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# Developing Irrigation Management at District Scale Based on Water Monitoring: Study on Lis Valley, Portugal

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Received: 27 December 2019; Accepted: 30 January 2020; Published: 5 February 2020



**Abstract:** Irrigation districts play a decisive role in Portuguese agriculture and require the adaptation to the new water management paradigm through a change in technology and practices compatible with farmers' technical know-how and economic sustainability. Therefore, improvement of water management, focusing on water savings and increasing farmers' income, is a priority. In this perspective, an applied research study is being carried out on the gravity-fed Lis Valley Irrigation District to assess the performance of collective water supply, effectiveness of water pumping, and safety of crop production due to the practice of reuse of drainage water. The water balance method was applied at irrigation supply sectors, including gravity and Pumping Irrigation Allocation. The average 2018 irrigation water allocated was 7400 m<sup>3</sup>/ha, being 9.3% by pumping recharge, with a global efficiency of about 67%. The water quality analysis allowed identifying some risk situations regarding salinization and microbiological issues, justifying action to solve or mitigate the problems, especially at the level of the farmers' fields, according to the crops and the irrigation systems. Results point to priority actions to consolidate improved water management: better maintenance and conservation of infrastructure of hydraulic infrastructures to reduce water losses and better flow control; implementation of optimal operational plans, to adjust the water demand with distribution; improvement of the on-farm systems with better water application control and maintenance procedures; and improvement of the control of water quality on the water reuse from drainage ditches. The technological innovation is an element of the modernization of irrigation districts that justifies the development of multiple efforts and synergies among stakeholders, namely farmers, water users association, and researchers.

**Keywords:** public irrigation systems; water quality in agriculture; rural development; Operational Groups; EPI-AGRI; Lis Valley; Portugal; gravity-flow irrigation district; irrigation modernization

## 1. Introduction

Irrigation districts with gravity-fed and conveyance canals have specific operative and water distribution characteristics. The management becomes complex when water flow is manually controlled, appealing to the active participation of farmers in the establishment of calendars and irrigation times to achieve equitable water partition by on-farm fields. Management is hampered in water running systems without upstream reservoirs that ensure the availability of inlet flows, requiring high distribution flexibility on the collective conveyance. In addition, the water reuse from the drainage ditches allows mitigating the water shortage, with higher distribution equity and water productivity. In this context of irrigation water reuse, controlling its physicochemical and microbiological quality is of utmost importance to prevent and control the health safety of farmers, food and consumer safety, as well as soil salinization. Under such conditions, these systems require a highly interactive management approach between the water users association and the farmer-beneficiaries themselves [1]. The rational management of collective irrigation should be based on an information system, with data from field monitoring, that provides key knowledge such as irrigation water volumes demanded and supplied, energy consumed on irrigation and drainage, costs of maintaining and conserving infrastructure, cultivated crops, and applied irrigation systems. Several examples of models and procedures have been developed and applied: Playán et al. [2] developed a database tool for enhancing irrigation district management; Dedrick et al. [3] proposed the concept of the Management Improvement Program; and Sagardoy et al. [4] and Mateos et al. [5] presented a scheme irrigation management information system.

The development of modern water management systems (conservation, storage, irrigation, and drainage) allows for environmentally and economically sustainable solutions [6]. Technological innovations, namely on the management process, tend to emerge in response to water scarcity, soil constraints, climate change, and also new economic opportunities [7]. On one hand, consumer demand for food products is changing for economic reasons and for the perception of sustainability issues related to production. On the other hand, water management requires the modernization of systems compatible with the overall development of the economy. The improvement of water management, at the irrigation district level, is usually a complex task that requires multiple actions and significant resources. The water monitoring is a basic process to improve irrigation district management, providing information about delivery and demand water quantity, and irrigation and drainage water quality, on space and time, identifying the infrastructures and operation bottlenecks, health, and environmental risks, and the required farm practices adjustments to cope with water scarcity and quality problems. These aspects are elements of the irrigation systems governance issue, and as Lenton [8] concluded, should support farmers in adopting more environmentally friendly practices that would contribute to irrigation sustainability.

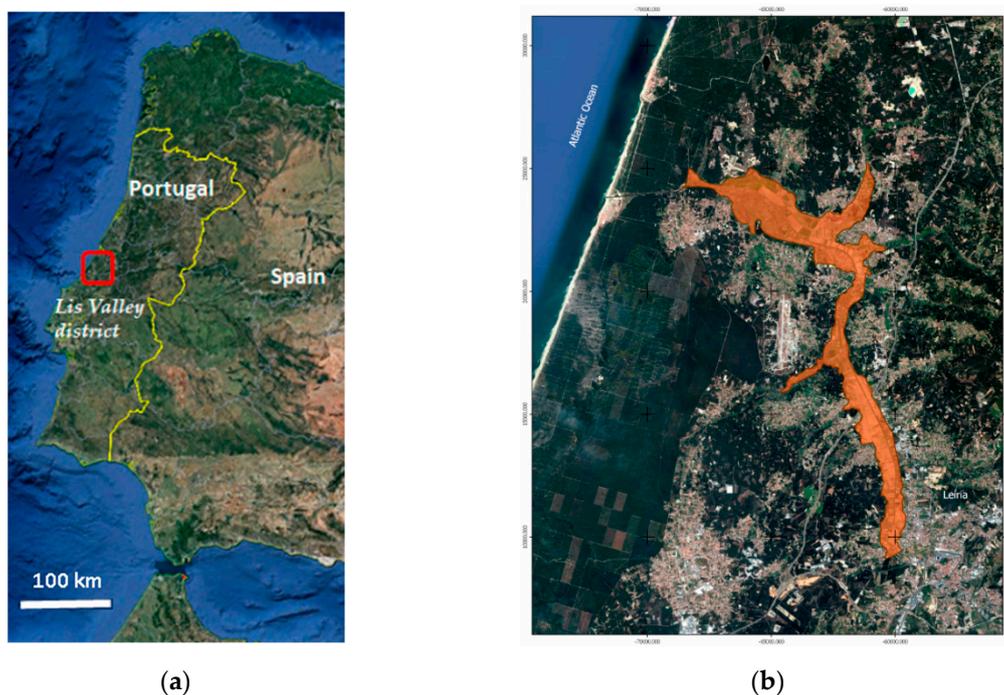
With regard to irrigation conditions in Portugal, it should be highlighted that the entrepreneurial competitiveness of the Portuguese agriculture depends heavily on irrigation [9], a situation evidenced by the Value of Standard Production of more than 5000 €/ha in irrigation and only 800 €/ha in the rainfed agriculture [10]. Irrigation competitiveness results from increased land productivity and control of the effects of climatic variability, but also from the possibility of producing crops with higher added value, such as horticultural crops. Therefore, all efforts to improve irrigation water management are of great use in the development and sustainability of Portuguese agriculture. Climate change scenarios that indicate a decrease in available water resources [11] also determine higher strategic importance and priority in irrigation development.

This paper presents a study of a gravity-fed irrigation district, the Lis Valley, carried out on the framework of an Operational Group of EIP-AGRI [12], focusing on the results of the 2018 season. The overall objective is the improvement of water management, as a result of monitoring at district and on-farm scales. The specific objectives consider the following improvements: performance of collective water supply, effectiveness of water pumping, and safety of crop production due to the practice of reuse of drainage water.

## 2. Materials and Methods

### 2.1. Study Area

Lis Valley Irrigation District (LVID) is a public irrigation district managed by a Water Users' Association (WUA), located in the Coastal Center of Portugal (coordinates  $39^{\circ}51'22.1''\text{N}$   $8^{\circ}50'56.1''\text{W}$ ), belonging to the counties of Leiria and Marinha Grande (Figure 1). The total area is about 2000 ha, and the main crops are forage corn, forage grass, horticultural, orchards, and rice. The hydraulic infrastructures have the objectives of perimeter drainage defense through slope collectors and valley ditches, the irrigation water supply through a canal conveyance system, and the field drainage based on a ditch network. Water is supplied by an open-channel conveyance network from weirs installed along the Lis river and tributaries, having the primary network with a length of about 44.5 km, and by pumping from drainage ditches [13].



**Figure 1.** Location of the Lis Valley Irrigation District (a) in Portugal and (b) in Leiria and Marinha Grande counties (source: Google Maps, <https://maps.google.pt>).

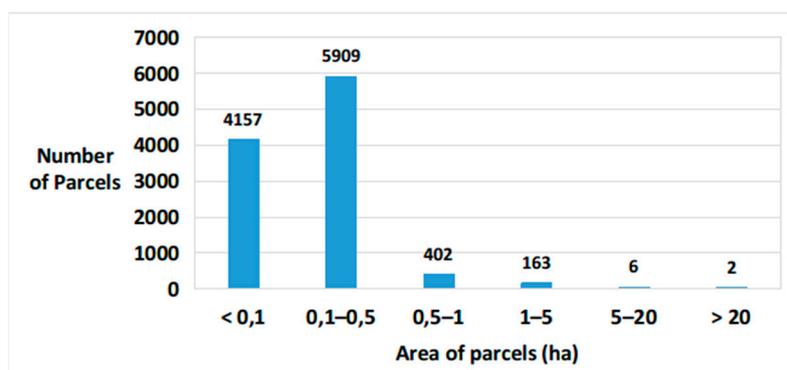
The water conveyance and distribution for the irrigation district is subdivided into supply sectors (hereinafter referred to as sectors). Each sector comprises a main canal, gravity-fed by a river diversion from a weir. During the irrigation peak period, the downstream irrigated areas of some sectors are not fully supplied. To overcome this problem, recharging water is pumped from the river or drainage ditches. The sectors are the main elements of the system operation by the WUA, which controls the inflow from the weir, the pumping recharge and the distribution to the secondary irrigation network, which consists of small lined or earthen channels to distribute the water to the field hydrants. This secondary component of irrigation network is managed by groups of local farmers, in articulation with the WUA. Sectors are identified by the name of the main canal (C1, C2, etc.). The canals C1 and C2 are quite long (ca. 10km), therefore being recharged by pumping stations at intermediate sections. Upstream of these canal sections there are the sectors C1A and C2A, and downstream, the sectors C1B and C2B. Overall, there are seven sectors, C1A, C1B, C2A, C2B, C4, C5, and C7 (Figure 2), with a total area of 1639 ha, corresponding to about 82% of total area. The remaining area excluded from this analysis for operational reasons, corresponds to marginal areas where, in general, the distribution of water is made directly by farmers, without a significant WUA intervention.

The hydraulic infrastructures of LVID were implemented in 1957, though having been partially rehabilitated and equipped with new weirs. There are frequent problems of water loss in the transport network, due to the weakness of certain canal sections, and the existence of aquatic vegetation in the canals that diminishes transport capacity and obstructs gates and hydrants. Critical issues to be addressed are the water scarcity (an endemic problem in summer months in Lis Valley), particularly in dry years, the related environmental risk related to soil salinization, and the economic impacts due to irrigation pumping from the drainage system and yield losses. The lack of automation mechanisms to control water levels in the network channels lead to malfunctions and a high labor load, which is partly mitigated with the participation of farmers in the operation of the main and secondary networks. Under the national rural development program, modernization works are planned to partially transform the water distribution network of the downstream area, under a pressurized system, which will change the water management paradigm, and stimulate agricultural development [14].



**Figure 2.** Location of supply sectors in Lis Valley Irrigation District (Source: Lis Valley Water Users’ Association (WUA)).

The soils are mainly modern alluvial with high agricultural quality, but some are poorly drained, with waterlogging and salinization risks, particularly on the downstream areas. The structure of the on-farm parcel property is characterized by a majority of small parcels (94.6% of which are smaller than 0.5 ha), with an average of 0.20 ha (Figure 3). This aspect is an effective constraint to the modernization of field irrigation and agricultural development and sustainability, which is being mitigated through an informal parceling of the fields done by farmers, through the leasing of the properties, as previously reported [15].



**Figure 3.** Number of parcels in Lis Valley Irrigation District (LVID) by classes of area.

The on-farm assessment of irrigation and drainage practices has great importance when regarding the general improvement of an irrigation district scale [16]. The prevailing dominant irrigation technology in LVID is the surface irrigation [17], by graded furrow or by flooding level basins, applied essentially to fodder maize and permanent pastures. In some cases, it is characterized by a poor land leveling and water distribution by unlined channel, resulting in reduced efficiency; however, the laser precision leveling is applied in the larger fields, which allows a great efficiency improvement [18]. In the majority of the cultivated area (79.3%) maize, pastures, and rice are grown (Table 1). Pastures are the dominant crop in C1A and C7 sectors, while rice is mostly grown in C5, and maize prevails in C2A, C2B, C4, and C5 sectors.

Rice is cultivated in traditional paddies, with ca. 10cm of ponding depth, and an irrigation frequency varying from daily to a few days. Water plays a main role in temperature regulation and weeds control. This crop is grown on lower soils with heavy texture, drainage problems, and a shallow groundwater table, totalizing an area of about 140 ha. The irrigation water is supplied from irrigation canals, or in some fields by farmer's pumping from ditches. The water shortage within the irrigation district is a major constraint to rice crop sustainability and expansion. An ongoing study [19] aiming for water-saving on rice irrigation is assessing the reduction of water depths, along the crop season, thus decreasing percolation and reducing irrigation water use, as well as the intermittent flooding practice [20].

Pressure systems are becoming of great importance with autonomous pumping. Examples are the drip or microsprinkler, which is the most representative, used for fruit plants, horticultural and nurseries, and sprinkler systems, including pivots, used for corn; meadows; and horticulture [21,22]. The drainage system works on the surface, through the leveling of the ground and the use of open drains, which lead the water to the collective main drainage network [23].

The need to improve the rural development conditions in the Lis Valley led to the creation of the Operational Group [24–26], aiming to enhance competitiveness and environmental quality through monitoring and experimental actions.

## 2.2. Water Supply Monitoring

The monitoring methodology of collective irrigation supply systems followed the methodology presented by [16,27,28], including the observations of operative practices and the measuring of supply discharges, to evaluate the water derived for irrigation and the energy consumed on pumping stations.

The most relevant measured data is the affluence discharge to each sector. For this purpose, the canal section velocity method was used, where the point velocities were measured with an electromagnetic current meter (brand, VALEPORT; model, EM flow meter model 801 flat), about once a week, allowing the determination of 10 days' time base of sector inflow volume. These punctual discharge measurements were empirically adjusted based on the record of inlet gates operation, particularly when the inflow was reduced during the night or during Sunday. Some sectors also have the pumping recharge. These field measurements follow the procedures presented by [29] and [30].

**Table 1.** Irrigated area and crops grown by Sectors, in 2018, in LVID.

Sector	C1A	C1B	C2A	C2B	C4	C5	C7	Total
Total area, ha	175.6	104.4	189.7	286.2	418.4	207.6	257.1	1639
Irrigated area, ha	114.2	82.8	159.5	214.7	292.8	166.1	205.7	1236
Irrigated area, %	65	80	85	75	70	80	80	75.5
Maize, %	20	18	43	33	61	60	9	38.4
Pastures, %	48	30	7	24	29	10	77	32.5
Horticulture, %	5.5	13	14.5	13	5	0	0	6.7
Rice, %	0	5	0	15	5	30	1	8.3
Vineyard, %	20	15	15	15	0	0	3	7.9
Fruits, %	6.5	19	20.5	0	0	0	10	6.2

To determine the water demand during the irrigation season—between May and October—10-day (decade) meteorological data ( $ET_0$ , reference evapotranspiration, and  $P$ , precipitation) were obtained from IPMA [31], regarding the Leiria site.

The crop evapotranspiration ( $ET_c$ ) of each sector, corresponding to the water used by the crop consumptively, was calculated with Equation (1) on a 10-days' time-step, from the reference evapotranspiration and the sector weighted crop coefficients ( $K_c$ ) [32]. The irrigation water used beneficially or the Net Irrigation Demand (NID) was calculated by Equation (2), being equal to the evapotranspiration deficit,  $ET_c - P$ , where  $P$  is the effective precipitation, being assumed that the initial soil water and the groundwater capillary rise contributions were not significant.

The evaluation of irrigation water delivery was based on a previously described methodology [16,33,34]. The water diverted for irrigation from its water sources, the Total Irrigation Allocation (TIA), was calculated with Equation (3), summing the Gravity Irrigation Allocation (GIA), with the Pumping Irrigation Allocation (PIA). The Global Irrigation Efficiency (GIE) is the ratio of irrigation water used beneficially (NID) to water diverted from its source (TIA) (Equation (4)).

$$ET_c = ET_0 \times K_c, \quad (1)$$

$$NID = ET_c - P, \text{ if } ET_c > P \quad (2)$$

$$TIA = GIA + PIA, \quad (3)$$

$$GIE = NID/TIA, \quad (4)$$

GIE is an integrative efficiency indicator, which relates water consumptively used by crops to the water used on irrigation at district scale [35–37]. It takes into account several processes of water flow, including the water diverted from its source transported to the farm, the application on the field, and the use by crop, being an assessment of the district-wide irrigation efficiency. Due to the large-scale scope of this procedure, some limitations are accepted, like the overestimating of TIA due to

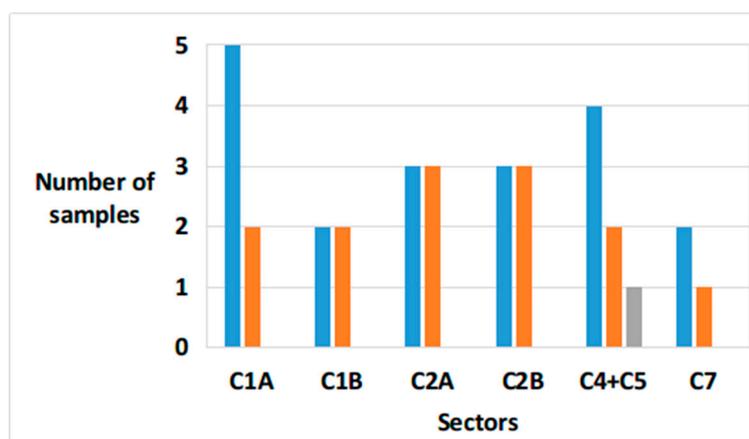
the double accounting of the reused water that has been upstream irrigation runoff, the overestimation of NID due to the null contribution of initial soil water and groundwater capillary rise to the crop evapotranspiration, and the neglecting of the deficit irrigation. These limitation issues could be more expressive during the crop developing phase, in the Spring season, but are not significant on the seasonal irrigation assessment.

### 2.3. Water Quality Monitoring

The methodology for monitoring water quality of irrigation and drainage networks followed the main guidelines proposed by Lothrop et al. [38]. It ensured the spatial representativeness of all irrigation sectors, through the sampling at the main inlet and outlet, and relevant intermediate sites, and also the seasonal irrigation representativeness, including the beginning and the peak periods of the irrigation, drainage, and groundwater. The sampling sites studied in 2018 are described in Figure 4. It is worth mentioning that some of these sampled sites on the drainage system have a double function: drainage and irrigation. The water sampling at the downstream Lis river section (Bajanca bridge site, Table 5) was done at low tide to avoid the influence of brackish seawater.

The physicochemical quality of the water samples was evaluated with a precalibrated in-situ portable multiparametric probe (SmarTROLL RDO Handheld, Fort Collins, CO 80524, USA) for the following parameters: Electrical Conductivity (EC,  $\mu\text{S}/\text{cm}$ ), Saturation of Dissolved Oxygen (SDO, %), Temperature (T,  $^{\circ}\text{C}$ ), and Total Dissolved Solids (TDS, ppm). Nitrates were also evaluated in the laboratory using ion chromatography. The results obtained were compared to the Maximum Recommended Values (MRV) of the Portuguese Irrigation Water Quality Standards [39].

Microbiological analyses of water samples included the enumeration of Total Coliforms (TC), expressed as the Most Probable Number (MPN/100mL) by the dilution method with the multiple fermentation tube technique and incubation at  $37^{\circ}\text{C} \pm 1^{\circ}\text{C}$  in an appropriate culture medium, in accordance with the analytical reference methods [39].



**Figure 4.** Number of sampled sites for water quality analysis per sector and water bodies: Irrigation (■), Drainage (■), and Groundwater (■), in 2018.

## 3. Results

### 3.1. Water Balance on Supply Sectors

The meteorological and crop coefficients decennial data are presented in Table 2. Note that on the 15th and 16th decades of 2018, significant precipitation (26.0 and 38.9 mm, respectively) occurred, thus no irrigation was applied. The hydraulic measurements revealed that the sector C2A had the maximum seasonal inflow and inlet discharge. Moreover, the irrigation period varied between 110 and 159 days among all sectors (Table 3). The transfer volume corresponds to the water transported on

the C1 canal from its inlet to the outlet of C1A, which is connected with the C1B inlet, where the pump recharge is made. The same applies to canal C2.

The results of the decennial water balance per sector show that on the 17th decade (June the 2nd) the TIA is lower than the NID. A similar situation occurred on the 18th decade for sectors C1A, C1B, and C2B (Figure 5). This result might be explained by the simplified methodological approach, which might have neglected the effective contribution of soil water. In fact, in these periods the precipitation was very frequent; therefore, soil water was enough for crop demand. Nevertheless, during the 17th and 18th decades, irrigation was applied in the sectors C2A and C7 due to particular crop demands. The peak supply period occurred between the 20th decade (July the 2nd) and the 24th (August the 3rd). Sectors C4 and C5 were analyzed together because they share the same surface drainage system, where the drainage water is reused for irrigation by pumping. A particular aspect of the runoff from rice paddies is that they drain to a ditch network that is an important water source for irrigation, implying a notable efficiency at the sector level, allowing the recovery of nutrients from drainage water [40]. The negative values of NID occur on decades, with a surplus of precipitation over the evapotranspiration, indicating that irrigation is unnecessary. The supply on the 15th, 16th, and 29th decades is explained by the time-step analysis of 10 days, and also by the delay on the inlet gates close up (Figure 5).

**Table 2.** Meteorological data and average crop coefficients per Sector, in 2018.

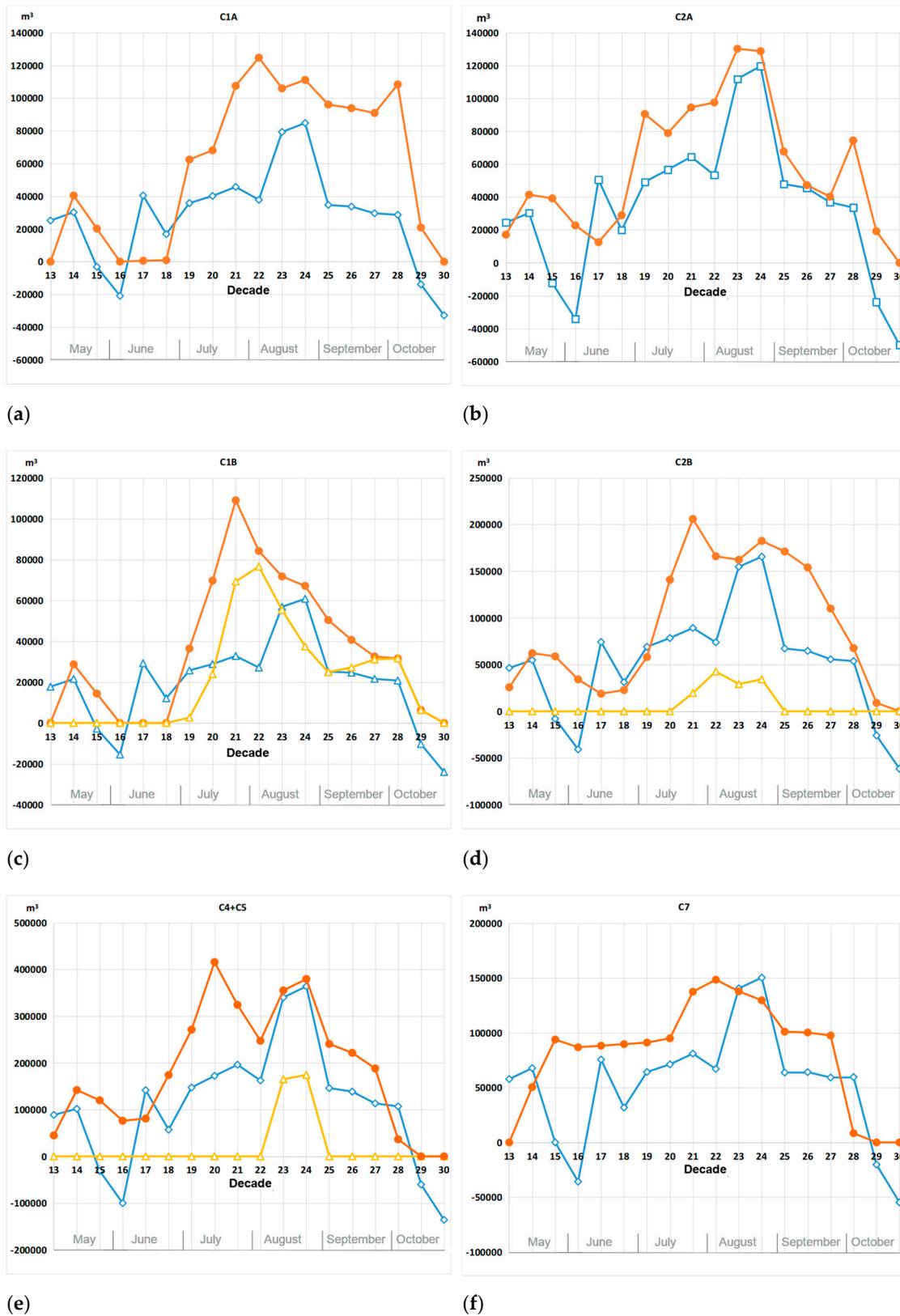
Month	May			June			July			August			September			October		
	Decade	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
ET <sub>0</sub> , mm <sup>(1)</sup>	35.4	41.6	31.6	25.5	44.7	37.9	37.0	38.6	43.9	37.0	76.3	82.0	35.8	35.4	33.9	34.8	21.3	19.8
P, mm <sup>(1)</sup>	0.0	0.5	26.0	38.9	1.8	17.6	1.7	0.1	0.1	0.7	0.3	0.7	0.9	0.0	0.1	0.0	27.4	42.9
K <sub>c</sub> <sup>(1)</sup> (C1A)	0.62	0.65	0.74	0.81	0.83	0.85	0.89	0.91	0.91	0.91	0.91	0.91	0.87	0.83	0.77	0.72	0.71	0.71
K <sub>c</sub> (C1B)	0.61	0.64	0.72	0.79	0.83	0.85	0.89	0.90	0.90	0.90	0.90	0.90	0.87	0.84	0.77	0.72	0.70	0.70
K <sub>c</sub> (C2A)	0.43	0.47	0.58	0.69	0.75	0.79	0.88	0.92	0.92	0.92	0.92	0.92	0.86	0.81	0.68	0.61	0.58	0.58
K <sub>c</sub> (C2B)	0.61	0.63	0.71	0.78	0.81	0.85	0.92	0.95	0.95	0.95	0.95	0.95	0.90	0.85	0.77	0.72	0.72	0.72
K <sub>c</sub> (C4)	0.53	0.53	0.59	0.66	0.72	0.78	0.91	0.97	0.97	0.97	0.97	0.97	0.91	0.84	0.72	0.66	0.66	0.66
K <sub>c</sub> (C5)	0.57	0.57	0.63	0.69	0.75	0.81	0.93	0.99	0.99	0.99	0.99	0.99	0.93	0.87	0.75	0.69	0.69	0.69
K <sub>c</sub> (C7)	0.79	0.80	0.82	0.84	0.86	0.87	0.89	0.90	0.90	0.90	0.90	0.90	0.89	0.88	0.85	0.83	0.82	0.82

<sup>(1)</sup> Leiria data [31], in decades (counts from the beginning of the year); ET<sub>0</sub>, reference evapotranspiration; P, precipitation; K<sub>c</sub>, crop coefficient per Sectors: C1A, C1B, C2A, C2B, C4, C5, C7.

**Table 3.** Irrigation supply and outflow characteristics per Sector, in 2018.

Sector	C1A	C1B	C2A	C2B	C4	C5	C7
Maximum Discharge (l/s)	231	152	401	244	369	168	240
Average Discharge (l/s)	119	68	195	120	156	71	120
Nb. of Days with Supply	125	110	159	159	146	151	140
Inflow (10 <sup>3</sup> m <sup>3</sup> year <sup>-1</sup> )	1289	1958	2682	1776	1966	1012	1456
Outflow (10 <sup>3</sup> m <sup>3</sup> year <sup>-1</sup> )	237	—	1650	—	—	—	—

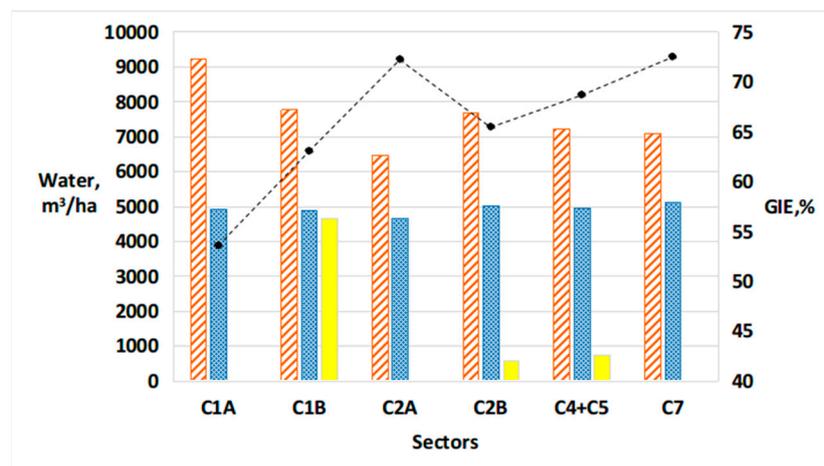
The TIA values of the 2018 irrigation season per sector varied between 6470 m<sup>3</sup>/ha and 9220 m<sup>3</sup>/ha (C1A and C2A, respectively), with an average of 7400 m<sup>3</sup>/ha. The NID values ranged between a minimum on sector C2A (4670 m<sup>3</sup>/ha), and a maximum on sector C7 (5130 m<sup>3</sup>/ha), with an average of 4950 m<sup>3</sup>/ha. The pumping allocation recharge corresponds to 60% in the C1B sector, 10% in sectors C4 and C5, and 7.6% in the C2B sector, with a global average of 9.3% (Figure 6).



**Figure 5.** Net irrigation demand, or deficit of precipitation ( $ET_c - P$ ) ( $\diamond$ ), Total Irrigation Affluence (TIA) ( $\circ$ ), and Pumping Irrigation Affluence (PIA) ( $\triangle$ ) by Sectors: C1A (a), C2A (b), C1B (c), C2B (d), C4+C5 (e), and C7 (f); decade values in cubic meter, in 2018.

The GIE varies between 0.53 and 0.72 (in Sectors C1A, C2A, and C7, respectively), with an average of 0.69 (Figure 6). Generally it can be concluded that the supply was adequate, according to the on-farm irrigation demand, with a satisfactory water distribution equity, as a result of strong collaboration between WUA and farmers. The GIE average value of 0.69 (varying from 0.53 to 0.72) is considered satisfactory [41]. However, this data did not provide enough information to allow splitting this efficiency in the off- and on-farm components. On one hand, the main canals transport efficiency is very variable, sometimes lower than 70%. On the other hand, the observed field irrigation leads to the conclusion that on-farm application efficiency varies between 65% and 90%, according to the irrigation method from the surface to the drip systems. As previously mentioned, major water losses by surface runoff had conditions to be reused downstream. Therefore, these apparent losses became beneficial water use, thus allowing an increased efficiency.

A water supply challenge would be set if all of the total equipped areas of LVID would be fully irrigated. This issue deals with the maximum discharge of main canals and recharge pump stations, and how to cope with the conveyance management with the probable water scarcity in the peak period, considering that actually only 75% of the total equipped area is irrigated (Table 1).



**Figure 6.** Total Irrigation Affluence (TIA) (▨), Net Irrigation Demand (NID) (▨), and Pumping Irrigation Allocation (PIA) (▨) in m<sup>3</sup>/ha; Global Irrigation Efficiency (GIE, %) (-●-); seasonal values per Sector, in 2018.

### 3.2. Water Quality

The pH values of water samples from the irrigation, drainage, and groundwater of supply sectors (Table 4) are within an acceptable range [39], in general, slightly above 7.0, except for sectors C4 and C5, whose values are within the range of 6.5–6.9, possibly because this area is supplied by another water source, the Aroeira river, a Lis tributary. Similar results were found in the Lis river water, from upstream to downstream of the irrigation district, including three intermediate sections (Table 5).

Regarding the water salinity, the results highlight higher values on water samples from the downstream area of the valley (sectors C4, C5, and C7). An area particularly saline is one close to the Monte Real Thermae, upstream of sector C7, where it was observed on groundwater at a 2 m depth a salinity of 4.26 PSU and an EC of 7640 μS/cm. The negative agricultural effect of this problem is controlled, as much as possible, by the direct river drainage of this area by pumping to the Lis river, downstream the last irrigation pumping station. The results of the salinity of Lis river water on LVID (Table 5) show a significant increase toward Lis mouth. Moreover, the river water downstream Salgadas weir is not feasible for irrigation. The low quality of the downstream section referring to salinity and TC is explained by the cumulative of several drainage ditches, aggravated by the fact that this river section is the effluent discharge site of an urban wastewater treatment plant.

The saturation dissolved oxygen (SDO,%) values of water samples (Table 4) were often higher than 50% for drainage, and oftentimes higher than 90% for irrigation. Note that, according to Skula et al. [40], though there are no references to irrigation water, it is recommended a value higher than 50% for drinking water, allowing the conclusion that dissolved oxygen in these water bodies is good or acceptable. The very low value for the groundwater sample (SDO = 28.9%) is explained by the local standing water condition on the piezometer.

In sectors C1B and C2B, the irrigation water (collected from the Lis river, upstream from the drainage ditches discharge) has a nitrate content of 17 mg/L, whereas in drainage water, these values were below 10 mg/L (Table 4). Sector C7 shows a trace value of nitrates in the drainage network, which might be explained by the dominant cultural system, permanent meadows, with null or reduced nitrogen fertilization. Countering this trend, in sectors C4 and C5, the irrigation water has a lower level of nitrates (7.1 mg/L) than the drainage water (8.6 mg/L), and the groundwater (9.0 mg/L), which is explained by the intensive production system, namely with soil manure amendment. Although the data is still scarce, it indicates that irrigation in the Lis Valley has no significant negative effect on the nitrate load on water resources. A clearer view will be possible when monitoring is concluded and extended to all sectors and quantifying the total nitrogen.

The analysis of water microbiological quality, assessed through the TC enumeration at the sector level, shows a spatial variation within the valley. In each sector, TC counts were higher in drainage than in irrigation water, except for sector C7, which revealed a different situation: the TC counts in drainage water were four times lower than that in irrigation water. This might be explained by the soil reducing effect on *Enterobacteriaceae* numbers and also by a lower soil manure amendment on pastures than in the crops of other sectors. The high TC values of irrigation water of sectors C1A and C2A (Lis river water at Arrabalde weir), and drainage water of sector C2A, is explained by contamination from external sewage sources from the irrigated area [42]. It is noteworthy that the TC load on the medium section of Salgadas weir is much lower the upstream one (Table 5), revealing the cleaning effect of the open hydraulic system, such referred before.

**Table 4.** Physicochemical and microbiological parameters of water sampled per sector and water body in 2018 (average  $\pm$  standard deviation).

Sector	Water Body	Water Quality Parameters					
		pH (6.5–8.4) *	EC, $\mu\text{S}/\text{cm}$ (1000) *	SDO, %	SDT, ppm (640) *	TC, $10^5$ MPN/100mL	Nitrates, mg/L (50) *
C1A	Irrigation	7.30	556.0	—	399.5	10.6	—
	Drainage	7.32 $\pm$ 0.1	783.7 $\pm$ 245.8	59.8 $\pm$ 9.5	509.4 $\pm$ 159.5	—	—
C1B	Irrigation	7.63 $\pm$ 0.1	849.9 $\pm$ 100.5	96.4 $\pm$ 1.1	552.4 $\pm$ 65.2	—	17 $\pm$ 2.8
	Drainage	7.32 $\pm$ 0.1	783.7 $\pm$ 245.8	59.8 $\pm$ 9.5	509.4 $\pm$ 159.5	—	<6.5
C2A	Irrigation	7.30	556.0	—	399.5	10.6	—
	Drainage	7.54 $\pm$ 0.27	620.67 $\pm$ 97.6	94.97 $\pm$ 7.3	403.9 $\pm$ 63.7	13.1	—
C2B	Irrigation	7.54 $\pm$ 0.17	753.2 $\pm$ 237	96.2 $\pm$ 2.2	489.5 $\pm$ 154	—	17 $\pm$ 2.8
	Drainage	7.52 $\pm$ 0.2	558.8 $\pm$ 66.8	90.9 $\pm$ 6.2	363.2 $\pm$ 43.4	1.91	10
C4+C5	Irrigation	6.66 $\pm$ 0.98	494.5 $\pm$ 439	92.8 $\pm$ 9.1	321.6 $\pm$ 286.6	2.70	7.1 $\pm$ 1.3
	Drainage	6.84 $\pm$ 0.32	972.9 $\pm$ 245.4	81.2 $\pm$ 5.2	632.9 $\pm$ 165.6	7.20	8.6 $\pm$ 3.5
	Groundwater	6.52	1472	28.9	959.5	—	9 $\pm$ 8.5
C7	Irrigation	7.26 $\pm$ 0.3	627.38	88.86	409.58	4.70	—
	Drainage	7.45 $\pm$ 0.08	705.3	78.56	458.4	1.15	<3

EC—Electrical Conductivity; SDO—Saturation of Dissolved Oxygen; SDT—Dissolved Solids; TC—Total Coliforms.  
\* Maximum Recommended Values according to the Portuguese Irrigation Water Quality Legislation [39].

The TC values do not allow comparisons with the Portuguese legislation [39] regarding the irrigation water since it establishes, as maximum, a recommended value of 100 MPN/100mL restricted to the fecal coliforms group. However, all the TC enumerations, both from irrigation and drainage water samples, are above the maximum admissible value (10.000 MPN/100mL) to aquaculture and

bathing [39]. On the other side, irrigation water quality standard [43] refers to quality requirements for the reuse of urban wastewater treated in the irrigation of agricultural, forestry, ornamental, nursery, lawn, and other green spaces. Relative to the microbiological quality requirements, that standard [43] has taken into consideration the use of irrigated crops (e.g., human or animal consumption, or industrial crops) and the respective irrigation method applied is less restrictive and more flexible than [39]. According to Monte and Albuquerque [44], the Portuguese legislation [39] is very demanding since the water in most rivers does not have fecal coliforms content below 100 MPN/100mL.

The identification of situations of microbial contamination risk in irrigation water of LVID, whose main responsibility is external to agriculture, requires special precautionary measures, in particular regarding the safety of farmers and consumers. These risks will also need to be assessed for the influence of agricultural activity within the irrigation district, particularly at the drainage network level.

**Table 5.** Physicochemical and microbiological parameters of water sampled, at Lis river sections, in 2018, in LVID (average values).

River Section	Water Quality Parameter				
	pH	EC, $\mu\text{S/cm}$	SDO, %	SDT, ppm	TC, $10^5$ MPN/100mL
Upstream, Arrabalde weir	7.30	556.0	—	399.5	10.6
Medium, Amor ditch mouth	7.34	776.0	100	504.6	—
Medium, Salgadas weir	7.26	627.4	88.86	409.6	4.70
Medium, Junceira bridge	7.29	1958.7	79.16	1273.1	—
Downstream, Bajanca bridge	7.08	2777.2	94.47	1807.2	46.0

EC—Electrical Conductivity; SDO—Saturation of Dissolved Oxygen; SDT—Dissolved Solids; TC—Total Coliforms.

#### 4. Discussion

The rationalization of water management in LVID should be based on improving forecasting of irrigation water demand throughout the crop season and across the various supply sectors. This determination requires knowing the crop pattern per sector and the respectively applied field irrigation methods. Distribution system operation planning must meet this water demand through the operating mode of the water intakes and regulating and pumping mechanisms. The functional relationship between the collective distribution network and on-farm irrigation is a key element in overall district performance. Actual real-time operation of the distribution system will depend on crops' development and the existing weather conditions, especially the precipitation during the Spring season. To this end, it is essential to link farmers' water demand information with WUA's short-term demand forecast to establish the operational supply data, namely the inflow flow rates and timing. Adjustment between supply and demand and distribution of water on sectors should be made according to the criterion of better efficiency, losses control, and better spatial distribution equity. These issues meet with the conclusions of several authors [45–48].

LVID's practical conditions highlight a set of problems that limit the best system performance. As the network of conveyance system is by open canal, one problem is the existence of a high quantity of debris on water, namely aquatic vegetation, due to the charge on nutrients on water from its original source on rivers. This problem requires high maintenance hand labor and cost, making it a lowly effective task because the network is very extensive, with a total of 180 km including the secondary canals, and this work is only well feasible during the non-irrigation period. Its impact is a reduction of canals discharge capacity, gates clogging, and loss of accuracy of managing water control. Equipment to remove this debris is required, like screens and trash racks, and these have been developed for screening irrigation water. Possible solutions, described by Replogle and Kruse [16] and Skogerboe and Merkley [49], are screens placed below canal drops that use the energy flow to move the trash far enough away from the overfall to allow the water to pass through, or using water wheels or electric motors to power brushes that pass repeatedly over the screen surface, moving trash to one side.

In addition, there is uncertainty about the available flow rates at the source because the river flow has no regularization by reservoirs, and it suffers a significant decrease in the summer period. Given this reality, irrigation water management is based on quasi-real-time supply adjustment in the very short time of a few hours or a few days, taking into account the following: (i) The relative independence of the supply of several sectors allows that the decision-making is made with higher proximity of the users, creating higher management flexibility. In its turn, cooperation behavior among the group of users at the secondary canal level facilitates the management and favors the equity of water distribution, particularly on the downstream ones. WUA's position of arbitration and regulation is fundamental to guarding and moderating the possible focus of conflict between users. This example meets many cases in which participatory irrigation district management has shown good results [1,50,51]. In reinforcing the importance of this issue, Ricart et al. [52] present a study that analyzes how to improve irrigation water governance, bearing in mind the balances that must be involved. (ii) The supply water scarcity risk and the deficiency of the conveyance system lead to the need to install recharge pump stations from drainage water. So, the drainage system also works complementary with the irrigation one, like an off-field water reservoir. This supply recharge by pumping is done particularly during peak periods to supply the downstream areas, having a very relevant role in their irrigation. Rice crop is especially favored by this highly flexible supply. On one hand, it reduces the risk of water scarcity, and on the other hand, allows the pumping directly from the ditches to the farmers' private pressurized systems. These complementary drainage-irrigation networks are fundamental to achieve a good performance of the irrigation district. However, the water reuse by pumping has a significant cost that is supported by WUA when it refers to the collective supply, or by the farmers when it is done at field level.

The assessment of supply sectors requires also information from the field irrigation demand, because it influences the irrigation duration, frequency, and applied volumes [16,37]. The Operational Group project will study the on-farm management, evaluating farmers' fields, according to the type of soil, crops, production technologies, and irrigation methods. It will consider representative sprinkler and micro-irrigation of vegetables, surface or sprinkler irrigation with fodder corn and permanent pastures, paddy rice, and drip irrigation of apple fruits. The methodology to follow [53] includes the soil water content measurement, the irrigation applied depths, the field distribution uniformity, the soil fertility, the water table depth, and crop productivity.

The physicochemical and microbiological quality of water samples reveals: (i) A significant source of problems is external to the irrigation district, as various measurements demonstrate. Thus, it is up to the WUA and farmers to adapt the operating mode and technologies to minimize the negative impacts of these problems. Water quality monitoring in the district is a very important procedure to know the local reality over time and allow adjustments to be as effective as possible, as highlighted by [38,54,55]. (ii) The organic load of livestock applied to the soil in certain areas of the district makes the emerging microbiological risk significant [56]. (iii) The downstream part of the district has hydrogeological characteristics of significant salinity, which is a risk factor for soil due to capillary rise or drainage water reuse [57]. Surface drainage water, groundwater, and soil monitoring play an important role in assessing the problem to determine action in the most severe cases.

Poor water quality leads to multiple risk problems, requiring protection, adaptation, or mitigation measures: (i) Judicious use of manure as soil fertilizer, which should be appropriately composted in farms and slaughterhouses treatment plants [58]. Cautions should be reinforced when applied to horticultural crops, or crop handling, to protect environmental and public health problems due to microbes and other contaminants like antibiotics [56]. (ii) Choice of irrigation technology should take into account irrigation water quality and should be adjusted according to the risk assessment for the farmer and the consumer of the product. For fresh crops, preference should be given to drip irrigation; surface furrow irrigation has no special restrictions for other crops and sprinkler irrigation is preferentially dedicated to forage crops, or crops with post-harvest processing. Farmers should be informed about special hygiene and safety precautions where microbiological contamination is most at risk [59].

From the study, the following future research topics are presented: (i) A framework to develop irrigation management operational plans, based on monitoring, simulation, and forecasting tools to integrate multiple information, and to provide water demand and supply data to operate the conveyance system [60,61]. Thus, monitoring information, such as collective network performance, water quality, crop mapping, and water use conditions and economics, could be applied in a timely manner to system management, for improved water management, and better conveyance distribution, especially in times of scarcity and cost reductions, according to WUA's objective [62,63]. (ii) Actions directed at farmers carried out by WUA and other stakeholders, to improve irrigation on the field by experimenting and demonstrating the various irrigation technologies, with the best adaptation to local conditions. Attending to the full context of local water use is critical to understanding the irrigation methods that are selected by farmers. Several authors [50,64–66] present studies demonstrating this in several regions, like Mauritania, southwestern United States, Southern Ethiopia, and the Mediterranean. (iii) Recommend further studies in the canal supply system maintenance and monitoring, aiming higher reliability, efficiency, and automaticity, and to achieve a higher level of water, energy, and labor savings [67]. Discharge measurement, debris and trash water cleaning, and water loss control are the main issues. New methodologies allow modeling-based multidisciplinary approaches [68], or the use of sensing equipment/information technologies to create management support warning systems [69].

## 5. Conclusions

The 2018 results of LVID water monitoring shown a Total Irrigation Allocation of 7400 m<sup>3</sup>/ha, being 9.3% by pumping recharge. The Global Irrigation Efficiency was 67%, varying between 53% and 72% among sectors. Higher efficiency results from the reuse of drainage water by pumping, thus resulting in increased cost for energy consumption. The results of the physicochemical and microbiological analysis allowed us to conclude that surface and subsurface waters indicate risk situations at pH, salinization, and microbiology level, justifying action to solve or mitigate these problems, especially at the level of the farmers' field.

Results point to priority actions to consolidate improved water management: better maintenance and conservation of infrastructure of hydraulic infrastructures to reduce water losses and better flow control; implementation of optimal operational plans, to adjust the water demand with distribution; improvement of the on-farm systems with better water application control and maintenance procedures, reducing labor and increasing the distribution uniformity, applying irrigation scheduling plans based on monitoring systems, using weather stations combined with soil moisture devices or crop remote sensing; and improvement of water quality control on the water reuse from drainage ditches. Technological innovation is an element of the modernization of irrigation districts, which justifies the development of multiple efforts and synergies among stakeholders, namely farmers, water users association, and researchers.

**Author Contributions:** J.M.G., M.N., H.D. and M.T. conceptualized and design the study; S.F., M.N., R.E., H.D. and J.M.G. performed the field experiments; P.A., O.F., I.M.D. and S.F., performed laboratory experiments; I.M.D., T.V., F.O., M.G., H.D., P.A., O.F., S.F., and M.N. analysed and validated the data; J.M.G. wrote the paper with contributions from the other authors. All authors have read and agree to the published version of the manuscript.

**Funding:** This research was conducted within project Grupo Operacional para a Gestão da Água no Vale do Lis, PDR2020-1.0.1-FEADER-030911, funded by Program PDR2020, co-funded by FEDER, Innovation Measure, Portugal. The research relative to rice irrigation was supported by the Project "MEDWATERICE", PRIMA/0005/2018, funded by the Portuguese Science and Technology Foundation (FCT).

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Playán, E.; Sagardoy, J.A.; Castillo, R. Irrigation governance in developing countries: Current problems and solutions. *Water* **2018**, *10*, 1118. [[CrossRef](#)]

2. Playán, E.; Cavero, J.; Mantero, I.; Salvador, R.; Lecina, S.; Faci, J.M.; Andrés, J.; Salvador, V.; Cardeña, G.; Ramón, S.; et al. A database program for enhancing irrigation district management in the Ebro valley (Spain). *Agric. Water Manag.* **2007**, *87*, 209–216. [[CrossRef](#)]
3. Dedrick, A.R.; Clyma, W.; Palmer, J.D. A management improvement process to effectively change irrigated agriculture. In *Planning for Water Shortages. Water Reallocations and Transfers. Drought Management*; Schaack, J., Wilson, D.S., Anderson, S.S., Eds.; U.S. Committee on Irrigation and Drainage: Denver, CO, USA, 1989; pp. 45–58.
4. Sagardoy, J.A.; Pastore, G.; Yamashita, I.; Lopez-Cortijo, I. *SIMIS: Scheme Irrigation Management Information System*; FAO: Rome, Italy, 1999.
5. Mateos, L.; López-Cortijo, I.; Sagardoy, J.A. SIMIS: The FAO decision support system for irrigation scheme management. *Agric. Wat. Manag.* **2002**, *56*, 193–206. [[CrossRef](#)]
6. Backeberg, G.R. Innovation through research and development for irrigation water management. *Irrig. Drain.* **2014**, *63*, 176–185. [[CrossRef](#)]
7. Lenton, R. Irrigation in the twenty-first century: Reflections on science, policy and society. *Irrig. Drain.* **2014**, *63*, 154–157. [[CrossRef](#)]
8. Ostrom, E. *Crafting Institutions for Self-Governing Irrigation Systems*; Center for Self-Governance: San Francisco, CA, USA, 1992.
9. Silva, F.G. The future of irrigation in an integrated logic of water resources management. *AGROTEC* **2018**, *27*, 46–49. (In Portuguese)
10. INE. *Farm Structure Survey*; INE: Lisbon, Portugal, 2017. (In Portuguese)
11. Sordo-Ward, A.; Granados, A.; Iglesias, A.; Garrote, L.; Bejarano, M.D. Adaptation effort and performance of water management strategies to face climate change. Impacts in six representative basins of Southern Europe. *Water* **2019**, *11*, 1078. [[CrossRef](#)]
12. European Commission. EIP-AGRI. Available online: <https://ec.europa.eu/eip/agriculture/en> (accessed on 5 December 2019).
13. COBA. *Environmental Impact Study of the Lis Valley Reparcelling Project*; IHERA: Lisbon, Portugal, 2001. (In Portuguese)
14. MAM-GPP. *Mainland Rural Development 2014–2020 Program*; MAM-GPP: Lisbon, Portugal, 2014. (In Portuguese)
15. Ferreira, S.; Oliveira, F.; Gonçalves, J.M.; Silva, F.G.; Teixeira, M.; Gonçalves, M.; Eugénio, R.; Damásio, H. Promote the sustainable development of the territory by agricultural innovation. Challenges of organic farming in the Lis Valley, Portugal. In *Proceedings of the 10th Iberian Agroengineering Congress, Huesca, Spain, 3–6 September 2019*; pp. 606–622. (In Portuguese). [[CrossRef](#)]
16. Replogle, J.A.; Kruse, E.G. Delivery and distribution systems. In *Design and Operation of Farm Irrigation Systems*, 2nd ed.; Hoffman, G.J., Evans, R.G., Jensen, M.E., Martin, D.L., Elliot, R.L., Eds.; ASABE: St. Joseph, MI, USA, 2007; pp. 347–391.
17. Walker, W.R.; Skogerboe, G. *Surface Irrigation: Theory and Practice*; Prentice Hall, Inc.: Englewood Cliffs, NJ, USA, 1987.
18. Pereira, L.S.; Gonçalves, J.M. Surface irrigation. In *Oxford Encyclopedia of Agriculture and the Environment, Subject: Sustainability and Solutions, Agriculture and the Environment*; Oxford University Press: Oxford, UK, 2018. [[CrossRef](#)]
19. MEDWATERICE. Medwaterice Home Page. Available online: [www.medwaterice.org](http://www.medwaterice.org) (accessed on 15 December 2019).
20. De Maria, S.C.; Rienzner, M.; Facchi, A.; Chiaradia, E.A.; Romani, M.; Gandolfi, C. Water balance implications of switching from continuous submergence to flush irrigation in a rice-growing district. *Agric. Water Manag.* **2016**, *171*, 108–119. [[CrossRef](#)]
21. Martin, D.; Kincaid, C.K.; Lyle, W.M. Design and operation of sprinkler systems. In *Design and Operation of Farm Irrigation Systems*, 2nd ed.; Hoffman, G.J., Evans, R.G., Jensen, M.E., Martin, D.L., Elliot, R.L., Eds.; ASABE: St. Joseph, MI, USA, 2007; pp. 557–631.
22. Evans, R.G.; Wu, I.; Smajstrala, A.G. Microirrigation systems. In *Design and Operation of Farm Irrigation Systems*, 2nd ed.; Hoffman, G.J., Evans, R.G., Jensen, M.E., Martin, D.L., Elliot, R.L., Eds.; ASABE: St. Joseph, MI, USA, 2007; pp. 632–683.

23. King, L.G.; Willardson, L.S. Drainage systems. In *Design and Operation of Farm Irrigation Systems*, 2nd ed.; Hoffman, G.J., Evans, R.G., Jensen, M.E., Martin, D.L., Elliot, R.L., Eds.; ASABE: St. Joseph, MI, USA, 2007; pp. 289–319.
24. RRN. Grupo Operacional para a Gestão da Água no Vale do Lis. Available online: <https://inovacao.rederural.gov.pt/2/81-grupo-operacional-para-a-gestao-da-agua-no-vale-do-lis> (accessed on 5 December 2019).
25. Oliveira, M.F.; Silva, F.G.; Ferreira, S.; Teixeira, M.; Damásio, H.; Ferreira, A.D.; Gonçalves, J.M. Innovations in sustainable agriculture: Case study of Lis Valley irrigation district, Portugal. *Sustainability* **2019**, *11*, 331. [[CrossRef](#)]
26. Gonçalves, J.M.; Nunes, M.; Eugénio, R.; Ferreira, S.; Amador, P.; Filipe, O.; Duarte, I.M.; Margarida Teixeira, M.; Marques, H.; Oliveira, F.; et al. Case study of water monitoring in the Lis Valley irrigation district, Portugal. In Proceedings of the 10th Iberian Agroengineering Congress, Huesca, Spain, 3–6 September 2019; pp. 649–660. (In Portuguese). [[CrossRef](#)]
27. Pereira, L.S.; Cordery, I.; Iacovides, I. Improved indicators of water use performance and productivity for sustainable water conservation and saving. *Agric. Water Manag.* **2012**, *108*, 39–51. [[CrossRef](#)]
28. Clemmens, A.J. Accuracy of project-wide water uses from a water balance: A case study from Southern California. *Irrig. Drain. Syst.* **2008**, *22*, 287–309. [[CrossRef](#)]
29. Lencastre, A. *General Hydraulics*; Hidroprojecto: Lisbon, Portugal, 1983. (In Portuguese)
30. Replogle, J.A.; Howell, T.A.; Solomon, K.H. Measuring Irrigation Water. In *Management of Farm Irrigation Systems*; Hoffman, J., Howell, T.A., Solomon, K.H., Eds.; ASABE: St. Joseph, MI, USA, 1990; pp. 315–370.
31. IPMA. IPMA Home Page. Available online: [www.ipma.pt](http://www.ipma.pt) (accessed on 10 November 2018).
32. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements*; FAO Irrigation and drainage paper 56; FAO: Rome, Italy, 1998; 300p.
33. Renault, D.; Vehmeyer, P.W. On reliability in irrigation service preliminary concepts and application. *Irrig. Drain. Syst.* **1999**, *13*, 75–103. [[CrossRef](#)]
34. Mateos, L. Identifying a new paradigm for assessing irrigation system performance. *Irrig. Sci.* **2008**, *27*, 25–34. [[CrossRef](#)]
35. Burt, C.M.; Clemmens, A.J.; Strelkoff, T.S.; Solomon, K.H.; Bliesner, R.D.; Hardy, L.A.; Howell, T.A.; Eisenhauer, D.E. Irrigation performance measures: Efficiency and uniformity. *J. Irrig. Drain. Eng.* **1997**, *123*, 423–442. [[CrossRef](#)]
36. Molden, D.J.; Gates, T.K. Performance measures for evaluation of irrigation-water-delivery systems. *J. Irrig. Drain. Eng.* **1990**, *116*, 804–823. [[CrossRef](#)]
37. Nam, W.-H.; Hong, E.-M.; Choi, J.-Y. Assessment of water delivery efficiency in irrigation canals using performance indicators. *Irrig. Sci.* **2016**, *34*, 129–143. [[CrossRef](#)]
38. Lothrop, N.; Bright, K.R.; Sexton, J.; Pearce-Walker, J.; Reynolds, K.A.; Verhougstraete, M.P. Optimal strategies for monitoring irrigation water quality. *Agric. Water Manag.* **2018**, *199*, 86–92. [[CrossRef](#)]
39. Portuguese Irrigation Water Quality Legislation. In *Law Decree 236/98, Water Quality Standards*; FAO: Rome, Italy, 1998. (In Portuguese)
40. Shukla, A.; Shukla, S.; Hodges, A.W. Recovering nitrogen from farm-scale drainage: Mechanism and economics. *Trans. ASABE* **2018**, *61*, 197–206. [[CrossRef](#)]
41. Wolters, W. *Influences on the Efficiency of Irrigation Water Use*; ILRI publication: Wageningen, The Netherlands, 1992.
42. Vieira, J.; Fonseca, A.; Vilar, V.J.P.; Boaventura, R.A.R.; Botelho, C.M.S. Water quality in Lis River, Portugal. *Environ. Monit. Assess.* **2012**, *184*, 7125. [[CrossRef](#)]
43. IPQ. *Portuguese Standard on Urban Wastewater Reuse Treated in Irrigation*; NP 4434; IPQ: Lisbon, Portugal, 2006. (In Portuguese)
44. Monte, H.; Albuquerque, A. *Wastewater Reuse*; Guias Técnicos Series; ISEL-ERSAR: Lisbon, Portugal, 2010. (In Portuguese)
45. Gorantiwar, S.D.; Smout, I.K. Model for performance based land area and water allocation within irrigation schemes. *Irrig. Drain. Syst.* **2006**, *20*, 345–360. [[CrossRef](#)]
46. Kaune, A.; Werner, M.; Rodríguez, E.; Karimi, P.; de Fraiture, C. A novel tool to assess available hydrological information and the occurrence of sub-optimal water allocation decisions in large irrigation districts. *Agric. Water Manag.* **2017**, *191*, 229–238. [[CrossRef](#)]

47. Li, M.; Fu, Q.; Singh, V.P.; Liu, D. An interval multi-objective programming model for irrigation water allocation under uncertainty. *Agric. Water Manag.* **2018**, *196*, 24–36. [[CrossRef](#)]
48. Li, X.; Huo, Z.; Xu, B. Optimal allocation method of irrigation water from river and lake by considering the field water cycle process. *Water* **2017**, *9*, 911. [[CrossRef](#)]
49. Skogerboe, G.V.; Merkley, G.P. *Irrigation Maintenance and Operations Learning Process*; Water Resources Publications, LLC: Highland Ranch, CO, USA, 1996.
50. Mateos, L.; Lozano, D.; Baghil, A.B.O.; Diallo, O.A.; Gómez-Macpherson, H.; Comas, J.; Connor, D. Irrigation performance before and after rehabilitation of a representative, small irrigation scheme besides the Senegal River, Mauritania. *Agric. Water Manag.* **2010**, *97*, 901–909. [[CrossRef](#)]
51. Vandersypen, K.; Keita, A.C.T.; Lidon, B.; Raes, D.; Jamin, J.-Y. Didactic tools for supporting participatory water management in collective irrigation schemes. *Irrig. Drain. Syst.* **2008**, *22*, 103–113. [[CrossRef](#)]
52. Ricart, S.; Rico, A.; Kirk, N.; Bülow, F.; Ribas-Palom, A.; Pavón, D. How to improve water governance in multifunctional irrigation systems? Balancing stakeholder engagement in hydro-social territories. *Int. J. Water Res. Dev.* **2018**, *35*, 491–524. [[CrossRef](#)]
53. Merriam, J.L.; Keller, J. *Farm Irrigation System Evaluation: A Guide for Management*; Utah State University: Logan, UT, USA, 1978.
54. Stine, S.W.; Song, I.; Choi, C.Y.; Gerba, C.P. Application of microbial risk assessment to the development of standards for enteric pathogens in water used to irrigate fresh produce. *J. Food Prot.* **2005**, *68*, 913–918. [[CrossRef](#)]
55. Winfield, M.D.; Groisman, E.A. Role of nonhost environments in the lifestyles of *Salmonella* and *Escherichia coli*. *Appl. Environ. Microbiol.* **2003**, *69*, 3687–3694. [[CrossRef](#)]
56. Amador, P.; Fernandes, P.; Prudêncio, C.; Duarte, I. Prevalence of antibiotic resistance genes in multidrug-resistant enterobacteriaceae on Portuguese livestock manure. *Antibiotics* **2019**, *8*, 23. [[CrossRef](#)]
57. Hoffman, J.; Shalevet, J. Controlling salinity. In *Design and Operation of Farm Irrigation Systems*, 2nd ed.; Hoffman, G.J., Evans, R.G., Jensen, M.E., Martin, D.L., Elliot, R.L., Eds.; ASABE: St. Joseph, MI, USA, 2007; pp. 160–207.
58. Cameira, M.R.; Li, R.; Fangueiro, D. Integrated modelling to assess N pollution swapping in slurry amended soils. *Sci. Total Environ.* **2020**, *713*, 136596. [[CrossRef](#)]
59. Ricart, S.; Rico, A.M.; Ribas, A. Risk-yuck factor nexus in reclaimed wastewater for irrigation: Comparing farmers' attitudes and public perception. *Water* **2019**, *11*, 187. [[CrossRef](#)]
60. Gonçalves, J.M.; Pereira, L.S.; Fang, S.X.; Dong, B. Modelling and multicriteria analysis of water saving scenarios for an irrigation district in the upper Yellow River Basin. *Agric. Water Manag.* **2007**, *94*, 93–108. [[CrossRef](#)]
61. Karleuša, B.; Hajdinger, A.; Tadić, L. The application of multi-criteria analysis methods for the determination of priorities in the implementation of irrigation plans. *Water* **2019**, *11*, 501. [[CrossRef](#)]
62. Calera, A.; Campos, I.; Osann, A.; D'Urso, G.; Menent, M. Remote sensing for crop water management: From ET modelling to services for the end users. *Sensors* **2017**, *17*, 1104. [[CrossRef](#)]
63. Salomón-Sirolesi, M.; Farinós-Dasí, J. A new water governance model aimed at supply–demand management for irrigation and land development in the Mendoza River Basin, Argentina. *Water* **2019**, *11*, 463. [[CrossRef](#)]
64. Frisvold, G.; Sanchez, C.; Gollehon, N.; Megdal, S.B.; Brown, P. Evaluating gravity-flow irrigation with lessons from Yuma, Arizona, USA. *Sustainability* **2018**, *10*, 1548. [[CrossRef](#)]
65. Awel, S.M.; Tena Alamirew, T.T.; Michael, A.W. Performance assessment of community managed irrigation practices in the Wesha small-scale irrigation project, Southern Ethiopia. *Irrig. Drain. Syst. Eng.* **2018**, *7*, 3. [[CrossRef](#)]
66. Masseroni, D.; Ricart, S.; Cartagena, R.F.; Monserrat, J.; Gonçalves, J.M.; de Lima, I.; Facchi, A.; Sali, G.; Gandolfi, C. Prospects for improving gravity-fed surface irrigation systems in Mediterranean European Contexts. *Water* **2017**, *9*, 20. [[CrossRef](#)]
67. Stringam, B.L.; Gill, T.; Sauer, B. Integration of irrigation district personnel with canal automation projects. *Irrig. Sci.* **2016**, *34*, 33–40. [[CrossRef](#)]

68. Luppi, M.; Malaterre, P.-O.; Battilani, A.; Federico, V.D.; Toscano, A. A multi-disciplinary modelling approach for discharge reconstruction in irrigation canals: The Canale Emiliano Romagnolo (Northern Italy) case study. *Water* **2018**, *10*. [[CrossRef](#)]
69. Soto-Garcia, M.; Del-Amor-Saavedra, P.; Martin-Gorriz, B.; Martínez-Alvarez, V. The role of information and communication technologies in the modernisation of water user associations' management. *Comput. Electron. Agric.* **2013**, *98*, 121–130. [[CrossRef](#)]



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