

## Article

# Assessment of Irrigation Water Performance in the Nile Delta Using Remotely Sensed Data

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**Abstract:** A comprehensive framework for irrigation water performance assessment (IWPA) based on satellite data was proposed. This framework consists of external IWPA (EIWPA) and internal IWPA (IIWPA). The EIWPA indicates the water supply as well as agricultural and economic performances. On the other hand, the IIWPA expresses the temporal and spatial performances of irrigation water use adequacy (*PA*), equity (*PE*), and dependability (*PD*) indicators. This framework was applied to the irrigation scheme of the Al-Qased canal in the Nile Delta, Egypt, during the winter between 2015 and 2016. The crop water requirements ( $ET_c$ ) were calculated using the Surface Energy Balance Algorithm for Land (SEBAL) model and Landsat 8 images. Three classes, from “good” to “poor,” to classify the EIWPA and IIWPA values were proposed. The EIWPA was classified as “poor” in irrigation efficiency (51.2%) due to the oversupply of irrigation water in relation to the  $ET_c$  while the economic indicators showed that the net profit was 7.84% of the gross value of crop production. The *PE*, *PD*, and *PA* were classified as “fair,” which indicated a non-uniform irrigation water distribution between the head and tail branch canals. Moreover, the irrigation water was inadequate during the growing months and could not meet the  $ET_c$ . The framework presented an efficient tool for the IWPA in terms of spatial, temporal, agricultural, and economic performances.

**Keywords:** irrigation water performance; water supply performance; economic performance; spatial performance; temporal performance; remote sensing; SEBAL

## 1. Introduction

Water scarcity is a serious problem around the world especially in arid regions. These regions face a great challenge due to limited water resources. Among them, Egypt is facing a great challenge due to its limited water resources [1]. Additionally, a shortage of irrigation water supply from the Nile River is expected after the construction of the Grand Ethiopian Renaissance Dam. Hence, the effective management of these limited water supplies is considered a key consideration for future developments [2,3]. Clearly, the agricultural sector is the largest consumer of water resources around the world [4]. Effective planning and management as well as the sustainable production growth of irrigated agriculture can be achieved in two ways. Either new irrigation projects can be established or existing irrigation systems can be evaluated and their performance can be enhanced [5,6]. Recently, improving the performance of irrigation systems proved to be more reliable than establishing new

irrigation projects [7,8]. The term, “irrigation water performance (IWP),” for various irrigation levels (i.e., field, irrigation system, and basin) was defined as a systematic observation, documentation, and interpretation of the activities relevant to irrigated agriculture [9]. It can be quantified by factors such as water inflows and outflows, crop water demand, water use, system losses, and crop yield [7,10].

Irrigation water performance assessment (IWPA) is the first step toward ensuring sustainable agricultural development and any improvement of the irrigation water management [11]. The IWPA could be classified into external (EIWPA) and internal (IIWPA) performance assessments [12]. The EIWPA is related to the overall state of the irrigation system [13]. It focuses on the water efficiency, environmental impacts, and water productivities of the irrigation system. It can be used to monitor the IWP of the irrigation system over time and to compare the IWPs of different irrigation systems. However, it cannot provide the decision-makers with required information concerning trouble locations and their causes in the irrigation system in order to improve them [13]. While the IIWPA describes the internal irrigation processes and the water allocation of an irrigation system, it focuses on the comparison of the delivered water supplies and the water demands. It evaluates the temporal and spatial performance variations of the irrigation system using equity, adequacy, efficiency, and dependability indicators [8]. An adequacy indicator expresses the ability of the delivered water supplies to meet the water demands. An equity indicator measures the fairness of the irrigation water distribution, according to the water demands. Furthermore, a dependability indicator expresses the ability of the irrigation system to deliver the required irrigation water to the water users at the right time [14]. Recently, the IIWPA was performed around the world to evaluate the internal irrigation processes [15–18]. Using both EIWPA and IIWPA is very critical for identifying all of the processes in the irrigation system [19].

Each IWPA has a different set of indicators. These indicators were introduced in the 1970s to characterize the hydrological behavior of the irrigation schedules using a few understandable numbers [20–26]. Several studies have defined the sets of indicators that describe the irrigation water performance [14,27–29]. These indicators were applied to evaluate the existing practices and recommend improvements in both irrigation efficiency and water productivity [5]. Despite the number of reported irrigation performance indicators, it is necessary to adjust new techniques and approaches to existing management practices. Currently, satellite remote sensing (RS) and the geographic information system (GIS) presented themselves as important tools for providing regional information on the agricultural and hydrological conditions of the land surface [30]. The first attempt to use remote sensing techniques in irrigation application was in 2006 [31]. The irrigation efficiency of an irrigation scheme was estimated based on the  $ET_c$  derived from the SEBAL algorithm. The IWP of the Gediz basin in Turkey was assessed based on the  $ET_c$  derived from the SEBAL algorithm [32]. The results indicated that the SEBAL algorithm was efficient in assessing the IWP. Moreover, numerous researchers used the  $ET_c$  derived from the remote sensing data in assessing the irrigation water performance around the world [32–34].

Several studies have reported the IWPA in the Nile delta, Egypt [35–37]. An overall “poor” performance of the Nile delta was reported in 2008 by EIWPA using remote sensing techniques and a moderate resolution imaging spectroradiometer (MODIS) with 250 m resolution [35]. The irrigation water management of old lands in the Nile Delta was assessed at three levels: the main canals, the branch canals, and the on-farm level [35]. About 53% of the annual irrigation water supply on the main canal level was returned to drainage and saline groundwater sinks. An oversupply of irrigation water and a potential for water savings in the Nile delta was reported by the EIWPA [35]. Furthermore, a “fair” IWPA for the Nile delta was reported during the summer season of 2008 (from May to October) by using adequacy  $<0.89$  and dependability indicators  $>0.11$  [37] while a “good” IWPA was reported during the winter season of 2008 (from November to April) using adequacy, dependability, and equity indicators of  $<0.89$ ,  $>0.11$ , and  $>0.11$ , respectively [37].

Despite the number of reported studies, most studies carried out in the Nile delta focused on the EIWPA. However, the IIWPA was not assessed due to the lack of field measurements. Moreover,

a framework for both EIWPA and IIWPA has not yet been proposed to assess the irrigation water performance in the Nile delta. Furthermore, the common types of performance indicators for the Nile delta were mainly related to irrigation efficiency, water balance, economic aspects, social and environmental objectives, or system maintenance. However, the equity, adequacy, and dependability indicators are worse than the irrigation efficiency since an insufficient water supply is considered the most critical problem specifically at the ends of the irrigation networks and canals in the Nile delta [37]. Additionally, previous studies used satellite images with a coarse resolution [35]. Therefore, there is an urgent need for an updated and more detailed assessment of the irrigation water and its economic return in the Nile Delta. To the best of our knowledge, an assessment of the irrigation water performance in the Nile Delta, using fine resolution remotely sensed data, has not yet been addressed. Hence, the main objective of this study was to provide a comprehensive framework for the irrigation water performance assessment in the Nile delta in terms of both external and internal performances including the agricultural and economic dimensions. This framework consists of the same indicators as those employed in previous studies of the Nile delta in order to compare the IWP over time. Additionally, it uses indicators that were not used before for the Nile delta. Moreover, this study aims to evaluate and update the economic situation of the irrigation water in order to support the decision-makers in managing the water resources. This framework was applied to the Al-Qased canal in the Nile delta as a case study. Additionally, the crop water requirements at a regional scale were calculated by using the Surface Energy Balance Algorithm for Land (SEBAL) model and Landsat 8 images (30 m resolution) to assess the irrigation water performance in the Nile Delta.

## 2. Materials and Methods

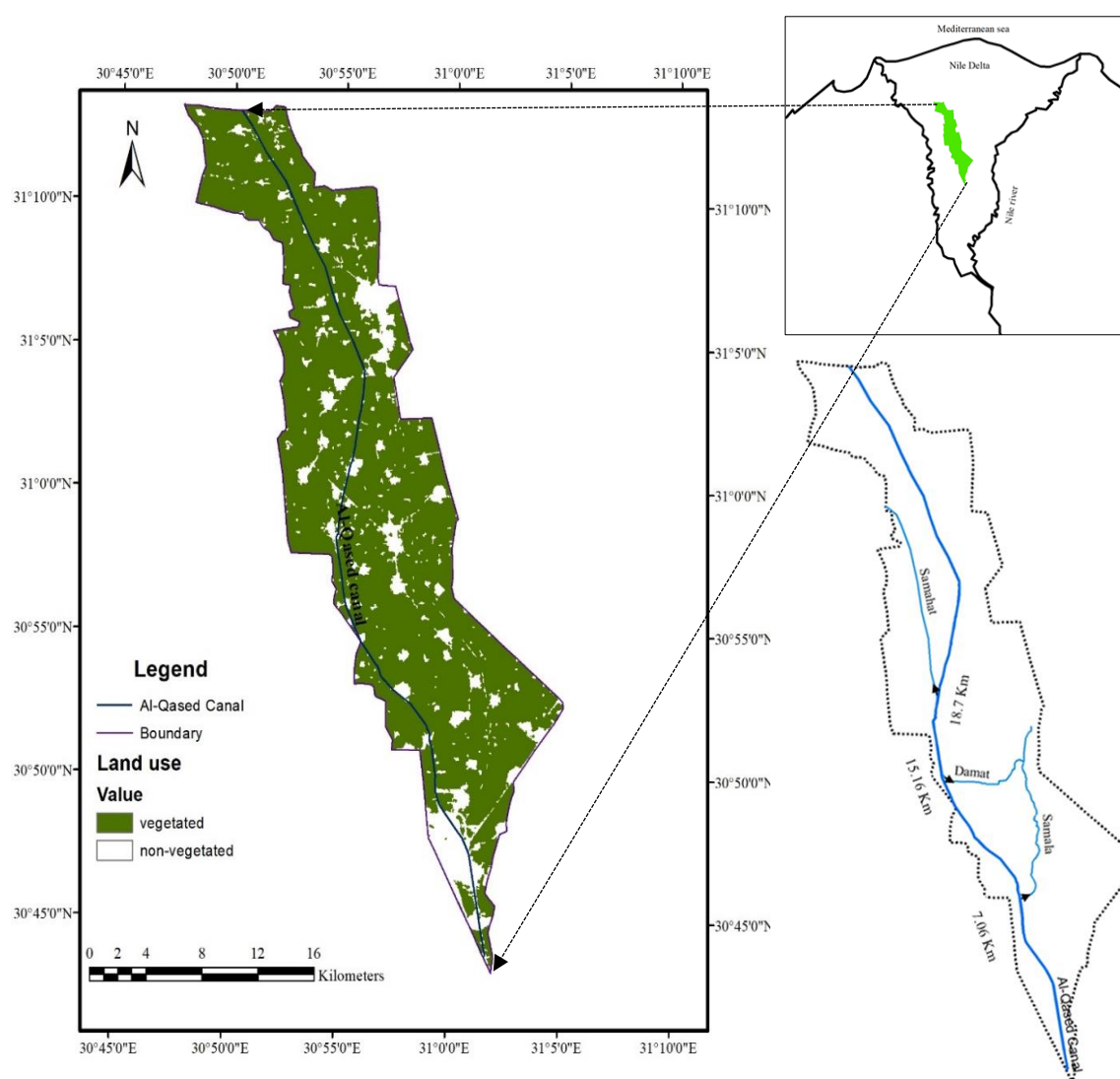
### 2.1. Study Area

An irrigated area in the central portion of the Nile delta was selected to evaluate the performance of the irrigation water in the Nile delta, Egypt. The study area is located between latitudes of  $31^{\circ}45' - 30^{\circ}50'$  N and longitudes of  $30^{\circ}50' - 31^{\circ}50'$  E. The main irrigation water resource in the study area is the Al-Qased canal, which feeds branches and distributary canals to deliver irrigation water to the irrigated areas [38]. This is shown in Figure 1. The Al-Qased main canal is considered one of the largest water streams in the Nile delta.

According to the water budget of Egypt in 2010, the Nile River is considered the main source of surface water supplies in Egypt [39]. It contributes 95% of the total water supplies in the water budget. The groundwater represents about 16% of the total water supplies in Egypt [39,40]. The Al-Qased canal receives approximately  $380 \text{ Mm}^3$  of fresh irrigation water annually from a series of main canals such as Qanat Tana Al-Melahia and Bahr Shebean. Then it transfers the irrigation water to branch canals [41]. The surface irrigation water in the Al-Qased canal is controlled by head regulators and cross regulators. Furthermore, it flows to branch canals due to gravity and is then lifted to fields through marwas and mesqas. The Egyptian Ministry of Water Resources and Irrigation (MWRI) controls the distribution of surface irrigation water between the main and branch canals, according to the monthly crop water requirements [36]. However, the irrigation water distribution between marwas, mesqas, and fields is not controlled by the MWRI. Hence, the study area has a surface water distribution that is inadequate for farmers. Hence, the groundwater wells are drilled and operated by farmers at the farm scale [41]. The water of the Al-Qased canal is mainly used for the irrigation of surrounding areas along its branch canals.

The command area of the canal is about  $420 \text{ km}^2$  (42,000 hectares) [41]. Flooding irrigation is the common irrigation method in the study area [42]. Rainfall in the Nile delta is very limited with less than 200 mm per year. This rainfall mainly occurs during the winter season from December to April. Temperatures during the summer reach an average of  $30^{\circ}\text{C}$  in July and, in winter, the recorded average is  $14^{\circ}\text{C}$  in January [36,43]. Agriculture rotation in the study area consists of three seasonal crop patterns: a winter crop pattern, starting from November to May, which is followed by a summer

crop pattern of six months (May to October). In addition, the period from August to October is called the Neely crop pattern [36]. The winter crop pattern consists of three seasons: A beginning season, which runs from November to December, a growing season, which extends from January to March, and a harvesting season starting in April and ending in May [38]. The main winter crops in the Al-Qased command area are wheat and clover. However, the main summer crops are maize and rice [38]. Between 2015 and 2016, the wheat fields constituted 43% of the winter crop pattern. However, the clover fields accounted for about 35%, which is shown in Table 1.



**Figure 1.** Study area map showing the location of the Al-Qased canal, branch canals, and land uses.

**Table 1.** Crop patterns of The Al-Qased canal and the Samla, Damat, and Samahat branch canals.

Crops	The Al-Qased Canal	Samla Branch Canal	Damat Branch Canal	Samahat Branch Canal
Wheat (hectare)	18,272	1612	2112	1699
Clover (hectare)	14,715	1254	1173	1369
Other crops (hectare)	9013	717	1408	838
Sum (hectare)	42,000	3582	4693	3906

The Al-Qased canal has three major branch canals: The Samla, Damat, and Samahat canals, which is shown in Figure 1. The Samla, Damat, and Samahat canals are connected at 7.06, 15.16, and 18.7 km of the Al-Qased canal and represent the head, middle, and tail branch canals, respectively. Their command areas represent about 30% of the total command area of the Al-Qased canal, which is shown in Table 1. The Samla canal is 10.38 km in length and has a 17.85 km<sup>2</sup> command area. The Damat canal is 11.54 km in length and has a 19.53 km<sup>2</sup> command area. The Samahat canal is 15.16 km in length and has a 26.46 km<sup>2</sup> command area. Their winter crop patterns are shown in Table 1.

## 2.2. Irrigation Water Balance and Evapotranspiration

The water balance for the study area was calculated based on the water supplies, demands, and losses. The water supplies consist of surface water, groundwater, and precipitation. The surface water supply data were collected from the MWRI for the period from November 2015 to October 2016. The groundwater abstraction was estimated based on field measurements by El-Agha et al. from 2014 to 2016 [41]. They surveyed the density, types, and depths of drilled wells in the study area. Then, they estimated the groundwater abstraction by meeting with farmers and questionnaires about the operating schedule of the wells [41]. The precipitation records were collected from a weather station in the study area. The precipitation ranged from 0.0 to 12.67 mm during the winter season (from November 2015 to May 2016). While the water losses consist of surface runoff, seepage, and percolation, the surface runoff and percolation could not be estimated due to the lack of field data. The seepage from irrigation canals was estimated based on Equation (1) [44].

$$S = C \times L \times P \times \sqrt{R} \quad (1)$$

where  $S$  is seepage losses along the canal (m<sup>3</sup>/s/km),  $L$  is length of the canal (m),  $P$  indicates the wetted perimeter of the canal's cross section (m),  $R$  indicates the hydraulic mean depth (m), and  $C$  is a varied coefficient depending on the soil nature.

The water demands for the study area consist of irrigation water requirements for crops (i.e., crop water consumption) using drinking water requirements and water consumption for industrial activities. The drinking water requirements are calculated based on the inflow of potable water treatment plants (PWTPs) along the canal. The required water for the PWTPs and water for industrial consumption were collected from the MWRI of Egypt. The crop water consumption is represented by the actual evapotranspiration ( $ET_c$ ) [38]. The  $ET_c$  in the study area during the winter season (from November 2015 to May 2016) was estimated using metrological records and the remote sensing technique (the SEBAL algorithm) [45]. The metrological records include temperature (maximum, minimum, and average), relative humidity ( $RH$ ), wind speed, precipitation, and surface pressure. Additionally, a set of six cloud-free (<10% clouds) Landsat 8 images were used in the SEBAL algorithm with 30 m resolution to calculate  $ET_c$ , which is shown in Table 2 [45]. A series of computations of the net surface radiation ( $R_n$ ), soil heat flux ( $G$ ), and sensible heat flux to the air ( $H$ ) were used in the SEBAL algorithm to calculate the latent heat flux ( $\lambda ET_c$ ), which is shown in Equation (2) [46].

$$R_n = G + H + \lambda ET_c \quad (2)$$

$\lambda ET_c$  is the instantaneous latent heat flux, which was used to compute the instantaneous evaporation  $ET_{inst}$  (mm/h) using Equation (3).  $ET_{inst}$  represents the spatial distribution of the hourly  $ET_c$  of all crops in the study area [47].

$$ET_{inst} = 3600 \times \frac{\lambda ET}{\lambda} \quad (3)$$

where  $\lambda$  is the latent heat of vaporization (J/kg) and 3600 is the conversion from seconds to hours (ref).



The reference evapotranspiration ( $ET_o$ ) was estimated using the FAO Penman-Monteith formula (Equation (4)) [48] and the meteorological records.

$$ET_o = \frac{0.408 \Delta (Rn - G) + \gamma \left( \frac{900}{T + 273} \right) u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)} \quad (4)$$

where  $Rn$  is the net radiation ( $\text{MJ}/\text{m}^2/\text{day}$ ),  $T$  represents the mean daily air temperature at 2.0 m height ( $^{\circ}\text{C}$ ),  $G$  is the soil heat flux density ( $\text{MJ}/\text{m}^2/\text{day}$ ),  $e_s$  expresses the saturation vapor pressure (kPa), and  $e_a$  is the actual vapor pressure (kPa). In addition,  $u_2$  is the wind speed at 2.0 m height (m/s),  $\gamma$  is a psychrometric constant (kPa/ $^{\circ}\text{C}$ ), and  $\Delta$  is the slope vapor pressure curve (kPa/ $^{\circ}\text{C}$ ).

Daily  $ET_c$  ( $ET_{c-24}$ ) was estimated by using Equation (5). Furthermore, the  $ET_c$  for the periods between the satellite overpass ( $ET_{c-period}$ ) was estimated by using Equation (6) [47].

$$ET_{c-24} = ET_o \cdot f \times ET_{o-24} \quad (5)$$

where  $ET_o \cdot f$  is the reference evapotranspiration fraction, which is the ratio of  $ET_{inst}$  to  $ET_o$ , and  $ET_{o-24}$  is the cumulative 24-h  $ET_o$  for the day of the satellite overpass [47].

$$ET_{o-period} = (ET_o \cdot f)_{period} \times \sum_1^n ET_{o-24} \quad (6)$$

where  $n$  is the number of days between the satellite overpasses.

The potential evapotranspiration ( $ET_p$ ) was estimated by using Equation (7) [49] shown below.

$$ET_p = ET_o \times K_c \quad (7)$$

where  $K_c$  is the crop coefficient. This is affected by the crop characteristics, length of each growing stage, irrigation schedules, and climate conditions.

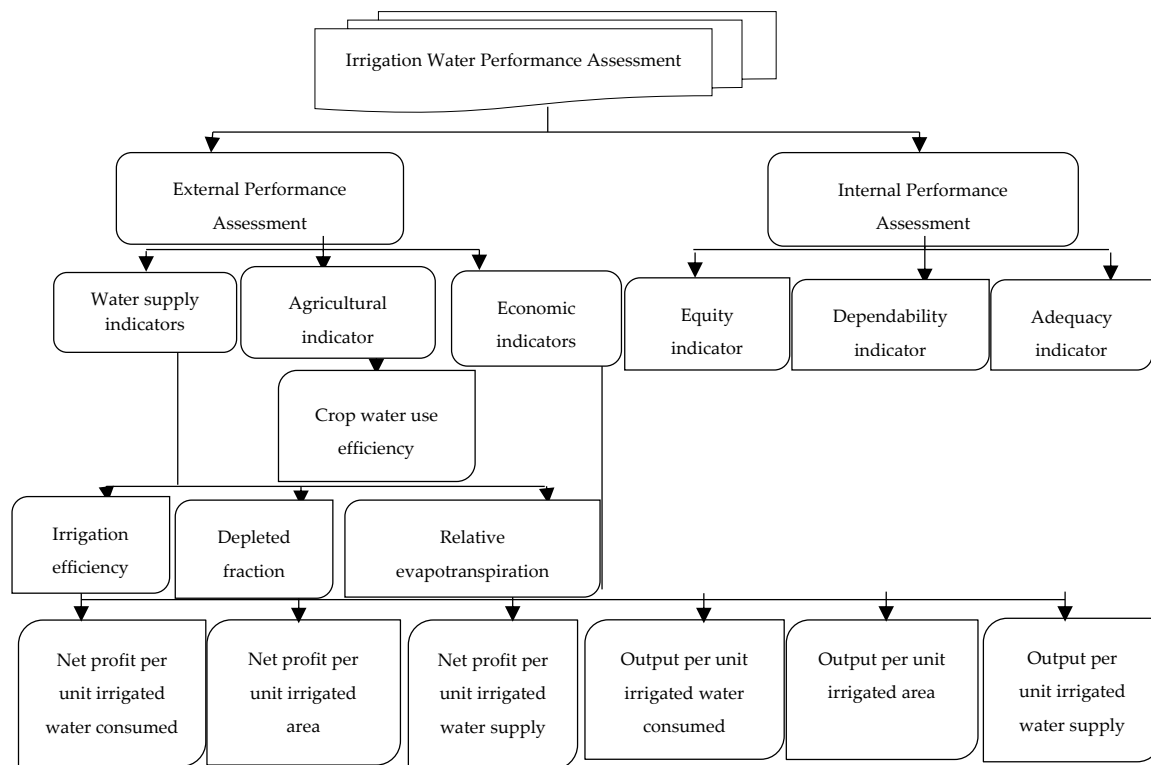
The accuracy of the SEBAL algorithm was tested for the Nile delta using 21 ground points of different crops. A regression model of the simulated  $ET_c$  of the SEBAL algorithm and the actual  $ET_c$  based on the data of ground points and the FAO-Penman Monteith formula was used. The results showed that the SEBAL algorithm was efficient in estimating the  $ET_c$  in the Nile delta with  $R^2 = 98\%$  [45].

**Table 2.** Details of the Landsat8/ETM satellite images over the center of the Nile delta.

Acquired Date	Path/Row	Pixel Size (m)	Coordinate System/Datum	Zone
20 November 2015	177/38	30	UTM/WG84	36
6 December 2015	177/38	30	UTM/WG84	36
24 February 2016	177/38	30	UTM/WG84	36
11 March 2016	177/38	30	UTM/WG84	36
28 April 2016	177/38	30	UTM/WG84	36
30 May 2016	177/38	30	UTM/WG84	36

### 2.3. The Irrigation Water Performance Assessment Framework

An IWPA framework based on remotely sensed data was proposed. We formulated two irrigation water performance assessment models: An external irrigation water performance assessment (EIWPA) model and an internal irrigation water performance assessment (IIWPA) model, which is shown in Figure 2.



**Figure 2.** Schematic diagram of the framework of the irrigation water performance assessments.

### 2.3.1. The External Irrigation Water Performance Assessment

The EIWPA based the on water supply as well as agricultural and economic performance indicators was proposed. The water supply indicators assess the water supplies in relation to crop consumption. These indicators help managers evaluate the water stress and improve water use management. The agricultural indicators define the output of the irrigation system in terms of water productivity while the economic indicators evaluate the benefits of current water use practices.

- *The water Supply Indicators*

The water supply indicators include irrigation efficiency ( $E_i$ ), the water depleted fraction ( $DF$ ), and relative evapotranspiration ( $RET$ ), which is shown in Figure 2. The  $E_i$  consists of two components including water conveyance efficiency ( $E_d$ ) and water application efficiency ( $E_a$ ) (Equation (8)). The  $E_i$  depends on the irrigation network distribution, soil properties, crop type, and metrological records (i.e., temperature, wind speed, precipitation, etc.) [50,51]. The  $E_i$  can be expressed as follows (Equation (9)).

$$E_i = E_d \times E_a \quad (8)$$

$$E_i = (W_c/W_{sg}) \times 100 \quad (9)$$

where  $W_c$  refers to the crop water consumption and  $W_{sg}$  refers to the surface and groundwater supplies. Three classes of water supply performance were proposed according to the value of  $E_i$  (Table 3).

The  $E_d$  is the ratio of the delivered water by a conveyance system ( $W_d$ ) to the water that is introduced to the conveyance system from the source ( $W_t$ ). It is calculated below (Equation (10)) [52].

$$E_d = (W_d/W_t) \times 100 \quad (10)$$

The  $E_a$  is the ratio of the water that is stored in the root zone of crops in a farm ( $W_s$ ) to the delivered irrigation water to the farm ( $W_f$ ) (Equation (11)) [53].

$$E_a = (W_s/W_f) \times 100 \quad (11)$$

The  $DF$  expresses the ratio of the  $ET_c$  to the total water inflow [sum of surface and groundwater supplies ( $W_{sg}$ ) in addition to precipitation ( $P$ )], which is shown in Equation (12) [9,54].

$$DF = ET_c/(W_{sg} + P) \quad (12)$$

The  $DF$  could be used to assess the water consumed by crops and identify the water consumption of crops over time [55]. The  $DF$  quantifies the surface water balance [55]. Furthermore, the  $DF$  could be an effective tool for monitoring the groundwater storage. The groundwater storage is considered stable if the seasonal  $DF$  is about 0.6 while the extra irrigation water will be stored at a  $DF$  lower than 0.6. However, if  $DF$  exceeds 0.6, the extra amount of irrigation water will be drained to the surface and ground drains [9].

The  $RET$  is the dimensionless ratio of the  $ET_c$  to the  $ET_p$ , which is shown in Equation (13) below [9].

$$RET = ET_c/ET_p \quad (13)$$

The  $RET$  was used to express the crop water stresses in the study area. Bandara [55] reported that the critical value of  $RET$  was 0.65. Furthermore, a crop water stress was experienced at  $RET < 0.65$ . However,  $RET \geq 0.65$  indicated sufficient water supplies. Recently, managers tended to monitor the relationship between the crop yield, crop water use, and growing stage to propose an efficient irrigation schedule [55]. Moreover, managers used the  $RET$  to estimate the changes in evapotranspiration and detect the crop water-stress [55].

**Table 3.** Standards of performance indicators for an irrigation scheme [14].

Indicator	Classes of Irrigation Water Performance		
	Good	Fair	Poor
Irrigation Efficiency ( $E_i$ )	0.85–1.0	0.7–0.84	<0.70
Adequacy ( $P_A$ )	0.90–1.0	0.8–0.89	<0.80
Equity ( $P_E$ )	0.0–0.1	0.11–0.2	>0.2
Dependability ( $P_D$ )	0.0–0.1	0.11–0.2	>0.2

- *The agricultural indicator*

The agricultural indicator was expressed in terms of water productivity [8]. The water productivity could be assessed at the field scale using the crop water-use efficiency ( $CWUE$ ) [56]. The  $CWUE$  is the ratio of one crop yield ( $Y$ ) to its amount of  $ET_c$  (Equation (14)) [57].

$$CWUE = (Y/ET_c) \quad (14)$$

- *The economic indicators*

Two groups of economic indicators were used to assess the economic performance of irrigation water. The first group uses the gross value of crop production in addition to the value of the unit water supplies (i.e., surface water and groundwater),  $ET_c$ , and the area of irrigated lands [54]. The gross value of crop production is the crop yield multiplied by the price of the crop plus indirect crop profits.

In the first group, three indicators were proposed, which are shown below.

1. Output per unit of irrigation water supplies = the gross value of crop production/the required water supplies for this production ( $LE/m^3$ ).



2. Output per unit of the irrigated area = the gross value of crop production/the irrigated area for this production (LE/hectare).
3. Output per unit of the irrigation water consumed = the gross value of crop production/the volume of ETc of these crops (LE/m<sup>3</sup>).

The second group, which was based on the net profit of crop production, was proposed. The net profit is the difference between the gross value of the crop production and the total cost of this production. The indirect crop profits are the values of the crops consumed by the farmers. Additionally, the total cost of the crop production (i.e., land preparation, seeds, plantations, diesel, maintenance of pumps, harvesting and postharvest, etc.) were considered in the calculations. Three indicators were proposed, which are discussed below.

1. Net profit per unit of irrigation water supplies = the net profit of crop production/the required water supplies for this production (LE/m<sup>3</sup>).
2. Net profit per unit of the irrigated area = the net profit of crop production/the irrigated area for this production (LE/hectare).
3. Net profit per unit of the irrigation water consumed = the net profit of crop production/the volume of ETc of these crops (LE/m<sup>3</sup>).

### 2.3.2. The Internal Irrigation Water Performance Assessment

The IIWPA based on three indicators was proposed to consider the spatial and temporal variations of irrigation water performance, which is shown in Figure 2. These indicators were the adequacy, equity, and dependability. Three performance classes were proposed for each indicator, which is shown in Table 3.

- *The adequacy indicator*

The adequacy indicator ( $P_A$ ) represents the ability of the irrigation system to deliver the required irrigation water [58]. The adequacy indicator is the ratio of the delivered water ( $Q_D$ ) to the required irrigation water ( $Q_R$ ) for an area ( $R$ ) over a period  $T$  (Equation (15)).

$$P_A = \frac{1}{T} \sum_T \left( \frac{1}{R} \sum_R \frac{Q_D}{Q_R} \right) \quad (15)$$

If  $Q_D \geq Q_R$ , the  $P_A$  will be  $>1.0$ , which indicates that the delivered water is adequate [37]. In such cases, the  $P_A$  is considered equal to 1.0 in the evaluation [37].

- *The equity indicator*

The equity indicator ( $P_E$ ) expresses the spatial uniformity and fairness of the irrigation system in delivering the required irrigation water [11]. The coefficient of variation ( $CV_R$ ) expresses the spatial variation for the ratio of  $Q_D/Q_R$  at time  $T$  (Equation (16)) [59].

$$P_E = \frac{1}{T} \sum_T CV_R \left( \frac{Q_D}{Q_R} \right) \quad (16)$$

where  $CV_R$  is the spatial coefficient of variation for the ratio ( $Q_D/Q_R$ ) over a region  $R$ . If  $P_E$  is equal to or almost equal to zero, the irrigation system is considered to deliver the irrigation water in equity values to the water users [37].

- *The dependability indicator*

The dependability indicator ( $P_D$ ) expresses the reliability of the irrigation system to deliver the required irrigation water at a specific time (Equation (17)) [11].

$$P_D = \frac{1}{R} \sum_R CV_T \left( \frac{Q_D}{Q_R} \right) \quad (17)$$

where  $CV_T$  is the temporal coefficient of variation for the ratio ( $Q_D/Q_R$ ) over a period  $T$ . If  $P_D$  is equal to or almost equal to zero, the irrigation system is considered to deliver sufficient irrigation water to the water users at the specific time [37].

#### 2.4. Application of the Irrigation Water Performance Assessments

The EIWPA and IIWPA were applied to the irrigation scheme of the Al-Qased canal, Nile delta, Egypt during the winter season (from November 2015 to May 2016). The EIWPA was applied to the whole study area using the water supply along with the agricultural and economic indicators. The water supply indicators were calculated based on the estimated water balance of the Al-Qased canal. The water supply indicators in terms of  $E_i$ ,  $DF$  and  $RET$  were calculated at monthly (from November 2015 to May 2016) and seasonal scales (for the winter season). The agricultural indicator was calculated for two major crops (i.e., wheat and clover). The yield and  $ET_c$  of the wheat and clover were collected from previous studies [45,49]. The economic indicators were calculated for the wheat, clover, and winter crop patterns. The agricultural and economic indicators were calculated at a seasonal scale.

Furthermore, the IIWPA was applied to three main branch canals (i.e., Samla, Damat, and Samahat), which represent about 30% of the total command area of the Al-Qased canal. These branch canals are located at the head, middle, and tail of the Al-Qased canal, which is shown in Figure 1. The spatial performance variation was assessed using the  $P_A$  and  $P_E$ . Moreover, the  $P_A$  and  $P_D$  were used to assess the temporal performance variation. The  $Q_D$  at each branch canal was obtained from MWRI. While the  $Q_R$  for all of the crops in each branch canal was estimated using remotely sensed  $ET_c$  produced by the SEBAL algorithm and Landsat 8 [45,49].

### 3. Results and Discussion

#### 3.1. Water Balance along the Al-Qased Canal

The water balance over the study area during the winter season (from November 2015 to May 2016) was estimated, which is shown in Table 4. The surface water is the main water supply in the study area with 65.38% of the total supplies. This supply is controlled and managed by the MWRI to satisfy the irrigation, industry, and drinking water demands in the study area. The surface water supply during the winter (from November 2015 to May 2016) and summer seasons (from May to October 2016) is shown in Figure 3. The summer season had higher supplies when compared to the winter season. The surface water supply reached a peak of 107.15  $\text{Mm}^3$  in July 2016 while the lowest water supply was recorded in January 2016. This could be attributed to the difference between the crop patterns in the summer and winter seasons. During the summer, large areas in the Nile delta were cultivated by rice, which is one of the high water consuming crops [35].

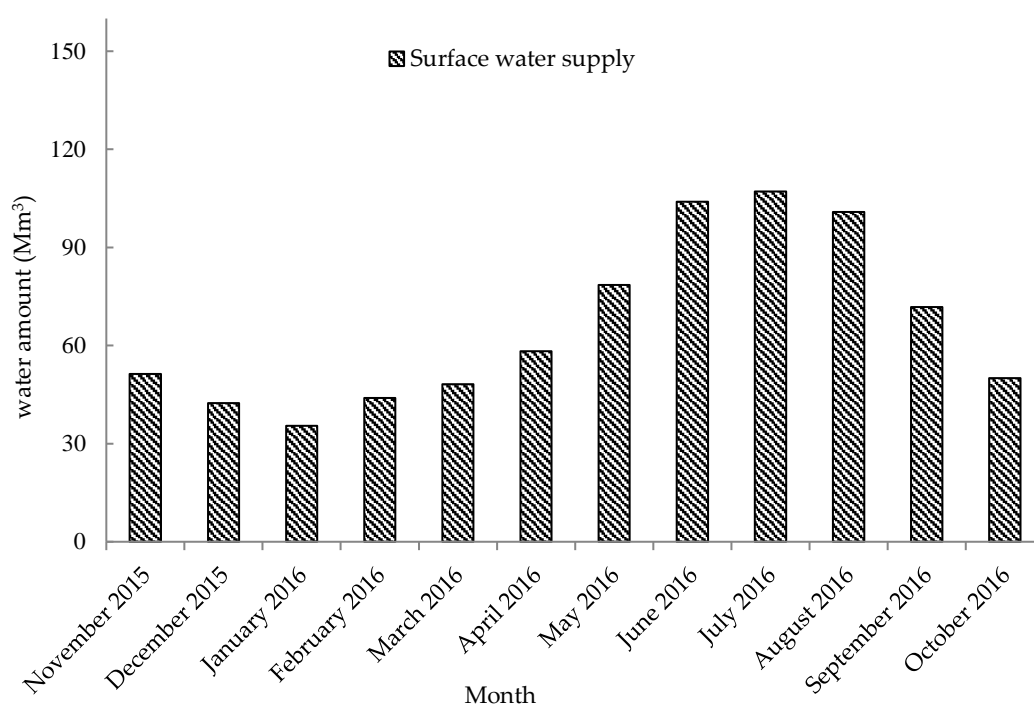
The groundwater of 150  $\text{Mm}^3$  was abstracted during the winter season [41], which is shown in Table 4. It represents about 31.64% of the total water supplies. Due to the aridity of the region, only 2.98% of the total water supplies were obtained from the precipitation.

The water losses due to seepage were estimated at 4.92  $\text{m}^3/\text{s}$  (220.28  $\text{Mm}^3$ /winter season). However, the surface runoff and percolation could not be assessed due to a lack of field data. However, the percolation water from the irrigation systems to the groundwater recharge in the Nile delta is about 25 mm/day [60]. The Crop water consumption was the largest consumer with 45% of the total water supplies. The SEBAL model with Landsat 8 images (fine resolution) was used to assess the  $ET_c$  distribution over the Nile Delta with a high accuracy ( $R^2 = 98\%$ ) [45]. Hence, the remotely sensed  $ET_c$  would significantly enhance the accuracy of the IWPA in the study area. The  $ET_c$  varied from 125 to 650 mm in the winter season, which is shown in Figure 4 [45]. The  $ET_c$  had lower values in the southern part of the study area than in the northern part. This was due to the high abstraction of groundwater in the southern part, which substantially reduced the  $ET_c$  [45]. The drinking water requirements were abstracted for three PWTs along the Al-Qased canal with a discharge of 35,430  $\text{m}^3/\text{day}$  (MWRI).

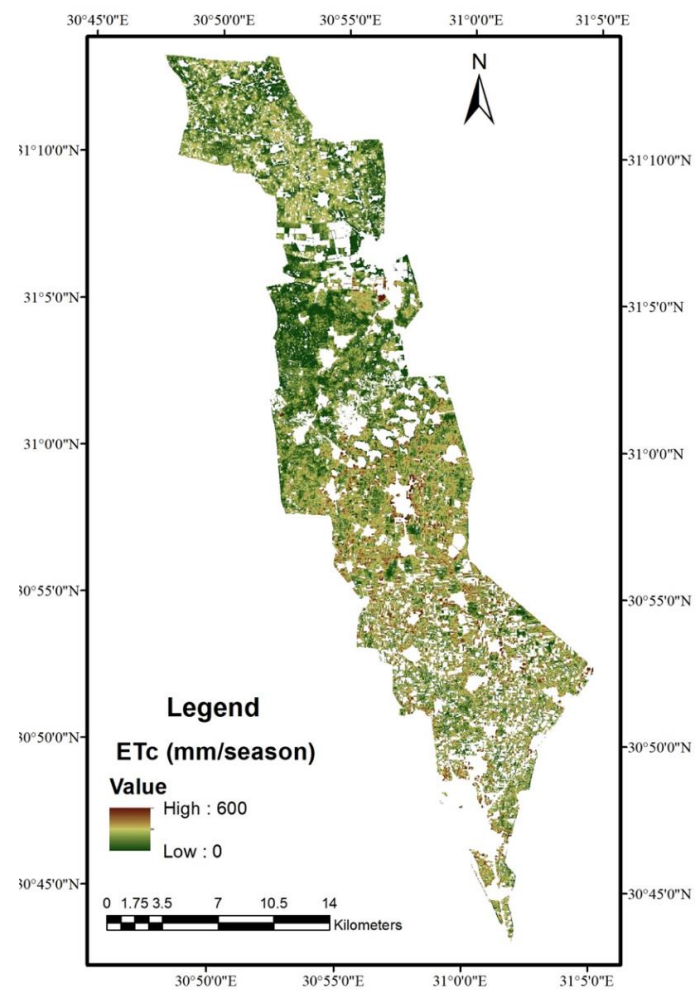
**Table 4.** Water balance in the study area during the winter season (from November 2015 to May 2016).

	Sector	Water Volume (Mm <sup>3</sup> /Season)	Ratio
Input	Surface water supply	310	65.38%
	Groundwater	150	31.64%
	precipitation	14.1	2.98%
	Sum	<b>474.1</b>	<b>100%</b>
Output	Crop water consumption	210	45.0%
	Potable water treatment plants	6.48	1.38%
	Industrial water consumption	30	6.33%
Losses	Seepage losses in the irrigation canals	220.28	47.2%
	Other losses (surface runoff, evaporation losses, etc.)	NC	NC

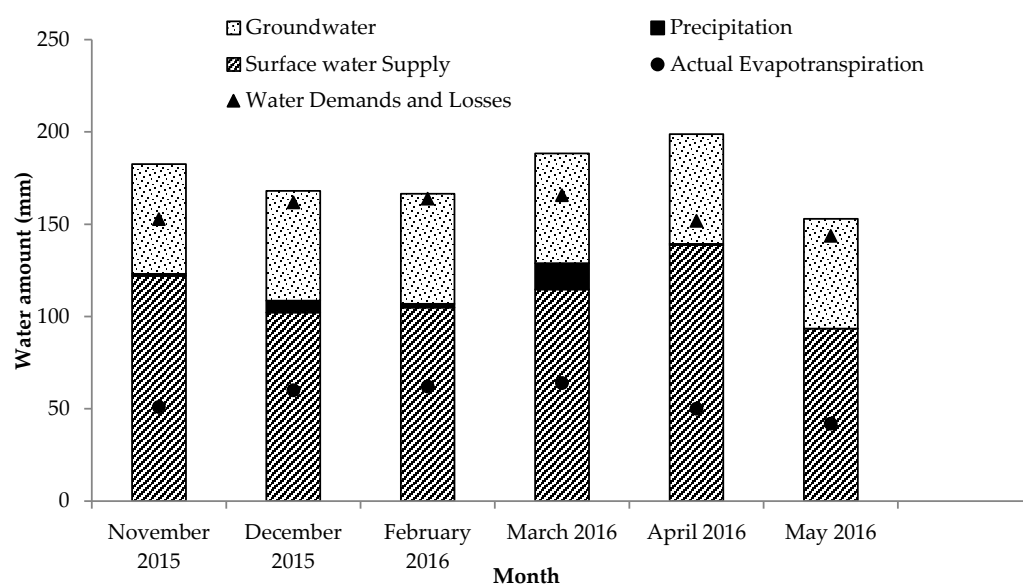
NC: Calculated values are not expressed due to lack of measurements.

**Figure 3.** Surface water supply of the Al-Qased canal during the winter season (from November 2015 to May 2016) and summer season (from May to October 2016).

The monthly water balances in the study area during the winter season from 2015 to 2016 are shown in Figure 5. The results indicate that the water supplies were almost sufficient to meet the water demands in December 2015 and February 2016. This could be attributed to the high crop water consumption during the growing months. However, an oversupply in March 2016 occurred due to higher precipitation. Moreover, in November 2015 and April 2016, the water supply was higher than the demand. This could be due to the low crop water consumption in November (beginning season) and April (harvesting season). The results indicated that there was no need to reuse agricultural drainage water (ADW) for irrigation purposes in the study area during the winter season. The ADW reuse is widely practiced in the Nile delta by pumping ADW from the main drains into the main irrigation canals [61]. These results are consistent with Khater et al. [37] who noticed that there is no need to reuse ADW to satisfy the irrigation water requirements in the Nile delta during the winter of 2008.



**Figure 4.** Actual evapotranspiration ( $ET_c$ ) of the study area during the winter (from November 2015 to May 2016).



**Figure 5.** Monthly water balance of the study area during the winter season (from November 2015 to May 2016).

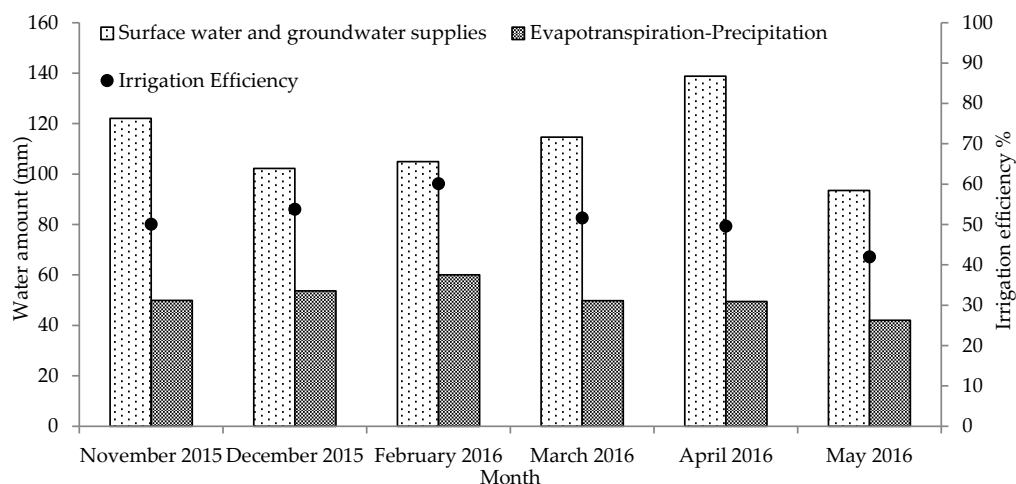
### 3.2. The External Irrigation Water Performance Assessment

The EIWPA was evaluated using three categories of indicators for the Al-Qased command area. These categories include water supply, agricultural indicators, and economic indicators. This assessment was estimated by using the water balance of the study area during the winter season (from November 2015 to May 2016), which is shown in Table 4.

- *Irrigation efficiency ( $E_i$ )*

The monthly  $E_i$ , water supplies, and actual evapotranspiration minus precipitation ( $ET_c - P$ ) in the study area are shown in Figure 6. The results showed that the monthly  $E_i$  was classified as “poor” performance (i.e.,  $E_i \leq 70\%$ ) during the winter season. This could be attributed to the oversupply of irrigation water rather than the actual requirements. The  $E_i$  gradually increased from November 2015 to February 2016. The  $E_i$  was 50.08%, 53.8%, and 60.09% in November, December, and February, respectively. This may be a consequence of the increase in  $ET_c$  due to the growth of plants and, simultaneously, the decrease in surface water supply, which is shown in Figure 3. However, the  $E_i$  dropped to 51.59% and 49.63% in March 2016 and April 2016, respectively. This may be due to the increase in surface water supplies from 104.90 mm in February to 114.61 and 138.75 mm in March and April, respectively. Nevertheless, the lowest value of  $E_i$  was 44.93% in May. The  $ET_c$  experienced the lowest value during the harvesting month of 42.0 mm in May. A moderate surface water supply of 93.48 mm was experienced in May.

The seasonal  $E_i$  and  $E_d$  were calculated using Equations (9) and (10) during the winter season. The seasonal  $E_i$  was 51.20%, which was classified as “poor” performance. Furthermore, the  $E_d$  was 56.26%, which refers to higher losses in the conveyance system. This could be due to the high seepage losses in the irrigation canals (i.e., 220.28 Mm<sup>3</sup>/season, 47.20%). These results are consistent with Khadr et al. [36] who found that the seasonal  $E_i$  for the center of the Nile delta during the winter of 2012 was 45.0% and the same irrigation practices were applied with a slight difference in the crop patterns and water supplies. Greater attention should be devoted to reducing the seepage losses through the irrigation canals in order to improve the irrigation efficiencies.



**Figure 6.** Average monthly water supplies (i.e., surface and groundwater), actual evapotranspiration minus precipitation ( $ET_c - P$ ), and the irrigation efficiency of the study area during the winter season (from November 2015 to May 2016).

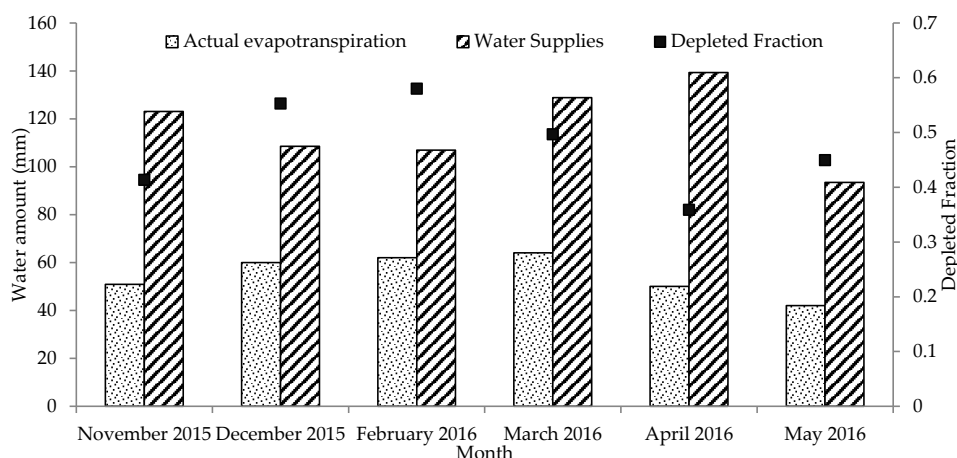
#### 3.2.1. Water Supply Indicators

- *The depleted fraction*

The monthly  $DF$  values of the study area ranged from 0.359 to 0.570 during the winter season (from November 2015 to May 2016), which is shown in Figure 7. The  $DF$  increased from November

to February (0.414 to 0.580). This was due to the increment in  $ET_c$  and, simultaneously, the decrease in water supplies. From March to April, the  $DF$  decreased from 0.497 to 0.359, respectively. This could be due to the decrease in  $ET_c$  from 64 to 50 mm during the harvesting season. During May, the  $DF$  increased to 0.449 since the  $ET_c$  and water supplies reached their lowest values of 42.0 and 93.0 mm, respectively.

Recently, Bos et al. [9] reported that the critical values of the  $DF$  ranged from 0.50 to 0.70 with an average of 0.60 for arid and semi-arid regions. The seasonal  $DF$  was 0.475 in the study area during the winter season (from November 2015 to May 2016). This indicates an increase in the groundwater recharge. Similar results were obtained by Al-Agha et al. [35] who reported that the  $DF$  ranged from 0.270 to 0.774 during the winter between 2008 to 2009 in the Nile delta. They noted that the annual  $DF$  was 0.48, which indicates a potential groundwater recharge. Furthermore, Doorenbos [60] reported that the irrigation systems in the Nile delta contribute 0.25 mm/day to the groundwater recharge.



**Figure 7.** The actual evapotranspiration ( $ET_c$ ), water supplies, and depleted fraction ( $DF$ ) of the study area during the winter season (from November 2015 to May 2016).

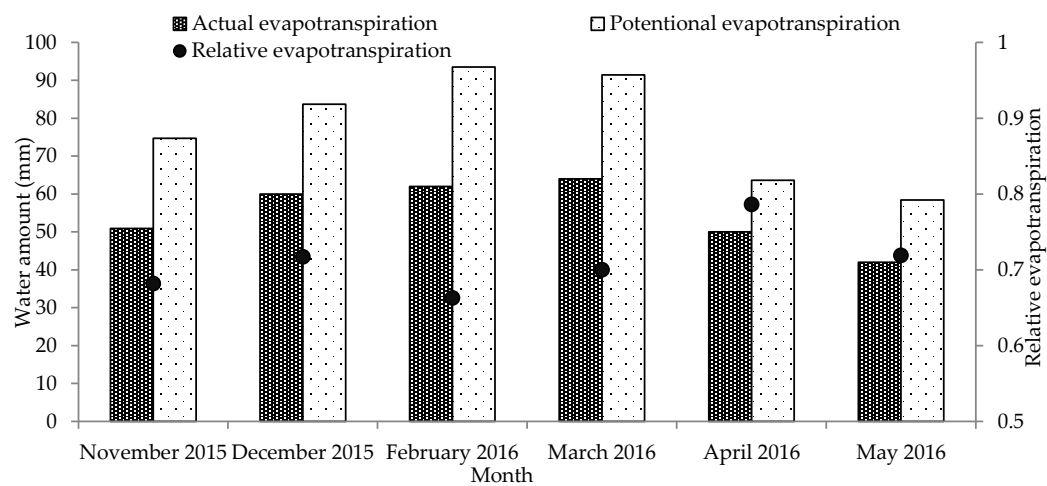
- *Relative evapotranspiration*

The monthly  $RET$  in the study area during the winter season (from November 2015 to May 2016) is shown in Figure 8. The results showed that the  $RET$  was higher in April and May and reached 0.786 and 0.719, respectively. This could be due to the decrease in the  $ET_c$  and  $ET_p$  during the harvesting season. The  $RET$  increased from November to December (0.682 to 0.717). This could be attributed to the increase in the  $ET_p$  and  $ET_c$ . Furthermore, the  $ET_c$  increased from 60 mm in December to 64 mm in March. Consequently, the  $RET$  decreased from 0.717 to 0.699, respectively. Moreover, the seasonal  $RET$  of the study area was 0.711 during the winter season.

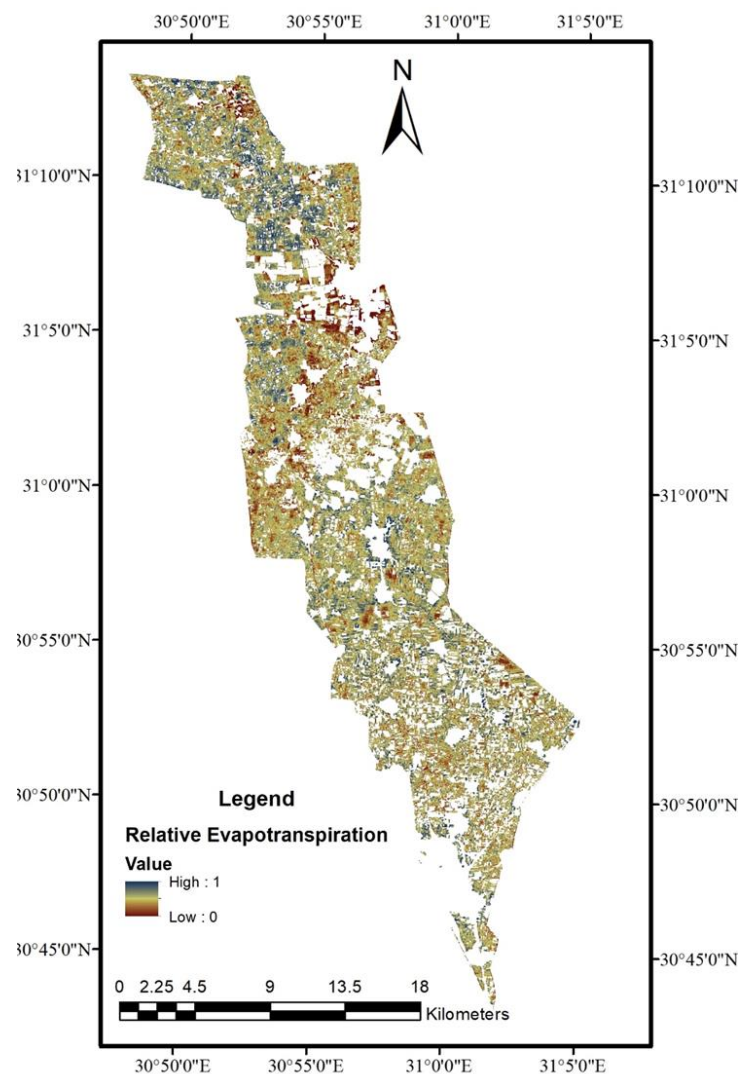
The crop water stresses in the study area were estimated during the winter season using  $RET$ . The monthly  $RET$  ranged from 0.663 to 0.786. Subsequently, no significant crop water stresses were experienced in the study area. Similar results were reported by Al-Agha et al. [35] who reported that the  $RET$  during the winter from 2008 to 2009 ranged from 0.64 to 1.0 and, consequently, no significant crop water stresses were experienced in the center of the Nile delta.

Furthermore, the regional distribution of seasonal  $RET$  during the winter season is shown in Figure 9. The average  $RET$  was  $\geq 0.65$  in the northern region of the study area and no crop water stresses were experienced. However, the southern region of the study area had an average  $RET$  of  $< 0.65$ , which indicates crop water stresses. Subsequently, the abstraction of groundwater in the southern region of the study area was high enough to satisfy the irrigation water requirements. These results are consistent with Al-Agha et al. [41] who reported that the abstraction of the groundwater in the southern region of the center of the Nile Delta is higher than its value in the northern region.





**Figure 8.** Actual, potential, and relative evapotranspiration of the study area during the winter season (from November 2015 to May 2016).



**Figure 9.** Distribution of the relative evapotranspiration of the study area during the winter season (from November 2015 to May 2016).

### 3.2.2. Agriculture Indicator

The crop water productivity of wheat and clover were assessed using *CWUE*, which is shown in Table 5. This was due to their high participation in the winter crop pattern (42% and 35%, respectively). The wheat yield was about 6.5 ton/hectare while the clover yield was about 71.429 ton/hectare in the Nile delta with sufficient water supplies [49]. The results showed that clover had a higher *CWUE* than wheat (15.38 and 1.55 kg/m<sup>3</sup>, respectively). This could be attributed to the high clover yield. Furthermore, the *CWUE* for wheat is higher than its value (1.05 kg/m<sup>3</sup>), which is reported in the Nile delta between the winters of 2008 and 2009 [35]. The high *CWUE* for wheat was due to the oversupply of irrigation water in the study area during the winter season between 2015 and 2016. These oversupplies resulted in an increase in the *ET<sub>c</sub>* and, consequently, the *CWUE* [62]. Similar results of the *CWUE* for wheat were reported in the north of the China plain using the SEBAL algorithm with National Oceanic and Atmospheric Administration (NOAA) images. It ranged from 0.5 kg/m<sup>3</sup> to 1.67 kg/m<sup>3</sup> during the winter of 2008 [62]. Additionally, it ranged from 0.734 to 0.933 kg/m<sup>3</sup> in the loss plateau of China during the winter of 2002 [63].

**Table 5.** Crop water use efficiency (*CWUE*) for the Al-Qased command area during the winter season (from November 2015 to May 2016).

Crop	Yield (Ton/Hectare/Season) [36]	Actual Evapotranspiration (mm/Season) [33]	<i>CWUE</i> (Kg/m <sup>3</sup> /Season)
Wheat	6.50	400	1.55
Clover	71.4	465	15.38

The results showed that clover had a higher *CWUE* than wheat in the Nile delta. Hence, increasing the clover participation in the winter crop pattern will enhance the crop water productivity and the agricultural performance in the Nile delta. The *CWUE* proved its reliability as a useful tool in designing the crop pattern.

### 3.2.3. Economic Assessment

The total costs of wheat and clover productions during the winter season between 2015 to 2016 were collected from the farmers in the study area, which is shown in Table 6. The total costs were 18,810 and 17,143 LE/hectare for wheat and clover, respectively. The cost of field rent, preparations, and irrigation services were the same for wheat and clover productions. However, the cost of labor, seeds, fertilization, resistance pests, harvest, and transportation were higher for wheat production than clover production, which is shown in Table 6. The Gross value and total cost of wheat production were 19,812 and 18,810 LE/hectare, respectively. Hence, the net profit of wheat production was 1002 LE/hectare. Nevertheless, the gross value and total cost of clover production were 19,286 and 17,143 LE/hectare, respectively. Thus, the net profit of clover production was 2143 LE/hectare. This high net profit could be attributed to the high clover yield and the relatively low total cost of production.

The net profit of the Al-Qased command area was 60.82 million LE, which represents 8.25% of the gross value of winter crop production during the winter season. Similar results were reported during the winter of 2012. The net profits represented 7.84% of the gross value of winter crop production in the center of the Nile Delta [38].

The economic indicators for the Al-Qased command area during the winter season are shown in Table 7. The output per unit of irrigation water supplies for the winter crop pattern was 1.60 LE/m<sup>3</sup>. However, the net profit per unit of irrigation water supplies for the winter crop pattern was 0.13 LE/m<sup>3</sup>. Al-Agha et al. [35] reported that the output per unit of irrigation water supplies for the winter crop pattern from 2008 to 2009 was 0.88 LE/m<sup>3</sup> in the center of the Nile delta. The weak profits motivated farmers to immigrate to urban areas and change the land use of their fields.

**Table 6.** Economic analysis of crops in the Al-Qased command area during the winter season (from November 2015 to May 2016).

Crop		Wheat	Clover
Yield	Ton/hectare	6.50	71.43
Costs			
Rental value of one hectare		10,714	10,714
Preparation of land		476	476
Seeds		2381	1190
Fertilization	LE/hectare	2262	1310
Irrigation		357	357
Harvest		2619	3095
Total costs		18,810	17,143
Local price	LE/ Ton	2700	270
Indirect profit of crop	LE/hectare	2262	0
Gross value of production	LE/hectare	19,812	19,286
Net profit	LE/hectare	1002	2143

**Table 7.** Economic indicators for the Al-Qased command area during the winter season (from November 2015 to May 2016).

Crop	Wheat	Clover	Winter Crop Pattern
Output per unit of irrigation water supplies (LE/m <sup>3</sup> )	—	—	1.60
Net profit per unit of irrigation water supplies (LE/m <sup>3</sup> )	—	—	0.13
Output per unit of the irrigated area (LE/hectare)	17,549.99	19,285.70	17,558.31
Net profit per unit of the irrigated area (LE/hectare)	1002.37	2142.84	1447.97
Output per unit of the irrigation water consumed (LE/m <sup>3</sup> )	5.01	5.78	3.51
Net profit per unit of the irrigation water consumed (LE/m <sup>3</sup> )	0.37	0.64	0.29

The outputs per unit of the irrigated area for wheat and clover were 17,549.99 and 19,285.70 LE/hectare, respectively. However, the net profit per unit of the irrigated area was 2142.84 LE/hectare for clover, which was significantly higher than that of wheat (1002.37 LE/hectare). This was due to the high clover yield, which is shown in Table 6. The output per unit of the irrigated area for the winter crop pattern was 17,558.31 LE/hectare while the net profit per unit of the irrigated area was 1447.97 LE/hectare. This low profit indicates poor water resource management in the center of the Nile delta.

The output per unit of the irrigation water consumed for the clover was 5.78 LE/m<sup>3</sup> while it was 5.01 LE/m<sup>3</sup> for the wheat. Moreover, the net profit per unit of the irrigation water consumed for clover and wheat were 0.64 and 0.37 LE/m<sup>3</sup>, respectively. This could be due to the high net profit of clover in comparison to wheat, which is shown in Table 6. The net profit per unit of the irrigation water consumed for wheat ranged from 0.04 to 0.30 US\$/m<sup>3</sup> (0.32 to 2.40 LE/m<sup>3</sup>) in the Nile Delta during the winter of 2008 to 2009 [35]. The output per unit of the irrigation water consumed for the winter crop pattern in the Al-Qased command area was 3.51 LE/m<sup>3</sup> while the net profit per unit of the irrigation water consumed was 0.29 LE/m<sup>3</sup>.

The economic assessment showed that the clover was more efficient than the wheat in consuming the water supplies and using the irrigated lands in the Nile delta during the winter season. Hence, increasing the clover participation in relation to wheat in the winter crop pattern would enhance the economic performance of the irrigation water in the study area.

### 3.3. The Internal Irrigation Water Performance Assessment

#### 3.3.1. Temporal Assessment

The IIWPA of the Al-Qased command area was performed at a temporal scale using  $P_A$  and  $P_D$  for the Samla, Damat, and Samahat branch canals, which is shown in Table 8. The  $Q_D$  and  $Q_R$  of the branch canals during the winter season are shown in Table 8. For the Samla canal, the  $P_A$  was classified as “good” during the winter months. This could be attributed to the oversupply of irrigation water at the head branch canals. Farmers at the head branch canals use excess amounts of irrigation water and there is no monitoring of the irrigation water distribution for the branch canals. However, for the Damat canal, the  $P_A$  was classified as “good” in November and May. This was due to the low amount of required irrigation water during the beginning of the harvesting seasons. Nevertheless, the  $P_A$  was “poor” during the growing season due to the high amount of required irrigation water. For the Samahat canal, a similar  $P_A$  classification was observed during the winter months, which is shown in Table 8.

**Table 8.** The adequacy, equity, and dependability indicators for the Samla, Damat, and Samahat branch canals during the winter season (from November 2015 to May 2016).

Month	November 2015	December 2015	February 2016	March 2016	April 2016	May 2016	$P_D$ ( $CV_T$ )	Average $P_D$ ( $CV_T$ )
Branch canal			Samla					
$Q_D$	7.15	6.39	6.01	6.58	7.97	4.30		
$Q_R$	3.30	3.41	4.03	3.67	4.87	1.15		
$P_A$ ( $Q_D/Q_R$ )	1.00	1.00	1.00	1.00	1.00	1.00	0.00	
Level	Good	Good	Good	Good	Good	Good	Good	
			Damat					
$Q_D$	3.90	3.48	3.28	3.23	4.06	3.70		
$Q_R$	4.29	4.40	5.15	6.81	5.92	1.51		
$P_A$ ( $Q_D/Q_R$ )	0.91	0.79	0.64	0.47	0.69	2.46	0.23	0.15
Level	Good	Poor	Poor	Poor	Poor	Good	Poor	Fair
			Samahat					
$Q_D$	3.90	3.48	3.28	3.23	4.06	2.30		
$Q_R$	3.58	3.72	4.38	5.96	5.27	1.26		
$P_A$ ( $Q_D/Q_R$ )	1.09	0.94	0.75	0.54	0.77	1.83	0.21	
Level	Good	Fair	Poor	Poor	Poor	Good	Poor	
Average $P_A$ level			0.85					
$P_E$ ( $CV_R$ )	0.04	0.10	0.19	0.37	0.16	0.00		
Level	Good	Good	Fair	Poor	Fair	Good		
Average $P_E$ ( $CV_R$ ) Level			0.14					
			Fair					

During the winter season, the  $P_D$  was classified as “good” in the Samla canal where there was an oversupply of the delivered irrigation water to the head branch canals. However, it was classified as “poor” in the Damat and Samahat canals. This was due to the low amount of delivered irrigation water, which was a consequence of the high amount of required irrigation water during the growing season.

Similar results were reported by Khater et al. [37] in which the  $P_D$  was classified as “good” at the head branch canals and “poor” at the tail branch canals in the Nile delta during the winter of 2008. However, the  $P_A$  was classified as “good” due to the high delivered irrigation water during the winter of 2008. Reusing extra amounts of ADW in the irrigation process would upgrade the  $P_A$  and  $P_D$  to “good” during the winter months [37].

#### 3.3.2. Spatial Assessment

The IIWPA of the Al-Qased command area was applied at a spatial scale using the  $P_A$  and  $P_E$  for the Samla, Damat, and Samahat branch canals, which is shown in Table 8. During the beginning of the harvesting seasons (i.e., November 2015 and May 2016), the  $P_A$  was classified as “good” in the

Samla, Damat, and Samahat branch canals. This could be attributed to the low amount of required irrigation water during these seasons. During the growing season, the  $P_A$  was “good” in the Samla canal. Nevertheless, it ranged from “poor” to “fair” in the Damat and Samahat canals. This was due to the high amount of required irrigation water and the low amount of delivered irrigation water at the middle and tail branch canals.

The  $P_E$  was classified as “good” during November, December, and May in the study area. This was due to the low required irrigation water during the beginning of the harvesting seasons. However, it was classified as “fair” and “poor” during the growing season, which is shown in Table 8. Farmers at the middle and tail branch canals use ADW to satisfy the irrigation water requirements during the growing season. Khater et al. [37] noted that the  $P_E$  was classified as “good” in the Nile delta during the winter of 2008. Moreover, the additional amounts of ADW would significantly improve the  $P_E$  during the winter season in the Nile delta.

### 3.3.3. Average Performance Assessment

The seasonal  $E_i$  was classified as “poor” (51.2%) in the study area during the winter season, which indicates that the water supplies were higher than the crop water requirements. Additionally, 47.2% of water supplies were lost as seepage losses in the irrigation canals. The average  $P_E$  and  $P_A$  in the study area were classified as “fair” (0.14 and 0.85, respectively). However, the  $P_E$  in the study area was classified as “good” during the beginning and harvesting seasons (i.e., November, December 2015 and May 2016), as shown in Table 8. During these seasons, the required irrigation water was low. For the growing season, the  $P_E$  was classified as “fair” and “poor” in the study area. Hence, the delivered irrigation water was adequate in the study area during the beginning of the harvesting seasons. However, during the growing seasons, it was inadequate and not able to meet the crop water requirements.

The average  $P_D$  was classified as “fair” (0.15) in the study area during the winter season. This result clarified that the delivered irrigation water was inadequate when it was required. The  $P_D$  of the head branch canal was classified as “good” when the delivered irrigation water was higher than the required irrigation water. Nevertheless, the  $P_D$  of the middle and tail branch canals was classified as “poor.” This was due to the low delivered irrigation water.

The overall performance of the Al-Qased command area was classified by using the  $E_i$ ,  $P_E$ ,  $P_A$ , and  $P_D$  during the winter season. The average  $E_i$  was classified as “poor” while the average  $P_E$ ,  $P_A$ , and  $P_D$  were classified as “fair.” The results showed that the study area received more irrigation water than was required during the winter season between 2015 and 2016. Nevertheless, some regions in the growing season did not receive enough irrigation water. Hence, the water supplies in the Nile delta need more efficient water distribution policies.

## 4. Conclusions and Recommendations

A comprehensive framework for irrigation water performance assessment (IWPA) based on remotely sensed data was proposed. The framework has two components: The first one is external IWPA (EIWPA) while the second is internal IWPA (IIWPA). The EIWPA indicates the water supply as well as the agricultural and economic performances. On the other hand, the IIWPA expresses the temporal and spatial performances of irrigation water using adequacy ( $P_A$ ), equity ( $P_E$ ), and dependability ( $P_D$ ) indicators. The framework was applied to an irrigation scheme in the Nile delta during the winter season (from November 2015 to May 2016). The crop water requirements were estimated by using the Surface Energy Balance Algorithm for Land (SEBAL) model. Three classes from “good” to “poor” were proposed to classify the EIWPA and IIWPA values. The EIWPA was classified as “poor.” This was due to the oversupply of irrigation water in relation to the crop water requirements. Additionally, the abstraction of groundwater was high in the study area during the winter season. The average water depleted fraction ( $DF$ ) in the center of the Nile delta showed a potential for a groundwater recharge. The EIWPA assessment emphasized the urgent need to manage the water

resources efficiently by reducing the water losses and satisfying the water demands. The economic performance indicated a low net profit of 7.84% of the total crop production. Nevertheless, the net profit of clover production was significantly more efficient than that of wheat (2143 and 1002 LE/hectare, respectively). Therefore, it is recommended that the clover participation should be greater than that of wheat in the winter crop pattern to enhance the economic performance of the irrigation water in the study area. Additionally, it will enhance the water productivity in the study area due to its high CWUE. However, social, environmental, and economic conditions should be taken into consideration in order to increase the clover participation in the winter crop pattern.

The IIWPA at spatial and temporal scales showed a non-uniform distribution of irrigation water between the head and tail branch canals with the right time and quantity manners. Hence, the delivered irrigation water was adequate in the study area during the beginning of the harvesting seasons. However, during the growing season, it was inadequate and not able to meet the crop water requirements. Hence, the groundwater and ADW reuse were used to meet the required irrigation water at the tail branch canals during the growing season.

The overall assessment showed that improving the IWP requires an efficient irrigation water distribution between the branch canals. Additionally, continuous monitoring of this distribution is required. Remote sensing techniques could provide managers with accurate data about the required irrigation water at a regional scale. Therefore, choosing the suitable accuracy and temporal scale of remotely sensed data was a critical issue. The SEBAL model with Landsat 8 images (fine resolution) efficiently provided an accurate  $ET_c$  distribution along the Nile Delta with  $R^2 = 98\%$ . Thus, the remotely sensed  $ET_c$  would significantly enhance the accuracy of the IWPA in the study area.

**Author Contributions:** Conceptualization, A.E. and M.K. Data curation, A.E. Formal analysis, A.E. Methodology, A.E. and M.K. Software, A.E. Supervision, M.K., S.K., and A.T. Writing—original draft, A.E. Writing—review & editing, M.K., A.A., and A.T.

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