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Evaluating the potential of aquaculture in the Hoa Binh reservoir with carrying capacity and water quality indices

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Abstract:

Not only does the Hoa Binh reservoir play essential roles in water storage for electricity generation and flood regulation, but also it has great potential to aid aquaculture production. Presently, aquaculture production sits at around 9,200 tons/year; however, a recent MARD circular (#16 in 2015) estimated that maximum production would approach 10,000 tons/year in the productive photic zone. This paper supports increased capacity towards a sustainable commodity production model by optimizing production levels and farming practices. To reach this goal, it is necessary to determine water quality parameters using the Relative Water Quality Index (ReWQI) and carrying capacity (CC) analysis. Data was obtained from 30 sites at upstream, midstream, and downstream sections of the reservoir during the 2019 dry and wet seasons. The results from the ReWQI reflected good water quality potential (rated between 92-100) for aquaculture. The total nitrogen (TN) and total phosphorus (TP) levels of 10,794.9 kg/day and 1,965.4 kg/day, respectively, indicate high biological productivity resulting in strong fish growth potential. CC analysis and overall water quality reflect the potential for sustainable and increased productivity to 22,730.4 tons/year, which is an increase in production of over 13,200 tons/year compared to the current period. To reach a higher yield of 40 kg/year/m^3 within each cage (5,040 kg/cage/year), the corresponding increase in number needs to be 4,510 cages based on a common cage size of 126 m^3 (6x6x3.5 m). In order to reach these future production goals, this work concludes that the local government should begin spatial planning decisions based on appropriate cage allocation and distribution with respect for regular monitoring of water quality and nutrient load capacity of the environment to reach sustainable aquaculture development.

Keywords: **aquaculture, carrying capacity, Hoa Binh reservoir, water quality index.**

Classification number: **5.1**

Introduction

Aquaculture in the Hoa Binh reservoir plays important roles in the nourishment and poverty alleviation of its local people. Hydropower development in the reservoir has created substantial revenue for Hoa Binh province and lent support to other economic sectors such as tourism and fish transportation, all of which have a positive impact on local fishers. In 2019, the Hoa Binh reservoir had 4,670 fish cages that reached an output of approximately 9,200 tons [1]. According to the province's socio-economic development plan, aquaculture output of the reservoir is expected to increase to over 10,000 tons [2]. Aquaculture in the Hoa Binh reservoir is expected to develop towards efficient commodity production along sustainable goals [3]. However, in recent years, aquaculture has been threatened by the deterioration of reservoir water quality due to waste produced by activities such as tourism, water transport, aquaculture itself, as well as from unregulated waste and human activity from upstream sources. This waste has contributed to worsening water quality in the reservoir and consequently affects aquaculture [4]. Given this situation, farm managers should ask themselves two questions: 1) is the water quality suitable for aquaculture and 2) what are the maximum and sustainable aquaculture potentials of the reservoir? To answer these questions, it is necessary to evaluate the required suitability of water quality for aquaculture, determine the CC of the aquatic environment, and determine the maximum output that

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*Corresponding author: Email: diepphan2014@yahoo.co.uk could be produced in the basin. Water quality for aquaculture is assessed using the ReWQI [5, 6] while CC is calculated using an FAO tool in combination with the Legovic model [7]. ReWQI is selected to assess the quality of water in the Hoa Binh reservoir because it summarizes the results of water quality parameters and dispenses identifiable results (such as Poor, Moderate, and Good) for water quality [8-10]. The ReWQI also takes into account the different qualities of water sampled from different parts of the reservoir, as well as a number of water quality parameters chosen for that site.

In aquaculture, CC is understood as the ability of the aquatic environment to sustainably support the biological load caused by aquaculture operations [11]. Environmental carrying capacity (ECC) modelling incorporates the ReWQI and CC results to better understand the impact of human generated activities on the sustainability of the reservoir. The ECC is used because it determines nutrient and pollution impacts along with input thresholds that the reservoir can withstand [12]. Aquaculture carrying capacity (ACC) is the main metric that determines the productivity level of farming within the threshold as set by the ECC. This value should not exceed the tolerance of the ECC in that area (based on the permissible limits of environmental quality standards). This analysis also includes two important indicators: TN and TP. These are essential components of aquaculture feed as well as indicators of natural organic matter in the reservoir. Together, these elements contribute to algal growth and primary production capacity of a water body [13, 14].

This study contributes to the project titled "Research solutions to develop aquaculture in large reservoirs towards efficient and sustainable commodity production" developed by MARD. The result of this study will lead to follow-up studies on detailed spatial planning for aquaculture, re-arrangement of cages, and identification of suitable locations for aquaculture.

Materials and methods

Study area

The Hoa Binh hydropower reservoir (Fig. 1) was built between 1979-1984 with a basin area of 53,600 km² and volume of 9.45 billion m^3 based on an average water level of 117 m. The reservoir has a multi-purpose design: it serves as a power generator that supplies electricity to the countryside, as well as a flood controller, natural disaster reducer, and a water supply for downstream areas [15]. The length of the reservoir is approximately 230 km and starts from the hydroelectric dam to the upper region of the Da river. Its location is 20°48'30.06" N; 105°19'23.53" E to 20°48'27.32" N; 105°5'42.22" E. Its rich aquatic diversity is attributed to the surrounding high mountains and thousands of hectares of vegetation and forests with high canopy coverage [16]. The main aquaculture species are *Bagarius bagarius*, *Mausoleum, yellow mausoleum, American catfish, red carp, black carp, and sturgeon* [16, 17].

Materials

In this study, eight water quality parameters (pH, temperature, DO, $N\text{-}NH_4^+$, $N\text{-}NO_2^-$, $N\text{-}NO_3^-$, TN, and TP) were sampled and analysed in June (dry season) and October (wet season) in 2019. Samples were taken at 2 depths (0.5 and 6 m) at 30 sites in across the upstream, midstream, and downstream areas of the reservoir (Fig. 1). Over the two seasons, 120 samples were collected and stored based on the Guidance of the National standards TCVN 6663-6:2008 [18], TCVN 5994:1995 [19], and TCVN 6663-3:2016 [20]. They were analysed based on the guide of APHA (2017) [21]. All collected samples were analysed at the Centre for Environment and Disease Monitoring in Aquaculture, Research Institute for Aquaculture No. 1 (RIA 1).

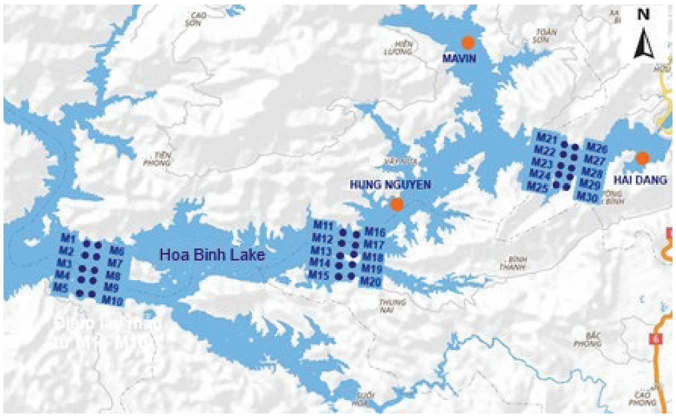

Fig. 1. A map of the Hoa Binh hydropower reservoir displaying the 30 monitoring sites (blue dots).

The ReWQI method

In this study, the ReWQI method is selected for analysis [5, 6]. The advantages of the ReQWI include the following: 1) the monitoring parameters do not coincide with the parameters defined in the issued guidelines of Vietnam WQI as well as other methods, which are difficult to apply; 2) the hierarchical scale depends on the survey parameter (n≥2), which is not self-regulating and therefore has no ambiguity; and 3) the weight is calculated according to the environmental standards of each unique parameter so it is not subjective and does not suffer from the virtual effect [5, 6].

The water quality parameters consist of pH, temperature, DO, $N\text{-}NH_4^+$, $N\text{-}NO_2^-$, $N\text{-}NO_3^-$, TN, and TP. In addition, Grade A1 surface water from the National Technical Regulations on Surface Water Quality (QCVN 08-MT:2015/BTNMT) and National Technical Regulations on Freshwater Fish Cage Culture - Conditions for Food Safety and Environmental Protection (QCVN 02-22:2015/BNNPTNT) are chosen for this evaluation. To analyse water quality parameters, the ReWQI equation is applied:

$$ReWQI = 100 * (1 - \frac{P_k}{P_n})$$

where $P_k = \sum_1^k W_i(q_i - 1)$; k is the number of parameters that do not fulfil the environmental standards ($qi>1$); $P_n = P_k + P_m$; n is the total number of observation parameters; $P_m = \sum_{i=1}^{m_1} W_i q_i + \sum_{i=1}^{m_2} W_i(1 - q_i)$; m_1 is the number of parameters with $q_i=1$; and m_2 is the number of parameters with $q_i<1$.

According to H.N. Pham (2020) [6], ReWQI is calculated using 5 steps given below:

Step 1. Calculate the individual indices or sub-indices, q_i, with the 6 water quality parameters pH, temperature, DO, $N\text{-}NH_4^+$, $N\text{-}NO_2^-$, and $N\text{-}NO_3^-$. These parameters are divided into 3 main groups:

Group 1: lower environmental standard: $N\text{-}NH_4^+$, $N\text{-}NO_2^-$, $N\text{-}NO_3^-$.

Group 2: upper environmental standard: DO.

Group 3: permitted standard in the fragment [a, b]: pH and temperature.

Step 2: Calculate the temporary weight $W_i^{'}$.

Step 3: Calculate the final weight W_i of each parameter i.

Step 4: Calculate the ReWQI.

Step 5: Apply the hierarchical rating scale (Table 1) for assessing water quality.

The water quality assessment hierarchy (5 levels) depends on *n* of the ReWQI. The calculation results of the rating scale of ReWQI (with n=6) are shown in Table 1.

Table 1. Hierarchical rating scale for assessing water quality with n=6.

ReWQI	Water quality	Colour	
92<ReWQI≤100	Good	Green	🟩
83≤ReWQI≤92	Moderate	Yellow	🟨
50<ReWQI≤83	Fair	Orange	🟧
17<ReWQI≤50	Poor	Red	🟥
0≤ReWQI≤17	Very poor	Brown	🟫

The ReWQI value of each monitoring site is compared with the classification in Table 1 to infer the water quality for that monitoring site.

In this study, the assessment of ReWQI gives an overall picture of the water quality at the surface and middle stratum of the fish cage culture area in Hoa Binh reservoir and serves as an indicator of pollution in cage culture areas and further zones for water quality. Consequently, the assessment guides managers to develop workable solutions to reduce pollution and plan for appropriate aquaculture development in Hoa Binh reservoir.

Calculating carrying capacity

In this study, carrying capacity is calculated by combining the FAO carrying capacity tool, the Legović, et al. (2008) method [7], and the method devised by Tran, et al. (2012) [14]. Considering that most of the lake is viable for aquaculture, this tool can be used efficiently and quickly to test multiple new sites for cage farming suitability. This tool helps build a relationship between the human, terrestrial, and aquatic farming pressures on the reservoir and makes an effort to strike a balance in a sustainable way. A few standard parameters are entered into the equation to determine acceptable maximum levels of production that do not adversely affect the ecosystem and hydrology of the reservoir. The aquaculture carrying capacity can be defined as:

$$ACC=ECC/PL$$

in which ACC is the aquaculture carrying capacity; ECC is the environmental carrying capacity of TN or TP; and PL is the pollutant load of TN or TP. The ECC is defined as:

$$ECC=(C_{max}-C_o)x(1+R)xVx10^{-3}$$

in which C_{max} is the concentration of organic and inorganic nutrient loads in the environmental standard (mg/l); C_o is the concentration of nutrients at the time of the study (mg/l); R is the water exchange rate of the basin; and V is the average volume of the water body (m^3) [13, 14].

The total human, cattle, and poultry populations, as well as the reservoir area, were entered into a spreadsheet using the Legović, et al. (2008) model [7].

Discharge sources from livestock, human

The nutrient load from $PL_{CN/H}=NxPL_i$

in which $PL_{CN/H}$ is nutrient load from livestock, people (kg/year); N is the population number (person), total cattle and poultry; PL_i is nutrient load rate i (kg/cattle or kg/poultry per year) [22]. Nutrient discharge rate in domestic wastewater: Acceptable treatment of TN is 1.0 and TP is 0.25; primary treatment of TN is 2.0 and TP is 0.5; untreated TN is 4.0 and TP is 1.0 [23].

Discharge sources from agriculture

$$PL_{NN}=SxPL_i$$

Similarly, agriculture discharge was calculated as: PL_{NN} is the nutrient discharge load from agriculture (kg/year); S is land use (km^2); PL_i is nutrient load rate is according to different kinds of cultural land use ($kg/km^2/year$) [7, 22, 24, 25].

Results

Results of assessing the suitability of water quality for aquaculture using ReWQI

Based on data from the 30 monitored sites, water quality is more suitable at 0.5 m than 6 m in both dry and wet season.

The maximum value of ReWQI at the sites at 0.5 m was 100 in both dry and wet seasons. The ReWQI at the 6 m depth ranged from 71 to 91 in the dry season and from 70 to 91 in the wet season in 2019. The results in Fig. 2 show that, water quality at the 30 sites during dry and wet seasons are at a "Good" level for aquaculture at 0.5 m. The ReWQI at 30 sites at 6 m are categorized as "Moderate" and "Fair" for aquaculture species. Among them, 18 sites had their water quality index categorized as "Moderate", and 12 sites categorized as "Fair" in the dry season. In the wet season, 15 sites were categorized as "Moderate" and 15 sites categorized as "Fair" water quality.

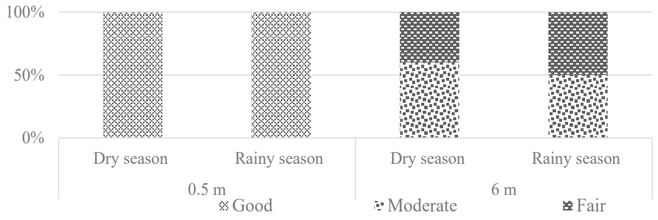

Fig. 2. Comparing water quality in 0.5 and 6 m depths.

In summary, the water quality at surface layer (0.5 m) is highly suitable for aquaculture. In the middle layer (6 m), water quality was "Moderate" to "Fair", consequently, the fish cages may require added aeration to improve the conditions.

Results of assessing the maximum aquaculture production by environmental carrying capacity assessment tool

Results of assessment of nutrient/pollutant load into Hoa Binh reservoir: anthropogenic sources accounted for 75% of the nutrient load, while the remaining 25% was from general agriculture such as rice farming and horticulture. The total nutrient loads from residential, livestock and agriculture waste are 4,647.4 kg TN/day and 1,918.0 kg TP/day respectively. In comparison, the dry season produced 1,859.0 kg TN/day and 767.2kg TP/day with the wet season producing 7,435.8 kg TN/day and 3,068.7 kg TP/day. The total pollutant load of waste from tourist activity was 1,946.4 kg TN/day and 486.6 kg TP/day during dry and wet seasons. The total pollutant load from discharge to the reservoir 566.1 kg TN/day and 440.3 kg TP/day in dry season; and 2,012.9 kg TN/day and 1,258.1 kg TP/day in the wet season. The total pollutant load of waste from aquaculture for TN was 6,423.5 kg/day and TP 271.3 kg/day. Emission factors for 1 ton of fish over one-year culture period was 0.857 kg/day/ton for TN and 0.036 kg/day/ ton for TP. Cage fish farming takes place directly on the reservoir surface all year-round, so the amount of waste from aquaculture was divided equally for the dry and wet seasons: TN was 6,423.5 kg/day and TP was 271.3 kg/day.

Results of ECC in Hoa Binh reservoir: the water exchange rate (R) was 2.359 in dry season and 8.089 in wet season and TN and TP in the reservoir were at oligotrophic levels (in the dry season, TN was 0.018 mg/l and TP was 0.015 mg/l; during the wet season TN was 0.012 mg/l and TP was 0.010 mg/l) [26, 27]). ECC calculations show that, in the dry season, TN was 34,214.6 kg/day and TP was 4,030.5 kg/day. In the wet season, TN was 109,696.6 kg/day and TP was 14,136.2 kg/day.

Results of ACC: based on a safety factor range from 0.3 to 0.7 in accordance with Circular 76/2017/TT-BTNMT [28], we chose a safety factor of 0.6 (60%). From results in Table 2, the Load ratio relative to ECC in the dry season was 31.6 and 9.8% in the wet season, which is within the 60% safety factor. Therefore, the amount of acceptable waste allowed to enter the reservoir in the dry season is 9,733.9 kg/day; while in the rainy season, the amount of waste permitted into the reservoir is 47,999.4 kg/day. With a Nutrient load rate of TN at 0.856 kg/day/ton fish, the ACC in dry season is 11,365.2 tons/season (productivity 2.8 tons/year) and the rainy season is 56,043.8 tons/season (productivity 13.82 tons/year).

Table 2. ECC aquaculture based on total nitrogen values.

Indicator	Unit	Dry season	Wet season
ECC	kg/day	34,214.6	109,696.6
ECC at 60% (ECC_{60})	kg/day	20,528.8	65,818.0
Total pollutant load ($\sum Q$)	kg/day	10,794.9	17,818.6
Load ratio relative to ECC	%	31.6	9.8
The amount of waste allowed into the reservoir: $ECC_{aquaculture}=ECC_{60}-\sum Q$	kg/day	9,733.9	47,999.4
Nutrient load rate from aquaculture (PL)	kg/day/ton fish	0.856	
$ACC=ECC_{aquaculture}/PL$	ton/season	11,365.2	56,043.8
	ton/year	22,730.4	112,087.5
Productivity (area 8,110 ha)	ton/ha/year	2.80	13.82

In this study, the TN/TP ratio in the dry and wet seasons is 1.2, which is less than 10, indicating that TN is the limiting factor of the reservoir and a major factor affecting the growth of algae in the reservoir [27]. ACC in the dry season is 22,730.4 and 112,087.5 tons/year in the wet season. Consequently, the output of 22,730.4 tons/year in the dry season is determined as the ACC for aquaculture production in Hoa Binh reservoir.

According to Vietnam Standards (QCVN 02-22:2015/MARD), the density of cages in the flowing water area can occupy a maximum of 0.2% of the water surface area, equating to 162,200 m^2. The size of a common cage with dimensions of 6x6x3.5 m has a volume of 126 m^3. From Table 3, we can calculate the fish capacity for each cage at between 35-40 kg/year/m^3. This yield was consistent with the survey carried out by Phan, et al. in 2018 [29] as well as the Research Institute for Aquaculture No.2 in 2019 [30] and Dieu (2020) [31]. We can also calculate the number of cages required for the lake, as described in Table 3.

Table 3. Number of cages allowed to be installed in Hoa Binh reservoir.

Cage surface area	Cage volume	Weight of fish per m^3	Fish weight per cage per year	Production threshold of fish in kg per year	Number of cages in reservoir	Surface area of cages in reservoir
m^2	m^3	kg/m^3	kg/cage/year	Ton/year	cages	m^2
(a)	(b)	(c)	(d=bxc)	(e)	(f=e/d)	(g=fxa)
36	126	20	2,520	22,730.4	9,020	324,720.0
		25	3,150		7,216	259,776.0
		30	3,780		6,013	216,468.0
		35	4,410		5,154	185,554.3
		40	5,040		4,510	162,360.0
36	126	50	6,300	22,730.4	3,608	129,888.0

Based on the surface area capacity of the lake, it can be seen that the maximum number of cages is 4,510 cages (volume of 126 m^3/cage) with a suitable water surface area of 162,360.0 m^2. The productivity of cages can vary depending on the cultured species and the production capacity of the farm, but the maximum is 40 kg/m^3.

Discussion

The results of the 2019 assessment of surface water quality at 30 monitoring points in Hoa Binh reservoir show that surface (0.5 m) water quality was categorized as "Good" for aquaculture while the middle layer (6 m) was deemed "Moderate" or "Fair" for aquaculture. The significance of the ReWQI as a practical tool is its combination of multiple water parameters such as pH, temperature, DO, $N\text{-}NH_4^+$, $N\text{-}NO_2^-$, and $N\text{-}NO_3^-$ into one metric. Meanwhile, the ECC index is measured against multiple pollution factors and their thresholds. By combining these indicators, this study is able to more accurately determine the extent and potential for aquaculture capacity. The parameters TN and TP are limiting factors and the difference in water quality between the two water depths suggests that there are other factors that still need to be considered when analysing the benefits of this tool; these factors include, for example, population changes, point source and non-point sources of pollution, as well as unpredictably low water levels filling the dam. Combining these data would enable managers to determine the future rate of expansion and evaluate the choice of other suitable aquaculture sites based on site characteristics and proximity to human activity. Comparing studies from 1992 to 2010 and in 2018 [15], water quality in the Hoa Binh reservoir has tended to deteriorate somewhat. This makes it increasingly necessary to maintain environmental monitoring and provide recommendations when the conditions are not suitable for aquaculture.

Depending on the fish species, an annual production of 22,730.4 tons/year measured during the dry season was preferred as the target range rather than 112,087.50 tons/year during the wet season due to the fact that the annual growth cycle of fish production takes approximately twelve to fifteen months. This conservative but realistic estimate is due to the fact that cages cannot be restocked with juvenile fish during the higher water levels in the wetter months. This is also due to the fact that TN is a limiting factor affecting biological growth in the reservoir throughout most of the year. Thus, the recommended potential for annual aquaculture production was determined to be 22,730.4 tons/year. At this stage, farmers should not target the higher ACC value, however, future farming methods using different species may be able to overcome this limitation. The suggested maximum number of cages is therefore 4,510 for the reservoir with an annual production target of 5,040 kg per cage per year based on approximately 35 to 40 kg/m^3 of fish per cage at the grow out stage.

It is therefore our recommendation that farmers need to apply appropriate fish density and improve feed formulations and feed controls to avoid negatively affecting water quality in order to sustainably cultivate fish [32]. In addition, coordinated cage placement would take advantage of freshwater flows and oxygen renewal in accordance with better management practices as a means of improving ecological and economic sustainability in farming practices. Aquaculture-based nutrient load sources of TN in the reservoir are 6,423.5 kg/day during the dry season and similar during the wet season. While suitable water quality is evident in the surface trophic layer, the nature of the aquatic environment means that it is difficult to determine where or how nitrification negatively impacts production. Future research would include monitoring water quality data in order to plan ahead and detect future spikes in nutrient loads compared with the existing data.

This is the first study on carrying capacity in the Hoa Binh reservoir, and, as such, only answers the question of how many tons of aquatic products can be raised in the reservoir in accordance with the environmental load. In order to determine the area and quantity to be farmed in each specific location, it is necessary to identify the potential sites for farming along with detailed spatial planning to distribute the number of cages accordingly. This study is part of a result of a project at the ministerial level of agriculture. Thus, VIFEP/MARD can use these results for follow-up studies. Based on these results, MARD should propose regulations that allow fish to be raised to the threshold of an environmental carrying capacity instead of the regulations in the National Technical Regulation Number 02-22:2015 of MARD on "freshwater fish cage culture - conditions for food safety and environmental protection".

Conclusions

The multiple competing functions of the hydropower reservoir between farming and human activity requires careful planning based on reliable data and forecasting. Based on the two research questions stated in the introduction regarding suitable water quality and maximizing aquaculture potential, this study proves that planners and farmers can be guided to utilize aquatic resources responsibly and should be provided with data that is relevant and practical. The expansion of aquaculture should be considered against these findings and therefore determine the pace and volume of this development. Since water quality indirectly impacts farmers and their profits, these findings will help determine how intensively fish cages should be managed when considering water quality, pollutant loads, pollutant sources, and environmental carrying capacity. Regular monitoring of increases in P and N, as well as water quality indices in the designated sites along the reservoir, would dictate decision making for more productive sites for cage culture. Further eutrophication cannot be eliminated totally, therefore, monitoring is required to mitigate the negative effects of poor water quality.

COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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