Full Water Quality Monitoring of a Traditional Flow-Through Rainbow Trout Farm

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Abstract: Traditional freshwater rainbow trout farms are still popular in some European countries such as Poland, France and Ireland. These systems generally operate in flow-through configuration. The impact such production systems might have on water quality remains mostly unknown. The present study was set up to fulfil this objective of monitoring water quality on different fish farm locations in order to identify the impacts of the whole farm (comparison of farm inlet and outlet) and at pond scale in order to understand the water quality dynamics and to better understand the impact of multiple water reuse (water passes) in a given pond on water quality. In the absence of any sort of water treatment, an increase in the number of water passes was shown to create an increase in ammonium concentration along the farm. Finally, this traditional flow-through rainbow trout production system was revealed to almost be at its full carrying capacity with respect to internal water quality parameters and fish welfare. To increase fish production, some water treatment techniques (solid/liquid separation, nitrification) would have to be introduced in order to optimize the rearing water quality for fish growth and to minimize the release of pollutants in the receiving water to limit the impact on the environment.

Keywords: rainbow trout; traditional flow-through; pond-based; rearing water quality; environmental impact

1. Introduction

With the wild fish catching capacities reached and the overall human population increase, fish produced through aquaculture is and will be more and more an important food source for human consumption in the near future [1,2]. Aquaculture production increased more than five-fold from 1990 to 2012, while the world capture fisheries increased by only 8% at the same time [3]. The future and current intensification of this activity is associated with more and more stringent environmental regulations to ensure a sustainable and environmentally friendly production process/model [4–6]. At European scale, freshwater fish farming is essentially regulated through the water framework directive (WFD), which aims at achieving good chemical and ecological status of the rivers [1,7,8].

The traditional freshwater fish farming industry generally operates using flow-through systems (FT) without any water treatment, the dissolved oxygen (DO) levels in the culture water being maintained by relatively high volumes of water abstracted and flowing through the fish farm. The oxygen loss due to both fish activity and sediments is generally compensated by mechanical aerators such as paddle-wheels. In traditional FT systems, this aeration allows the fish farmers to use the water several times in different ponds before release (multi-pass); however, the impact of

this water reuse on water quality and the potential accumulation of waste in the rearing water has not been clearly identified so far. When the amount of DO is too low in the fish farm inlet water, fish farmers generally use supplementary oxygenation systems such as oxygenation cones in order to maintain optimum DO levels. Furthermore, fish farming activity generates dissolved and solid wastes such as nutrients (nitrogen and phosphorus) and organic matter from fish excreta and uneaten feed. Therefore, if the effluent is discharged untreated, it could potentially impact the discharge water quality compared to make-up water, and as a consequence impact the receiving water quality [9–14].

In Ireland, a large proportion of the freshwater production is still carried out using traditional FT systems without, or with very limited, water treatment before discharge. To the best of our knowledge, there is no existing published data on the effluent quality and flow, allowing estimation of pollutants fluxes and the potential impact the fish farming activity might have on water quality in Ireland. Models could be employed for the evaluation of organic matter (OM), nitrogen and phosphorus fluxes from feed composition and fish data (stocking density, average fish mass, overall fish mass) by the nutritional method [15]. However, missing data on fish/feed (especially on feed composition, ingested feed quantity, digestibility coefficients and the proportion of uneaten feed must be available according to [15]) forced us to evaluate the different fluxes by the hydrobiological method (involving flow measurements and water quality analysis).

Traditional flow-through systems generally involve a multi-use (or multi-pass) of water, with water passing through different ponds with no water treatment before being released to the receiving water, although some reuse might involve a supplementary oxygenation step. The objective of this study was to assess the water quality at different farm levels (pond, 1-pass, 2-pass and 3 or more pass ponds, whole farm) of a traditional rainbow trout farm in Ireland. To that aim, the whole farm (inlet/outlet and strategic fish farm locations) was monitored during two consecutive dry days. The monitoring program included water physico-chemical quality (dissolved oxygen, turbidity, nitrate, ammonium, and pH) and flow measurement in order to determine the flow dynamic of the whole farm and its different ponds. Each parameter was monitored on an hourly basis at the different selected farm locations in order to study fluxes and to identify any diurnal variation.

2. Results and Discussion

2.1. Fish and Flow Parameters

The table below summarizes the data related to (i) the biomass for each pond (i.e., total biomass, number of fish, average fish weight and stocking densities) that were obtained from the fish farmers, and (ii) flow values that were measured for each monitored pond (Tables 1 and 2).

Table 1. Outcome of fish data for the whole fish farm at the moment of the experiment. The figures 0, 1, 2 and 3 for ponds number are theoretical numbers of water uses (see Figure 7).

Pond	Volume	No. of Fish	Average Weight	Biomass	Stocking Density
	m^3		**g/Fish**	**kg**	**kg/m^3**
1_1	121	3000	667	2000	17
1_2	144	3069	558	1713	12
1_3	147	12,000	170	2040	14
1_4	153	7696	610	4695	31
1_5	140	9736	800	7789	56
1_6	159	12,000	170	2040	13
1_7	122	5409	980	5301	43
1_8	86	15,750	200	3150	37
1_9	68	0	/	0	0
1_{10}	56	10,500	260	2730	49
1_{11}	44	10,500	260	2730	62
1_{12}	41	0	/	0	0
1_{13} after harvest	33	10,080 nd	240	2400 600	73 19
1_{14}	25	10,080	220	2218	89
1_{15}	32	8000	280	2240	70
1_{16}	39	8000	220	1760	45
1_{17}	36	8000	220	1760	49
1_{18}	16	0	/	0	0
2_1	592	6000	1600	9600	16
2_2	207	6500	1300	8450	41
2_3	256	11,041	1330	14,685	57
3_2	301	1800	1100	1980	7
3_3	435	1283	1400	1796	4

Table 2. Outcome of flow data measured on the selected fish farm locations at the moment of the experiment. Standard deviation (St. Dev.); Minimum (Min.); Maximum (Max.).

Pond	Mean Value	St. Dev.	Min.	Max.	Number	Comment
	L/s	**L/s**	**L/s**	**L/s**		
1_5	19.9		17.5	24.5	35	
1_{13}	7.3	0.1	7.3	7.4	10	
1_{15}	6.8	0.7	5.9	7.5	39	
2_1	−1.8	0.2	−1.3	−2.1	11	2_1 outlet 1
	35.2	2.3	29.8	37.2	42	2_1 outlet 2
	66.1	4.3	0.0	96.3	370	recirculation
2_2	6.0	0.8	4.4	7.7	23	2_2 outlet 1
	34.5	0.8	33.2	35.7	21	2_2 outlet 2
2_3	76.1	7.8	57.6	148.5	473	Farm outlet 1
3_2	50.3	7.7	34.1	63.9	20	
3_3	58.1	21.5	0.0	112.7	565	Farm outlet 2

Table 1 shows the range of fish sizes being reared at the time of the experiment (170–1600 g/fish). Different stocking densities were also observed in the different ponds (4–89 kg/m^3).

The flow measurements showed a flow dynamic slightly different than what was expected initially in terms of number of water passes. For example, a negative flow value was obtained between 2_1 and 2_2 ponds (Table 2). This might be a consequence of the recirculation pump in operation in 2_1 that would have applied a suction of the water from 2_2 (average recirculation flow of 66 L/s, see Table 2). This demonstrated that 2_2 was completely isolated from 2_1 and therefore isolated from any recirculated water. This is the reason why, contrary to initial expectations where it would have been a "3-pass

pond", 2_2 was considered as a "2-pass pond", as it only received water from 1_{8-12} ponds (i.e., "1-pass ponds"). Furthermore, we observed that the average flow from 2_2 to 2_3 pond was very limited (i.e., 6 L/s, see Table 2). This is why 2_3 pond was considered a "mostly 2-pass pond", as it received water from six "1-pass ponds" (i.e., 1_{13-18} ponds at 7 L/s each, see Table 2) and only one "2-pass pond" (i.e., 2_2 pond at 6 L/s, see Table 2).

Temperature was monitored in different ponds during the experiment and water temperature was 8–9.5 °C in all ponds during the whole experiment.

2.2. Impact of the Whole Fish Farm on Water Quality

The objective was to assess the overall impact of the farm on water quality (i.e., farm influent vs. effluent water quality). Farm inlet (before oxygenation, feeding channel, i.e., 0_0) and farm outlet water quality were compared. Differential concentrations ($\Delta_C(t)$, see Equation (1)) were calculated between inlet and mean outlet concentrations between the two outlets (considering the two farm outlets from 2_3 and 3_3 ponds had similar flows, see Table 2) monitored during the two days of experiment for all the studied parameters (see Section 3.2).

The figure below presents an outcome of the differential values obtained between the fish farm outlets and inlet for five parameters (i.e., DO, turbidity, nitrate (NO_3–N), ammonium (NH_4–N) and pH) during the two days of monitoring (Figure 1).
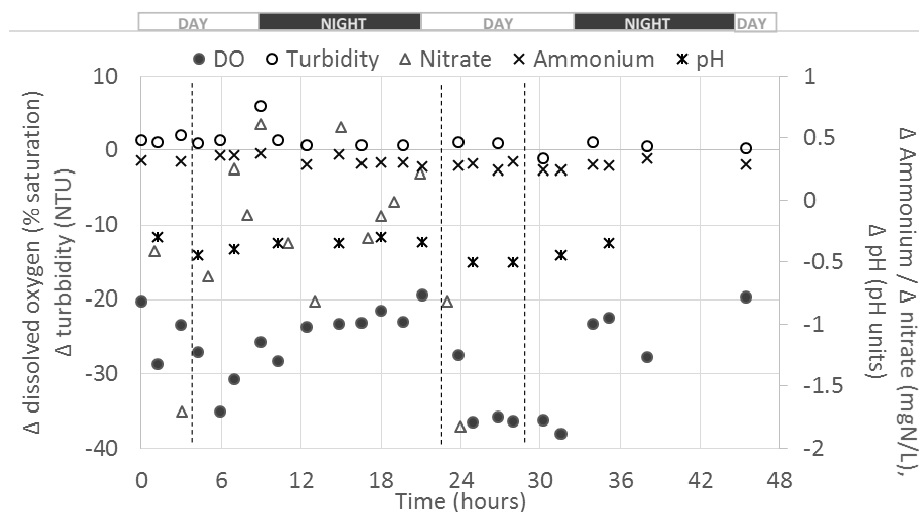

Figure 1. Whole farm differential values between outlets and inlet of dissolved oxygen (DO), turbidity (in NTU (Nephelometric Turbidity Unit)), nitrate, ammonium and pH during the monitoring program. Vertical dash lines represent feeding times.

Globally, negative Δ_C were observed for DO, pH and NO_3–N for the duration of the monitoring. Such results were expected for DO and pH due to O_2 consumption by fish and sediments and the CO_2 production leading to a pH drop, as observed on other studies [16,17]. However, positive Δ_C were observed for turbidity and NH_4–N, meaning that the farm activity "created" solids and NH_4–N. Except for NO_3–N and DO, $\Delta_C(t)$ appeared relatively stable all along the experiment and no diurnal effect was observed at this overall farm scale. For DO, higher absolute $\Delta_C(t)$ (i.e., down to almost −40%) were observed during the days compared to night times (i.e., about −20%); this might be due to the higher O_2 consumption by fish during the day due to the occurrences of feedings and higher fish activity [18].

The table below summarizes these data by providing average and associated standard deviation of the overall farm $\Delta_C(t)$ values (Table 3). This presentation of the overall farm mean Δ_C shows a global picture of the influence of the fish farm on water quality. Associated fluxes calculated as presented in Section 3.4 (Equations (2) and (3)) are also presented.

Table 3. Summary of the overall farm differential data between outlets and inlet. Turbidity (Turb.); nitrate (NO_3–N); ammonium (NH_4–N); not applicable (NA).

	DO		Turb.	NO_3–N	NH_4–N	pH
	%	mg/L	NTU	mgN/L	mgN/L	
mean difference	−27.39	−3.09	1.19	−0.36	0.30	−0.39
st. dev.	6.05	0.67	1.44	0.72	0.04	0.07
min.	−38.10	−4.33	−1.10	−1.83	0.24	−0.50
max.	−19.40	−2.25	6.01	0.61	0.38	−0.30
count	24		16	15	21	11
flux (mg/s) *	NA	−413.9	159.3	−48.6	40.4	NA
flux (g/h) *		−1489.9	573.5	−174.8	145.4	
flux (g/h/kg$_{fish}$) **		−0.018	0.007	−0.002	0.002	
flux (mg/h/kg$_{fish}$) **		−18.37	7.07	−2.16	1.79	

* fluxes calculated at farm scale using the average cumulated outlet flow rate of 134 L/s (see Table 2); ** fluxes calculated considering a total biomass reared on farm of 81,094 kg (see Table 1).

One of the parameters most affected by the farm was the DO saturation rate, with an average global "loss" of about 27% between farm inlet and outlet despite supplementary aeration/oxygenation steps on the farm (see Figure 7). Considering the total biomass and the outlet flows measured, mean DO F value was −18.4 mgO$_2$/h/kg$_{fish}$.

An increase in turbidity values from farm inlet to outlet was observed with an average positive Δ_C of about 1.2 Nephelometric Turbidity Unit (NTU). This value appears relatively low compared to values measured at the outlets of some ponds (up to 20 NTU), and this may be due to the sedimentation of suspended solids in ponds, which would have lowered the release of suspended solids at the farm outlet. A peak in turbidity increase (i.e., $\Delta_C(t)$ of 6 NTU) was observed at the beginning of the first night of the monitoring (Figure 1) which could be due to fish metabolism and the release of faeces a few hours after the afternoon feeding [16–18]. In terms of flux, average F value was 7.1 NTU/h/kg$_{fish}$.

A global average drop in NO_3–N concentrations of about 0.36 mgN/L between farm inlet and outlet was observed (Table 3). As shown on Figure 1, and regarding the relatively high standard deviation associated to the average differential value for this parameter (i.e., 0.72 mgN/L), a high variability of NO_3–N Δ_C during the experiment (i.e., range −1.83–+0.61) was observed. A negative value of average flux of −2.2 mgN/h/kg$_{fish}$ was obtained.

As expected, NH_4–N appeared to be "produced" by the farm, with a positive average Δ_C of 0.30 mgN/L (see Table 3). This represents a significant increase regarding the average farm inlet concentration of about 0.30 mgN/L (see Supplementary Materials). This Δ_C remained stable all along the experiment, with a relatively narrow range observed (0.24–0.38 mgN/L). Therefore, the release of NH_4–N by the farm seemed not be affected by light and feeding regimes. It is noticed that this apparent NH_4–N "production" might be an artefact due to the overall pH drop of 0.39 units (Table 3) that would have changed the ammonia equilibrium through the ionized form, NH_4–N. An average F value of 1.8 mgN/h/kg$_{fish}$ was obtained.

An average pH decrease of about 0.39 pH units between farm inlet and outlet was observed (Table 3) that might a consequence of a CO_2 production by fish metabolism [16–18]. This Δ_C remained stable all along the experiment with a relatively narrow range observed (−0.50–−0.30 pH units, see Table 3).

2.3. Comparison of the Water Quality from Inlet/1-Pass/2-Pass/3 Pass Ponds

The objective of this part of the study was to identify trends between the water quality of the farm inlet, 1-pass, 2-pass and 3-pass waters in order (i) to check if fish farm inlet water impacted water quality flowing through the farm and (ii) to identify potential trends in water quality parameters throughout the farm.

According to the flow measurements performed, only 2$_2$ and 2$_3$ ponds were considered as "2-pass ponds" (see Table 2 and Section 2.1). Ponds 3$_2$ and 3$_3$ were considered as "at least 3-pass ponds"

because, as explained before, they received some recirculated water from 2_1 (see Table 2 and Section 2.1). It is noticed that 2_1 pond was kept alone for this analysis because it had the specificity to receive directly recirculated water from 1_{1-7}. This made the number of water passes of this pond difficult to evaluate from the flow measurements performed.

Average values for inlets (after supplementary oxygenation, i.e., 1_{13} and 1_{15} inlets), 1-pass (1_{13} and 1_{15} outlets), 2-pass (or "mostly 2-pass ponds", i.e., 2_2 and 2_3 outlets) and "at least 3-pass ponds" (i.e., 3_2 and 3_3 outlets), 2_1 outlet and associated standard deviation were calculated. The two "1-pass ponds" monitored (i.e., 1_{13} and 1_{15}) were considered separately because of the 1_{13} pond harvesting that occurred after 24 h into the monitoring period. For more simplicity, in the following paragraphs the terms "2-pass ponds" and "3-pass ponds" will be employed instead of "mostly 2-pass ponds" and "at least 3-pass ponds", respectively. The overall results for all the different pond categories (number of water passes) and for all the monitored parameters are presented on the figure below (Figure 2).
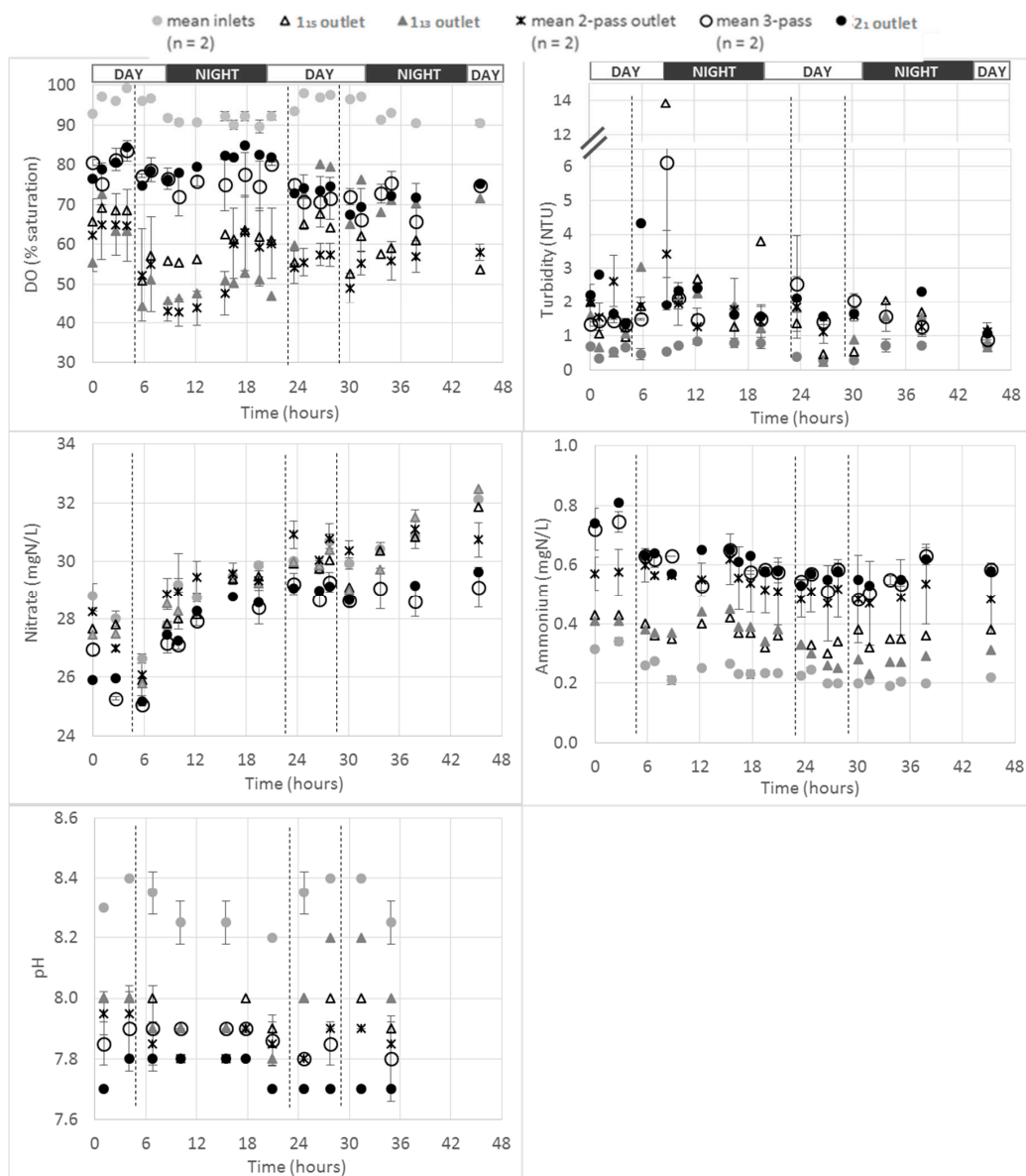

Figure 2. Average evolution of water quality (i.e., dissolved oxygen saturation rate, turbidity, nitrate, ammonium and pH) at the farm inlets and in "1-pass", "2-pass", "3-pass" and 2_1 ponds outlets. Vertical dash lines represent feeding times.

2.3.1. Dissolved Oxygen

As expected, over the whole farm, the most oxygenated waters were the fish farm inlet waters, with saturation values in the range 85–100%. A higher DO saturation rate was measured during day time compared to night time (average DO values of 96% and 84%, respectively). These higher DO values during the day might be a consequence of the plants and phytoplankton photosynthesis occurring with sunlight and producing O_2 [17]. The same trend was observed at the inlets of $1_{13}/1_{15}$ ponds after supplementary oxygenation by the two oxygenation cones located in the inlet channels 0_2 and 0_3 (see Figure 7) and that were in operation continuously during the whole monitoring program. However, the impact of the oxygenation cones on the level of DO saturation of the water appeared to be negligible during day time (i.e., 2–3% higher in the oxygenated water (i.e., $1_{13}/1_{15}$ ponds inlets) than in the inlet water from the inlet channel 0_0, see Supplementary Materials). This impact was revealed to be higher at night time with a difference between oxygenated and non-oxygenated water up to 10% (i.e., 84% and 94% for non-oxygenated and oxygenated water respectively, see Supplementary Materials).

The monitoring of the three "1-pass ponds" showed that a systematic drop in the DO level was observed after every feeding event. This drop appeared to occur immediately after feeding. This would coincide with an increase in fish activity and in the metabolic demands associated with digestion [18].

Interestingly, the "3-pass ponds" did not show the least oxygenated water, with values in the range 65–85% of DO saturation at their outlets. According to the flow measurement performed (see Table 1), it was demonstrated that those ponds were fed more or less directly by recirculated water (i.e., water from 2_1 pond). This demonstrated the efficiency of applying recirculation/supplementary oxygenation and the associated impact on DO saturation rate observed all along the farm from 2_1 pond to the 3_3 farm outlet (see Figure 7).

The least oxygenated ponds were the "2-pass ponds", with values in the range 45–65%. These values were in the same range than the ones observed for "1-pass ponds" water from 1_{15} (i.e., 50–70%), demonstrating the ability of paddle-wheel aerators to compensate for the loss of oxygen that occurred in those "2-pass ponds" due to fish/sediments consumption. Furthermore, the two "2-pass ponds" were not fed in any way by recirculated water (aeration of these ponds relied only on paddle-wheel aerators, see Table 2 and Section 3.1), and that could explain the relative low oxygen saturation levels observed in those ponds compared to the "3-pass ponds". Among the two "2-pass ponds", 2_3 pond had a higher DO saturation at its outlet than 2_2 pond during the whole monitoring period (see Supplementary Materials); this might be due to the differences in aeration systems from one pond to another (i.e., 2_2 being aerated with two paddle-wheel aerators and 2_3 with only one paddle-wheel, see Figure 7). This observation would confirm the ability of paddle-wheel aerators in compensating for the DO loss due to fish and sediments. Furthermore, 2_1 and 3_2 ponds outlets had similar DO profiles during the experiment (see Supplementary Materials). Thus, the aeration systems in operation in 3_2 (i.e., two paddle-wheels see Figure 7) were efficient enough to maintain the DO saturation levels higher than 70%. However, it was observed that DO levels were generally lower in 3_3 than in $2_1/3_2$ ponds showing that the aeration system (i.e., one paddle-wheel, see Figure 7) was not efficient enough to maintain the same DO level in this pond.

2.3.2. Turbidity

As expected, the lowest turbidity levels and variability were observed for the farm inlet waters. However, the comparison of the different pond classes is not straightforward. The potential sedimentation of solids along the farm might be a potential explanation of the difficulty to analyze the results for this parameter [16,18]. The relatively low turbidity values measured (a few NTU) and the potentially high uncertainty associated with turbidity measurements at these low levels might be another potential explanation. However, the same peak of turbidity was observed for the two "1-pass ponds" (1_{13} and 1_{15}) on the first day of monitoring (at about 8 h monitoring time) and the same general turbidity profiles were observed for those two ponds (Figure 2). The fact that the turbidity measurements were repeatable from those two ponds with similar fish characteristics (i.e., same total

biomass and average fish weight, see Table 1) indicates that the turbidity measurements performed were accurate and reliable. The greater variability in turbidity was observed for the 1-pass ponds outlets (i.e., 1_{13} and 1_{15}). This may be due to the sedimentation of suspended solids all along the farm that would have smoothed the associated turbidity profiles [16,18].

2.3.3. Nitrate

The same profile was observed for NO_3–N concentrations at any farm level for the duration of the monitoring. The general increase of concentration observed at farm inlet was also observed at each level of water passes. However, the ponds associated to the highest levels of passes (i.e., "3-pass ponds" and 2_1) were associated to the lowest NO_3–N concentrations (i.e., in the range 25–29 mgN/L) while the farm inlet concentrations were in the range 26–32 mg/L. It is noteworthy that the "3-pass ponds" and 2_1 pond (all fed with recirculated water) showed similar NO_3–N profile. This demonstrated that, as for the DO profile, 2_1 pond could not be considered a "2-pass pond" for the NO_3–N profile. Additionally, the "2-pass ponds" were not affected in terms of the NO_3–N concentration profile by the fish farming activity. This was highlighted by the comparison with the farm inlet NO_3–N concentrations that were observed to be in similar range than 2-pass ponds all along the experiment (range of 2-pass ponds 27–32 mgN/L).

2.3.4. Ammonium

A clear distinction between NH_4–N levels at the farm inlets, "1-pass", "2-pass" and "3-pass ponds" outlets was observed. As expected, the higher the number of passes is, the higher the NH_4–N concentration. This demonstrates the progressive accumulation of NH_4–N across the whole farm due to fish excretion and/or to progressive dissolution of sediments [16,18].

Farm inlet NH_4–N concentrations were in the range 0.20–0.34 mgN/L.

The "1-pass pond" outlets' NH_4–N concentrations were in the range 0.30–0.45 mgN/L (before 1_{13} harvest). It is noteworthy that almost the exact same NH_4–N profile was obtained at the outlet of both "1-pass ponds" (i.e., 1_{13} before harvest and 1_{15}); then, lower values were observed after 1_{13} harvest during the second day of monitoring. This highlighted both (i) the good quality and reproducibility of the data generated regarding the use of the multisensor probes in terms of NH_4–N monitoring and (ii) the impact of fish in NH_4–N production in a pond.

The "2-pass ponds" average NH_4–N outlet concentrations were in the range 0.47–0.62 mgN/L, which is a higher level than the ones observed for "1-pass ponds". A great variability between the values measured for the two "2-pass ponds" considered (i.e., 2_2 and 2_3) was observed; the NH_4–N concentrations were indeed systematically higher for 2_2, by about 0.1 mgN/L. This could be due to the different receiving waters for those two ponds (2_2 received water from the five $1_{8–12}$ "1-pass ponds" (not monitored during this study) and 2_3 pond received water from the six $1_{13–18}$ "1-pass ponds"). This could also be due to the different biomass reared in both 2_2 and 2_3 ponds (see Table 1).

The "3-pass" and 2_1 ponds NH_4–N outlet concentrations were in the range 0.49–0.81 mgN/L, which was the highest range recorded over the whole farm. This observation is in agreement with both (i) the expected NH_4–N accumulation across the whole farm and (ii) the water recirculation without any nitrification step to oxidize NH_4–N (into NO_2–N and NO_3–N) leading to an NH_4–N accumulation within the recirculation loop. This underpinned the impact of recirculation on the 2_1 pond water quality. It is noticed that the 2_2 pond outlet NH_4–N concentrations were in the same range that those measured at "3-pass pond" outlets.

2.3.5. pH

As expected, an impact of the farm on pH values was observed with a general decrease of pH across the whole farm, likely due to the CO_2 production by fish metabolism [17].

The inlet mean values were in the range 8.2–8.4 pH units with lower values generally observed at night. The "1-pass pond" outlets' pH values were measured in the range 7.9–8.0 (before harvest for 1_{13}

pond). It is interesting to observe values up to 8.2 pH units after harvest at the 1_{13} pond outlet (similar to the values observed at the inlet). This highlights the impact of fish on pH variation. The "2-pass ponds", "3-pass ponds" and 2_1 pond outlets pH values were in the range 7.8–7.95 and 7.8–7.9 and 7.7–7.8 pH units, respectively. The lowest values were therefore observed for the recirculated water from the 2_1 pond. This again demonstrated the impact of recirculation on water quality. This could be due to the recirculation loop that could have brought back water with low pH into this pond. As mentioned before, this could explain the high NH_4–N concentration measured in this pond.

Of note is that the ponds with the highest number of water passes had the lowest pH values and the highest NH_4–N concentrations. At low pH (i.e., <8), and at the temperatures measured during this monitoring program, the ionized form of ammonia (NH_4–N, relatively non-toxic to fish) is highly predominating compared to the toxic unionized form (NH_3–N). Therefore, the highest NH_4–N concentrations observed in the high number of passes ponds could be just an artefact due to pH variation and not due to an accumulation of fish wastes.

2.4. Impact of 1-Pass Ponds on Water Quality

Three different "1-pass ponds" were intensively monitored during the experiment (i.e., 1_5, 1_{13} and 1_{15}, see Figure 7). As for the whole farm, $\Delta_C(t)$, calculated as explained in Section 3.4 and using Equation (1), are presented. Fluxes, calculated as explained in Section 3.4 (Equations (2) and (3)), are also presented. The flux values will be specifically discussed in Section 2.5 below.

2.4.1. 1_{15} Pond

The figure below presents the pattern of Δ_C between the outlet and inlet of 1_{15} pond during the monitoring program (Figure 3).

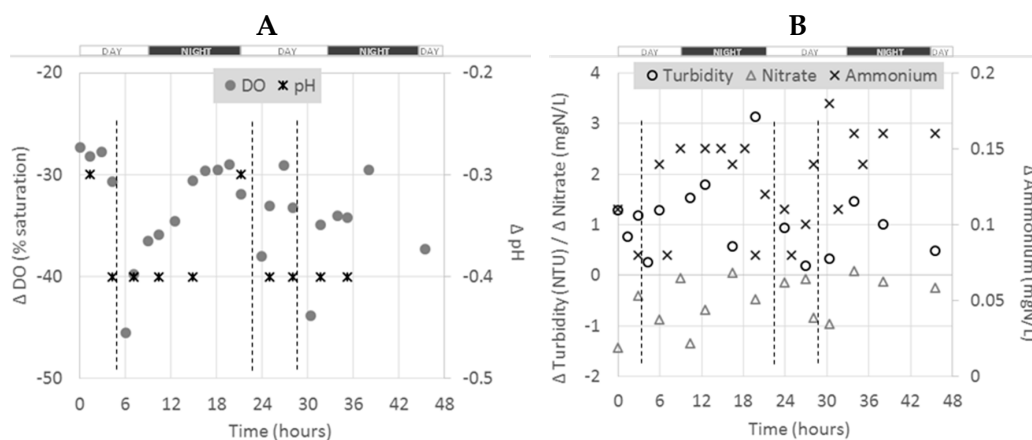**Figure 3.** Pond 1_{15} differential values between outlet and inlet for dissolved oxygen and pH (**A**) and for turbidity, nitrate and ammonium (**B**) during the monitoring program. Vertical dash lines represent feeding times.

As for the whole farm scale, different trends were observed, depending on the parameter considered at this pond scale. Negative Δ_C were obtained for pH, DO and NO_3–N. Positive values were obtained for turbidity and NH_4–N. For NO_3–N, a general increase in Δ_C from the beginning to the end of the experiment (from −1.5 to about 0 mgN/L) was observed. The Δ_C for NH_4–N was higher during night times. Dissolved oxygen showed diurnal variation also, with higher consumption (or lower Δ_C) during day time with drops likely to be due to feedings [19]. No clear trends or diurnal variation were observed for the other parameters.

The Δ_C data are summarized in the table below, which provides average values, associated standard deviation and the calculated fluxes for each parameter (Table 4). Fluxes data, as described in Section 3.4 are also presented.

Table 4. Summary of the 1_{15} pond differential data and fluxes between outlets and inlet.

	DO		Turb.	NO$_3$–N	NH$_4$–N	pH
	%	mg/L	NTU	mgN/L	mgN/L	
mean difference	−33.50	−3.80	1.85	−0.50	0.13	−0.38
st. dev.	4.88	0.53	3.15	0.50	0.03	0.04
min.	−45.50	−5.04	0.18	−1.43	0.08	−0.40
max.	−27.30	−2.92	13.32	0.08	0.18	−0.30
count	24		16	15	21	10
flux (mg/s) *	NA	−26.6	12.9	−3.5	0.9	NA
flux (g/h) *		−95.7	46.5	−12.7	3.2	
flux (g/h/kg$_{fish}$) **		−0.043	0.021	−0.006	0.001	
flux (mg/h/kg$_{fish}$) **		−42.74	20.76	−5.65	1.44	

* fluxes calculated at 1_{15} pond scale (including the impact of fish and sediments) with the average flow rate of 7 L/s (see Table 2); ** fluxes calculated considering a total biomass reared in 1_{15} pond of 2240 kg (see Table 1).

2.4.2. 1_{13} Pond

As for 1_{15} pond, the figure below presents the evolution of Δ_C between outlet and inlet of 1_{13} pond during all the monitoring program (Figure 4). It is noticed that this pond was partially harvested on day two of the experiment (after about 24 h of monitoring) (see Table 1).
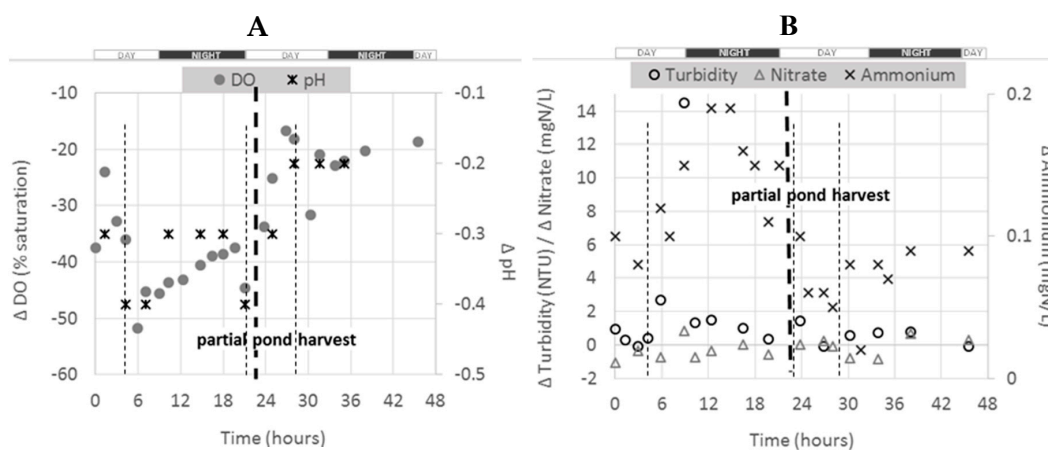

Figure 4. Pond 1_{13} differential values between outlet and inlet for dissolved oxygen and pH (**A**) and for turbidity, nitrate and ammonium (**B**) during the monitoring program. Vertical light dash lines represent feeding times.

As for the whole farm and the 1_{15} pond, negative Δ_C values were observed for NO$_3$–N, pH and DO and positive ones for turbidity and NH$_4$–N. Before harvest, Δ_C for NH$_4$–N were higher at night, confirming the observations made for 1_{15} pond (see Section 2.4.1). After harvest, all Δ_C profiles changed for all parameters and all the absolute values were lower. As expected, the effect of the fish activity in this pond was therefore reduced after harvesting, as the total biomass was reduced (see Table 1).

The Δ_C data are summarized in the table below, which provides average values, associated standard deviation and the calculated fluxes for each parameter before and after harvest (Table 5). Fluxes data, as described in Section 2.4 and according to Equations (2) and (3) are also presented.

Table 5. Summary of the 1_{13} pond differential data and fluxes between outlets and inlet before and after harvest.

	Before Harvest						After Harvest					
	DO		Turb.	NO$_3$–N	NH$_4$–N	pH	DO		Turb.	NO$_3$–N	NH$_4$–N	pH
	%	mg/L	NTU	mgN/L	mgN/L		%	mg/L	NTU	mgN/L	mgN/L	
mean difference	−40	−4.55124	2.295	−0.37125	0.136364	−0.34286	−23.01	−2.607	0.561667	−0.06714	0.07	−0.225
st. dev.	6.685	0.708759	4.367466	0.590507	0.036952	0.053452	5.641208	0.630768	0.579738	0.568997	0.02357	0.05
min.	−51.8	−5.73	−0.06	−1.06	0.08	−0.4	−33.7	−3.83	−0.08	−0.85	0.02	−0.3
max.	−24.1	−2.87	14.52	0.86	0.19	−0.3	−16.8	−1.92	1.45	0.67	0.1	−0.2
count	14		10	8	11	7	10		6	7	10	4
flux (mg/s) *	NA	−31.8587	16.065	−2.59875	0.954545	NA	NA	−18.249	3.931667	−0.47	0.49	NA
flux (g/h) *		−114.691	57.834	−9.3555	3.436364			−65.6964	14.154	−1.692	1.764	
flux (g/h/kg$_{fish}$) **		−0.04779	0.024098	−0.0039	0.001432			−0.10949	0.02359	−0.00282	0.00294	
flux (mg/h/kg$_{fish}$) **		−47.788	24.0975	−3.89813	1.431818			−109.494	23.59	−2.82	2.94	

* fluxes calculated at 1_{13} pond scale (including the impact of fishes and sediments) with the average flow rate of 7L/s (see Table 1); ** fluxes calculated considering a total biomass reared in 1_{13} pond of 2400 kg and 600 kg before and after harvest respectively (see Table 1).

The comparison of 1_{15} and 1_{13} ponds before harvest (similar total and average fish weight in those two ponds as presented in Table 1) showed very similar values, demonstrating the reproducibility of our approach. The effect of harvesting on the differential values appears very clear when results before and after harvest are compared. Mean DO consumption dropped from 40 to 23%, the mean pH difference dropped from 0.34 to 0.23 pH units, mean turbidity production dropped from 2.30 to 0.56 NTU and the mean NH_4–N production dropped from 0.14 to 0.07 mgN/L.

It is noteworthy that despite the fact that the 1_{13} pond was harvested and that only 600 kg of fish remained after harvest, the pond fluxes in terms of DO and NH_4–N are not negligible. This underpins the potential impact of the sediments accumulated at the bottom of the tank might have on DO consumption or NH_4–N production. The role of sediments on the residual Δ_C values obtained after harvest will be discussed in Section 2.5.

2.4.3. 1_5 Pond

The figure below presents the evolution of Δ_C between outlet and inlet of 1_{13} pond during the entire monitoring program (Figure 5).
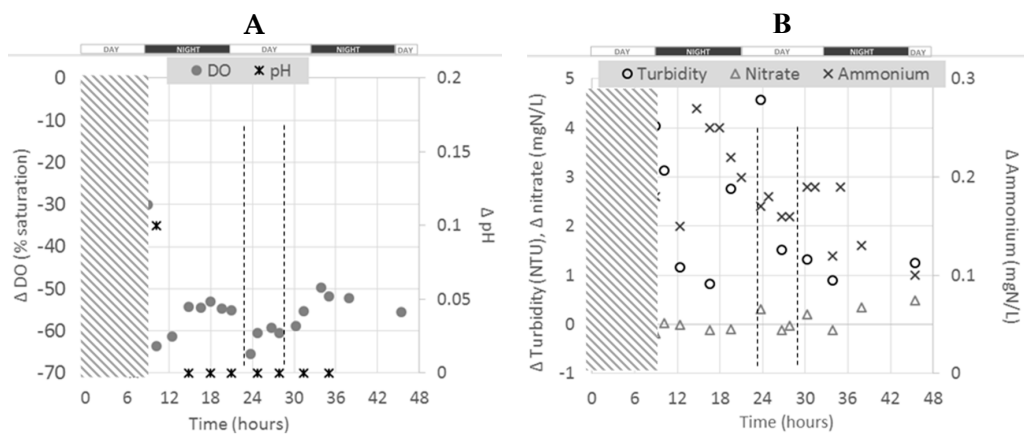

Figure 5. Pond 1_5 differential values between outlet and inlet for dissolved oxygen and pH (**A**) and for turbidity, nitrate and ammonium (**B**) during the monitoring program. The inlet monitoring location was changed after 8 h of monitoring. Vertical dash lines represent feeding times.

This pond had three main particularities compared to $1_{13}/1_{15}$ ponds regarding DO:

(1)   It was supplied with super-saturated water from the recirculation loop (average 140% saturation rate, see Supplementary Materials),
(2)   It had a paddle-wheel aerator running during the experiment (see Figure 7),
(3)   Bigger fish than in $1_{13}/1_{15}$ ponds were reared (average weight of 800 g and 220–240 g respectively, see Table 1)

The table below presents a summary of the Δ_C values observed for all parameters during the whole experiment (Table 6). The amount of data is lower for this pond because the initial inlet monitoring location had to be changed for another during the experiment as the initial one was observed to be unsuitable for monitoring.

Table 6. Summary of the 1_5 pond differential data and fluxes between outlets and inlet.

	DO		Turb.	NO$_3$–N	NH$_4$–N	pH
	%	mg/L	NTU	mgN/L	mgN/L	
mean difference	−56.82	−6.41	1.49	0.08	0.18	0.01
st. dev.	4.42	0.49	1.87	0.22	0.05	0.04
min.	−65.50	−7.39	−2.57	−0.12	0.10	0.00
max.	−49.70	−5.48	4.58	0.49	0.27	0.10
count	17	17	10	11	16	8
flux (mg/s) *	NA	−128.1	29.8	1.6	3.7	NA
flux (g/h) *		−461.2	107.1	5.8	13.2	
flux (g/h/kg$_{fish}$) **		−0.059	0.014	0.001	0.002	
flux (mg/h/kg$_{fish}$) **		−59.21	13.75	0.75	1.69	

* fluxes calculated at 1_5 pond scale (including the impact of fishes and sediments) with the average flow rate of 20 L/s (see Table 2); ** fluxes calculated considering a total biomass reared in 1_5 pond of 7789 kg (see Table 1).

A relatively high DO consumption rate of 59 mgO$_2$/h/kg$_{fish}$ compared to the ones found for 1_{13}/1_{15} ponds (43 and 48 mgO$_2$/h/kg$_{fish}$, respectively; see Tables 3 and 4) was observed. The NH$_4$–N production rate was found to be similar to what was found for the other "1-pass ponds" and for the whole farm (Table 3).

Contrary to the other "1-pass ponds" monitored (i.e., 1_{13} and 1_{15}), a paddle-wheel aerator was employed in this pond for supplementary aeration (Figure 7) and thus, had to be considered in the DO mass balance for this 1_5 pond. However, the impact of the paddle-wheel aerator in increasing DO levels in the pond could not be assessed.

These results regarding the higher DO consumption rate in 1_5 compared to 1_{13}/1_{15} ponds was unexpected for at least two reasons:

(1) The presence of a paddle-wheel aerator should have increased the DO amount received by the pond, and therefore decreased the overall consumption rate (because the calculation did not into account the O$_2$ input from the paddle-wheel aerator).
(2) From the literature [16], bigger fish are supposed to consume less O$_2$ by mass unit than smaller ones, and the comparisons of results obtained for 1_5 and 1_{13}/1_{15} ponds appeared not to confirm this statement.

The different hypotheses that might explain these results could be:

- In relation to the very high initial DO saturation rate at the inlet of this 1_5 pond (i.e., 140% on average) that would have modified the O$_2$ liquid/air equilibrium and therefore could have caused a faster decrease in DO concentration within the pond (which would have caused the O$_2$ loss by liquid/air transfer higher and give a higher apparent consumption rate).
- In relation to sediment amount at the bottom of this pond that could be higher per square meter than in 1_{13}/1_{15} ponds that could have caused a higher sediment DO consumption rate for this 1_5 pond.

2.5. Outcome on Fluxes

The figure below presents the mean *F(t)* values calculated from Equation (3) for (i) the three "1-pass ponds" monitored (i.e., 1_5, 1_{13} before and after harvest and 1_{15} ponds) and (ii) the whole farm (Figure 6).
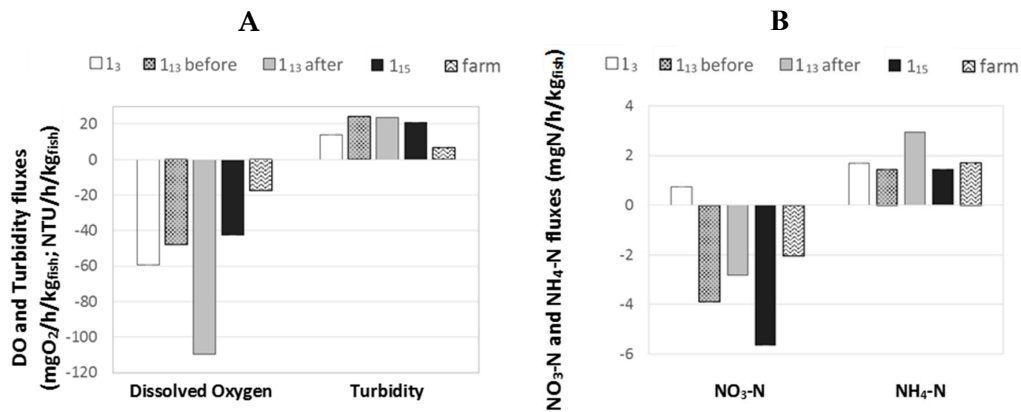
Figure 6. Mean fluxes calculated for DO, turbidity (**A**), NO_3–N and NH_4–N (**B**) at different farm levels (1-pass ponds and whole farm).

The differences in DO fluxes between 1_3 and the other "1-pass ponds" were already discussed in a previous Section (Section 2.4.3) and it was assumed that the higher fluxes observed in 1_3 pond were due to a higher initial DO saturation rate. It is confirmed here that 1_{13} pond before harvest and 1_{15} pond had similar DO fluxes, with F values being -48 and -43 mgO_2/h/kg_{fish} respectively. The lower F value observed for the whole farm (i.e., F = -18 mgO_2/h/kg_{fish}) can be explained by the supply of oxygen given by both aeration and oxygenation devices across the farm that would have lowered the apparent loss of O_2 at farm scale. The highest F value observed for 1_{13} pond after harvest (i.e., -109 mgO_2/h/kg_{fish}) could be an artefact due the impact of sediments (fish faeces and uneaten feed) on the overall DO consumption. The same observation can be done for NH_4–N flux with a very high F value observed for 1_{13} after harvest compared to other ponds. It is noteworthy that no data were generated in order to quantify the potential impact of other compartments (plants, algae, phytoplankton, soil etc.) on the DO/NH_4–N levels in ponds. However, no diurnal variation was observed in DO consumption after harvest in pond 1_{13} (Figure 5); this observation would confirm that the impact of phytoplankton and plants was negligible compared to the impact of sediments and fish.

For turbidity, F values for 1_{13} before and after harvest and for 1_{15} were similar (i.e., 24.1, 23.6 and 20.8 NTU/h/kg_{fish} respectively). The F value for 1_5 pond was slightly lower (i.e., 13.8 NTU/h/kg_{fish}), which could be caused by the higher size of this pond and lower water velocity, which would enhance the settling capacities of this pond, increasing the amount of solids removed from water and thus the F value for turbidity. At farm scale, F value was even lower (i.e., 7.1 NTU/h/kg_{fish}); this observation could be due to the settling capacity of the whole farm [16,18].

For NO_3–N, a negative flux was observed for all ponds except 1_3 pond. This pond was the only one to receive some recirculated water which could have created this flux difference and this apparent NO_3–N production by the pond by bringing back some low NO_3–N content water into the loop.

3. Materials and Methods

3.1. Farm Description

The studied fish farm was an earth pond-based rainbow trout farm operating mostly in FT configuration with an additional recirculation loop involving a supplementary oxygenation step. The general layout of the fish farm and the different monitoring locations are presented on the figure below (Figure 7). Fish of different growth stages were distributed into the different ponds according to their weight. Fish were fed manually twice a day until apparent satiation with manufactured pellets (Efico Alfa from Biomar, Brande, Denmark, 41−44% protein, 25−28% lipid, 16−19% carbohydrate, 0.8−2.4% fiber, 4−7% ash, 0.9% total phosphorus, according to the supplier) of different size (pellets diameter) according to the size/weight of fish to be fed in each of the different ponds (see Table 1).
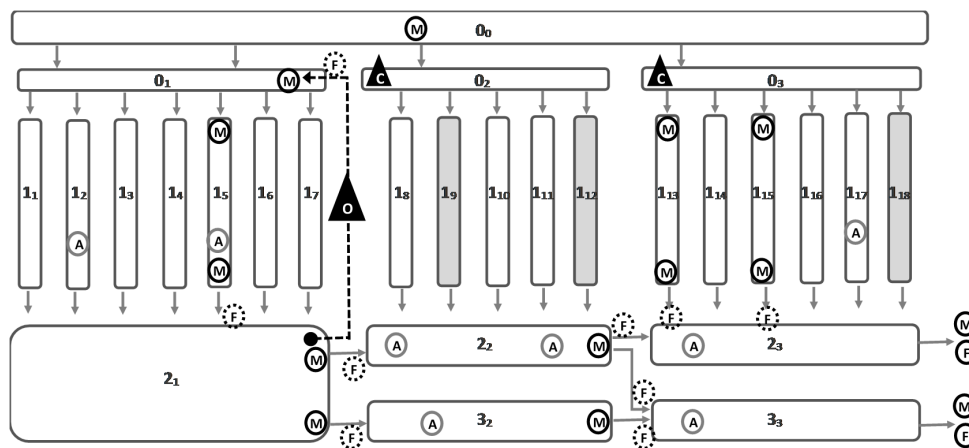
Figure 7. Fish farm general layout (A: paddle-wheel aerator, C: oxygen cone; O: high pressure oxygenator; M: physico-chemical monitoring location; F: water flow monitoring location). Some ponds (i.e., 1_9, 1_{12} and 1_{18}) were not stocked at the moment of monitoring, they are represented in grey. The figures 0, 1, 2 and 3 are theoretical numbers of water uses.

Supplementary oxygenation of the inlet water was achieved using oxygenation cones with supplementary aeration provided within the ponds by mechanical aerators (paddle-wheels) (Figure 7). Additionally, there was a partial recirculation of the water from 2_1 pond to 0_1 pond also involving a supplementary oxygenation step. It is noteworthy that this recirculation was applied without any water treatment system (i.e., neither solid removal nor nitrification step applied), hence this farm would still fall within the classification of "flow-through farm".

According to the farm layout and the flow dynamic we initially defined the expected number of water passes for each pond. For one given pond, the number of water passes was defined as the number of ponds the water flowed through. As an example, all the ponds labelled $1_{1–18}$ were considered as 1-pass ponds.

3.2. Water Quality and Flow Monitoring

Water quality parameters (pH, DO, NO_3–N, NH_4–N, temperature) were analyzed in situ using a multi-sensor probe (YSI, Xylem Inc., Tunbridge Wells, United Kingdom).

Flows were monitored in different farm locations (Figure 7) using ultrasonic flow meters (Nivus PCM4 portable ultrasonic flow measurement devices, Eppingen, Germany). Both 2_3 and 3_3 ponds outlets were monitored continuously and some other locations (1_5, 1_{13}, 1_{15}, 2_1, 2_2 and 3_2 ponds outlets) were monitored at set intervals during the monitoring program in order to understand the whole farm dynamic and to be able calculate/estimate fluxes at (i) farm outlet, and (ii) within the farm. It is noteworthy that the assumption was made that farm inlet flow (not measured) was equal to the farm outlet flow and that no water loss occurred within the farm.

3.3. Experimental Set-Up

The objective was to assess flows and water quality dynamic over the whole fish farm. As all the fish farm locations could not be monitored continuously due to lack of both time and human resources, choices of the farm locations to monitor were made in order to cover most of the farm operation and to fulfil the objectives presented in Section 1. To that aim, the farm locations monitored were the following:

(1) The general inlet channel 0_0 as the fish farm inlet (i.e., before supplementary oxygenation by the cones, see Figure 7).

(2) The inlets and outlets of three "1-pass ponds" (i.e., 1_5, 1_{13} and 1_{15}, see Figure 7) that were chosen both to represent the diversity of the farm (i.e., different average fish weights, total biomass in

1_5 and $1_{13}/1_{15}$ ponds with larger fish in 1_5 as presented in Table 1) and to generate results from similar ponds in order to obtain a duplication of the results and confirm that the protocol set-up was accurate (i.e., 1_{13} and 1_{15} with similar average fish weight and total biomass, see Table 1).

(3) The outlets of all the other ponds (i.e., 2-pass, 3-pass and more) in order to identify the dynamic of the farm and to assess the influence of the number of water passes on water quality.

(4) The recirculated water (from 2_1 to inlet channel 0_1, see Figure 7) in order to assess the impact of the recirculation loop on water quality.

Due to limited personnel resources and time operational constraints, only the ponds outlets' water quality was monitored. For simplification purposes, outlet concentrations were considered as equal to those encountered within the pond themselves.

A period of two consecutive dry-weather days of monitoring was considered in order to avoid any effect on flows that would have been created by rain. It was checked that no rain event was observed upstream during the whole experiment and the week before.

3.4. Data Treatment

Differential concentrations ($\Delta_C(t)$) were calculated as being the difference between outlet and inlet concentrations for a given parameter at a given time. These concentrations were calculated using the following equation (Equation (1)):

$$\Delta_C(t) = C_{outlet}(t) - C_{inlet}(t) \tag{1}$$

where $\Delta_C(t)$, generally expressed in mg/L (except for turbidity and pH), represents the differential concentration of a given parameter at the given time t.

These $\Delta_C(t)$ were calculated at (i) farm scale ($C_{outlet}(t)$ being the mean value calculated for the two farm outlets (i.e., 2_3 and 3_3) for a given time and $C_{inlet}(t)$ the value measured at farm inlet (i.e., 0_0) at the same time for a given parameter) in order to study the impact of the whole farm on water quality, and (ii) at pond scale in order to study the impact of each monitored pond on water quality and to assess the influence of water passes on water quality. The $\Delta_C(t)$ were calculated for all monitored times and also averaged for the duration of the monitoring. Hence, a positive value for $\Delta_C(t)$ would mean an increase in the concentration of a given parameter from inlet to outlet, and therefore a "production" by the farm (or by the pond considered); similarly, a negative $\Delta_C(t)$ value would mean a decrease in the concentration of a given parameter from inlet to outlet and therefore a "consumption" by the farm (or by the pond considered).

From the obtained $\Delta_C(t)$ values, flow values were used to calculate fluxes ($f(t)$, generally expressed in mg/h, except for pH and turbidity) both at farm and pond scales for all the monitored parameters. The $f(t)$ were calculated as follow (Equation (2)):

$$f(t) = \Delta_C(t) \times Q_{outlet}. \tag{2}$$

where $f(t)$ (mg/h) is the flux of a given parameter from the whole farm or from a given pond and Q_{outlet} (L/h) the flow at the outlet of the farm or of a given pond.

Those fluxes were converted using the total biomass in presence in each pond (see Table 1) to obtain fluxes in mg/h/kg$_{fish}$. according to the following equation (Equation (3)):

$$F(T) = \frac{f(t)}{m_{T,pond}} \tag{3}$$

With $m_{T,pond}$ (kg$_{fish}$), the total biomass in the pond considered.

All $F(t)$ values were averaged for the farm and for the monitored ponds for all the monitored parameters to obtain comparable mean flux values between the different ponds monitored.

4. Conclusions

A traditional flow-through rainbow trout farm was monitored extensively for the first time in Ireland. It is recalled that traditional flow-through systems still represent 90% of the trout production at the country scale today, and even if practices are evolving through recirculated aquaculture systems (RAS), this type of practice remains very common at the EU scale (France, Poland, Czech Republic, etc.). Therefore, the results and observations from this study are very relevant to the industry.

A combination of flow and water quality monitoring made it possible to understand the dynamics of water and its nutrient and dissolved oxygen content. To allow for a better understanding and analysis of the results, the concept of "multi water passes" was defined as the number of ponds the water flows through before release at the farm outlet. The flow measurements performed illustrated the difficulty in assigning a number of water passes to each pond, and the results obtained were not in agreement with the expected number of water passes (negligible or even negative flows observed at some farm locations). Thus, this study gives the impact and limits of multi water reuse on water quality and of the implementation of supplementary aeration/oxygenation, still practiced broadly in Ireland and in Europe. Furthermore, this study made it possible to attain proper and independent monitoring of the effluent water quality of the farm effluent and of the impact it might have on the receiving water quality.

The impact of water passes on water quality was identified, with a notable increase in NH_4–N concentrations when the number of water passes increases. However, the loss in DO was globally compensated by the oxygenation/aeration technologies (oxygenation cones, recirculation loop and paddlewheel aerators) employed onsite. The role of sediments in DO consumption and NH_4–N production was clearly identified as being substantial, and sediments could be responsible for a significant DO consumption, which has to be compensated by the operation of some oxygenation/aeration devices with their associated costs (energy, investment). It is, therefore, recommended for fish farmers still employing traditional flow-through systems to "de-sludge" their ponds more frequently in order to limit DO loss and NH_4–N increase in the rearing water.

The industry has to produce more to be economically viable in the future [20]. However, it was shown during the present study that ammonium levels increased with the number of water passes, and that it could reach concentrations up to almost 1 mgN/L in ponds. This shows that increasing production in the same farm configuration would increase nutrients concentration even more, which could hamper production due to an expected impact on fish health from this concentration [21]. Thus, with regards to fish welfare, the outcomes of this study make it possible to identify areas and practices within the FT systems that show water quality levels close to threshold levels for fish welfare. From this, appropriate actions and practices can be implemented. Therefore, if this fish farm were to produce more, some water treatment processes (solid/liquid separation, nitrification) would have to be set up in order to both limit the build-up of nutrients in the rearing water and to reduce the nutrient release in the effluent to fulfil the WFD objectives. It also identifies performances of the industry with respect to the WFD, criteria thereby facilitating gap analysis for the implementation of water treatment technologies. Finally, this study also acts as a benchmark for the industry to define what improvements are required and develop a roadmap for the sustainable development of the freshwater aquaculture sector in Ireland and beyond (specifically for trout production).

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