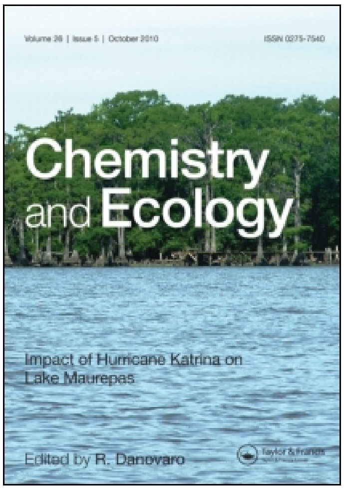

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Aquaculture effects on some physical and chemical properties of the water column: A meta-analysis

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Aquaculture effects on some physical and chemical properties of the water column: A meta-analysis

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More than 30 peer-reviewed articles (1980–2005) were analysed using meta-analytical reviewing techniques, and about 340 study cases were used to test whether aquaculture facilities had any effects on physical and chemical variables. The analysis tested differences between experimental conditions vs. chosen-by-author controls. Across all study cases, cultivated organisms (fish, shrimps and bivalves) did not have any clear effects on the water temperature and salinity. Dissolved oxygen also was found to be unaffected by aquaculture practices. On the other hand, crowding led to significant pH variations, which was more accentuated in shrimp ($d_+ = 0.66$; $P < 0.05$) than in fish farming plants ($d_+ = -0.15$; $P > 0.05$). Water transparency and turbidity were significantly affected by shrimps and fish farming.

Keywords: Aquaculture; Meta-analysis; Physical variables; Shrimp; Fish; Bivalve

1. Introduction

The environmental impacts of aquaculture are of increasing concern in modern approaches towards the sustainable use of water resources. Many papers have been published in the last two decades on the effects of aquaculture facilities on the surrounding water column [1], sediments [2], and the biota [3]. However, the effects of aquaculture on the physical and chemical properties of the water column have been almost neglected because of its highly dynamic properties, which in turn might impair any appreciable detection of changes in ecological processes induced by human pollution. Nevertheless, many authors have recently demonstrated that the water column can also record some effects on short- and medium-temporal terms [4–6]. Indeed, under continued organic pollution such as that induced by aquaculture [7, 8], a comprehension of water-column dynamics is needed to solve the most complex dynamics of the underlying sediment.

Possible deviations from natural patterns of responses by the biota can be better investigated by including reliable information on water-column dynamics. Most knowledge gained so far on this topic has already been incorporated in the national environmental impact assessment

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(EIA) protocols of many countries worldwide [9, 10], but analysis of the literature from the last decades has highlighted a large number of unclear aspects.

Many seminal reviews [11, 12], reports, and books [13, 14] have attempted to delineate the trend of aquaculture effects on the environment, but most of the information, since it is spatially and temporally fragmented, is still insufficient to define the precise dynamics and magnitude of the impacts.

In this regard, even peer-reviewed papers very often lack an experimental approach, data collected too often remain linked to local dynamics, or there is a general inhomogeneity in the use of environmental descriptors. Thus, the resulting literature on aquaculture effects on the surrounding waters presents a highly fragmentary panorama from which is not possible to gain any real knowledge on the ecology of water columns under organic enrichment.

Insights into the general environmental effects of aquaculture may be gained using meta-analytic techniques, which aim to provide a quantitative estimate of aquaculture effects using data amassed from the current peer-reviewed literature.

Meta-analysis, as opposed to other review techniques, offers major advantages for research synthesis in ecology [15]. Indeed, meta-analysis is a quantitative tool available to ecologists who wish to obtain general knowledge about the magnitude of a certain effect across the current literature, whether that effect is different among contrasting categories of studies and how much variation is explained both within and among categories.

The present analysis aims to understand whether water-column physical and chemical dynamics are generally affected by aquaculture facilities. The specific goals of the present analysis are to estimate: (1) the degree of heterogeneity of results reported from studies studying the effects of aquaculture on the physical and chemical features of the water column; (2) the effect of aquaculture loadings on physical and chemical features of the water column across the 1980–2005 peer-reviewed literature; and (3) the differential effects of aquaculture loadings on changes of each single physical and chemical variable.

2. Materials and Methods

2.1 *Literature search, meta-analysis criteria and data eligibility*

Data on the effects of aquaculture loadings on physical variables of the water column were obtained from a literature search using the Aquatic Science and Fisheries Abstracts (ASFA) and other databases such as Bio-One or Zoological Records which are available on-line. The scope of this search ranged between 1980 and the present, and when grey literature, internal reports, or unpublished data were not readily available on-line, a number of authors were personally contacted to obtain their publications. The search focused only on widespread and easily accessible sources, such as those published in peer-reviewed journals between 1985 and 2005. While the potential loss of useful data found in grey literature and internal sources is an important meta-analytic concern, it is hoped that considering only peer-reviewed articles ensured a consistent high quality of data that is often not found in other less established sources. As major journals tend to publish only significant results [16], thereby generating a potential publication bias and distorting the direction of true effect [17], the peer-review process is the best method to reduce the likelihood of potential quality biases in reviewing.

The search process resulted in about 100 peer-reviewed articles, which were then checked against the required criteria for meta-analysis. Unlike descriptive reviews, meta-analysis requires the quantitative measure of variance to be stated by each study [17]. Therefore, data obtained included the means for the control and treatment groups, their standard deviations, and their sample sizes [17] in order to calculate meta-analytic statistics. In the present meta-analysis, control groups are represented by data collected from areas chosen by each author where the effects of aquaculture facilities were assumed to be absent. The treatment group is represented by data collected from areas, sites, ponds, or tanks used by each author for testing effects of experimental response variables (hereafter referred to as 'impact'). In more than 50% of the studies, it was not possible to extrapolate deviations or sample sizes, and these were therefore excluded from the meta-analysis.

2.2 *Meta-analysis methodology*

Meta-analysis feasibility [17–20] depends on obtaining an estimate of the effect size (i.e. the magnitude of the effect of interest) from each investigation. The present analysis was concerned with the differential effect exerted by different cultivated organisms – shrimps (SHR), fish (FISH), bivalves (BIV), and polyculture (POLY) – on physical and chemical variables of the water column (table 1). The most common measure of effect size is the difference between means of controls and impacts, standardized by dividing by the pooled standard deviation [21]. This standardized mean difference, Hedges' d (hereafter called simply d), is conventionally

Table 1. Literature used for the meta-analysis, reared organisms and physical and chemical variables measured in each study.

Study	Type	Variables
[50]	SHR	TEMP, SAL, pH, OD
[51]	FISH	TEMP, pH, OD, Secchi
[52]	FISH	TEMP, pH, OD, Secchi
[53]	FISH	TEMP, pH
[54]	FISH	Secchi
[55]	SHR	TEMP, pH, OD
[56]	FISH	TEMP, pH, OD, NTU
[57]	FISH	TEMP, pH, Secchi
[58]	FISH	OD
[59]	FISH	OD
[60]	SHR	NTU
[61]	SHR	TEMP, SAL, pH, Secchi
[62]	BIV	OD, NTU
[63]	FISH	pH, OD, Secchi
[64]	SHR	TEMP, SAL, pH, OD
[65]	SHR	SAL, pH, NTU
[66]	SHR	SAL, pH, OD, Secchi
[67]	SHR	SAL, Secchi
[68]	FISH/BIV	TEMP, OD
[69]	FISH	OD, Secchi
[70]	FISH	OD
[71]	SHR	SAL, OD
[72]	SHR	SAL, pH, OD
[73]	POLY	OD
[74]	FISH	pH, OD, Secchi
[75]	FISH	Secchi
[76]	FISH	SAL, pH, OD
[77]	SHR	TEMP, SAL, pH, OD
[78]	FISH	pH, OD
[79]	FISH	pH, OD, Secchi
[43]	FISH	OD, Secchi
[80]	FISH	OD

Note: TEMP = water temperature (°C); SAL = salinity; OD = dissolved oxygen ($mg\,l^{-1}$); Secchi = transparency by means of the Secchi disk depth (m); NTU = water turbidity by multiprobe measuring nephelometric turbidity units, unit.

considered to be 'large' for values >0.8, which means that the impact group mean is eight-tenths of a standard deviation greater than that of the control group, 'medium' for values between 0.5 and 0.8, and 'small' when *d* is between 0.2 and 0.5 [21]. The usual method is to provide 95% confidence intervals (CI) for *d* as well, and when the CI overlaps zero, there is no significant difference between controls and impacts. Another fundamental step of meta-analysis is to calculate the cumulative effect size representing the overall magnitude of the effect in all investigation. When the calculated CI of the cumulative effect size does not bracket zero, it is considered to be significantly different from zero [21]. In addition, to calculate the degree of heterogeneity among study cases and to estimate whether the effect size *d* was homogenous among studies, *Q* statistics was used [17].

The meta-analysis approach used here was similar to that reported in Sarà (2007) [1] according to Gurevitch *et al.* [15] and Hedges and Olkin [17]. First, tests were carried out to determine whether all studies shared a common effect size. From this step, one can establish that the hypothesis of equality among effect sizes is rejected for highly heterogeneous studies not differing for the sampling errors. Next, the data were analysed in groups to estimate the singular effect of aquaculture on each variable and the effect of the different cultivated organism.

Means and sample size data were taken from publication tables and figures. Data from figure formats were captured from plots using TechDig (rel. 2.0d), for which the error margin was estimated at around 0.2−0.5%.

Once all the data had been obtained and entered into an MS Excel spreadsheet, the entire data set was standardized both for the type of deviation (standard deviation or standard error) and for the measurement units. In the present meta-analysis, all deviations were transformed to standard deviations using the calculator included in the MetaWin 2.0 software [19]. Since one of the major concerns of a meta-analyst is the publication bias (i.e. the selective publication of articles showing certain types of results in preference to those showing other types of results, substantially increasing the risk of distortion of the true effect) the *d* normal quantiles were plotted vs. the standardized mean effect [19]. The normal quantile plot also allowed for the study of the possible deviations of the studied cases. Furthermore, the Rosenthal index enabled the estimation of the fail-safe number, i.e. the number of non-significant, unpublished, inaccessible or missing studies that would need to be added to a meta-analytic dataset in order to change the results of the meta-analysis from significant to non-significant [16, 19]. All calculations were carried out using MS Excel and MetaWin 2.0 [19].

3. Results and discussion

There are very few papers describing the effects of cultivation of marine organisms on physico-chemical variables of the water column (about 32 for a total of 343 study cases; table 1). There are relatively few useful data extrapolated for the meta-analysis, since many of those encountered in the literature did not reported consistent means, standard deviations, and sample sizes. The final compiled data set was highly reliable.

The present investigation is the implementation of a previous study based on the meta-analytical approach and aimed at assessing the impacts of aquaculture on the water column [1]. Most of the previous attempts aimed at this topic, though based on a much larger number of data from the literature, typically used a qualitative approach, so that the information extrapolated from those studies was generally unreliable and based on correlative inferences [14, 22]. On the other hand, this study allowed us to obtain a more reliable picture of the effects of aquaculture on physical and chemical features of the water column with a smaller but more coherent number of cases.

Table 2. Effects of the organisms' type on temperature across the literature.

Organism	df	d_+	95% CI	P	Qw	P
SHR	23	0.12	−0.79/0.31	>0.05	120.02	<0.05
FISH	21	−0.01	−0.01/0.08	>0.05	5.71	>0.05
BIV	3	0.08	−0.95/0.97	>0.05	0.01	>0.05
ALL	49	0.01	−0.07/0.09	>0.05	127.25	<0.05
Rosenthal					0.0	

Note: SHR = shrimps; FISH = fish; BIV = bivalves; ALL = all organisms together; df = degrees of freedom; d_+ = mean size effect; 95% CI = 95% confidence interval; P = probability level; Qw = estimate of heterogeneity among studies; Rosenthal=estimation of the fail-safe number; note that the size effects for each organism have been calculated separately from each other, but included in the same table for a better description of phenomena.

Overall, the picture derived from this meta-analysis showed that physical variables of the water column were not affected by aquaculture. Temperature and salinity did not show any effect across the current literature (Tables 2–3). This result indicates that large crowds of cultivated organisms and their related biological activities would have irrelevant effects on the thermohaline conditions of the water column, which instead will depend more upon macro-regional factors such as climate, hydrodynamics, coastal morphology, and proximity to other bodies of water such as rivers, lagoons, or the open sea.

On the contrary, temperature and salinity can have significant effects on the metabolism, inducing fluctuations of the excretions and feeding ratios of cultivated organisms. The most important effect of temperature on marine organisms is the excretion of nitrogen: the higher the temperature, the higher the nitrogen excretion and the feeding ratios. This has been observed and tested particularly in fish [23]; for example, it is valid in *Cyprinus carpio* [24, 25], *Lepomis macrochirus* [26], *Dicentrarchus labrax* [27], *Pleuronectes platessa* [28], *Onchorynchus mykiss* [29], and *Abramis brama* [30]. On the other hand, increasing salinity, inducing changes in the osmotic pressure [32], determines a decrease in nitrogen-excretion ratios [31]. Such an effect can be observed in transitional waters such as estuaries, where the continuous mixing of fresh and sea waters can determine wide fluctuations of N excretions by cultivated organisms.

Finally, the indirect effects of temperature and salinity on the metabolism of reared organisms can result, through a cascade including altered N production, in relevant changes of important ecological rates like prokaryote and primary production, which are dependent on temperature and nutrient availability.

Many investigations devoted to the assessment of the impacts of aquaculture on the surrounding ecosystems used physical variables merely as descriptors of the water-body environmental features. The mere use of temperature and salinity as supporting variables comes to light from the large amount of investigations describing the cultivation effects on biological rates comparing farms located at different latitudes and in different local conditions. In such cases, when biological differences such as bacterial activities were detected among farms, only a

Table 3. Effect of shrimps on salinity across the literature.

Organism	df	d_+	95% CI	P	Qw	P
SHR	32	0.09	−0.04/0.22	>0.05	487.27	<0.05
Rosenthal					119.90	

Note: df = degrees of freedom; d_+ = mean size effect; 95% CI = 95% confidence interval; P = probability level; Qw = estimate of heterogeneity among studies; Rosenthal = estimation of the fail-safe number; note that the size effects for each organism have been calculated separately from each other, but included in the same table for a better description of phenomena.

few papers attempted to separate the portion of variance due to the effects of temperature and salinity differences in the different water bodies from that due to cultivation activities and the amount of cultivated biomass. In other words, these attempts can be invalidated by the fact that the results of these studies are typically site-dependent and thus useless for their generalization.

Fluctuations of dissolved oxygen (DO) concentrations and the possible oxygen depletion of aquafarm waters, observed in certain cases, are clearly dependent on the size and intensity of the aquaculture operation (i.e. the oxygen demand of both the cultured stock and the waste released) and on the topography–hydrography of the water body. Indeed, in many proposed EIA guidelines or protocols [e.g. 10], DO is always listed among the most important variables to be mandatorily measured. This relies on two basic principles: (1) a higher total weight of fish per unit volume of water can lead to increased activity and thus increased respiration as a result of overcrowding [33]; and (2) oxygen depletion implies alterations in the ecosystem structure such as during dystrophic crises in stagnant shallow conditions like shrimp ponds [14, 22]. Many previous reviews reported that DO concentration falls far below saturation in natural water bodies in the case of excessive phytoplankton growth. A decrease in DO in the water column around fish cages has been documented on several occasions [34–43]. Although the dataset suffers from high levels of heterogeneity (except for bivalves; table 4), the present meta-analysis shows that DO seems overall to be unaffected by aquaculture practices (table 3). The DO concentration ranges fell well within the limits given in the literature ($\sim 6.2 \pm 2.3$ mg l^{-1}; min 0.0 mg l^{-1} and max $\sim$13 mg l^{-1}) [e.g. 14], with negligible differences between controls and impacts in polyculture cases ($d_+ = -1.80$; $P > 0.05$), and the largest, though not significant, differences were observed for fish culture ($d_+ = 0.02$; $P > 0.05$). However, all types of cultivated organisms including fish did not have significant size effects, and the dataset appeared to be sufficient for describing the phenomenon (table 4). This is quite surprising because the DO has always been used as an immediate descriptor of aquaculture effects in both offshore and inland plants [e.g. 14], but in the analysed papers, the link with primary and bacterial productions is more wished rather than tested. One of the most important positions supported by the literature, which probably stems from mesocosm studies is that DO concentration depends on the amount of cultivated biomass: the higher the cultivated biomass, the lower the DO concentrations around farms. I attempted to test this by fitting a meta-analytical regression using the size effect and quantity of biomass extrapolated by each paper, but there was a profound lack of data across the literature in reporting biomass data. Most of the papers did not report complete and sufficient data to be extrapolated for statistically carrying out this correlation. Thus, the relationship between cultivated biomass in each situation and oxygen concentrations in the surrounding waters has likely been supposed rather than tested. Dissolved oxygen thereby appears to be commonly used as a mere local

Table 4. Effect of organism type on dissolved oxygen across the literature.

Organism	df	d_+	95% CI	P	Qw	P
SHR	24	−0.44	−0.62/−0.26	>0.05	228.84	<0.05
FISH	95	0.02	−0.04/0.07	>0.05	1602.82	<0.05
BIV	10	−0.06	−0.39/0.27	>0.05	4.42	>0.05
POLY	5	–1.80	–2.92/−0.69	>0.05	250.52	<0.05
ALL	133	−0.03	−0.08/0.02	>0.05	2131.28	<0.05
Rosenthal					2273.20	

Note: SHR = shrimps; FISH = fish; BIV = bivalves; ALL = all organisms together; df = degree of freedom; d_+ = mean size effect; 95% CI = 95% confidence interval; P = probability level; Qw = an estimate of heterogeneity among studies; Rosenthal = estimation of the fail-safe number; note that the size effects for each organism have been calculated separately from each other, but included in the same table for a better description of phenomena.

descriptor of the quality of aquaculture water masses and not as a functional descriptor of water-column dynamics or as a response variable cross-correlated to others. Consequently, even though it is possible to generally observe that DO concentrations might be affected by aquaculture [2, 44], the current literature is insufficient to address properly the relationship between aquaculture effects and DO depletion in the surroundings as a paradigm of aquaculture ecology. Thus, across the current literature, the tendency to see DO concentration differences among controls and impacts does not necessarily imply that DO is (1) a reliable and efficient water-column descriptor of aquaculture effects or (2) a possible descriptor of effects deriving from aquafarm facilities. Consequently, much more research is needed to clarify this point.

Water pH is an important descriptor of the water-column dynamics because pH has a significant influence on the action of the toxic activity of a number of dissolved substances, which affect aquatic organisms such as ammonia, hydrogen sulfide, and heavy metals. Nevertheless, little attention has been paid to pH across the current literature (only 19 meta-analysable studies, for a total of 70 cases). The only usable cases for this meta-analysis were derived from fish and shrimp studies, as no useful bivalves or polyculture cases were found (table 5).

Across this dataset, pH values were 7.2 ± 0.5 and 7.0 ± 0.4, respectively, for controls and impacts in fish studies, and 7.8 ± 0.8 and 7.6 ± 0.7, respectively, for controls and impacts in shrimp studies. Theory would suggest a decrease in pH values corresponding to excessive respiration of organisms, and an increase due to photosynthesis [45]. Thus, the crowding and related excretion rates should determine pH variations as an indirect effect deriving from enhancement of primary production rates. Furthermore, the influence of sediments on the water column in shallow environments through resuspension of sedimentary reduced compounds should play an important role in changing the pH of the water column.

Across the analysed dataset, these dynamics appear not to be evident, although a certain effect could be perceived. On average, a slight tendency to acidification of impacted waters due to biological activity was detected, and was more accentuated in shrimp ($d_+ = 0.66$; $P < 0.05$; table 5) than in fish farming plants ($d_+ = -0.15$; $P > 0.05$; table 5). Thus, due to the shallowness of shrimp ponds (depth $\sim$1 m), chemical compounds derived from anaerobic processes of organic-matter reduction can enter the water column and induce a deviation of its chemical quality causing significant differences between controls and impacts [1]. In contrast, when the sediments and overlying waters were physically uncoupled due to the higher depths of water columns [3] like those used to cultivate fish, there was a lower contribution of reduced compounds to the water column, resulting in negligible differences among controls and impacts and a negligible size effect (table 5). In addition, if fluctuations of pH in the water column directly depend on cultivated biomass, a significant relationship between size effects and biomass should be detected. Similarly to the DO dataset, this hypothesis was not testable and consequently not valid from the point of view of the present review, because of the major lack of useful quantitative data on cultivated biomass reported in the relevant literature. This

Table 5. Effect of organisms' type on pH across the literature.

Organism	df	d_+	95% CI	P	Qw	P
SHR	35	0.66	0.53/0.80	<0.05	802.50	<0.05
FISH	33	−0.15	−0.23/−0.06	>0.05	205.04	<0.05
ALL	68	0.08	0.01/0.15	<0.05	1113.15	<0.05
Rosenthal					0.00	

Note: SHR = shrimps; FISH = fish; ALL = all organisms together; df = degrees of freedom; d_+ = mean size effect; 95% CI = 95% confidence interval; P = probability level; Qw = an estimate of heterogeneity among studies; Rosenthal = estimation of the fail-safe number; note that the size effects for each organism have been calculated separately from each other, but included in the same table for a better description of phenomena.

Table 6. Effect of organism types on transparency (Secchi) across the literature.

Organism	df	d_+	95% CI	P	Qw	P
SHR	6	0.82	0.33/1.31	<0.05	46.27	<0.05
FISH	31	−0.22	−0.30/−0.15	>0.05	168.95	<0.05
ALL	37	−0.19	−0.26/−0.12	>0.05	241.19	<0.05
Rosenthal					52.7	

Note: SHR = shrimps; FISH = fish; ALL = all organisms together; df = degrees of freedom; d_+ = mean size effect; 95% CI = 95% confidence interval; P = probability level; Qw = an estimate of heterogeneity among studies; Rosenthal = estimation of the fail-safe number; note that the size effects for each organism have been calculated separately from each other, but included in the same table for a better description of phenomena.

position contradicts the common opinion reported in the current qualitative reviews [e.g. 14], which assert the relationship between the amount of cultivated biomass and water-column descriptors like pH.

In conclusion, from the analysed literature, pH differences among controls and impacts, when they could be significantly detected, depend on intrinsic morphological and hydrodynamic features of the water bodies (depth, water movements, etc.) receiving farming wastes rather than on the biological effects exerted by the cultivated biomass.

Another possible effect due to coastal aquaculture could be a reduced light availability in the surrounding waters. The effect on the water transparency results directly from an increase in suspended particles and is also an indirect result of nutrient enrichment of the water column [46]. Wallin and Hakanson [47] have proposed the Secchi disk depth as a key response variable for measuring the effect of discharge from facilities (but in GESAMP reports is still judged as 'non-specific indicator of questionable value in many locations'), while the Nephelometric Turbidity Unit (NTU) method has only been recently included in monitoring protocols. The positive relationship between the discharge of particulate material from facilities and the turbidity of surrounding waters appears to be well defined. Thus, any resulting enhancement of phytoplankton growth and detrital accumulation in the water column could be detected as a decreased Secchi disk depth or as increased NTU values. The meta-analysis results are in accordance with this assumption, as both the Secchi disk depth (table 6) and the NTU values (table 7) showed overall that transparency–turbidity features were significantly affected by aquaculture. Although the useful dataset from a meta-analytical point of view was relatively limited (a maximum of 37 study cases were obtained from fish study cases using the Secchi disk depth as an eater transparency descriptor), it was sufficiently robust in describing the phenomenon (tables 6–7). The Secchi disk depth and NTU methods are significantly affected by the cultivation of both shrimps ($d_+ = 0.82$; $P < 0.05$ and $d_+ = 1.87$; $P < 0.05$, respectively; tables 6 and 7), and fishes, with the NTU method able to detect a larger effect ($d_+ = 2.23$;

Table 7. Effects of organism type on turbidity (NTU) across the literature.

Organism	df	d_+	95% CI	P	Qw	P
SHR	8	1.87	1.63/2.10	<0.05	37.44	<0.05
FISH	2	2.23	0.45/4.00	<0.05	11.73	<0.05
BIV	5	0.25	−0.18/0.67	>0.05	0.40	>0.05
ALL	15	1.45	1.27/1.63	<0.05	123.32	<0.05
Rosenthal					1693.80	

Note: SHR = shrimps; FISH = fish; ALL = all organisms together; df = degree of freedom; d_+ = mean size effect; 95% CI = 95% confidence interval; P = probability level; Qw = an estimate of heterogeneity among studies; Rosenthal = estimation of the fail-safe number; note that the size effects for each organism have been calculated separately from each other, but included in the same table for a better description of phenomena.

$P < 0.05$; table 7) than the Secchi disk depth method ($d_+ = -0.22$; $P > 0.05$; table 7). In the case of bivalve farming, NTU appeared to be unaffected ($d_+ = 0.25$; $P > 0.05$; table 6), although the data set was very limited.

In the case of shallow ponds, it would be very interesting to separate the two different effects of turbidity due to biological activities of organisms from wind-induced resuspension due to the shallowness of the ponds. In no paper did the authors allude to the potential effect of wind-induced sediment resuspension, and if an enhancement in turbidity is observed, it is argued to be an effect due only to biological activities by cultivated organisms. These results, being somehow contradictory, produce a general trend of effects, but the relationships between water column variables and the extent of facilities still remain largely unknown.

4. Conclusions

The combination of the results of past reviews and books with those derived from this meta-analysis shows a certain consistency of the effects of aquaculture on the physical–chemical properties of the water column across the current literature: the higher the extent of aquaculture facilities, the higher the effects on the surrounding water column. Nevertheless, this quantitative analysis pointed out that this general tendency of worldwide aquaculture is not proven definitely. Many funds from local-to-international institutions are provided all around the world to investigate the environmental effects of aquaculture, but perhaps much more efficient and focused research is needed to clarify the relationships among the extent of operations, local hydrodynamics, and the relevant effects on the surroundings. The consequences of possible effects of aquaculture on the water column in terms of possible hypernutrification are complex, and to date, these relationships remain poorly understood. Although there are a large number of warnings on correct application of environmental protocols (see http://www.fao.org), ecological variables chosen in most of the available studies are often used as descriptors of local conditions rather than as response variables of ecological processes. Changes of temperature and salinity due to local conditions, hydrodynamics, coastal features, etc. possibly produce changes in organism N excretion and feeding ratios. These can induce changes in nutrient profile in the surrounding water columns determining changes in primary and bacterial production rates, thus potentially creating conditions for a deviation from natural common patterns of DO, pH, and turbidity values. In most of the papers related to the relationship between aquaculture and the changes in the water-column characteristics, physical–chemical descriptors of the water column conditions appeared to be used per se rather than in an ecological context. The lack of such an approach leads to a partially limited vision of the actual patterns operating in nature, and can only show the direction or trends of natural phenomena. This is more accentuated when we investigate highly dynamic environments such as the water column. The results of the present meta-analysis provide new insights into the actual extent of the aquaculture effects on the environment and provide a new route for future studies, which should therefore be based on the following principles:

(1) Strong experimental approaches must be adopted which warrant the possibility of a generalization of phenomena unlinking them from local situations [48, 49].
(2) Experimental designs should be employed to obtain data meeting the common statistical assumptions, as most papers violate almost all of them (normality, variance homogeneity, independence, and randomness).
(3) Data should be obtained from variables showing significant effects under different conditions to gain a better assessment of the actual impacts.

(4) An ecosystemic approach must be adopted, starting from the study of each variable as a small part of the whole, but trying to link each variable consistently to the dynamics of the others.
(5) The presentation in peer-reviewed papers of operational data (biomass, species, hydrodynamics, general wind conditions, fetches) should be homogenized to facilitate comparisons among different situations.

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