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Effect of Water Management Technology Used in Trout Culture on Water Quality in Fish Ponds

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Abstract: Pond management requires that a specific fish culture is conducted while taking into account both production possibilities and profitability, as well as the impact it may have on the natural environment. This study aimed to evaluate the effect of three water management systems used in rainbow trout culture on water quality in fish ponds. It was conducted at six trout farms and differing in water management strategy. After water had flown through the fishing ponds, its quality was significantly less impaired at farms operating in the flow and cascade systems. In turn, waters discharged from farms using the recirculation system were characterized by the poorest quality and lowest values on the Water Quality Index (WQI). It was found that the flow and cascade systems can be used to maintain the water quality and give less fish mortality for trout. It has been shown that the use of a water recirculation system in rainbow trout cultures significantly affects the quality of water in fishponds and can potentially lead to suppression of fish resistance and in extreme cases, to fish death. This study will help fish farmers in choosing the optimal variant of water management, taking into account both the best fish health with the least negative impact of fish farms on the environment.

Keywords: trout; fish ponds; water quality; CCME-WQI

1. Introduction

Intensive development of fishery has been observed in the past two decades. The increase in food production in the aquaculture is significantly faster than in other sectors manufacturing foods of animal origin [1–3]. The fishing industry is under a strong pressure from environmental conditions, the quality of which determines success in certain types of activities, and in some special cases, may even make them impossible. Fish are unable to separate their living space from the area where they leave their excreta. This deteriorates water quality in a production system and thereby contributes to poorer fish growth and to increased incidence of diseases [4,5].

Trout ponds are typically fed with water drawn from watercourses or water springs. As much as 86,000 m^3 of water is needed to produce 1 ton of trout [6,7]. The optimal conditions for the survival and growth of fish necessitate not only adequate amounts of water, but also the right temperature and high quality of water [8,9]. Trout aquaculture needs specific chemical and biological conditions. It is difficult to fully understand the biology and physiology of fish without having the knowledge of the physicochemical parameters of water, because the chemistry of water provides much information about the metabolism of a given ecosystem and explains general hydrobiological relationships [10–13].

Impurities and contaminants produced in the aquaculture may be divided into solid and dissolved ones. The first include mainly excreta and feed leftovers, whereas the dissolved ones (BOD, ammonia, phosphorus) derive from metabolites secreted by fish (through gills and with urine) or from degradation of suspended solids. It is estimated that in the intensive systems of aquaculture, only 20–40% of feedstuff mass are built into fish bodies, whereas the remaining part is excreted. The contribution of non-ingested feed varies between 5% and 15% [14].

The quantity of waste produced in fish ponds depends on such factors such as the following: feed mixture composition, fish species, or temperature. In turn, the amount of fecal wastes ranges from 0.2 to 0.5 kg dry matter per kg of feed mixture [15]. In all systems used in aquaculture, part of these wastes is discharged with post-production waters, however, their quantity and quality differ depending on the culture system. In the flow systems, all dissolved contaminants and solid impurities are released into the environment. It is assumed that the amount of wastes generated by fish farms operating in the recirculation systems is lower than that generated by farms based on standard flow systems due to lower water consumption [16].

The quality of water discharged from fish farms and its load of pollutants depend on a number of factors. These include the quality of water supplied to a fish farm, the species of fish, their rearing technology, the amount and quality of feed supplied to fish, and the meteorological and physiographic factors [17]. The use of surface waters for fish production may threaten water ecosystems to which water from fish farms is discharged, as this can alter their qualitative and quantitative parameters. Used water from fish farms is most often discharged directly to nearby water bodies [13,18,19]. The pollutants carried by water discharged from fish farms are mineralized, which can interfere with the biological balance within a water body that receives it, hence water from fish farms can be seen as a potential source of pollution [20].

This study aimed to evaluate the effect of three different systems of water management: flow system, cascade system, and recirculation system, used in rainbow trout culture on water quality in fish ponds.

2. Materials and Methods

The study covered six trout culture farms located across Poland differing in water management systems applied (Figure 1). They were divided into three groups (two farms each) in terms of water circuit technology, that is, farms operating in the flow system, cascade system, and recirculation system. The flow system consists in one-time use of water, that is, water that passed through the culture system is treated as wastewater and discharged outside the system. In the cascade system, water flows through subsequent ponds arranged in a series, and afterwards is discharged to a receiver. In turn, in the recirculation system, the pond is re-fed with most of water that had flown through it. Part of the water used is discharged outside fishing ponds, and this part is re-filled with fresh water. Little intensive recirculation is used at the analyzed farms, with water recirculation approximating 96%. Total exchange of water in ponds proceeds within 24 h. Farms operating in the flow system use ca. 30 m^3 of fresh water to produce 1 kg of fish. The cascade system consumes 20 m^3, whereas the recirculation system used ca. 3 m^3.

The volume of water flowing through the analyzed ponds differed depending on the type of water management solution. At the farms with the flow system, it accounted for 8–12 $dm^3 \cdot s^{-1}$; at those with the cascade system, for 28–36 $dm^3 \cdot s^{-1}$; whereas at farms operating in the recirculation system, for 300–350 $dm^3 \cdot s^{-1}$. The use of a recirculation system in fish farming causes an increase in the concentration of impurities in the water. To improve the water quality, it is subjected to pre-treatment on microsites and biofilters. Higher flow through the joints results in a faster total water exchange in the ponds. In addition, the more water flows through the pond, the lower the concentrations of pollutants are and the easier it is to remove them from the water.

At all analyzed farms, trouts were fed twice a day with a pelleted feed mixture composed of fish meal, blood meal, soybean meal, maize, wheat, poultry and fish fat, and soybean oil. The feed mixture also contained 70.4 $gN \cdot kg^{-1}$, 10 $gP \cdot kg^{-1}$, 6 $gNa \cdot kg^{-1}$, and 7 $gK \cdot kg^{-1}$.

For water quality assessment, sampling points were established at each farm at the site of water inflow to the farm and water outflow from fishing ponds. Analyses were accomplished within two years.

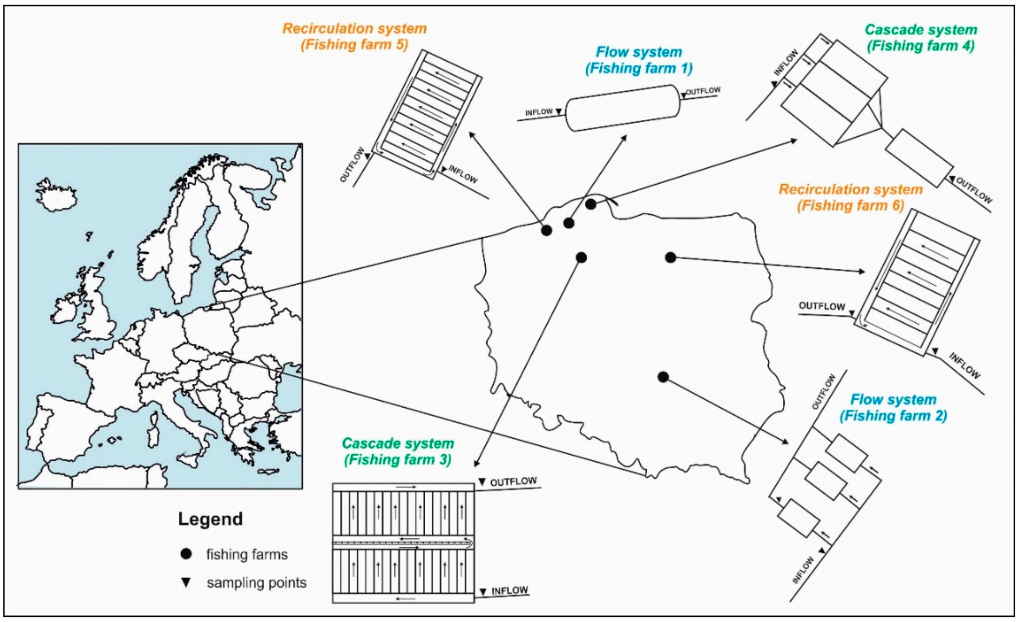


Figure 1. Location of fish farms.

Concentration of dissolved oxygen in water and water pH was measured at all sampling points using a multiparameter probe YSI 6600. In addition, water samples were collected from these points for laboratory analyses. Concentrations of total suspended solids, BOD_5, $N\text{-}NO_3$, $N\text{-}NO_2$, $N\text{-}NH_4$, $N_{Kiejdahl}$, and TP were determined according to the Standard Methods [21], whereas $N\text{-}NH_3$ concentration in water was computed from the following formula [22]:

$$N\text{-}NH_3 = (a) \times TAN\ (mg \cdot dm^{-3}) \quad (1)$$

(a)—mole reaction of un-ionized ammonia,
TAN—total ammonia nitrogen ($mg \cdot dm^{-3}$),

$$(a) = \frac{1}{1 + 10^{10.068 - 0.33T - pH}} \quad (2)$$

T—temperature of water in a fish pond,
pH—pH of water in a fish pond.

Calculation of Water Quality Index

The evaluate water quality, the Water Quality Index (WQI) was computed for water samples from each sampling point. The WQI may be computed with different methods [23–26]. In this study, we used a method developed by the Canadian Council of Ministers of the Environment (CCME) based on the following formula [27,28]:

$$CCME\text{-}WQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right) \quad (3)$$

The symbols used in the formula are in the Supplementary Information.

Water quality is established by referring the computed values of CCME-WQI to one of the five categories from the water quality rating (Table 1).

To enable the CCME-WQI calculation, eight physical and chemical parameters of water were used (DO, pH, suspended solids, BOD_5, TP, N-NH_4, N-NH_3, N-NO_2). Their limit values determining the possibility of these waters colonization by the Salmonidae fish were stipulated in the Regulation of the Minister of the Environment of 4 October 2002 on the requirements to be met by inland waters inhabited by fish in natural conditions [29] consistent with Council Directive 78/659/EEC on the quality of fresh waters needing protection or improvement in order to support fish life [30].

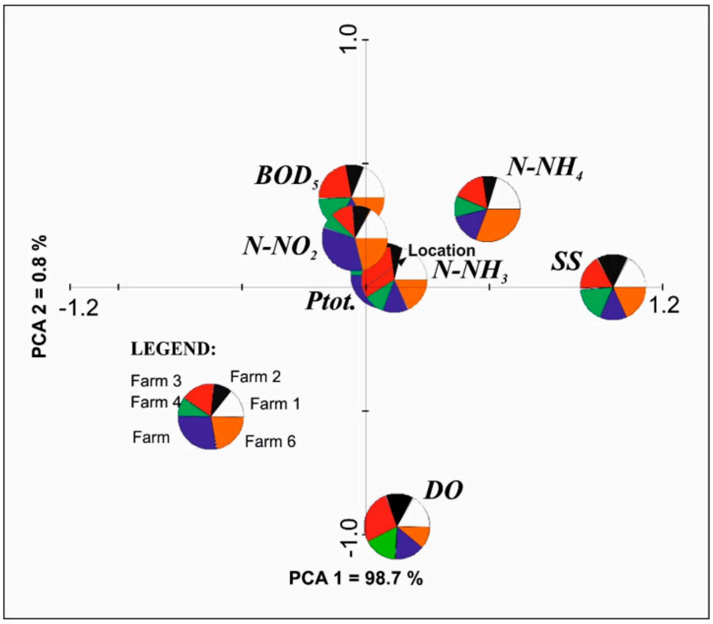
Table 1. Water quality rating [15].

Wqi Value	Water Quality	Description
95–100	Excellent	Water quality is protected with a virtual absence of threat or impairment, conditions very close to natural or pristine levels
80–94	Good	Water quality is protected with only a minor degree of threat or impairment, conditions rarely depart from natural or desirable levels
65–79	Fair	Water quality is usually protected but occasionally threatened or impaired, conditions sometimes depart from natural or desirable levels
45–64	Marginal	Water quality is frequently threatened or impaired, conditions often depart from natural or desirable levels
0–44	Poor	Water quality is almost always threatened or impaired, conditions usually depart from natural or desirable levels

In the present study, hierarchal cluster analysis has been employed in a dataset to detect similarity between the waters of a fisheries farm in terms of water quality parameters. The Euclidean distances were used as a measure of similarity between the water sampling sites, while the Ward's error sum of squares in the hierarchical clustering method was applied to minimise the increase in the within-group variance. Analysis of the relationship between physicochemical parameters of the studied waters was based on the principal component analysis (PCA) method.

3. Results

The quality of water inflowing to the fish farm met criteria set for inland waters inhabited by the Salmonidae fish in the Directive 78/659/EEC, in the case of most of the analyzed parameters. Only mean concentrations of N-NO_2 and suspended solids were negligibly exceeded (Table 2). Water inflowing to the farms operating in the recirculation system was also characterized by exceeded permissible concentration of total phosphorus, by 0.049–0.070 $mg \cdot dm^{-3}$ on average, and water inflowing to the farm No. 6, BOD_5 value exceeded by 0.1 $mg \cdot dm^{-3}$ on average. High oxygenation of waters was observed in the study period (from 8.27 ± 1.70 $mg \cdot dm^{-3}$ to 10.31 ± 1.22 $mg \cdot dm^{-3}$), which was negatively correlated with N-NO_3 concentration (Figure 2). The principal component analysis of correlations between concentrations of selected substances in waters inflowing to the trout ponds demonstrated that the first component (PCA1) described 98.7% of the total variance of data. The PCA showed also a statistically significant positive correlation between concentrations of SS and N-NH_4. Waters inflowing to the fish farms also had low and stable concentration of N-NH_4.



Axes	PCA 1	PCA 2	PCA3	PCA 4	Total variance
Eigenvalues:	0.987	0.008	0.005	0.001	
Species-environment correlations:	0.165	0.122	0.229	0,039	
Cumulative percentage variance					1.000
of species data:	98.7	99.5	99.9	100.0	
of species-environment relation:	98.7	99.1	100.0	100.0	
Sum of all eigenvalues					1.000
Sum of all canonical eigenvalues					0.027

Figure 2. Principal component analysis (PCA) of correlations between concentrations of selected substances in waters inflowing to trout ponds.

The fish farms got water from various rivers. For this reason, their chemical water composition was varied. The mean concentration of total nitrogen in water inflowing to the fish farms ranged from 0.53 mg·dm^{-3} to 2.27 mg·dm^{-3}. In water inflowing to the fish farm No. 1 and fish farm No. 3, it was mainly composed of organic nitrogen (69–70%) and N-NO_3 (18–19%).

An opposite observation was made in water inflowing to the fish farm No. 2, that is, total nitrogen was constituted by 80% of N-NO_3 and 17% of organic nitrogen. In waters inflowing to the fish farms No. 4 and No. 5, concentrations of these forms of nitrogen were similar and reached 39–42% (N-NO_3) and 52–53% (N_{org}). In turn, in water inflowing to the fish farm No. 6, total nitrogen was mainly constituted by N-NO_3 (55%), organic nitrogen (29%), and N-NH_4 (15%) (Figure 3).

The CCME-WQI index was used in the complex assessment of the quality of waters inflowing to fish farms in terms of their usability for rainbow trout culture. It refers the physicochemical parameters of water to the requirements to be met by inland water inhabited by the Salmonidae fish under natural conditions [31,32]. The computed CCME-WQI values enable the conclusion that waters inflowing to the fish farms No. 2, No. 3, and No. 4 were of the fair quality category (Table 3). Their quality was usually sufficient for trout culture, however, concentrations of substances periodically exceeded permissible values (Table 1).

Table 2. pH value and mean concentrations of selected substances in waters inflowing to the analyzed fish farms (mg·dm^{-3}).

Index	Objective Levels for Each Constituents as in EEC/78/669	Flow System		Cascade System		Recirculation System	
		Farm 1	Farm 2	Farm 3	Farm 4	Farm 5	Farm 6
Temperature *	<21.5	12.9 ± 3.6	10.8 ± 2.0	11.2 ± 1.2	10.8 ± 6.6	12.5 ± 3.7	8.9 ± 0.6
DO	>7.0	9.22 ± 1.95	8.61 ± 0.38	10.21 ± 0.43	10.31 ± 1.22	9.46 ± 1.80	8.27 ± 1.70
pH **	6.0–9.0	7.78–8.48	6.73–7.87	8.00–8.66	7.35–8.27	6.39–8.25	7.46–8.56
SS	<25	29 ± 29	30 ± 12	21 ± 7	33 ± 7	26 ± 11	42 ± 19
BOD_5	<3.0	2.5 ± 1.2	1.5 ± 0.5	2.1 ± 1.4	2.5 ± 1.1	2.6 ± 1.1	3.1 ± 1.1
TP	<0.2	0.118 ± 0.048	0.086 ± 0.095	0.096 ± 0.029	0.087 ± 0.026	0.270 ± 0.332	0.249 ± 0.095
N-NH_4	<0.78	0.106 ± 0.064	0.046 ± 0.029	0.059 ± 0.025	0.064 ± 0.043	0.094 ± 0.042	0.22 ± 0.136
N-NH_3	<0.020	0.004 ± 0.002	0.001 ± 0.001	0.004 ± 0.002	0.002 ± 0.002	0.003 ± 0.002	0.004 ±0.005
N-NO_2	<0.003	0.012 ± 0.010	0.008 ± 0.008	0.006 ± 0.001	0.006 ± 0.004	0.029 ± 0.010	0.021 ± 0.021
N-NO_3	–	0.177 ± 0.061	1.837 ± 0.290	0.099 ± 0.012	0.713 ± 0.205	0.575 ± 0.311	0.836 ± 0.258
N_{min}	–	0.289 ± 0.118	1.887 ± 0.294	0.164 ± 0.035	0.782 ± 0.235	0.698 ± 0.314	1.084 ± 0.285
N_{org}	–	0.713 ± 0.266	0.377 ± 0.219	0.369 ± 0.070	0.871 ± 0.629	0.745 ± 0.246	0.450 ± 0.121
N_{tot}	–	1.01 ± 0.22	2.27 ± 0.30	0.53 ± 0.06	1.65 ± 0.70	1.44 ± 0.32	1.53 ± 0.35

mean ± standard deviation, * °C, ** min−max.

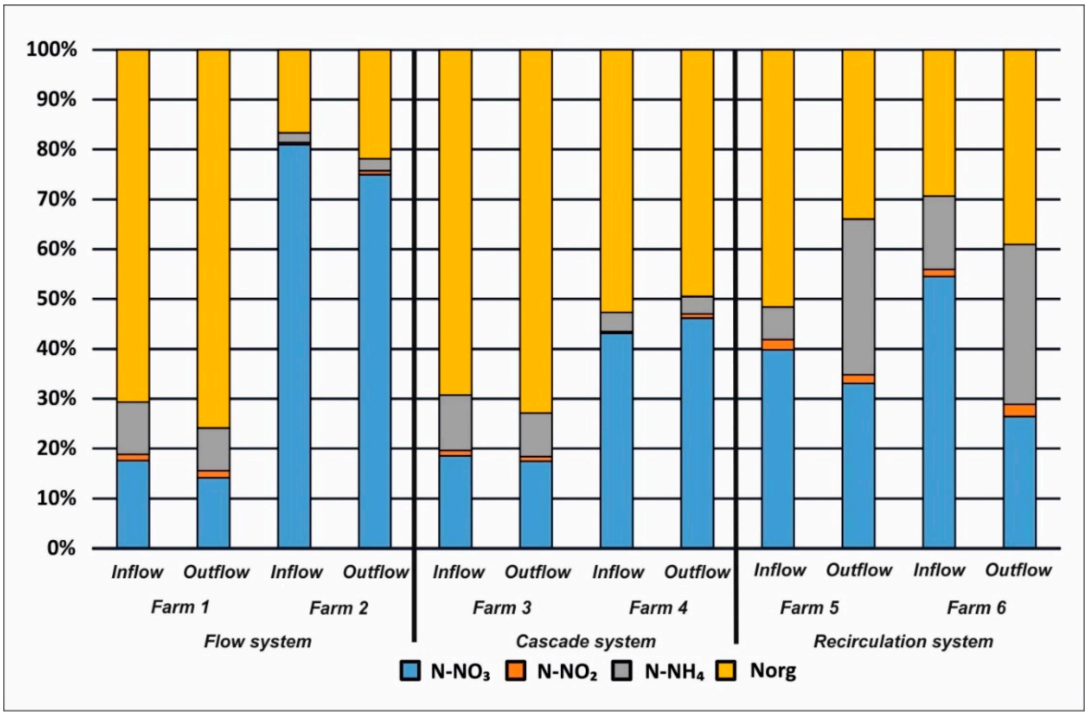


Figure 3. Contribution of particular forms of nitrogen in waters used in rainbow trout culture (%).

As indicated by the statistical analysis conducted with Ward's method, these waters represented a separate cluster of waters of a better quality (Figure 4). The second cluster included waters of a worse quality that were inflowing to the fish farms No. 1, No. 5, and No. 6. These farms were fed with waters of the marginal category, which means that these waters often pose risk to fish as their quality indicators exceed live-threating values (Supplementary Information).

The quality of water deteriorated once it flew through fish ponds at all fish farms studied. A significant increase was demonstrated in concentrations of N-NO_2 and suspended solids and in BOD_5 value, and a decrease in the concentration of dissolved oxygen (Table 3). The PCA showed a statistically significant correlation between N-NH_4 and BOD_5 (Figure 5). At farms operating in the recirculation system, the BOD_5 values permanently exceeded the limit value set in the requirements for inland water inhabited by the Salmonidae fish under natural conditions. The increase accounted for ca., 35% at farm No. 6, whereas at the fish farm No. 5, it was almost two-fold (Table 4). At the farms using the recirculation system, the concentration of N-NH_4 in water from fish ponds periodically exceeded the permissible values and reached values posing a threat to fish life. The PCA demonstrated a significant correlation between N-NH_4 concentrations and the TP value.

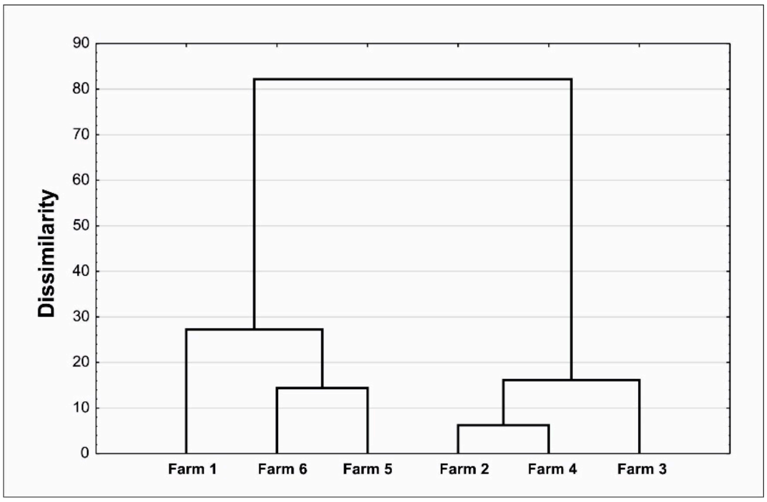
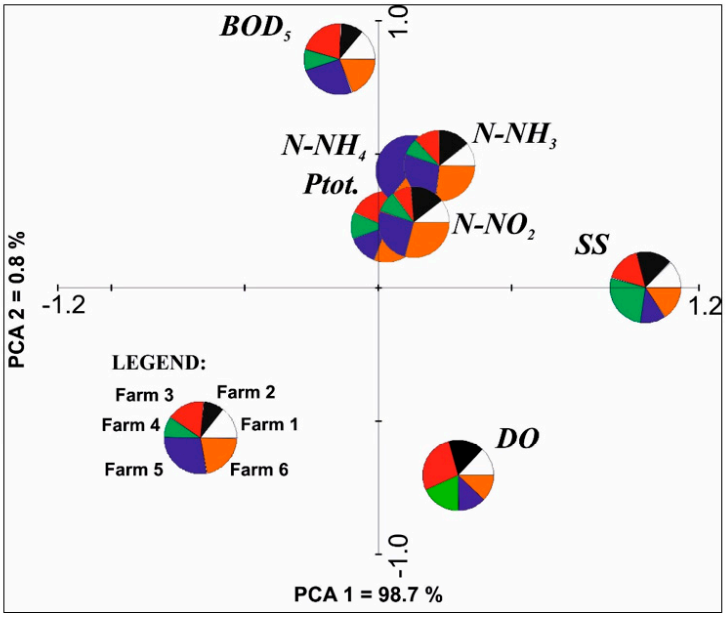


Figure 4. Grouping of waters inflowing to fish farms with the Ward hierarchical method.

The concentration of total nitrogen in water used for rainbow trout culture also increased and ranged from 0.71 mg·dm^{-3} to 2.63 mg·dm^{-3}. At the fish farms operating in the flow and cascade systems, concentrations of individual nitrogen forms in water outflowing from ponds was similar to those in water inflowing to the farms (Figure 3). At the farms using the flow system, the concentration of N-NO_3 decreased by ca. 5% and that of organic nitrogen increased by 5%. At the farms with the cascade system, organic nitrogen concentration decreased by 4% and concentrations of N-NO_3 and N-NH_4 increased by 2% in the outflow from farm No. 3, whereas in water discharged from the farm No. 4, organic nitrogen concentration decreased by 3%, whereas N-NO_3 concentration increased by 3%. An opposite situation was observed at farms operating in the water recirculation. In water outflowing from the farm No. 5, concentrations of N-NO_3 and organic nitrogen decreased by 6% and 18%, respectively, while that of N-NH_4 increased by 24%. Also, in water discharged from the farm No. 6, an increase by 17% was observed in the concentration of N-NH_4 and by 10% in the organic form of nitrogen, whereas a 28% reduction in the concentration of N-NO_3 occurred.

At the farms using the flow system of water management, the CCME-WQI value decreased by 2.70–6.64 after waters had passed through the fish ponds, which caused no changes in their quality category according to the scale proposed by the Canadian Council of Ministers of the Environment [28] (Supplementary Information). Waters discharged from the farm No. 1 were of the marginal category and these outflowing from the farm No. 2 were of the fair category.



Axes	PCA 1	PCA 2	PCA3	PCA 4	Total variance
Eigenvalues:	0.987	0.008	0.004	0.000	
Species-environment correlations:	0.176	0.614	0.230	0.188	
Cumulative percentage variance					1.000
of species data:	98.7	99.5	99.9	100.0	
of species-environment relation:	90.5	99.2	99.9	99.9	
Sum of all eigenvalues					1.000
Sum of all canonical eigenvalues					0.034

Figure 5. Principal component analysis of correlations between concentrations of selected substances in waters outflowing from trout ponds.

A similar observation was made for water outflowing from the farm No. 3. Despite a decrease in its quality index, the category of water used for trout culture did not change. An opposite situation occurred at the farm No. 4. Water passage through the fish pond caused its CCME-WQI to decrease by 11.97, which resulted in a change of its quality category from fair to marginal. The decreased value of the index was mainly attributable to an increased concentration of suspended solids (by 28 mg·dm^{-3}) and to a double increase in the concentration of N-NO$_2$.

Waters discharged from the farms working in the recirculation system were characterized by the lowest CCME-WQI values. Despite their CCME-WQI decrease by 11.01, the waters outflowing from the farm No. 5 kept their marginal category. The greatest deterioration in water quality was noted in the outflow from the farm No. 6. Water passage through fish ponds resulted in its CCME-WQI value decrease by 25.57, which caused a change in its quality category from marginal to poor, being the lowest in the scale. The quality of these waters was almost always unfavorable and significantly diverged from the desirable values (Table 1). The decrease in the CCME-WQI value was mainly because of increased concentrations of N-NH$_4$, TP, and N-NO$_2$.

The above data allows noticing a clear division of waters used in the fish farms into two groups: the first one including waters of better quality outflowing from the fish farms operating in the flow and cascade systems, and the second one including waters of significantly worse quality discharged from the fish farms using the recirculation system. This observation was confirmed by results of the statistical analysis of water quality parameters conducted with the Ward method (Figure 6).

Table 3. pH value and mean concentration of substances in waters outflowing from fish farms ($mg \cdot dm^{-3}$).

Index	Objective Levels for Each Constituents as in EEC/78/669	Flow System		Cascade System		Recirculation System	
		Farm 1	Farm 2	Farm 3	Farm 4	Farm 5	Farm 6
Temperature *	<21.5	12.4 ± 3.8	10.3 ± 2.0	11.2 ± 1.5	10.9 ± 6.6	14.0 ± 3.1	11.4 ± 2.9
DO	>7.0	8.66 ± 2.67	8.96 ± 0.74	8.97 ± 0.88	10.21 ± 1.54	8.23 ± 2.03	7.97 ± 1.57
pH **	6.0–9.0	7.85–8.32	7.05–8.35	6.94–8.25	7.41–8.12	7.64–7.97	7.32–8.52
SS	<25	35 ± 29	37 ± 25	23 ± 8	61 ± 13	32 ± 13	42 ± 13
BOD_5	<3.0	3.2 ± 1.1	1.9 ± 0.4	2.4 ± 1.4	1.8 ± 0.9	5.8 ± 0.4	4.2 ± 1.1
TP	<0.2	0.127 ± 0.036	0.076 ± 0.017	0.130 ± 0.037	0.111 ± 0.064	0.151 ± 0.035	0.336 ± 0.113
$N\text{-}NH_4$	<0.78	0.097 ± 0.064	0.064 ± 0.032	0.062 ± 0.020	0.053 ± 0.057	0.703 ± 0.267	0.581 ± 0.604
$N\text{-}NH_3$	<0.020	0.004 ± 0.002	0.005 ± 0.004	0.002 ± 0.001	0.002 ± 0.003	0.011 ± 0.004	0.010 ± 0.012
$N\text{-}NO_2$	<0.003	0.016 ± 0.010	0.020 ± 0.016	0.006 ± 0.001	0.013 ± 0.007	0.040 ± 0.024	0.044 ± 0.054
$N\text{-}NO_3$	–	0.161 ± 0.041	1.975 ± 0.356	0.124 ± 0.026	0.702 ± 0.322	0.747 ± 0.216	0.479 ± 0.191
N_{min}	–	0.275 ± 0.099	2.057 ± 0.373	0.192 ± 0.035	0.766 ± 0.341	1.490 ± 0.286	1.104 ± 0.540
N_{org}	–	0.864 ± 0.200	0.576 ± 0.206	0.516 ± 0.267	0.752 ± 0.228	0.766 ± 0.592	0.706 ± 0.248
N_{tot}	–	1.14 ± 0.23	2.63 ± 0.47	0.71 ± 0.25	1.52 ± 0.39	2.26 ± 0.50	1.81 ± 0.78

mean ± standard deviation, * °C, ** min−max.

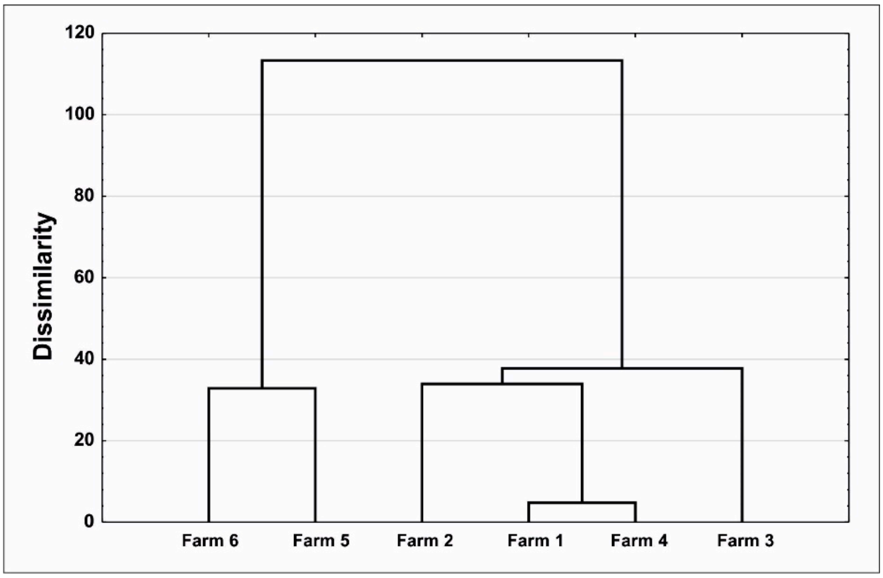


Figure 6. Grouping of waters outflowing from the fish ponds with the Ward method.

The mortality rate of fish was determined by the water management system used at fish farms, that is, by water quality in the fish ponds (Table 4). At the fish farms using the flow and cascade systems, fish mortality was similar despite various stock density and ranged from 0.62% to 0.64%. At the farms operating in the recirculation system, wherein water was of the poorest quality, fish mortality was statistically significant ($p < 0.05$), higher than at the other farm, and reached 0.96–0.98%.

Table 4. Mortality rate of rainbow trout (%).

		Water Management System					
		Flow System		Cascade System		Recirculation System	
		Farm 1	Farm 2	Farm 3	Farm 4	Farm 5	Farm 6
Mortality rate (%)		0.62 ± 0.13	0.64 ± 0.16	0.63 ± 0.17	0.64 ± 0.15	0.96 ± 0.16	0.98 ± 0.20
Stock density	($kg \cdot m^{-3}$)	0.4		3.5		7.0	
	(pcs/pond)	615 ± 266	607 ± 263	1005 ± 435	1020 ± 451	1754 ± 760	1656 ± 717

mean ± standard deviation

4. Discussion

Fish production is an important contribution to the economic sector of the European Union (EU) [31]. Trout production in Poland in the last five years has been on average 16,044 tons per year. It places Poland as one of the largest trout producers in the EU. Currently, the production of fish in aquaculture provides about 2% of the raw material for animal processing in Poland.

Trout culture requires detailed knowledge regarding conditions of the production process as well as chemical and biological factors of the environment. Both cost-effectiveness of the production process and impact of the production system on the natural environment should be taken into consideration when choosing the optimal water management technology in trout culture [32–34].

Oxygen concentration in water is one of the basic parameters that determine rainbow trout production. Fish tolerance to a low concentration of oxygen is short, species-specific, and fish size-dependent. Trout have high demands for oxygen, that is, at least 5–8 mg O_2 mg·dm^{-3} water [35,36]. Oxygen concentration decrease below 3 mg·dm^{-3} may lead to fish immunity suppression and this to their increased susceptibility to infections and parasite invasions. In extreme cases, it may be fatal to fish [37–40]. For this reason, artificial aeration of waters using pure oxygen was periodically used at the fish farms to maintain oxygen concentration in water at an optimal level.

Organic matter content in water, expressed by the BOD_5 value, is one of the key factors that determine usability of waters for rainbow trout culture. It is assumed that its value in waters intended for the culture of the Salmonidae fish should not exceed 3.0 mg·dm^{-3} [29,30,41–43]. The analyzed fish farms cultured rainbow trout using various water management systems. At farms operating in the cascade system, waters flew through subsequent ponds arranged in series; waters from higher located ponds were discharged untreated to the lower located ponds. In the recirculation system, most of the water that passed through the pond was re-fed to it. In the aforementioned systems, the multiple re-use of water resulted in its successively increasing contamination with undigested feed residues and fish metabolites, which contributed to organic matter level increase. Under such circumstances, bacteria degrading organic matter intensify their activity and, consequently, consume more oxygen. This, in turn, causes the BOD_5 value in pond water to increase [44,45], as indicated by the positive correlation between BOD_5 values and N-NO_2 and N-NH_4 concentration shown in our study. Nitrites may be associated with ammonia concentration in water [44,46,47].

Also, contribution of individual forms of nitrogen changed in the water from trout culture. At the farms using the flow and cascade systems, transformations of individual nitrogen forms were insignificant, whereas at farms operating in the recirculation system, waters were characterized by a significant increase in the concentration of ammonia nitrogen and by decreased levels of N-NO_3 and organic nitrogen. This was in part because of the ammonification of nitrogen contained in organic compounds present in water and administered feed [45–48]. Simultaneously, fish metabolites were accumulating in the waters that were re-used multiple times, which contributed to an increase in the level of ammonia nitrogen and this resulted in an increased concentration of N-NH_3 in waters at farms using the recirculation system. The concentration of non-ionized ammonia in the analyzed water did not exceed 0.020 mg·dm^{-3} and as such posed no threat to fish. According to Solbé and Shurben [49] and Randall and Tsui [50], considering the LC50 value per 24 h, N-NH_3 becomes toxic to the Salmonidae fish even at concentrations as low as 0.07–0.39 mg·dm^{-3}, whereas according to Svobodová et al. [44], at 0.5–0.8 mgNH_3·dm^{-3}.

In our study, we found a positive correlation between concentrations of N-NH_4 and non-ionized form of ammonia and the concentration of TP. It suggests intensive fish feeding to be the main source of biogenes in the analyzed waters. It is assumed that only some small parts of phosphorus and nitrogen contained in a feed mixture are inbuilt into fish biomass, while their greater parts remain in water, thus contributing to their increased concentrations therein [51–53].

The health status of fish in aquaculture conditions is affected by many factors. Apart from the biological value of fish, their mortality rate depends on elements associated with water quality in ponds [54,55]. A water management system applied at a fish farm had a significant effect on the chemical composition of waters, and for this reason was a factor that determined fish survivability. On farms benefiting from recirculation of water, where water quality was the poorest, fish mortality was higher compared with other farms. Use of a water recirculation system in rainbow trout cultures significantly affects the quality of water in fishponds and can potentially lead to suppression of fish resistance, and thus to their increased susceptibility to diseases and parasites, and in extreme cases, to fish death. Such dependence is confirmed by other authors [56–59].

The results of our study demonstrated a decrease in the quality of water that passed through the fish ponds. Its direct discharge to a receiver, without treatment, may pose threat to the natural environment [3,26]. Hence, a post-production water treatment system should be implemented at trout producing farms to minimize their negative effect on the environment.

5. Conclusions

Water quality is very important part of environmental management. When water quality is poor, it affects not only aquatic life but the surrounding ecosystem. For this reason, the use of the environment requires choosing the optimal technology that will allow the highest possible efficiency with the least adverse impact on waters.

In all farms studied, the water passing through the ponds in the trout farms deteriorated its quality. After passing through the fishing ponds, its quality was much less limited in farms operating in flow and cascade systems. The analysis did not show any significant differences in the impact on the quality of waters leaving the fish farms using the flow system and cascade. Water discharged from farms using the recirculation system was characterized by the worst quality and the lowest CCME-WQI values. Their quality was almost always weak and significantly deviated from the desired values. The outflow of water from fish farms using water recirculation was characterized by the lowest quality and the lowest values of the CCME-WQI index. However, their impact on the environment of the rivers water was the lowest because of the least amount of water needed to produce 1 kg of fish. This caused the load of pollutants flowing from the farm to the rivers to be the smallest.

It was found the flow and cascade systems can be used to maintain the water quality and give less fish mortality for trout. In farms operating in flow and cascade systems, the mortality rate of fish was similar, despite various resource densities. On farms benefiting from recirculation of water, where water quality was the poorest, fish mortality was higher compared with other farms. It has been shown that the use of a water recirculation system in rainbow trout cultures significantly affects the quality of water in fishponds and can potentially lead to suppression of fish resistance, and thus to their increased susceptibility to diseases and parasites, and in extreme cases, to fish death.

This study also showed that waters discharged from fish ponds may pose risk of receiver waters contamination. Hence, technical measures should be implemented to improve their quality.

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