was 66 ± 17 mm (CV = 26%), with monthly average values decreasing along the non irrigation season and increasing along the irrigation season, with recharge from irrigation taking place. Also, the water content in the aquifer was higher before the construction of the new La Violada Canal (W_{ph} = 80 ± 9 mm) than thereafter (W_{ph} = 55 ± 13 mm). The 1995-2008 annual average Q_b was 701 ± 182 mm/yr (CV = 26%), with a monthly trend and behavior before and after the construction of La Violada Canal similar to that for W_{ph}.

The main results from the monthly soil-aquifer balances are the CS and s estimates. Table 3 shows the sensitivity analysis performed to assess the best possible combinations of k (aquifer discharge coefficient) and $W_{ph\,0}$ (initial water storage in the aquifer) and the corresponding s and CS estimates for the 1998-2002 (s_1 and CS_1) and 2003-2008 (s_2 and CS_2) periods that minimize the sum of the absolute mean (ε_m) and the standard deviation [S(ε)] of the error (ε) of the water balances. The optimum values are also shown in Table 3. The range of variation of s and CS for each period was small, and the maximum absolute difference with the optimum CS estimate was 1.2 hm^3/yr for the 1998-2002 period and 0.8 hm^3/yr for the 2003-2008 period. Hence, the CS estimates were relatively constant regardless of the aquifer characteristics, giving confidence to these estimates.

The 1998-2008 annual average *CS* estimate for $k = 0.884$ and $W_{ph\,0} = 1.7$ hm^3 (optimum values obtained from the model) was 6.5 hm^3/yr, equivalent to 163 ± 80 mm/yr (CV = 49%). The mean annual *CS* estimate in the 1998-2002 period (old La Violada Canal in operation) was 9.8 hm^3/yr (Table 3), equivalent to 246 mm/yr and with all annual values well above 200 mm (Table 1), whereas the mean annual *CS* estimate in the 2003-2008 period (new La Violada Canal in operation) was 3.8 hm^3/yr (Table 3), equivalent to 94 mm/yr and with all annual values close to or below 100 mm (Table 1). These *CS* losses were 29% (1998-2002) and 17% (2003-2008) of the applied irrigation volumes (*I*) (VID lies at the head of the Monegros Scheme with the main canals around it conveying water for the whole scheme and thus *CS* is a much lower fraction of the total irrigation in the Monegros Scheme). The investment in lining La Violada Canal does not necessarily imply water savings at the watershed level from a quantity point of view, since most of these canal seepages return to the Gállego river through La Violada Gully and may be potentially used downstream by other users. However, this investment may lead to important water savings from a quality point of view, because the quality of these *CS* is degraded as it traverses the soil and mixes in the Gully with low quality drainage waters. Hence, as compared to canal waters, these seepages may be regarded as a loss in the water available downstream because its degraded quality may limit other potential uses within or outside the VID watershed. Canal seepages were high and comparable to other values reported in the literature. Thus, our seepage rates were equivalent to 1.81 L/s per 100 m of canal for La Violada, and 0.57 L/s per 100 m of canal for Monegros and Quiteria, similar to the ranges found in lined canals in India [0.71 to 1.88 L/s per 100 m (Rastogi and Prasad, 1992)] and in

Pakistan [0.8 to 1.11 L/s per 100 m (Arshar et al., 2009)]. As expected, these seepage rates were much lower than those for unlined canals [3.52 L/s per 100 m of canal; Ahmed and Umar (2008)]. In terms of mean annual seepage volumes per unit length of canals, *CS* was 0.57 hm^3 km^{-1} yr^{-1} for Violada and 0.19 hm^3 km^{-1} yr^{-1} for Monegros and Quiteria. This last value is similar to the range of 0.11-0.28 hm^3 km^{-1} yr^{-1} found by Leigh and Fipps (2003) for concrete canals in Texas, but the Violada value was much higher, indicating that the old canal was seriously deteriorated and that the construction of the new elevated canal was a sensible approach to decrease seepage losses.

These estimates assume that all the balance-estimated *CS* originated from the main canals (Violada, Monegros and Quiteria), neglecting the seepage from the secondary distribution system. If the seepages from the secondary ditches were considered, the actual seepage rates of the main canals would be somewhat lower, but there were not enough data to incorporate them into the balance.

The final water balance with the inclusion of *CS* (Table 1, eq. 5) had a mean closing error of 0.002 mm, equivalent to 0% of total outputs. This low error is the consequence of the conditions imposed to estimate *CS*. It is more relevant that the annual closing errors were in all cases low and within ±10% of total outputs (Fig. 5).

5. Conclusions

The sequential assessment of water balances in La Violada irrigation district (VID) was based on the successive incorporation of new terms as deemed necessary from the closing errors of each step-balance, coupled to a proper knowledge of the study area. This assessment proved to be a sensible approach to identify and estimate the main unknown water balance terms and to achieve a better understanding of the hydrologic system.

The analysis of long time-series hydrologic data in VID was appropriate to assess the need to incorporate critical water balance components such as canal seepage (*CS*) and actual crop's evapotranspiration (ET_a) instead of potential *ET* (ET_c). This approach enabled to obtain time-averaged values of the water balance components and to identify and quantify important changes affecting the hydrology of the system such as changes in irrigation practices and the rebuild of the old and deteriorated Violada canal that significantly reduced seepage losses. Particularly, the water balance performed showed that the construction of the new, elevated Violada canal was a sound investment, since *CS* decreased by 6.2 hm^3/yr after rebuild of the new canal. This important water saving in VID emphasizes the relevance of a proper maintenance of the distribution network.

Following the sequential improvements performed with this approach, the final water balances for the period 1998-2008 presented annual closing errors within ±10% of total outputs. Taking into account the complexity of the studied system, these low errors give confidence to the water balances performed and to the parameters estimated in VID.

These VID water balances could be improved if future work is devoted to (i) better ET_a estimates using the actual crop distributions upon the different soil types; (ii) more reliable estimates of groundwater inputs through improved mixing analysis and (iii) field measurements of canal seepages that will validate and/or refine the current estimates.

After the attainment of consistent water balances and hydrological parameter's estimates in VID, part II of this study will present the evolution of several irrigation performance indices along years 1995 to 2008 as affected by irrigation improvements that have taken place in this irrigation district.

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Figures

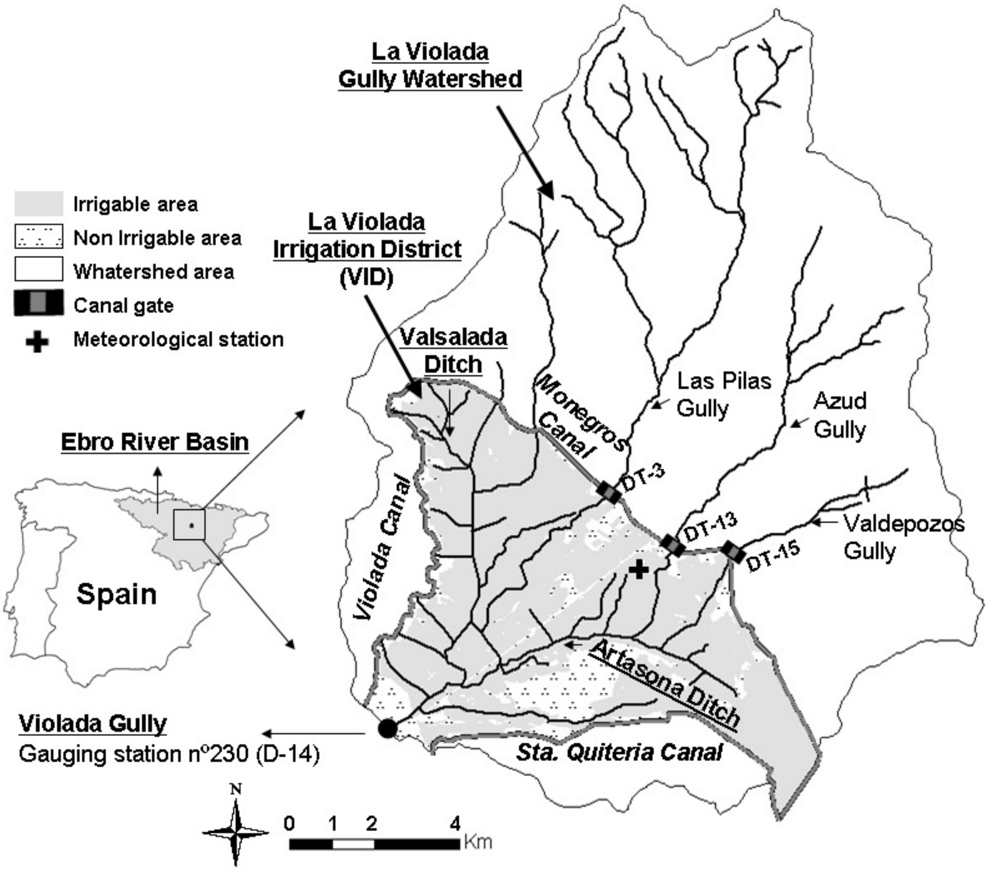

Figure 1.

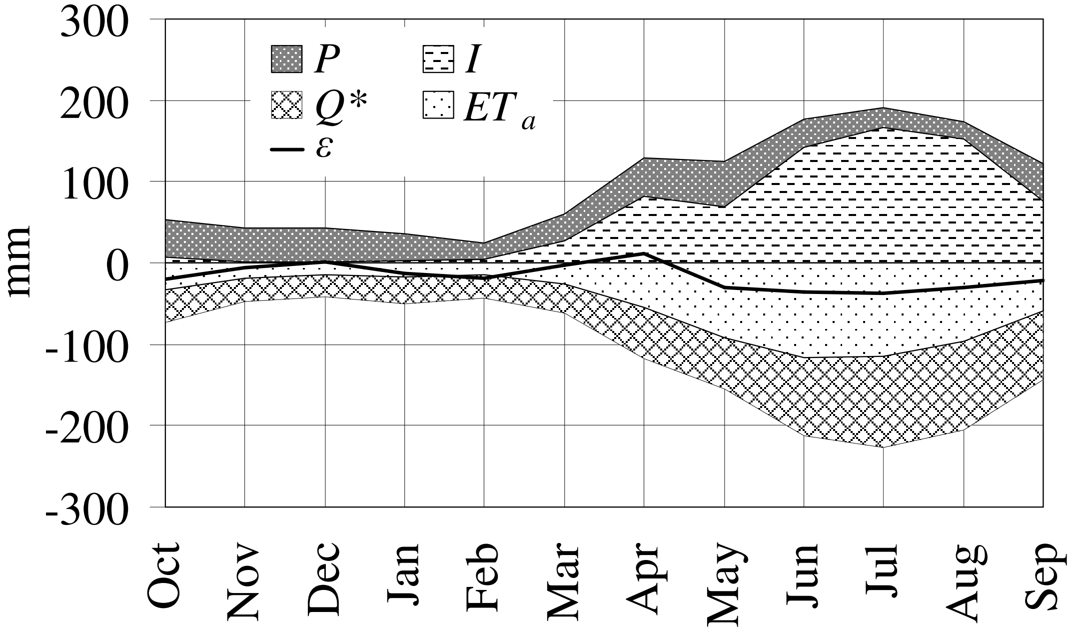
300
200
100
0
-100
-200
-300
mm
P
I
Q*
ET a
ε
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep

Figure 2.

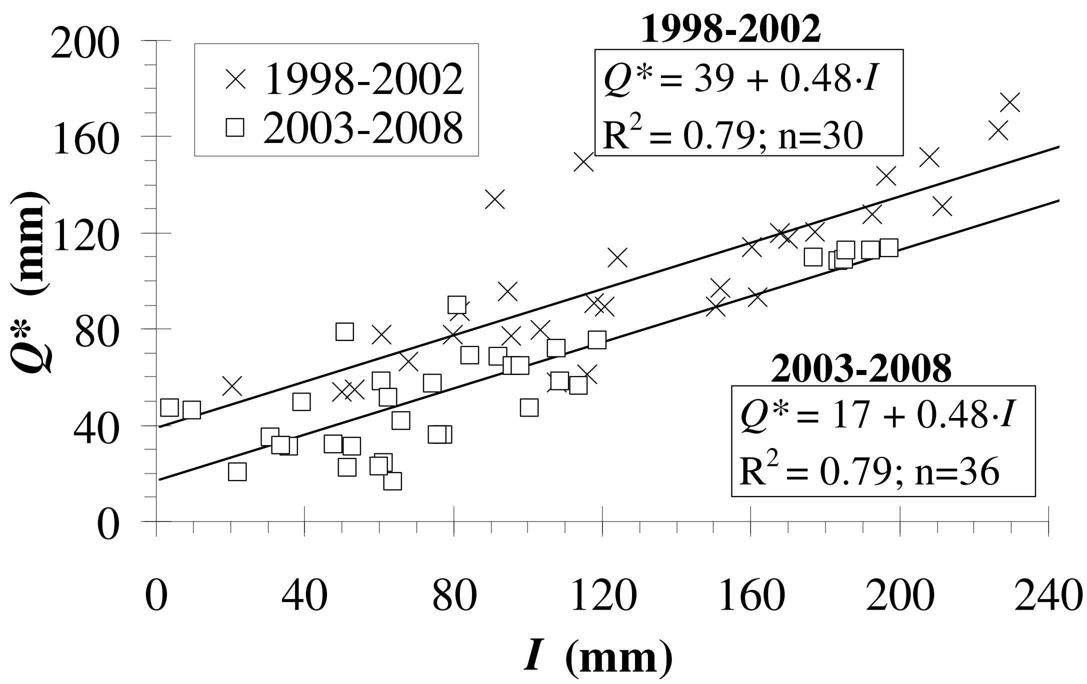
1998-2002
2003-2008
1998-2002
$Q^* = 39 + 0.48 \cdot I$
$R^2 = 0.79$; n=30
2003-2008
$Q^* = 17 + 0.48 \cdot I$
$R^2 = 0.79$; n=36
Q^* (mm)
I (mm)
0
40
80
120
160
200
240

Figure 3.

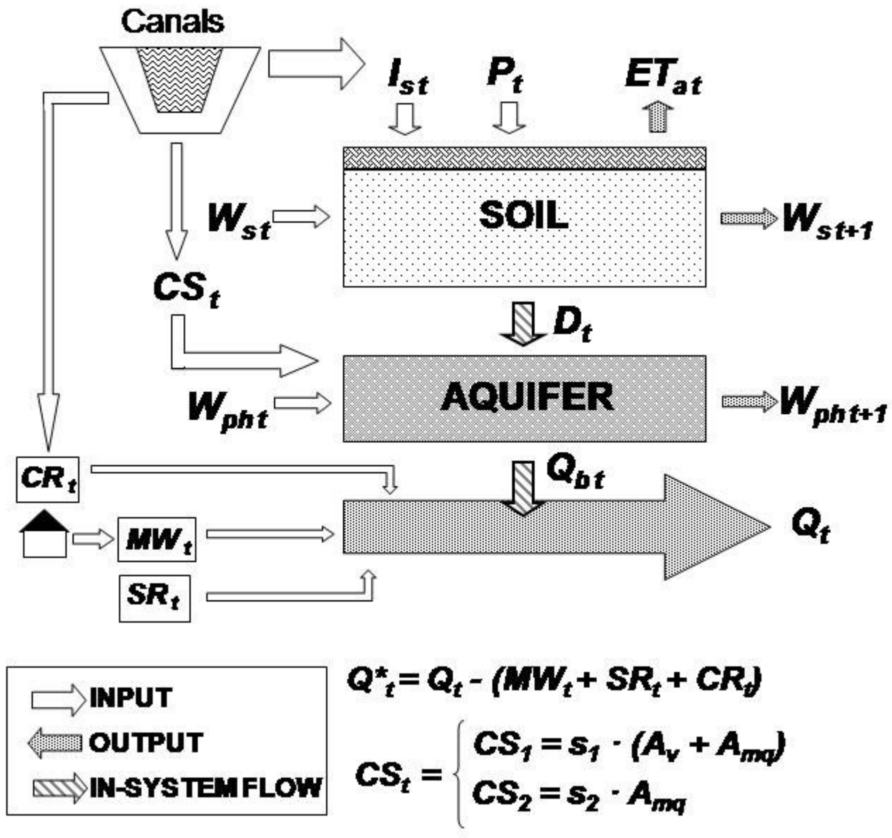
Canals
I st
P t
ET at
SOIL
W st
W st+1
CS t
D t
AQUIFER
W pht
W pht+1
CR t
Q bt
MW t
Q t
SR t
INPUT
OUTPUT
IN-SYSTEM FLOW
Q*t = Qt - (MWt + SRt + CRt)
CSt = { CS1 = s1 · (Av + Amq) ; CS2 = s2 · Amq

Figure 4.

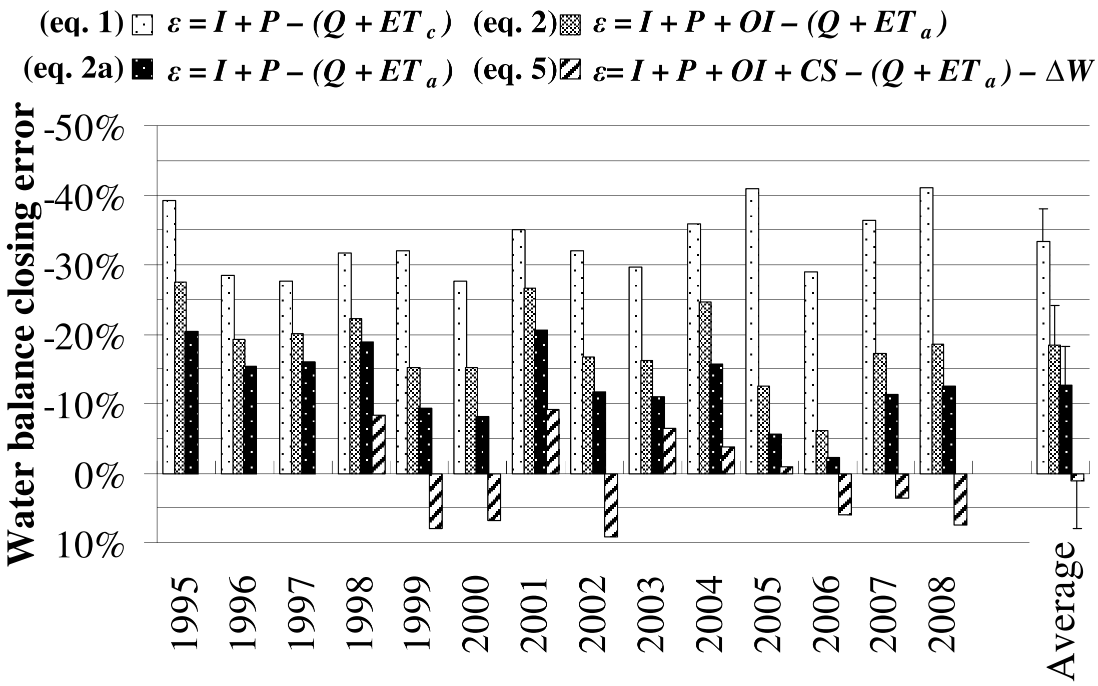
(eq. 1) ε = I + P − (Q + ET c)
(eq. 2) ε = I + P + OI − (Q + ET a)
(eq. 2a) ε = I + P − (Q + ET a)
(eq. 5) ε= I + P + OI + CS − (Q + ET a) − ΔW
Water balance closing error
-50%
-40%
-30%
-20%
-10%
0%
10%
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
Average

Figure 5.

Tables

Table 1. Sequential steps of the water balance performed in La Violada irrigation district along the 1995 to 2008 hydrological years. The numbers before the water balance errors in the table refer to the equations in the text.

Water balance components	Hydrological years														
	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	Mean
Irrigable area (ha)	3951	3951	3933	3950	3933	4001	4048	4052	4016	4018	4013	4013	4013	4013	3993
Irrigated area (ha)	3693	3732	3738	3762	3264	3806	3783	3805	3674	3798	3081	3762	3810	2198	3565
First step, simplified water balance (eq. 1)															
Irrigation, I (mm)	957	937	868	1026	663	787	919	777	792	738	421	544	542	274	732
Precipitation, P (mm)	299	585	648	358	427	538	549	375	542	432	297	456	369	363	446
Drainage, Q (mm)	1038	1125	1165	1059	659	854	1268	735	913	884	310	427	527	300	805
Potential Crop evapotranspiration, ET_c (mm)	1031	1003	931	966	944	978	990	958	982	941	906	979	907	779	950
(1) Error ($\varepsilon = I + P - Q - ET_c$)	*-812*	*-605*	*-579*	*-641*	*-514*	*-506*	*-790*	*-541*	*-562*	*-656*	*-499*	*-406*	*-522*	*-443*	*-577*
Second step, improved water balance (eq. 2)															
Canal Releases, CR (mm)	100	40	11	18	40	45	19	39	49	69	38	18	30	27	39
Surface Runoff, SR (mm)	18	27	58	34	26	55	90	23	23	60	7	12	25	11	34
Municipal Waste Waters, MW (mm)	7	7	7	7	11	11	12	8	10	7	11	11	9	10	9
Actual crop evapotranspiration, ET_a (mm)	696	761	731	719	627	708	735	647	677	667	510	638	574	482	655
(2) Error ($\varepsilon = I + P + CR + SR + MW - Q - ET_a$)	*-353*	*-290*	*-303*	*-335*	*-119*	*-126*	*-413*	*-161*	*-175*	*-245*	*-47*	*-25*	*-125*	*-98*	*-201*
Third step, final water balance (eq. 5)															
Canal Seepage, CS (mm)	-	-	-	245	234	259	245	248	101	90	92	94	96	91	163
(5) Error ($\varepsilon = I + P + CR + SR + MW + CS - Q - ET_a - \Delta W$)	-	-	-	*-147*	*104*	*107*	*-182*	*127*	*-104*	*-57*	*-7*	*63*	*39*	*59*	*-31*

Table 2. Estimation of groundwater inflows in La Violada irrigation district in the irrigation season, non irrigation season and hydrological year through a three components end-member mixing analysis. Q_0 = canal irrigation waters; Q_d = drainage waters from La Violada irrigation district; Q_g = groundwater inflows.

	Irrigation season			Non irrigation season			Hydrological year		
	Q_0	Q_d	Q_g	Q_0	Q_d	Q_g	Q_0	Q_d	Q_g
Year	% of total flow measured at La Violada Gully D-14 gauging station								
1995	21.5	76.5	2.0						
1996	26.6	67.3	6.2						
2007	21.7	76.4	1.9	20.2	78.5	1.3	21.4	77.4	1.2
2008	20.1	76.2	3.7	14.5	84.0	1.5	17.7	79.5	2.8
Average	22.5	74.1	3.5	17.3	81.3	1.4	19.5	78.5	2.0

Table 3. Estimates of average canal seepage losses (*CS*) for the 1998-2002 (CS_1) and 2003-2008 (CS_2) obtained for different hypothetical aquifer discharge coefficients (*k*) and initial water storages in the aquifer ($W_{ph\,0}$) and the corresponding seepage rates for each period (s_1 and s_2) that minimize the sum of the absolute mean (ε_m) and the standard deviation [S(ε)] of the error (ε, eq. 5) of the water balance [$|\varepsilon_m| + S(\varepsilon)$] from 1998 to 2008. The optimum values of *k*, $W_{ph\,0}$, s_1 and s_2 are also given.

	k	$W_{ph\,0}$ (hm^3)	s_1 (1998-2002) ($m^3m^{-2}d^{-1}$)	s_2 (2003-2008) ($m^3m^{-2}d^{-1}$)	CS_1 (1998-2002) (hm^3/yr)	CS_2 (2003-2008) (hm^3/yr)	$\varepsilon_m \pm S(\varepsilon)$ (·1000 m^3/month)
	0.3	1	0.069	0.020	11.7	3.0	3.7 ± 1383
	0.3	5	0.064	0.020	10.9	3.0	1.9 ± 1372
	0.3	10	0.058	0.020	9.8	3.0	1.3 ± 1380
	0.3	15	0.052	0.020	8.8	3.0	0.6 ± 1413
	0.5	1	0.063	0.023	10.7	3.5	2.7 ± 1170
	0.5	5	0.058	0.023	9.8	3.5	0.8 ± 1171
	0.5	10	0.052	0.023	8.8	3.5	0.2 ± 1223
	0.5	15	0.046	0.023	7.8	3.5	-0.5 ± 1321
	0.7	1	0.060	0.024	10.2	3.6	-2.4 ± 1049
	0.7	5	0.055	0.025	9.3	3.8	-4.2 ± 1066
	0.7	10	0.049	0.025	8.3	3.8	1.8 ± 1171
	0.7	15	0.043	0.025	7.3	3.8	1.2 ± 1347
	0.8	1	0.059	0.025	10.0	3.8	-0.1 ± 1022
	0.8	2	0.058	0.025	9.8	3.8	1.0 ± 1022
	0.8	3	0.057	0.025	9.7	3.8	2.2 ± 1026
	0.8	4	0.055	0.025	9.3	3.8	-3.1 ± 1036
	0.8	5	0.054	0.025	9.2	3.8	-1.9 ± 1050
	0.8	10	0.048	0.025	8.1	3.8	-2.6 ± 1186
	0.8	15	0.042	0.025	7.1	3.8	-3.2 ± 1403
	0.9	1	0.057	0.025	9.7	3.8	-5.1 ± 1015
	0.9	5	0.054	0.025	9.2	3.8	-0.5 ± 1054
	0.9	10	0.048	0.026	8.1	3.9	5.6 ± 1223
	0.9	15	0.042	0.026	7.1	3.9	4.9 ± 1483
Optimum	0.884	1.7	0.058	0.025	9.8	3.8	0.0 ± 1015