Article

Residence Time Analysis in the Albufera of Valencia, a Mediterranean Coastal Lagoon, Spain

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Abstract: The Albufera of Valencia is a coastal lagoon located in the western area of the Mediterranean Sea, in the Iberian Peninsula. It has an area of 23.1 km^2 and an average depth of only 1 m, with a maximum depth of 1.6 m. This lagoon is the remnants of an original and more extensive wetland of about 220 km^2 which is now mostly dedicated to rice cultivation. Surface water is supplied through several main and many secondary canals for a total of 64 water entry points and three exit points to the sea. It is difficult to evaluate the residence time due to the lack of reliable measurements of the inflow or outflow, as well as continuous measurements. Between 1988 and 2018, several procedures were used, the results of which are outlined in this document. Overall, a decrease in the inflow during these thirty years was observed and, therefore, it can be concluded that the residence time is increasing. There is a temporal variation during the year due to rainfall and cultivation periods. Likewise, the results found that the natural hydrological zoning of the lagoon causes a spatial heterogeneity with small Northern areas with low residence time of 4.7 days, almost on a weekly basis and large Western extensions with high residence time of 222.9 days. It is impossible to know this information if individual flow measurements are not taken from each of the main watercourses.

Keywords: coastal lagoon; hydrology; rainfall; residence time

1. Introduction

One of the variables of greatest interest in the knowledge of a water body is its renewal rate or residence time or renewal time; with all three of these measurements, the length of time that the entire water body would be renewed for can be determined if we consider the volume it has and the flow in or out [1]. The importance of this variable in water bodies lies in the fact that it will partly condition their condition, either because the water can be retained for years, as is the case with many lakes; or because the inflow of water is of such importance that the renewal is very fast and can take only a few hours, as is the case with some reservoirs.

The residence time (RT) leads in many cases to the duality of lake and river, indicating bodies of water of low renewal facing the river with maximum renewal, which are called lotic systems [2]. This is the mystery that Siddhartha recognizes by the river: "He could only know one secret of the river: the one that took hold of his soul; he realized that the water ran and ran, it always slipped, and yet it was always there, at all times; and yet it was always new water" [3]. However, in lentic ecosystems, with and without tidal influence, the importance of renewal is decisive in their hydrodynamics, influencing the physical, chemical and biological processes that take place in these water bodies [4]. On the one hand, the water masses subjected to the action of the tides suffer the flow produced

by the daily rise and fall of the tide and with it the consequent renewal [5]. This is the case of the Venice Lagoon (Italy), where the cleaning capacity of the basin is influenced by the renewal mechanism produced by the tidal exchange [6]. Moreover, the starting instant of a tidal cycle has a greater effect on the residence time of a water parcel than the duration of the cycle, as observed in Mahakam Delta (Borneo, Indonesia) [7]. In general, in coastal lakes connected to the sea, the water renewal rate of the lake depends not just on the tidal exchanges between the outer sea and the aquatic system but also on the combination of other factors such as wind, topography, bathymetry, density stratification and the freshwater runoff [8]. On the other hand, in other ecosystems more related to surface fresh water, the rapid renewal known as flushing is the conditioning factor of their function [9], which takes place when there are major water input pulses that renew the water of the aquatic ecosystem [10]. The principal natural factors that can promote a significant change in the regime of surface flows are related to variations produced by torrential rains and floods. When runoff reaches a lagoon water body, increased renewal can become significant in a short period of time [11]. Moreover, this natural function of surface waters can be altered by human action due to land use, agricultural activity and urban settlement consuming the water and detracting from the natural flows, as is the case in lakes located in areas of high urban density. This is the case, for example, of the Mar Menor lagoon (Spain), where, during the 1970s, the enlargement of one of the inlets provoked important hydrodynamic changes that resulted in a reduction of salinity, an increase in water renewal rates and extreme temperatures, with important consequences for the biodiversity of the lake and for sediment characteristics [12,13].

Depending on the size of the inputs and the volume of the water body, the variation in renewal can be significant [14]. The way to estimate the time of renewal is variable, and can be done with hydrodynamic models, used to simulate water surface elevation, exchanged flows and velocities [7,15], or by the use of tracers, such as the stable isotope ratios of hydrogen and oxygen or tritium-helium-3 isotope, among others [4,16], or by means of water balance when it is possible to make measurements of inflows or outflows.

In order to know the hydrological functioning of the Albufera, work has been carried out on multiple occasions over ten years to measure the inflows and outflows, as well as daily recordings of the level of the Albufera. The aim of this work is to study the residence time of the Albufera from the data collected during the period of 2004–2018, as well as to validate which methodology that has been used is the best to deduce the hydrological functioning of the lagoon.

2. Materials and Methods

2.1. Study Area

The Albufera of Valencia is a coastal lagoon whose origin is the closure of a marine gulf by a sandy bar formed with materials of fluvial origin, of which the characteristics are well described by Soria [17]. It is located in the east of the Iberian Peninsula, on the coast of the Mediterranean Sea, between the mouths of the Turia and Júcar rivers, about 10 km south of the city of Valencia (Figure 1). Although the lagoon has its own hydrological basin formed by small intermittent rivers that now flow into it, its hydrological functioning is related to the surrounding marsh currently used as rice fields during the summer and as a wetland in winter, whose waters come from the Júcar and Turia rivers. The catchment area is 917 km^2 [17]. Fifteen percent of the territory is occupied by urbanized areas near the city of Valencia, and 60% by irrigated agricultural areas in the lowlands. Twenty-five percent of the highlands of the basin are occupied by Mediterranean forests and rain-fed crops such as vines and olives as seen at CORINE Land Cover 2018 (Coordination of Information on the Environment Land Cover, European Environment Agency [18]). Dominant land heights are at the west of the basin, 920 masl.
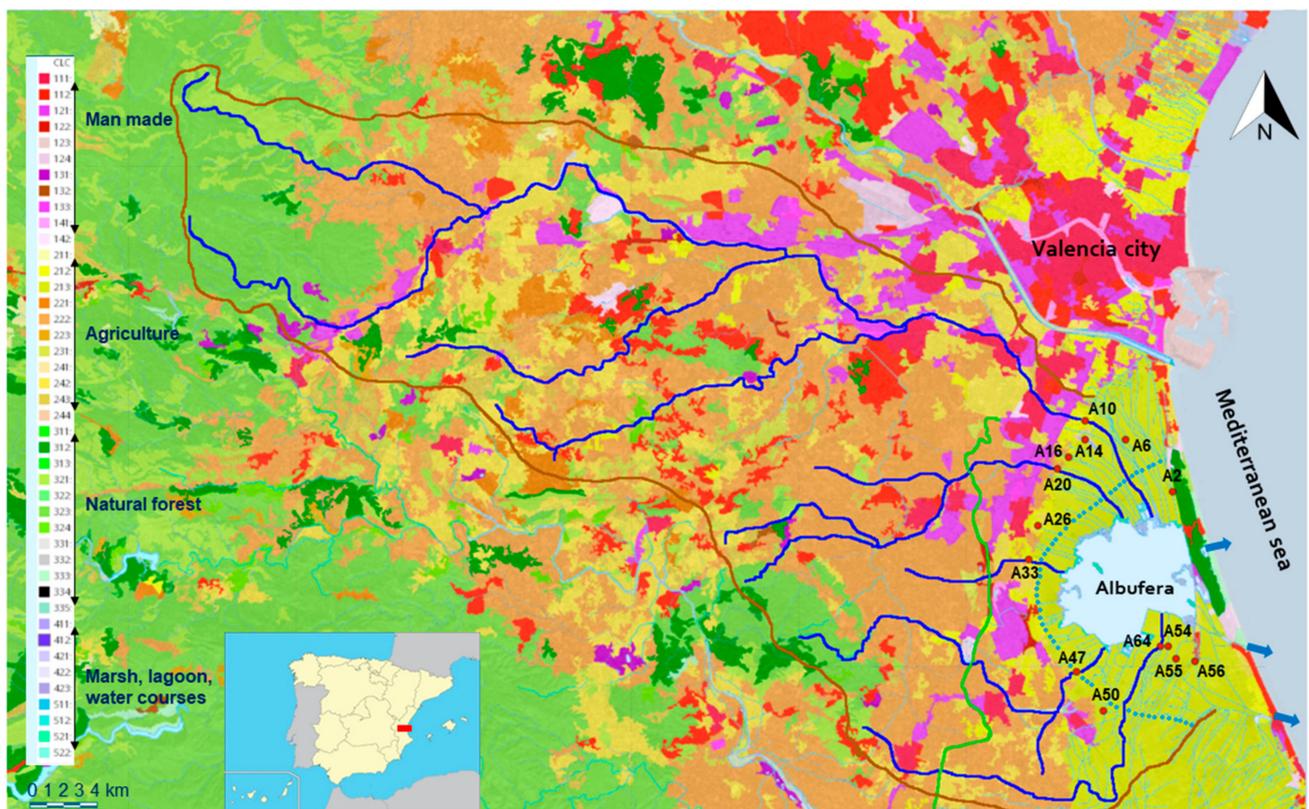
Figure 1. Situation of the Albufera of Valencia in the Iberian Peninsula. The blue lines indicate the natural courses affluent to the lagoon and main site sampling code used in the study. The light blue canals correspond to irrigation ditches in the rice fields. Green line indicates the course of Royal Canal of Jucar River (RCJ). The blue arrows indicate the location of the three communication canals between the lagoon and the Mediterranean Sea. The continuous brown line indicates the hydrologic basin. Dotted blue line indicates the polders area. Base image: CORINE Land Cover 2018 classification [18].

The lagoon is approximately circular, with a maximum diameter of 8 km and is part of the protected area of the Albufera Natural Park, which includes the lagoon itself, the surrounding marshland dedicated to rice cultivation and the sandy reef that separates the lagoon from the Mediterranean Sea. It is a shallow lagoon, barely 1 m deep on average and covering an area of 23.1 km^2. The average volume of the lagoon was estimated at 23 hm^3 [17], considering the bathymetry map for the maximum volume and the yearly average water level. In addition to the five natural watercourses that flow into it, the entire network of ditches that run through the rice fields end up in the lagoon, making a total of 64 canals through which the water flows in. The management of the water system is very complex and must consider environmental aspects, the interests of rice growers and the conservation of fisheries [19]. In theory, the lagoon and the sea are at the same level. However, the outlet to the sea is through three points from which the canals start, the water circulation of which is regulated by gates. In this way, in order to promote rice cultivation, sea water is prevented from entering during high tide and fresh water is released into the sea when the level of the lagoon is higher than sea level. If necessary, during floods, when the sea is high, it can be drained by forcing the water outflow by means of water pumping groups. Currently, the lagoon is freshwater (average conductivity: 2103 ± 603 µS cm^{-1} [20]). Its ecological status has been bad since 1974, always presenting a hypertrophic state with concentrations of chlorophyll *a* of over 100 mg m^{-3} except for some years, when during a few days at the end of winter there is an improvement in the trophic state [21], for causes rarely studied, where the concentration of chlorophyll *a* fell to below 1 mg m^{-3}; the last time this happened was on 14 March 2010 [22].

Albufera of Valencia is surrounded by rice fields that receive the necessary water supply from the Turia River in the northern area, water from the Royal Canal of Júcar river (RCJ) in the western area and water from the Júcar River in the southern area. The rice cultivation period begins in the month of May when the fields are flooded and the sowing is done, until the end of September when the harvest is done. The rice fields near the lagoon use the old bottom of the lagoon directly for the cultivation of rice, closing areas of the lagoon by means of earth dikes and reducing the water level to the 10 cm necessary for the cultivation of rice by means of pumping groups, which are located one in each area. Each closed area connected to this pumping point is locally called "Tancat" and works as an independent hydrological unit. The system is similar to polders in the Netherlands, which are areas of land reclaimed from marshes separated from the surrounding water by a dike and subsequently drained; these are also known as koogs, especially in Germany. Figure 1 shows in the area dotted in green the part of rice fields that make up the polders. During the time of cultivation, the pumps are continuously running by pumping the water into the canals of drainage that carry the water to the Albufera. The rest of the rice fields are the highlands, which require the input of surface water from the rivers through the canals and ditches to maintain its water level. From mid-October to the end of February the polders are flooded with the water level of the lagoon, maintaining continuity in the water level, for environmental reasons (maintaining the wetland). The highlands are also flooded a few centimeters to favor the presence of birds, which allows for hunting on certain dates regulated by the competent authorities.

In order to estimate the entrance flow to the lagoon, it has been necessary to measure the flow in the canals at points located near the lagoon where the inflow was measured, but not the recirculation of water from the last polder next to the lagoon. A total of 64 measurement points were used, covering all the inflow canals as well as some outlet points and internal circulation between canals. Figure 1 identifies the sampling points and natural streams that end in canals between rice fields and inflow to the lagoon.

2.2. Flow Measurement

The dimensions of the canals vary between one and fourteen meters wide and the water depth between zero and two meters, depending on the time of year and the canal under consideration. Therefore, although there is a general methodology for measuring the flow, it was done following several procedures. To make the flow measurement during the study period, different procedures were used which were all based on knowing the flow velocity and wetted section, applying the equation

$$Q = S \cdot V \tag{1}$$

where S is the section in m^2 and V the speed in $m\ s^{-1}$, being the result the flow in $m^3\ s^{-1}$.

The measurement of the speed was made by four direct and one indirect procedure. The use of one device or another was a result of the availability of the instruments over the years and the frequency of sampling. The procedure that required more effort was the measurement by means of the propeller reel. A universal OTT M1 (OTT Hydromet, Kempten, Germany) with an 8 cm helix and a pitch of $\frac{1}{2}$ turn and a SEBA C2 mini helix (SEBA Hydrometrie GmbH, Kaufbeuren, Germany) with a 5 cm helix and a pitch of 1/3 turn were used. The first one was used together with a detachable graduated steel bar of up to 4 m for measurements in large canals, several meters wide and more than one meter deep, from bridges over the canal. The second was used in ditches, attached to a removable steel bar of up to 1.5 m, usually in measurements from footbridges over the ditch. Knowing the number of helix turns in a given time, the speed of the current was calculated at several points across the width and at several vertical points. The procedure consisted of dividing the width of the canal into several vertical sections so that it was an even number, normally four subsections at least and one per meter at most. The vertical subsection was also divided into four other horizontal subsections with a minimum height of 10 cm. This provided a matrix of measuring points of at least 4 × 4, with 16 measuring

points in total. When water levels were less than 40 cm, one point was taken every 10 cm. In each point, the speed of water was measured during the time to count 100 helix turns, if time was between 30 and 300 s; if measuring time is less than 30 s, we counted turns during 30 s; if time is more than 300 s, we counted turns in 300 s.

The fastest and most technological procedure was to measure the average water speed using the ultrasonic velocity meter model Nivus equipped with a measuring probe flow measurement by means of ultrasonic cross correlation method (NIVUS GmbH, Eppingen, Germany). The probe was placed at the bottom of the canal by means of a pole and in one minute the average water speed of the whole canal was obtained on the meter's display. When the width was greater than 5 m, two speed measurements were made, one from the left and one from the right. This instrument also provided the water level at the speed measurement point.

From the measurements by the three instruments, whose results were coincidental within the range of accuracy of 2%, an adjustment was made for each measurement point in which the average speed in the measurement section was related to the subsurface speed. This was in order to be able to make speed measurements on other occasions using the procedure of colored waves or subsurface floats. For each canal, a constant value was estimated that related the speed measured in the center of the current by these procedures with the average speed of the canal, estimating the flow Qm according to Fisher's formula [23]:

$$Qm = S \cdot vs. \cdot K \tag{2}$$

where S is the section in m^2 and vs. is the subsurface velocity in m s^{-1}, and K is the empirical constant calculated for each canal resulting in the flow in m^3 s^{-1}.

As for the indirect procedure for measuring the flow rate is based on the volume of water discharged by a thin-plate weir. In some canals during the rice irrigation season, the water flow is retained by cross gates that serve to raise the water level, as described above. The water fills the canal and pours over the gate, forming what is known in hydraulics as a thin-walled chute. In this case, the flow that discharges Qv is calculated by applying a simplification of Bazin's formula [24] of the rectangular section spillway without contraction and with low water approach speed (as in the case study):

$$Qv = W \cdot Hv^{1.4815} \cdot K \tag{3}$$

where W is the width of the weir in m, Hv the height of the water above the weir in m, and K the empirical constant calculated for the weir whose value is 0.0619 being the result the flow rate in m^3 s^{-1}. The accuracy of K was sometimes verified by making a flow measurement by reel in a control section downstream and adjusting its value if necessary.

In addition, on some occasions the drainage from the lagoon to the sea in the three canals that link it was measured, using one of the methods described. Annual rainfall in the Albufera basin has also been collected using the rain gauge closest to the lagoon for the period 1988–2018 [25].

The residence time of the lagoon has been calculated from the volume and the values of the inputs or outputs, according to the formulas

$$RT = A/Vm \tag{4}$$

$$RT = Vm/Q \tag{5}$$

where Vm is the average volume of the lagoon (23 hm^3), A is the inflow or outflow volume during one year in hm^3 and Q is the flow in m^3 s^{-1}. The result for Formula (4) is the renewals rate in $years^{-1}$, and for Formula (5) can be expressed as residence time (RT) of days when working with smaller periods (as is our case), in which the number of days of the study period is considered.

2.3. Data Processing

Meteorological data is obtained from two stations near the Albufera: Valencia city (10 km) from 1988 to 2014 and Catarroja (2 km) from 2015 to 2018. The dataset was processed using the Excel spreadsheet for graphics and the descriptive statistics, and with PAST software [26] for other statistical analyses such as the trend analysis of the time series using the Mann-Kendall test for $p < 0.05$ and the study of correlation of the flow with rainfall.

3. Results

This study area has a Mediterranean climate. From 2006 to 2018, the annual average temperature was 18.3 °C, standard deviation is 5.1; absolute daily maximum 43.0 °C and minimum −0.6 °C. Rainfall is 472 mm yr^{-1}, standard deviation 205 mm; absolute maximum 841 mm in year 2007 and minimum 226 mm in 2014. The main rainfall period is in autumn when it rains half of the total rainfall of the year.

A total of 120 flow measurements were made over the ten years, including some periods in which no measurements were made (in years 2009, 2012 and 2013). During 2008–2009 the measurement was made weekly and in subsequent years at monthly intervals. Of the systems used for the measurement of water velocity, the ultrasonic velocity meter is the most suitable, due to the accuracy of the measurement and the speed with which it can be carried out. On the other hand, the cost of the equipment is three times higher than that of a propeller reel. Figure 2 shows the result of the total inflow measured on each of the dates. The maximum value measured was 18.7 $m^3 s^{-1}$ at the entrance to the lagoon, while the minimum value was slightly less than 1 $m^3 s^{-1}$. The average value is 6.66 $m^3 s^{-1}$ and the standard deviation is 3.69. The lagoon has permanent inflow, due to runoff and some springs in the catchment area; there are no periods of drought. However, the inflow is not distributed homogeneously throughout the year and shows differences between the months. The highest values occur in October and November, due to runoff from rainfall in the basin, followed by the months of May and June due to supplied water for rice fields (Figure 3).
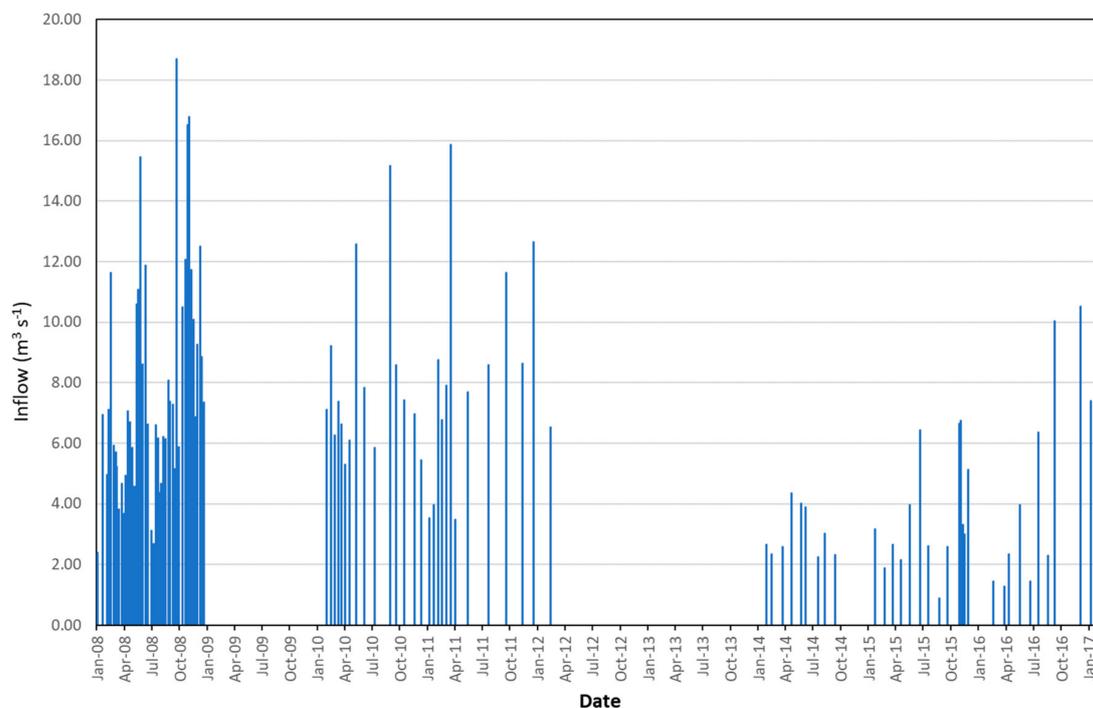

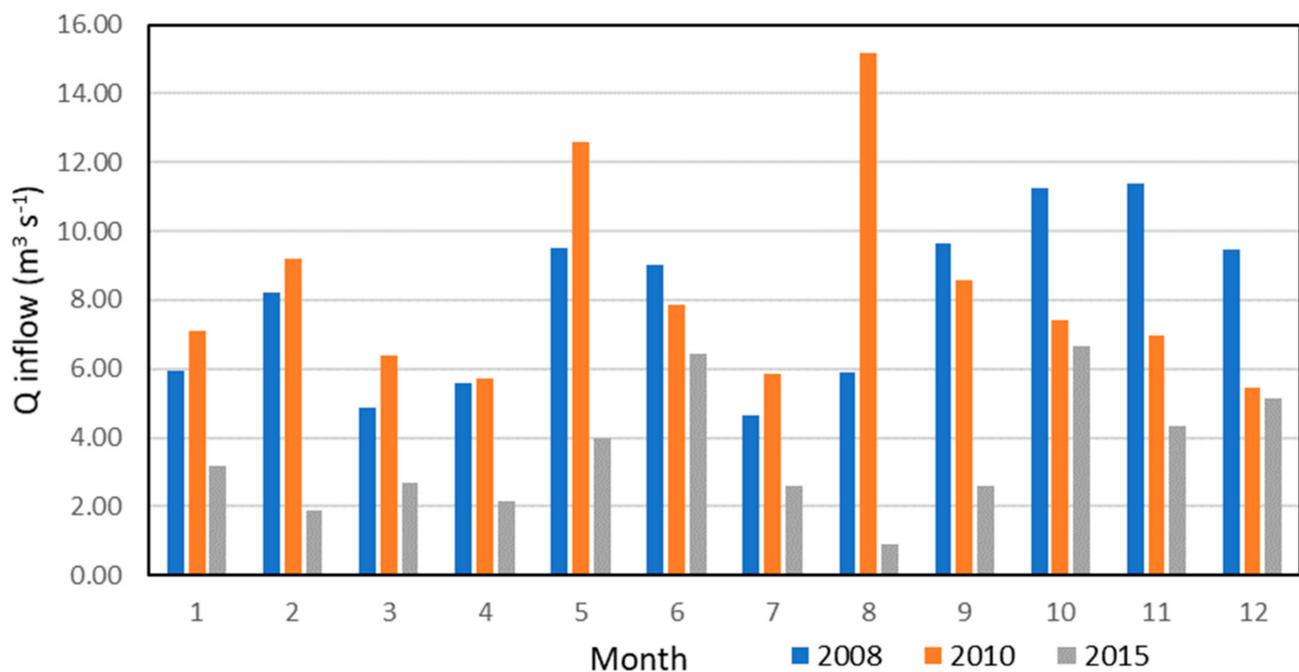**Figure 2.** Inflow to the Albufera in each of the sampling dates.

Figure 3. Average inflow in each month, estimated in three different years: 2008 (moist year), 2010 (intermediate) and 2015 (dry year).

In the study of the individual measurements for each canal, singular results were found, such as the case of canals with permanent flow (A10, A37, A47, A54, A64) connected with springs and the Júcar river. Others are irrigation ditches whose flow is intermittent and that only conduct water at irrigation periods, sometimes only one or two days a week (when it coincides with the date assigned in their irrigation calendar). In contrast, the canals near the lagoon in the polders area lead water from the lagoon to the rice fields during some periods of the year instead of flow to the lagoon, giving a negative measure (outflow instead of inflow). In addition, certain canals have been found whose water circulation is limited by means of gates, acting as distribution canals upstream of the gate; in this site, they maintain the high-water level and distribute the flows to the adjacent fields. Below the gates, the water level is about 50 cm lower and they collect the surplus water from the adjacent fields and carry it to the following lower fields, where the process is repeated.

The canals with the highest flow into the lagoon have been identified with the individual results. Figure 4 shows these values in a box and whiskers diagram, distinguished by areas of origin of the water, indicating those canals that have a negative value when they carry water outflow instead of inflow. The most interesting detail is that, of the 64 existing canals, only the 18 indicated have an appreciable flow. Of these, the important parts are the ten main canals.

The presentation of the results by water origin shows (Table 1) that the inputs are more important in those coming directly from the Júcar river, accounting for 51% of the average inflows, while the water coming from the Turia river accounts for 41% and those coming from the RCJ only 8%. Therefore, there is also an irregularity in the spatial distribution of the flows. It should also be noted that between two canals (A2 and A64), it accounts for 49% of the inflow to the lagoon. These canals also maintain a permanent flow into the lagoon throughout the year, independent from the period of rice cultivation and rainfall since they are supplied by the surplus water derived from the Turia River and water from urban treatment plants (A2) and from the Júcar River and some springs in the area (A64).
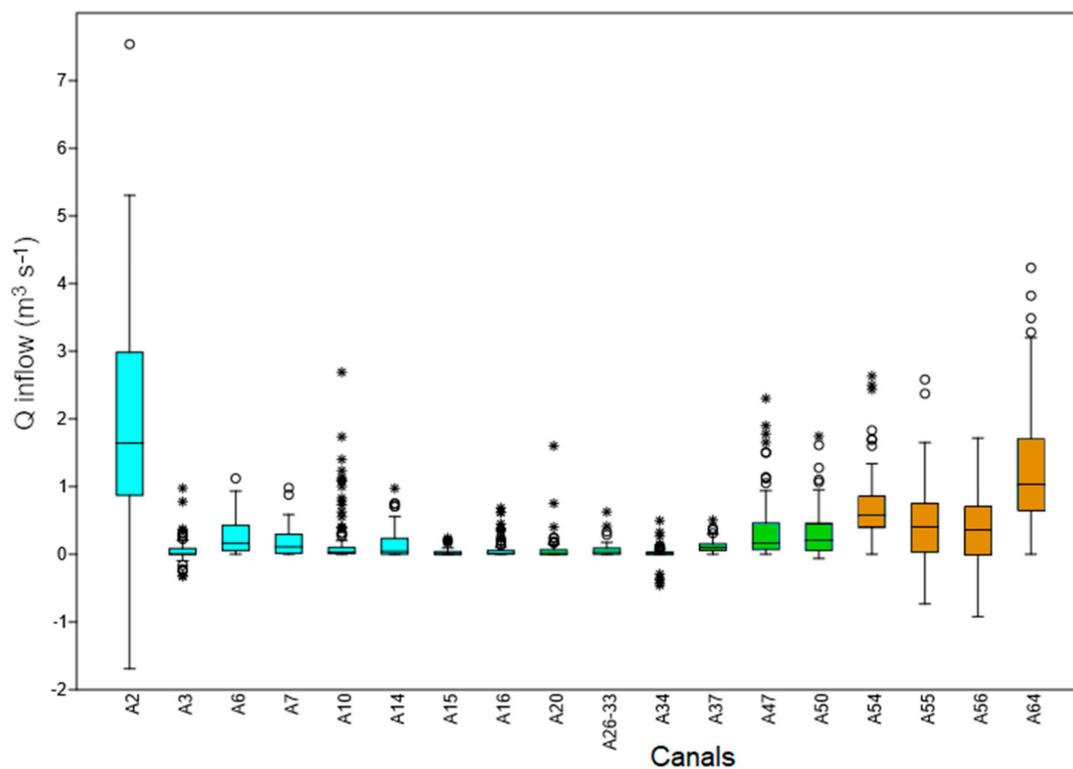
Figure 4. Average inflow for each of the most important ditches that inflow to the Albufera. Those identified with A2, A3, A34, A55 and A56 sometimes have reverse flow, and instead of water entering the lagoon, it is outflow. In blue color, waters coming from the Turia River; in green color, from the RCJ canal; in orange color, waters coming from the Júcar River. ○ and * indicates outlier values.

Table 1. Ubication of each sampling point (Latitude and Longitude in decimal degree, dd); dimensions of canal (width and depth in m); average inflow and standard deviation (SD) for each canal, grouped by the origin of the water inflow to the lagoon from the Turia River, the RCJ and from the Júcar River. In bold font, the canals connected to natural basins and its catchment area.

Origin	Canal	Lat. N dd	Long. W dd	Width m	Depth m	Basin Area km^2	Q Inflow m^3 s^{-1}	SD
Turia	A2	39.375	0.333	14.5	0.8	-	1.86	1.41
	A3	39.380	0.339	2.5	0.5	-	0.05	0.16
	A6	39.391	0.357	2.8	0.6	-	0.26	0.27
	A7	39.404	0.371	2.1	0.5	-	0.18	0.21
	A10	39.402	0.385	4.0	0.3	402.9	0.19	0.42
	A14	39.393	0.378	2.9	0.3	-	0.16	0.23
	A15	39.388	0.379	2.2	0.2	-	0.03	0.05
	A16	39.384	0.381	2.4	0.2	-	0.07	0.14
RCJ	A20	39.378	0.384	2.5	0.3	117.8	0.07	0.22
	A26	39.361	0.390	1.7	0.4	-	0.06	0.09
	A33	39.343	0.403	2.7	0.4	15.0	0.01	0.13
	A37	39.322	0.404	2.2	0.4	-	0.11	0.09
	A47	39.387	0.296	4.8	0.8	35.5	0.34	0.43
	A50	39.296	0.359	3.3	0.8	-	0.32	0.35
Júcar	A54	39.308	0.334	6.9	1.2	-	0.66	0.48
	A55	39.303	0.330	8.8	1.1	-	0.50	0.56
	A56	39.306	0.320	8.9	1.1	-	0.35	0.57
	A64	39.309	0.337	8.1	1.8	20.8	1.27	0.85

In the hydrological balance, neither the precipitation over the lagoon nor the losses by evaporation have been considered. Given that the average annual precipitation in the period 2008–2018 is about 472 mm and the potential evaporation is 1200 mm [27], the water balance would be negative if considered. In that case, the annual average should reduce the inflow by 0.14 $m^3 s^{-1}$, which is 2% of the total inflow. Therefore, the decrease in flow rate equivalent to the volume of water lost to evaporation is very small in relation to the total inflow.

The collection of all measured data, along with other studies shows that the annual contributions follow a downward trend and the rate of renewal is decreasing (Figure 5). The time series study using the Mann-Kendall test shows a statistically significant downward trend (S: −39, Z: 2.08, p (no trend): 0.037). Compared to annual rainfall, it has been observed that there is no significant correlation between these two variables in annual computations.
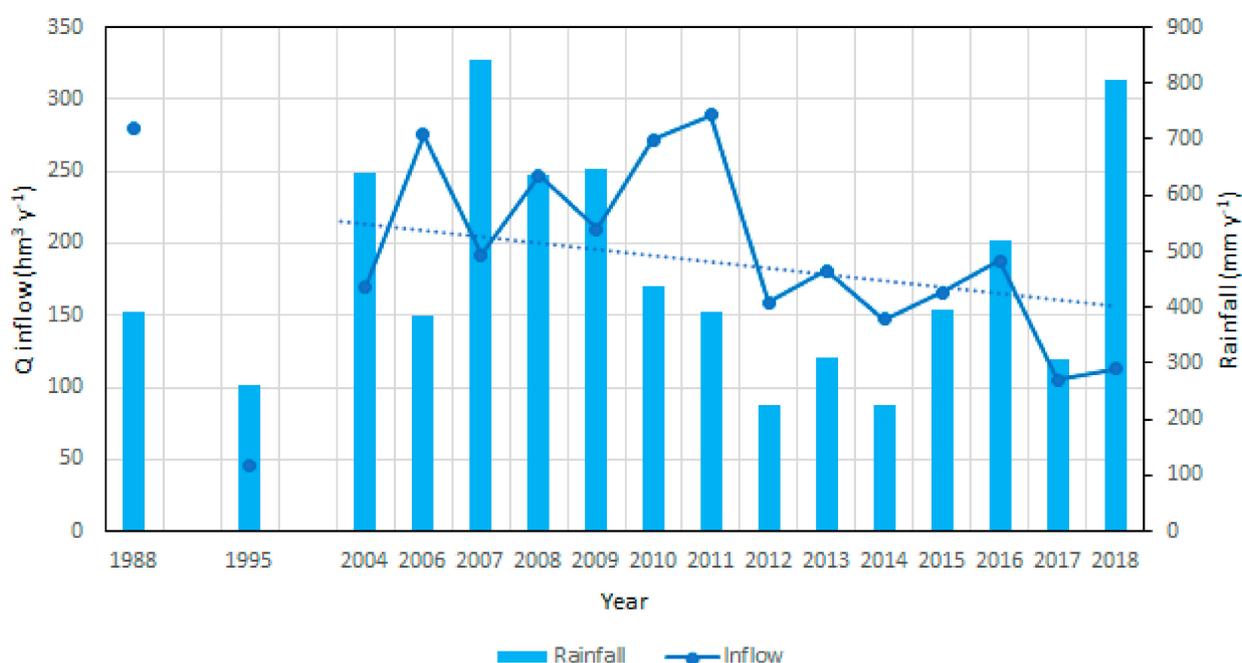

Figure 5. Annual contributions to the Albufera de Valencia showing the trend line and accumulated annual rainfall.

The RT of the entire lagoon was estimated according to Formula (4), and for the annual data between 2004 and 2018 an average of 42.9 days is obtained, with maximum values of 28.7 days in 2011 and minimum of 78.9 days in 2017. In other words, on average there are 8.4 renewals of the water body in a year. However, it was observed that throughout the year there is a temporal heterogeneity since the inflow is greater in autumn and spring and less in summer (Figure 3). With respect to water circulation, the bathymetry of the lagoon shows some deeper and other shallower areas, indicating the movement of water towards the outlets.

The lagoon has been divided into three zones according to the observed water surface flow and the boundary layer depth (Figure 6). The area of the northern zone is 7% of the surface and is supplied by water from the Turia river. The western zone is 77% and the southern zone 16%, both supplied by water from the Júcar river. Furthermore, given that the inflows present a spatial heterogeneity (Tables 1 and 2), the renewal is much greater in the north and south and scarce in the west. Renewal has been calculated from the sum of inflows in each zone and referred to the partial surface of lagoon for several years for each of the three zones and the results obtained (Table 2) show the great difference in the renewal of each zone. In annual computing, minimum value is in western zone 222.9 days and maximum in northern zone 4.7 days.
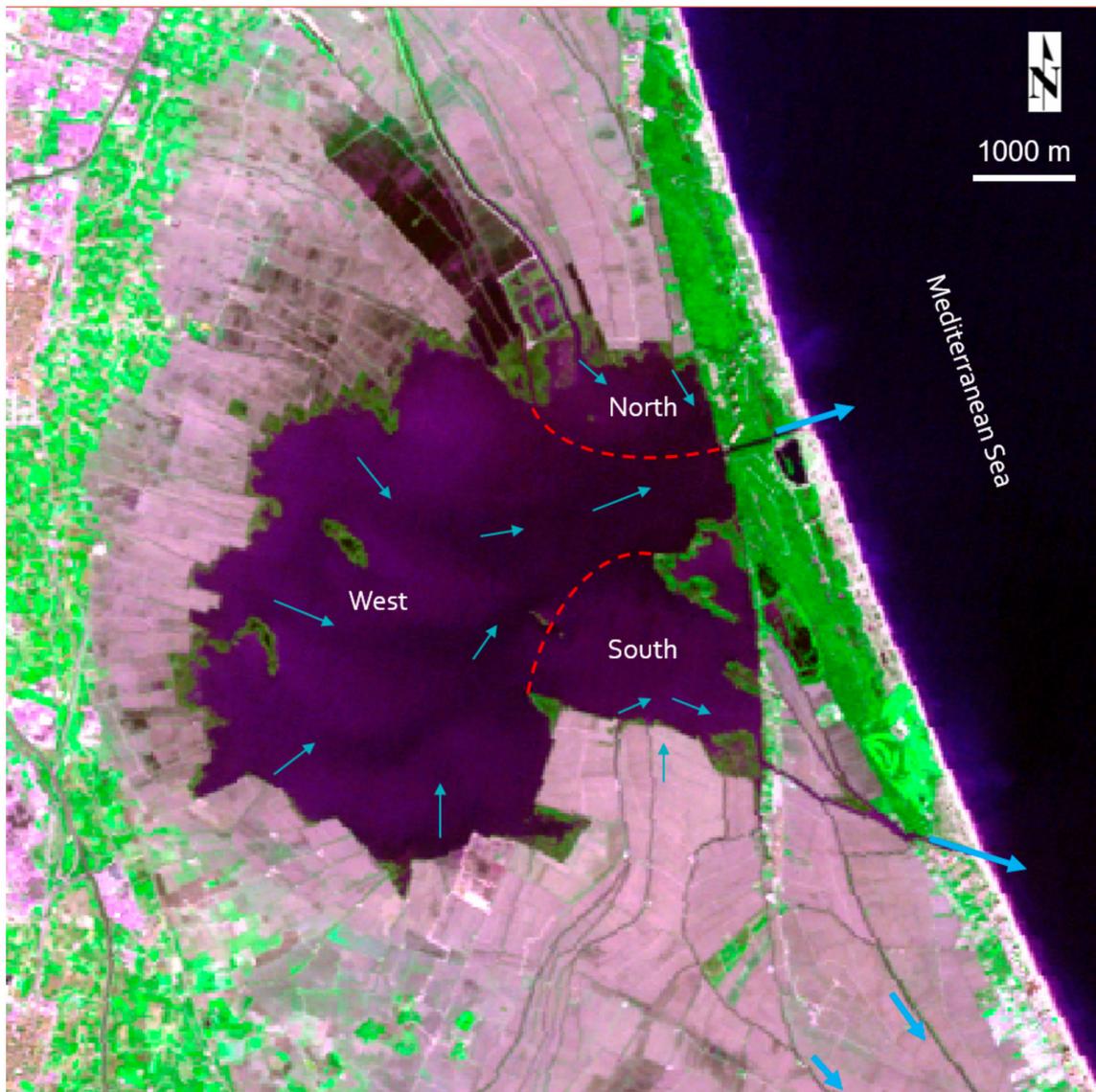
Figure 6. Distribution in zones and water circulation in the Albufera elaborated from the bathymetry of the lagoon and the observations in the lagoon itself. Landsat-5 base image in false natural color from 14 March 2010: Dark areas indicate greater depth (over 1.2 m) and light areas less depth (over 0.6 m).

The lagoon has been divided into three zones according to the observation of the direction of water flow and the morphology of the lagoon bottom based on the bathymetric map (Figure 6). The boundary of the zones are based on satellite observations during storm runoff (e.g., Figure 7). The area of the northern zone is 7% of the surface and is supplied by water from the Turia river. The western zone is 77% and the southern zone 16%, both supplied by water from the Júcar river. Furthermore, given that the inflows present a spatial heterogeneity (Tables 1 and 2), the renewal is much greater in the north and south and scarce in the west. Renewal has been calculated from the sum of inflows in each zone and referred to the partial surface of lagoon for several years for each of the three zones and the results obtained (Table 2) show the great difference in the renewal of each zone. In annual computing, minimum value is in the western zone at 222.9 days and maximum in the northern zone at 4.7 days.

Table 2. Time of residence in different years for each of the zones considered and for the entire lagoon. Qvol indicates the volume of water provided in each zone; RT, residence time.

Year	Zone	Qvol Inflow (hm^3 y^{-1})	RT Zone (day)	RT Lagoon (day)
1998	North	57	10.1	
	West	104	61.6	29.6
	South	119	10.9	
2008	North	103	5.5	
	West	10	222.9	33.5
	South	134	11.4	
2011	North	122	4.7	
	West	15	140.7	28.7
	South	152	10.8	
2015	North	25	20.2	
	West	12	174.6	49.9
	South	118	12.9	

Figure 7. Natural false color image of Landsat 5 from 27 October 2000, showing the contribution of yellowish turbid water through the canals in the northern zone and with less turbidity in the southern zone. It can be seen how the western zone had not these contributions and a renewal zone has been created from the north until the exit to the sea. With less intensity it also happens with the waters of the south zone.

4. Discussion

The first factor to be considered when attempting a hydrological study is the effort required to perform the hydraulic measurements. The difficulties in carrying out the measurements, as well as the necessary effort, understanding in this section the displacement and the work in each point, result in the hydraulic measurements not being carried out with the density that many of the studies on water masses require. In the case of reservoirs, where there are usually control points at the entrance and exit, it is much simpler. In the case of natural water bodies, such as lakes and lagoons, it is much more complicated. In our case of study, the Albufera of Valencia, the existence of 64 points of entry of water makes it a difficult task to find the initial measurement of the hydrological functioning of the lagoon, being time-consuming and economically expensive. It was not until 1988 that the first measurement campaigns were carried out by means of a project, with the aim of drawing up the Master Plan for Sanitation, given that the lagoon had become the destination of the waste water of the surrounding populations since 1970. In the year 1988, the first measurement campaign was carried out in all the irrigation canals and the first water balance was estimated with real measurements using a propeller reel [27], the results of which showed a possible decrease in the contributions to the lagoon with respect to the historical data on water inflows (estimated in a theoretical way, as the water inflow had never really been measured). The results showed an average flow of 8.88 m^3 s^{-1} and a residence time of 29.6 d. One of the most important findings obtained during that work was knowledge about through which canals most of the flowing water arrives, and in addition the importance of the ditches was categorized, so that by knowing the flow that circulates through some of them, the total flow contributed at a given time can be estimated; thus, sampling is achieved with less effort. The circulation areas of the lagoon are established and the heterogeneity in the renewal of the waters of the lagoon is verified.

Seven years later, in 1995, a second intensive measurement campaign was carried out, also in all the canals and also using the propeller reel. The aim was to find out their hydrological situation in more detail, since the modification of the irrigation system was planned to reduce the use of water, and with this a reduction in the contributions from the irrigation surplus was foreseeable. That year coincided with an exceptional drought, and the average flow contributed was 1.43 m^3 s^{-1}, leaving the residence time at 184.0 d, so the results can be considered as outliers.

In 2003–2004 another campaign was carried out with bimonthly measurement samples in all the canals in order to know the hydrological situation. In 2008 the most detailed measurement work ever carried out took place in order to make a hydraulic model of operation and future forecast in various scenarios of water use, the poor ecological state of the lagoon and water needs for its maintenance, which were set out in the Plan for Sustainable Development [28]. These works carried out weekly measurements in the main canals and monthly in all the canals during one year, using all the instruments described in the methodology. The results obtained a quality database and provided an average flow of 7.83 m^3 s^{-1} and a renewal rate of 33.5 d.

Subsequent monitoring studies were carried out from 2010 to 2018, but only monthly sampling or with more detail in some short periods of time to know nutrient loads, carbon flows and other variables on the functioning of the lagoon. The hydrological results show a decrease in inputs and therefore an increase in residence time, currently at 73.3 d in 2018. These results are much higher than those of other coastal areas, such as the Tagus River estuary, whose values are 22.8 d in the wide area [1], or the values of Dragon Lake in China [29] whose residence time is between 26.8 d and 75.5 d. On the opposite side is the Mar Menor [30] which ranges between 180 and 330 days, higher than the Albufera. Among the highest values in lakes, for example Lake Geneva has a renewal time of eleven years.

The average residence time of 42.9 days for the Albufera, based on the data from recent years, should be considered too high and is one of the causes contributing to the poor ecological status. The fact that the lagoon is not open to the sea prevents tidal exchanges. If we compare it with the case of the Venice lagoon [6] the renewal models there, as the water

entry, are influenced by the tides and the wind has an average value of 4.1 and 45.5 days in the worst exchange scenario. The lowest value of renewal in some areas is 55.6 days, far from the values that can present the Albufera of up to 222.9 days in the west area. The Scheldt estuary [31] presents values for favorable and unfavorable scenarios between 12 d in the Vlissingen zone and 110 d in the Antwerp zone (far from the mouth), showing the influence of tidal exchange. Also, in Pacific coastal lagoons in Polynesia it has been observed [32] that the most important factor correlated with the time of residence is the degree of opening to the sea, finding values in the range of 10 to 170 days, with an average value of 30 days. In the Gulf of California, the Soldado Lagoon presents values of about three days of renewal time, influencing a wide opening to the sea without obstacles [33]. The case of the Nokoué Lake shows us this importance of opening, when its communication with the sea was improved to allow the navigation of large boats [34], thus achieving a substantial modification of the sea water intake, passing its previous renewal time of one year to a range between 4 and 40 days (depending on the height of the tide), and altering the salinity of the lake as well, despite the freshwater contributions of its tributaries. This process also took place in the Menorca lagoon when the communication canal with the sea was dredged, reaching a residence time of only five days. Similar figures have also been measured in the Lobos lagoon (Gulf of California) with a residence time of between five days in summer and twelve days in winter [35].

Hence the importance for the Albufera that, if the exchange with the sea is not allowed, good quality water is provided from the rivers, similar to what was done in the "Aiguamolls de l'Empordà" Natural Park [36].

The work carried out by the National Hydraulic Administration has always considered the estimation of RT from the outflow measured by the three output points from the lagoon to the sea as a calculation measure. By means of ultrasonic meters, a database has been obtained with which the output volume and therefore the whole renewal time is estimated. However, this methodology is inadequate for this lagoon because the renovation presents an enormous spatial heterogeneity. The detail of the spatial heterogeneity has been observed in certain dates in which important rainfalls take place in the hydrological basin and through the natural canal's inflows with turbid waters of a different color from those of the lagoon. The case of the October 2000 flood shows the arrival of turbid waters through the A10 with silt and clay in suspension that extend through the rice fields and reach the lagoon through the canals of the northern zone. Figure 7 presents the view from the Landsat 5 satellite a few days after the rains and how the water brought in does not mix with the rest of the lagoon and circulates towards the sea outlet.

Similar work in other coastal lagoons, such as the Mar Menor [37], shows that the existence of areas with little renewal inside the lagoons is possible due to the influence of the geography and morphology of the lagoon on water circulation. In this case it is the existence of islands that condition the circulation.

The problem of poor water quality in the lagoon due to lack of renewal has also been detected in other places, such as the work of Cheng et al. [38] where poor quality areas in coves of the Three Gorges Reservoir are related to high renewal times of up to 50 days, while good quality areas have values of less than 5 days.

In the case of intense rainfall, typical of Mediterranean areas in autumn, the measure of renewal is very difficult to perform with the means presented in this work. Measurement personnel have difficulty accessing the measuring points and the danger of flooding is real. On these occasions it is useful as an estimate of the renewal to have the data on the conductivity of the water in the lagoon, before the rainy season and just to finish the episode. In some cases, the measure of renewal due to a decrease in conductivity has been estimated, observing that the surface rainwater runoff reaches the lagoon with a conductivity between 450 and 500 $\mu S\ cm^{-1}$. Knowing the conductivity of the lagoon on previous dates, it is possible to deduce (with some uncertainty) the renewal produced in the lagoon.

Finally, another case study should be noted: November 2015 when a controlled renewal experience was carried out, providing 10 hm^3 of surface water conducted through the canals of the western zone, which presents the least contribution and high residence time. The water flowed for two weeks, with an average total flow in that area of 1 m^3 s^{-1} and possible changes in the area quality water were observed by means of Landsat-8 satellite images estimating the measure of chlorophyll *a* in the lagoon (Figure 8). These unpublished results showed that a maintained flow contribution through that zone produced a decrease in the concentration of photosynthetic pigments, so the hypothesis that the contribution of good quality water flows could contribute to the improvement of the quality of the lagoon was verified, an aspect that had been discussed during years with the Administration by the experts and that had never been demonstrated experimentally.
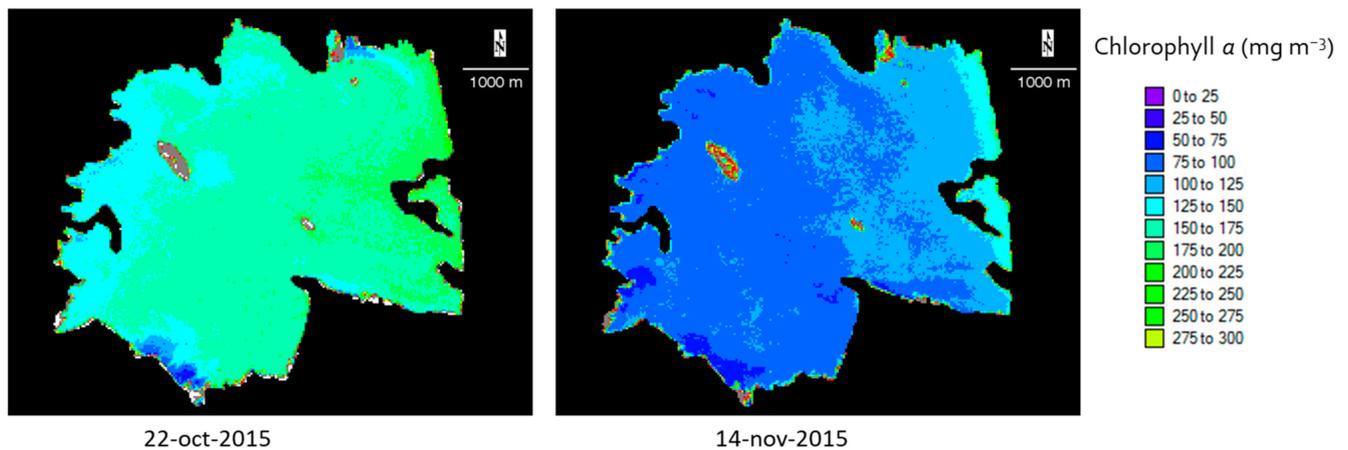

Figure 8. Measurement of chlorophyll *a* during autumn 2015 using Landsat-8 satellite images in the Albufera of Valencia on a previous date (October) and during the process of renewal by water supply from the west area (November).

The current situation indicates that, in general, water entering through southern canals only renews that sector of the lake with low residence time, but this water could make a greater contribution to the lake renovation if managers would move the entry point to the southwest as much as possible, thus impacting a sector that has low residence time. Considering the connection between irrigation canals, water coming from A64 could be diverted through A50 irrigation canal and then through A47 canal so that it finally enters into the southwest area of the lagoon, near the green filter created to minimize the nutrients in the treated water coming out of the Albufera-Sud sewage treatment plant [39].

5. Conclusions

The measurement of the residence time by means of flow measurements is a procedure that requires great effort due to the difficulty in performing hydrological measurements. The frequency of the sampling is one of the factors that will influence the results, especially at times of rain, when the weather is more unfavorable for field work by manual means. The better system to measure inflow in canals is the ultrasonic velocity meter, a fast and accurate method. In the case of the Albufera of Valencia, it has been found that the main part of the inflow arrives through ten main canals, so having an estimate of the volume of water that arrives in a given day is quite fast. However, the measurement by the outlet canals is only useful to know the overall residence time of the whole lagoon, since the entrances present a spatial heterogeneity in the distribution in the perimeter of the lagoon, and with this there is an uncertainty of the results in terms of renewal by the different areas. The average residence time of the lagoon is 42.9 days, but the differences in the entrances between the zones means that in the northern zone it is about 5 days (like other coastal lagoons) and in the western zone it can be more than 200 days; this has its influence on the water quality of the lagoon, which is currently poor. There is a decrease over time of the contributions, related to the decrease in water consumption in irrigation, since there

is no significant correlation between rainfall and contributions. The experiences of water management to increase the renewal and conservation of the lagoon in good condition, such as the one carried out in 2015, have given positive results and this line of action should be followed by the Administration.

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