Aquaculture Research

Aquaculture Research, 2017, **48**, 3433–3449 doi: 10.1111/are.13169

Carrying capacity and potential environmental impact of fish farming in the cascade reservoirs of the Paranapanema River, Brazil

Roberto Montanhini Neto, Helder Rafael Nocko & Antonio Ostrensky

Integrated Group of Aquaculture and Environmental Studies, Federal University of Paraná, Curitiba, Paraná, Brazil

Correspondence: R Montanhini Neto, Integrated Group of Aquaculture and Environmental Studies, Federal University of Paraná, Rua dos Funcionários 1540, 80035-050, Curitiba, Paraná, Brazil. E-mail: roberto.neto@ufpr.br

Abstract

The objective of this study was to simulate changes in water quality standards caused by the installation of aquaculture parks for caged fish farming in the eight large artificial reservoirs in the Paranapanema River according to the different scenarios of technical and legal limitations: (i) occupancy of 1% of the total surface of the reservoirs and (ii) occupancy according to the environmental carrying capacity. For water quality modelling, these two scenarios were simulated to determine the trophic state index (TSI) of each reservoir. Based on the total area of all reservoirs in the first scenario, the fish farm facilities would occupy 18.3 km^2 and have an annual fish production of an estimated 513 thousand MT. However, because of limitations in the carrying capacity, the annual production in the second scenario would be 98 thousand MT and the fish farm facilities would occupy 3.5 km^2. Simulating the TSI for the first scenario, approximately 75% of the total area of all reservoirs was estimated to change from oligo or mesotrophic conditions to eutrophic, supereutrophic and hypereutrophic conditions, and four reservoirs may become completely eutrophic (Canoas 2, Canoas 1, Taquaruçu and Rosana). For the second scenario, however, eutrophic areas accounted for less than 30% of the total, although the Taquaruçu and Rosana reservoirs were still at risk of total eutrophication. These results indicate as well-intentioned legislation can have unintended environmental consequences in dynamic social–ecological aquaculture systems as in the case of large reservoirs in the Paranapanema River.

Keywords: eutrophication, fish cage farming, fresh water, modelling, phosphorus

Introduction

The term ‘carrying capacity’ has been used by researchers since the end of the nineteenth century and employed by professionals from distinct sectors such as economics, biology, public sanitation, anthropology, fisheries, tourism, aquaculture, among others (Arrow, Bolin, Costanza, Dasgupta, Folke, Holling, Jansson, Levin, Mäler, Perrings & Pimentel 1995). Therefore, the meaning and interpreting carrying capacity presents variations according to these sectors. When applied to aquatic animal production, carrying capacity is usually related to environmental changes associated with production activities (Kautsky, Berg, Folke, Larsson & Troell 1997). For example, the carrying capacity of an ecosystem can be used to represent the maximum productivity; maximum tolerable organic loading capacity that can be absorbed and processed; and in the case of maximum productivity without causing significant negative impact to the environment or producing environmental changes that impact the farms during operations (Beveridge & Phillips 1993; Beveridge 1996; Pittroff & Pedersen 2001).

Another method of understanding this term is related to the maximum sustainable nutrient input that the water body can receive without exhibiting signs of eutrophication (Ganguly, Patra, Muduli, Vardhan, Abhilash, Robin & Subramanian 2015). In areas where aquaculture is practised, this concept may also be interpreted as the maximum aquatic animal biomass that can be maintained in an ecosystem to maximize production without negatively affecting its ecological and productive sustainability (Granada, Sousa, Lopes & Lemos 2015).

Within public management contexts, the performance of Brazilian aquaculture according to the capacity of ecosystems to process and assimilate any waste generated by the activity led to the regulation of water bodies intended for aquaculture in 2004 with the publication of the Interministerial Normative Instruction (INI) No. 06 (Brazil 2004). While the INI laying down additional rules for licensing areas for installation of aquaculture parks in the Union domain waters considers the need to determine the reservoir carrying capacity, it does not define exactly how it should be done. For example, the INI requires that the studies to demarcation of the areas for aquaculture parks: (i) describe the methodology used to define the environmental carrying capacity; (ii) describe methodological alternatives for setting the carrying capacity; (iii) justify the choice of the methodology in comparison with other alternatives; (iv) report the highest, average and minimum levels of reservoirs and their interrelations with the definition of carrying capacity; (v) describe the relationships and influences of other potentially polluting activities, current and potential of the water body, in determining the carrying capacity of the aquatic ecosystem; (vi) analyse the interactions of synergistic effects and cumulative impacts of aquaculture parks in the ecosystem carrying capacity located in reservoirs in the same river; (vii) describe the measures adopted for the management of the aquaculture park so it is not exceeded environmental carrying capacity. Namely, this law is absolutely not specific, enabling the carrying capacity of each reservoir can be set differently.

Certain models have been developed to predict the response of aquatic ecosystems to increased and potentially eutrophying nutrient loads from intensive aquatic animal production, and the majority of such models are empirical, based on field data and frequently subjected to calibration, testing, verification and modification (Byron & Costa-Pierce 2013). However, established models or even models considered ideal for estimating aquaculture carrying capacity are not available, which is a result of the practical difficulty in isolating the source of pollutant loads in large aquatic ecosystems (Bueno, Ostrensky, Canzi, de Matos & Roubach 2013). Nevertheless, applying robust methodologies that consider available methodologies in an integrated manner is essential for reducing environmental risks when implementing new aquaculture enterprises.

The Paranapanema River has a total length of 929 km, and it predominantly runs east–west and drains into the Paraná River, Prata basin, in south/south-eastern Brazil. Eight large hydroelectric plants are installed along the course of the Paranapanema River, and aquaculture enterprises intended for caged fish farming have been established in the artificial reservoirs, especially over the past decade, where this activity is still incipient and operates at a relatively small production scale (Felisberto & Rodrigues 2005; Nogueira & Jorcin 2006; Nogueira, Jorcin, Vianna & Britto 2006). However, within this same period, the Brazilian government began to foster programmes for developing aquaculture within Brazil's inland waters by implementing aquaculture parks. The Paranapanema River basin should now benefit from such federal programmes, which should boost fish production in these reservoirs.

This study aimed to estimate the carrying capacity of the eight large artificial reservoirs in the Paranapanema River channel for the implementation of aquaculture parks intended for caged fish farming. In addition, to estimate the effect of installing, these parks on the water quality standards in the respective reservoirs were simulated, based on different technical and legal scenarios: the limits estimated by carrying capacity modelling or respecting the Brazilian legislation respectively.

Materials and methods

Study region

The Paranapanema River is a tributary of the Paraná River (Prata basin). Located between 22° and 26° S latitude and 47° and 54° W longitude, this river runs east–west between 809 and 239 m altitude, and it forms a basin of approximately 100 800 km^2 (Jorcin & Nogueira 2008). The 930 km length of the river marks the division between south-eastern and southern Brazil (Fig. 1).

The Paranapanema River basin is divided into three regions in which eight large hydroelectric dams are located and arranged sequentially in cascade: High Paranapanema region, where the Jurumirim and Chavantes reservoirs are located;

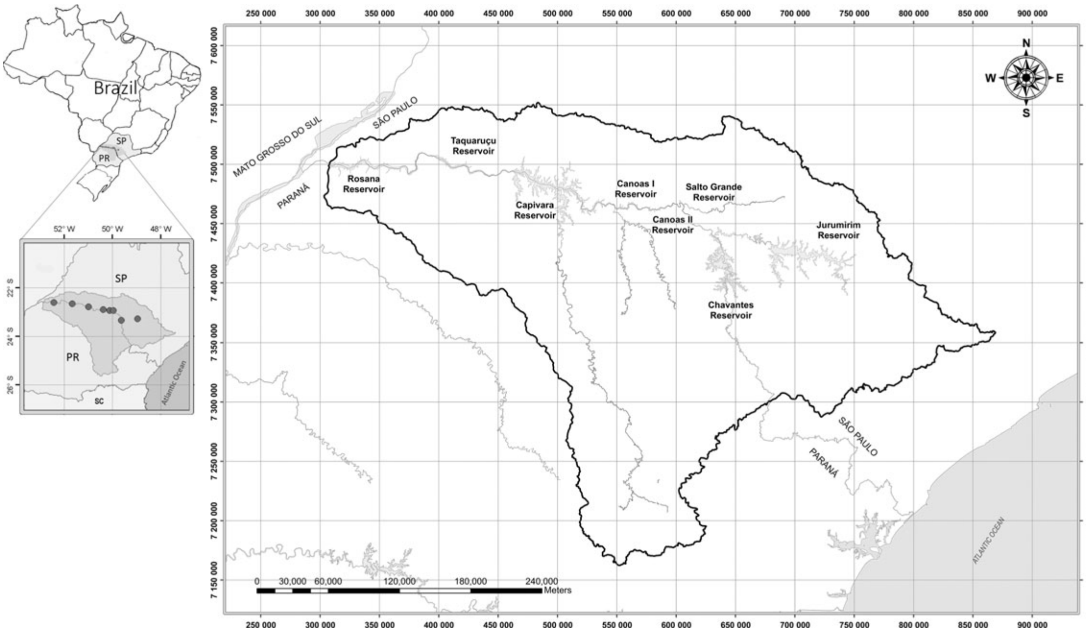

Figure 1 Geographical location of the Paranapanema River basin and arrangement of artificial reservoirs along its course.

Middle Paranapanema region, where the Salto Grande, Canoas II, Canoas I and Capivara reservoirs are located; and Low Paranapanema region, where the Taquaruçu and Rosana reservoirs are located (Felisberto & Rodrigues 2005). Three of these reservoirs (Jurumirim, Chavantes and Capivara) operate on a storage regime and have a markedly dendritic morphology, accumulating higher water volumes. The remaining reservoirs are characterized by low retention time and exhibit a more fluvial character and run-of-the-river regime (Salto Grande, Canoas II, Canoas I, Taquaruçu and Rosana; Table 1). In these reservoirs, oligomesotrophic conditions are dominant and tend towards mesotrophic conditions (Nogueira & Jorcin 2006).

Background and future scenarios

The starting point of the present study was the diagnosis of fish farms installed within the large reservoirs of the Paranapanema River according to

Table 1 Estimated maximum acceptable phosphorus load input from aquaculture enterprises in the artificial reservoirs of the Paranapanema River

Reservoir	Total surface area (ha)	Mean depth (m)	Annual water renewal rate	Phosphorus retention rate	Maximum phosphorus load (g ha^{-1} $year^{-1}$)*
Jurumirim	48 500	13	0.884	0.51	1500
Chavantes	40 000	22	0.964	0.48	2195
Salto Grande	1200	4	0.005	0.29	51 444
Canoas II	2300	9	0.014	0.30	46 961
Canoas I	3100	7	0.016	0.27	29 187
Capivara	57 600	18	0.621	0.49	2839
Taquaruçu	8000	8	0.022	0.51	37 270
Rosana	22 000	9	0.055	0.65	23 480
All	182 700	–	–	–	194 876

*According to the model proposed by Dillon and Rigler (1974) and considering a maximum total phosphorus increase of 5 mg m^{-3}, which is based on current legislation (Brazil 2013).

the results obtained by Montanhini Neto, Nocko and Ostrensky (2015). In that study, the most appropriate sites of each reservoir for installing aquaculture parks intended for caged fish production were identified, and potential aquaculture parks were geographically defined and sized based on criteria with technical, environmental and logistical favourability for the activity in the region. The water quality standards of the reservoirs were determined based on the results of this same study. These data allowed the authors to implement hydrological and hydrodynamic models that were generated and calibrated from the MOHID computational platform (Marine Environment & Technology Centre, Portugal).

In the present study, the estimated nutrient loads from potential aquaculture enterprises for installation in the proposed parks were added to these models, and possible changes in the water quality standards resulting from aquaculture activity and environmental effects of this activity under two technical scenarios were projected: (scenario 1) according to the occupancy limit of 1% of the respective surface area of each reservoir, which is based on the Interministerial Normative Instruction No. 7 of 28 April 2005 (Brazil 2005); and (scenario 2) according to the carrying capacity that was calculated using a statistical model proposed by Dillon and Rigler (1974) and based on data from the Brazilian National Water Agency (Brazil 2013). However, in this second case, because the estimated area was always higher than 1% of the reservoir surface, the legal occupancy limit was adopted (scenario 1).

Estimated carrying capacity

The environmental carrying capacity was calculated according to the data from Brazilian National Water Agency, which established that the maximum increase in total phosphorus in the aquatic environments promoted by aquaculture shall not exceed 5 mg m^{-3} (Brazil 2013).

The carrying capacity calculated using the mathematical model of Dillon and Rigler (1974) was implanted using the equations of total phosphorus mass balance under legal limit conditions according to the following equations:

$$L_{\mathrm{DR}} \leq \frac{\triangle[P] \times z \times \rho}{(1 - R)}$$

Considering that

$$R = \frac{[P]_{\mathrm{efl}}}{[P]_{\mathrm{afl}}}$$

$$z = \frac{V}{S_{m^2}}$$

$$\rho = \frac{Q}{V}$$

where

L_{DR} represents the maximum phosphorus load input from aquaculture in mg m^{-2} year^{-1};

$\triangle[P]$ represents the maximum variation accepted by Brazilian legislation for the total phosphorus concentration in mg m^{-3};

R represents the phosphorus retention rate of the reservoir (dimensionless);

z represents the mean depth of the reservoir in m;

ρ represents the annual water the annual water renewal rate of the reservoir in year^{-1};

$[P]_{\mathrm{efl}}$ represents the phosphorus concentration in the effluent of the reservoir in mg m^{-3};

$[P]_{\mathrm{afl}}$ represents the phosphorus concentration in the tributaries of the reservoir in mg m^{-3};

V represents the mean water volume of the reservoir in m^3;

S_{m^2} represents the mean surface area of the reservoir in m^2;

Q represents the annual effluent water volume of the reservoir in m^3 year^{-1}.

Based on the calculated value of the maximum phosphorus load input from aquaculture (transformed to g ha^{-1} year^{-1}), the carrying capacity of fish production in each reservoir was estimated using the following equation:

$$\mathrm{ECC} = \frac{S_{\mathrm{ha}} \times L_{\mathrm{ECC}}}{1000 \times \mathrm{CTD}_P}$$

where

ECC represents the environmental carrying capacity of cage fish production in 1000 MT year^{-1};

S_{ha} represents the mean surface area of the reservoir in ha;

L_{ECC} represents the maximum phosphorus load input from aquaculture in g ha^{-1} year^{-1};

CTD_P represents the quantity of phosphorus input to the environment from faeces originated from cage fish production in g MT^{-1};

Modelling of the carrying capacity according to future scenarios

The phosphorus load in faeces from caged fish production at 14.26 g MT^{-1} fish was used to calculate scenario 1 according to the values estimated by Montanhini Neto and Ostrensky (2013, 2015). When adopting the mean observed productivity for the cage production system within the region, the potential maximum fish production in each reservoir that meets the legal occupancy limit was estimated (scenario 2). This productivity was calculated according to cages with a 4-m^2 surface area and 6-m^3 working volume (model most commonly used in the region) and a mean production of 125 kg fish m^{-3} cycle^1 in 1.5 cycles $year^{-1}$, which produced an approximate value of 280 MT ha^{-1} $year^{-1}$ (only considering the area effectively occupied by farming structures). However, to increase the accuracy of the estimates, the data were calculated within a confidence interval range of ±15% for phosphorus loads and farming production.

In both simulated scenarios, the results obtained for the potential nutrient load input in the eight reservoirs were subjected to water quality modelling using the parameters that most directly interfere in the trophic state of water bodies, which were total phosphorus and chlorophyll α. To simulate the conditions with the highest pollution potential for caged fish production in these reservoirs, the maximum nutrient input values were considered under the most critical water flow conditions. Such conditions were used to determine the individual values for the trophic state index (TSI) calculated for each reservoir according to the values proposed by Cunha, Calijuri and Lamparelli (2013). The final results were presented as maps that identified the predicted trophic states for each simulated site with different colours.

Results and discussion

Table 1 shows the reference value used to estimate the environmental carrying capacity for each reservoir studied, which was obtained by applying the model by Dillon and Rigler (1974). The important variability of maximum acceptable phosphorus load input from aquaculture observed among reservoirs is mainly explained by the annual water renewal rate. This model gives a strong importance to the ‘flush effect’ observed in reservoirs with a rapid passage of water. This allows, for example, that reservoirs with smaller volumes might accept much higher loads of phosphorus without eutrophication risks compared with others water bodies with much higher volume of water. In this study, it was estimated that Salto Grande can accept a phosphorus load 35 times bigger than the load acceptable for Jurumirim. Although the water volume of the first reservoir represents less than 1% of the second one, Salto Grande can renew the total water content 200 times per year. On the other hand, Jurumirim takes more than 10 months to finish a complete renewal cycle.

Table 2 shows the fish production estimates according to scenarios 1 and 2. Only two reservoirs (Salto Grande and Canoas 2) indicated that the projected aquaculture parks will reach the maximum occupancy limit of 1% of the surface of the reservoirs (scenario 1). In the remaining reservoirs, the implementation potential would be limited by the estimated environmental carrying capacity (scenario 2). At the three largest reservoirs (Jurumirim, Chavantes and Capivara), which together represent 80% of the total surface of the eight reservoirs of the Paranapanema River combined, the limitations imposed by the estimated carrying capacity decreased the area available for implementing aquaculture parks by approximately 95% compared with the potential of scenario 1.

The combined area of all of the studied reservoirs totals 182 700 ha, and using 1% of this area would assign 1827 ha (or 18.3 km^2) for aquaculture. However, the Interministerial Normative Instruction No. 6 (Brazil 2004) establishes a specific ratio between the area effectively occupied by farming structures (cages) and total area of the park to be assigned (which should remain between 12 and 20%). This ratio is important for creating a dilution zone within the aquaculture parks, although it legally reduces the maximum area to be occupied by farming structures in the reservoirs. In the present study, an even more conservative effective occupancy of 10% was considered as a precautionary measure.

Considering the zootechnical indices employed for the estimations in this study, an annual production of 513.8 thousand MT of fish could be achieved (scenario 1). However, the annual fish production in the second scenario would be reduced to 98.1 thousand MT and the effective occupancy area of the farming structures would be reduced to 3.5 km^2. Therefore, by adopting the

Table 2 Estimated fish production based on the environmental carrying capacity or legal occupancy of the surface area for aquaculture purposes in the artificial reservoirs of the Paranapanema River

Reservoir	Maximum phosphorus load (MT res^{-1} year^{-1})*	Carrying capacity (kMT year^{-1})†	Production in 1% surface area (kMT year^{-1})‡	Limiting scenario
Jurumirim	72.75	5.1 (±0.7)	136.4 (±19.4)	Carrying capacity
Chavantes	87.80	6.2 (±0.9)	112.5 (±16.0)	Carrying capacity
Salto Grande	61.73	4.3 (±0.6)	3.4 (±0.5)	Legislation
Canoas II	108.01	7.6 (±1.1)	6.5 (±0.9)	Legislation
Canoas I	90.48	6.3 (±0.9)	8.7 (±1.2)	Carrying capacity
Capivara	163.55	11.5 (±1.6)	162 (±23.0)	Carrying capacity
Taquaruçu	298.16	20.9 (±2.9)	22.5 (±3.2)	Carrying capacity
Rosana	516.57	36.2 (±5.1)	61.9 (±8.8)	Carrying capacity
All	1399.05	98.1 (±13.8)	513.8 (±73.1)	Carrying capacity

*According to the model proposed by Dillon and Rigler (1974).

†Considering a phosphorus load of 14.26 g MT^{-1} of fish produced (Montanhini Neto & Ostrensky 2013) with a confidence interval of ±15% (values in parentheses).

‡According to current legislation (Brazil 2005) and considering a mean productivity of 280 MT ha^{-1} year^{-1} and confidence interval of ±15% (values in parentheses).

criteria that prioritize environmental safety, the productive potential would not be higher than 20% of the potential that could be achieved from occupying 1% of the total area of the reservoirs. The difference in productive potential achieved in each of the simulated scenarios shows the absolute lack of technical criteria applied by the Brazilian environmental legislation when considering an indiscriminate occupancy of 1% of the aquatic ecosystems for aquaculture.

Nevertheless, the environmental sustainability of these reservoirs would not be completely ensured by simply meeting the limits proposed by the calculated environmental carrying capacity. As mentioned, the assignment process of areas for aquaculture purposes considers a limit of up to 5 mg m^{-3} of total phosphorus from aquaculture inputs in the calculations. However, such laws ignore that the water body may contain phosphorus levels that exceed the recommended levels or, even worse, that the environment in question could already be eutrophic.

Our results indicate as well-intentioned legislation can have unintended environmental consequences in dynamic social–ecological aquaculture systems, as in the case of large reservoirs in the Paranapanema River. Thus, performing preliminary studies to diagnose the initial conditions of the water bodies in large reservoirs is as or perhaps more important than estimating the environmental carrying capacity itself when evaluating the implementation of new aquaculture enterprises or, as in this case, aquaculture parks. In addition to preliminary studies, it is imperative to monitor the water quality after implementing the enterprises to assess the real behaviour of the environment rather than relying on values predicted during the design phase.

Additionally, more robust models that can estimate the carrying capacity in tropical environments must be developed (Stagnitti 1997; Bolte, Nath & Ernst 2000; Byron & Costa-Pierce 2013). To improve the accuracy and fit of these models, greater relevance has been given to the level of detail of the hydrodynamic characteristics of water bodies and more comprehensive indices have been used, such as the TSI, which allows for more consistent predictions regarding the prevention of trophic state changes after implementing aquaculture enterprises (FAO 2013). However, obtaining accurate estimates based on mathematical modelling requires that the models be calibrated using actual data from each environment to be simulated, which was performed in the present study.

Figures 2–9 show the behaviour of the TSI along the eight reservoirs studied based on the nutrient loads from cage fish production and scales simulated for scenarios 1 and 2. Previous studies classified the artificial reservoirs of the Paranapanema River as being predominantly oligotrophic and mesotrophic (Pagioro, Velho, Lansac-Tôha, Pereira & Nakamura 2005; Nogueira *et al.* 2006), and similar conditions were observed when the water quality model was calibrated for the present

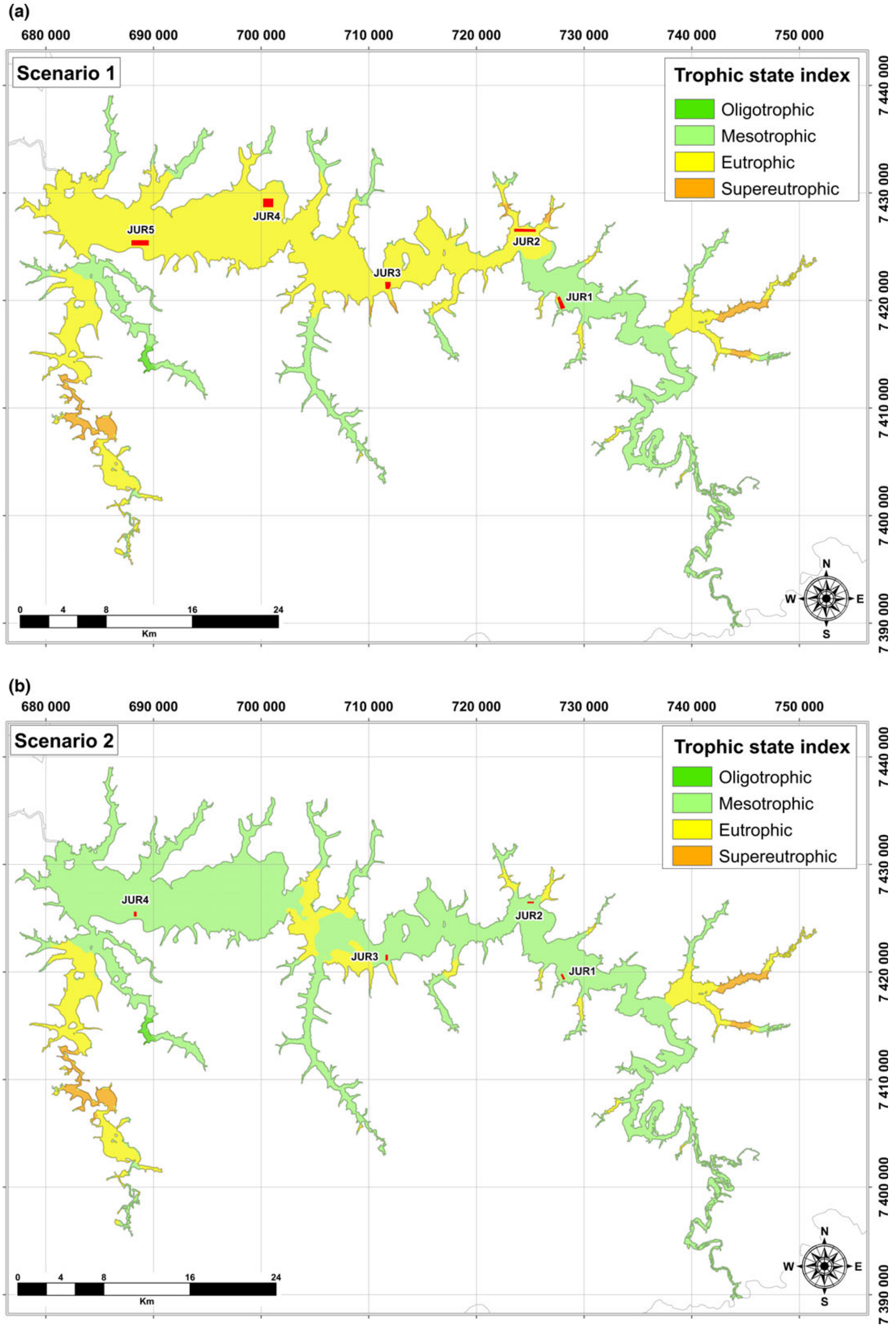

Figure 2 Graphical representation of the trophic state index simulated for scenarios 1 and 2 along the length of the Jurumirim reservoir. The aquaculture parks proposed for each scenario are marked in red. [Colour figure can be viewed at wileyonlinelibrary.com].

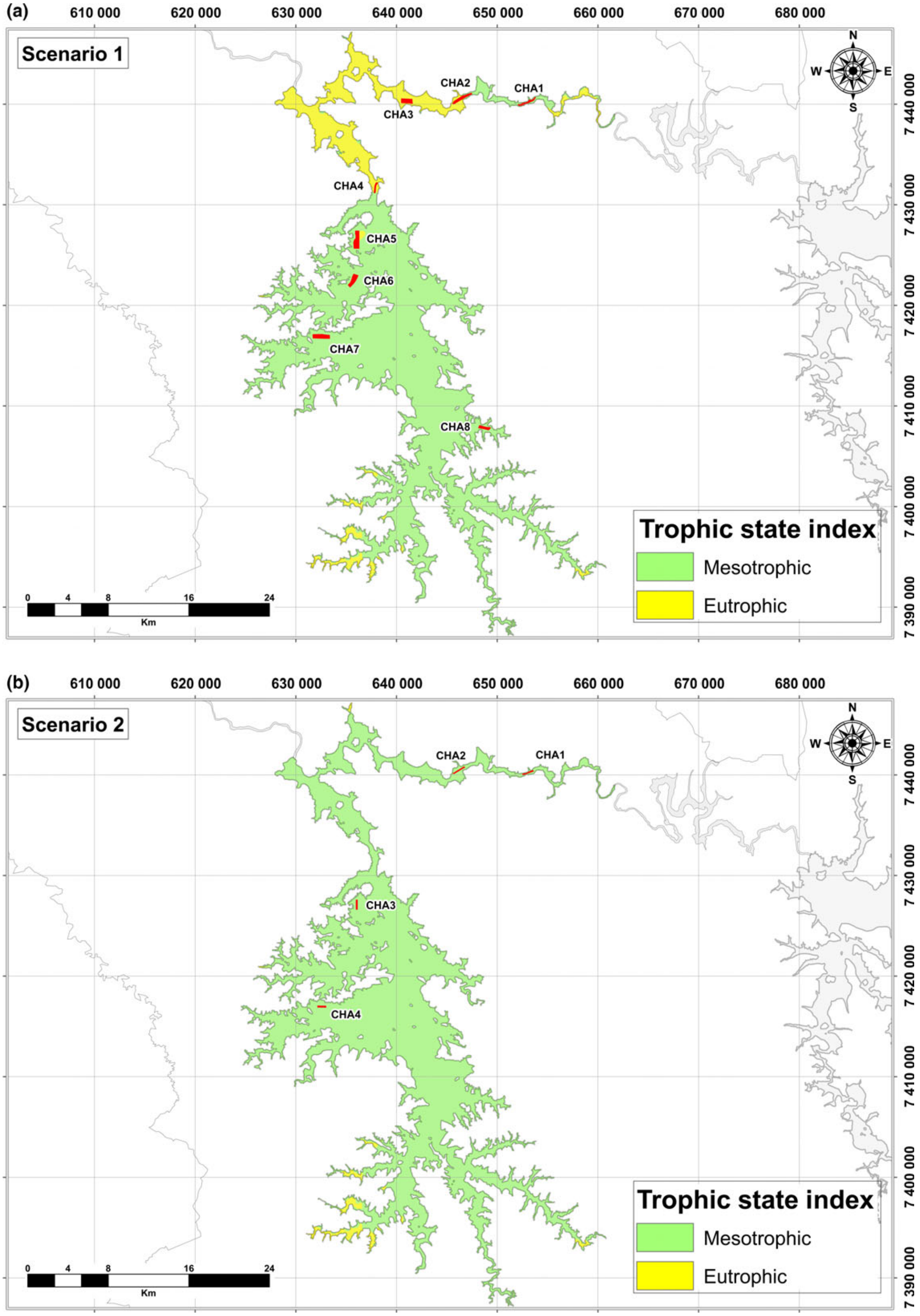

Figure 3 Graphical representation of the trophic state index simulated for scenarios 1 and 2 along the length of the Chavantes reservoir. The aquaculture parks proposed for each scenario are marked in red. [Colour figure can be viewed at wileyonlinelibrary.com].

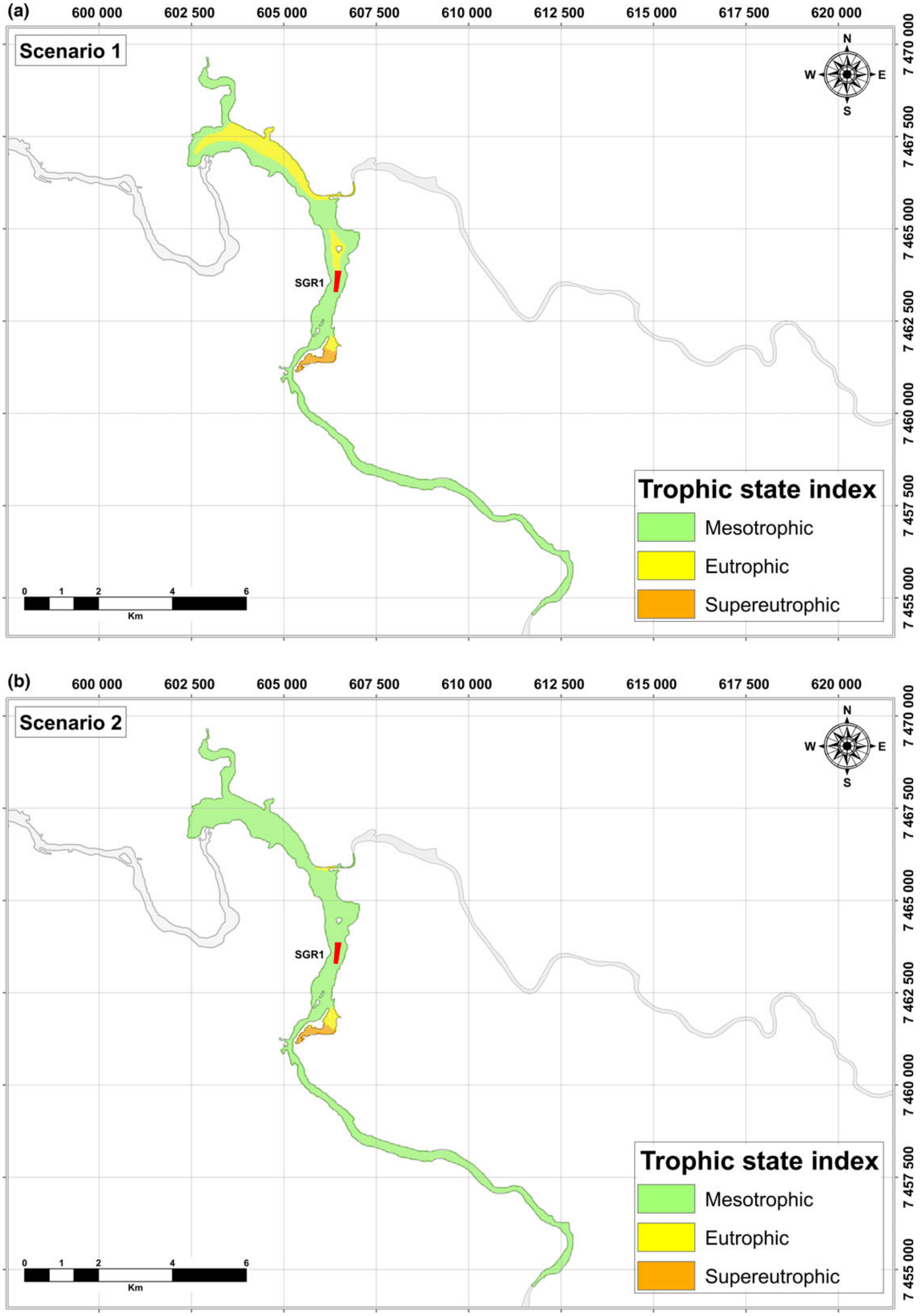

Figure 4 Graphical representation of the trophic state index simulated for scenarios 1 and 2 along the length of the Salto Grande reservoir. The aquaculture parks proposed for each scenario are marked in red. [Colour figure can be viewed at wileyonlinelibrary.com].

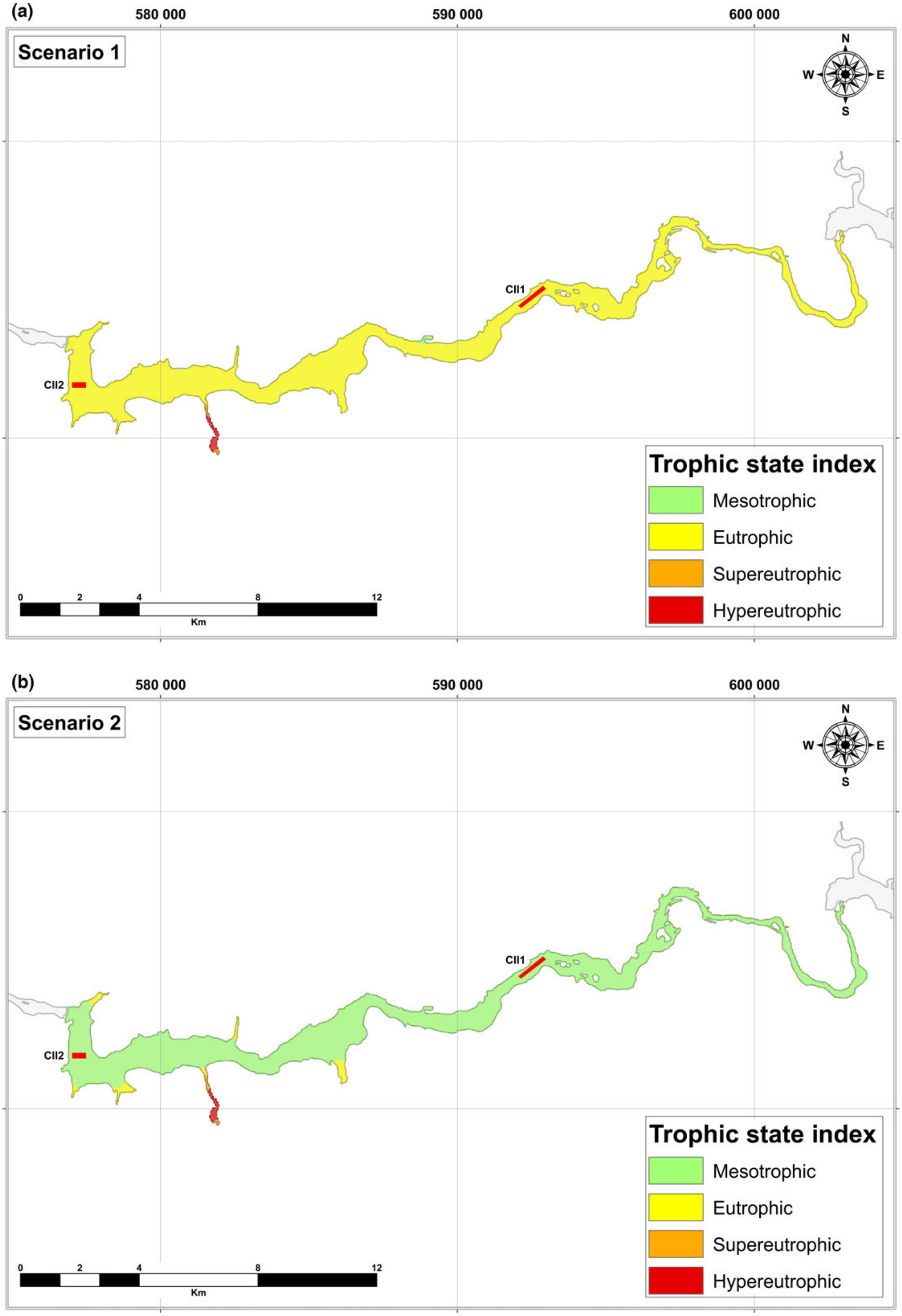

Figure 5 Graphical representation of the trophic state index simulated for scenarios 1 and 2 along the length of the Canoas 2 reservoir. The aquaculture parks proposed for each scenario are marked in red. [Colour figure can be viewed at wileyonlinelibrary.com].

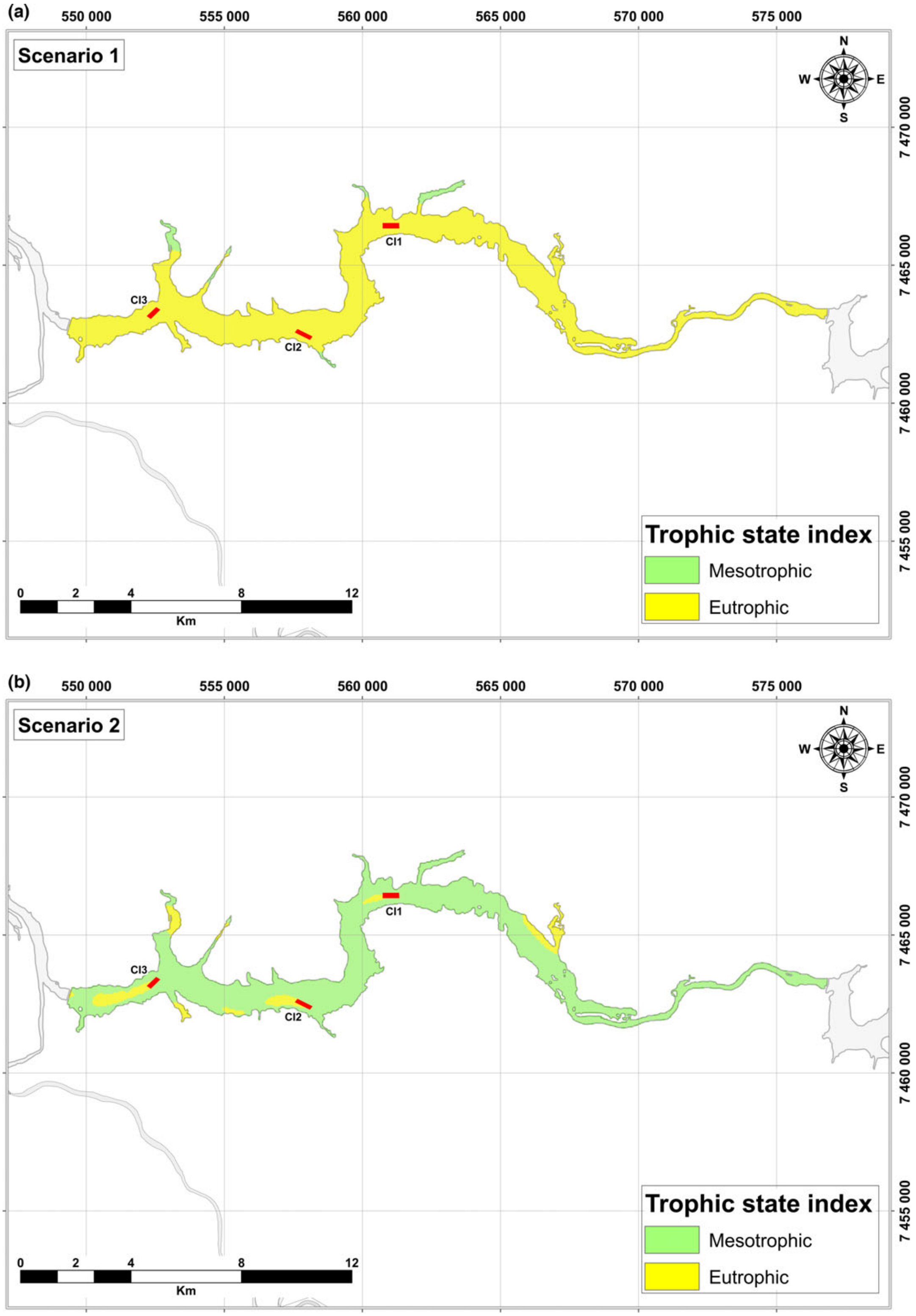

Figure 6 Graphical representation of the trophic state index simulated for scenarios 1 and 2 along the length of the Canoas 1 reservoir. The aquaculture parks proposed for each scenario are marked in red. [Colour figure can be viewed at wileyonlinelibrary.com].

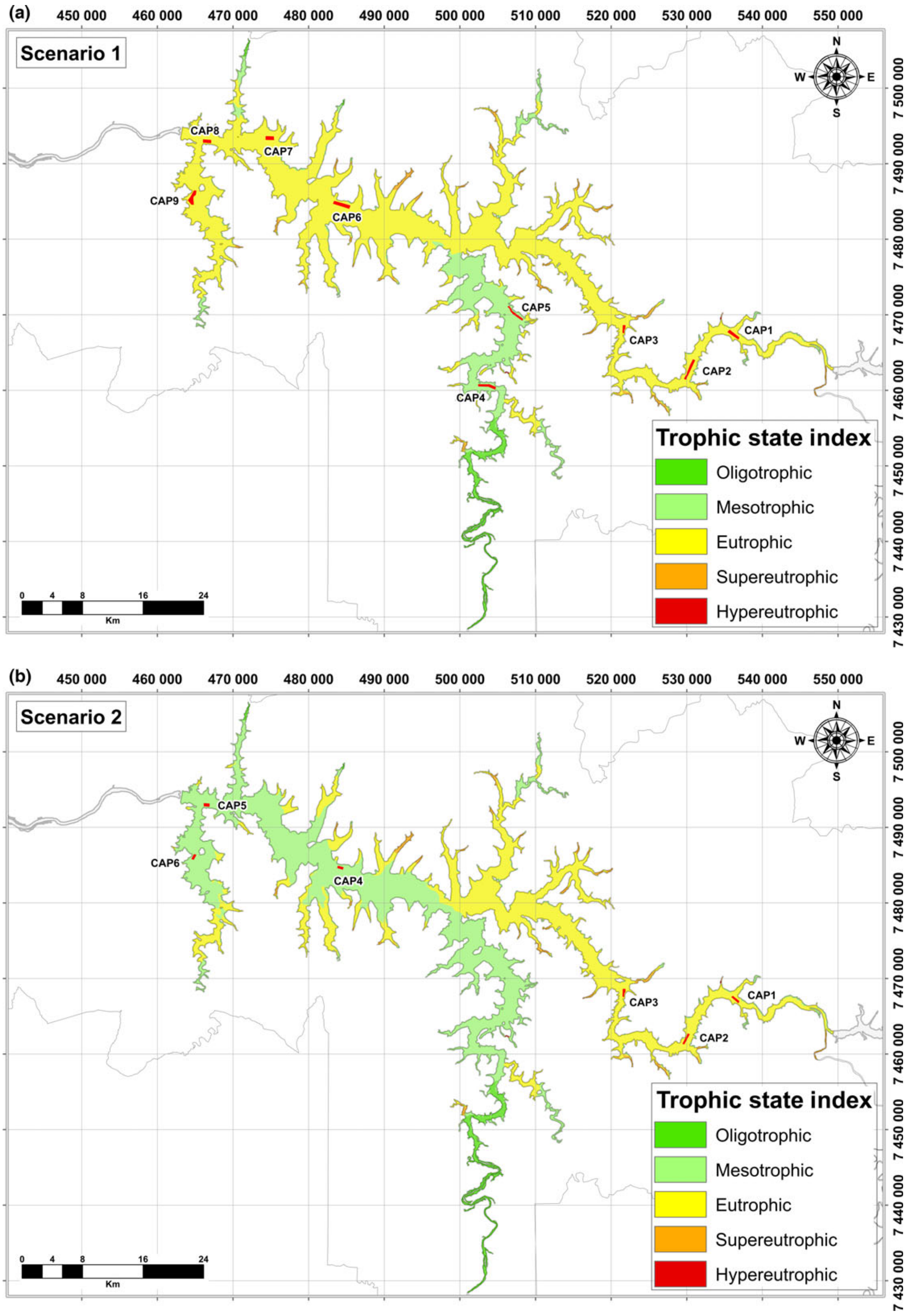

Figure 7 Graphical representation of the trophic state index simulated for scenarios 1 and 2 along the length of the Capivara reservoir. The aquaculture parks proposed for each scenario are marked in red. [Colour figure can be viewed at wileyonlinelibrary.com].

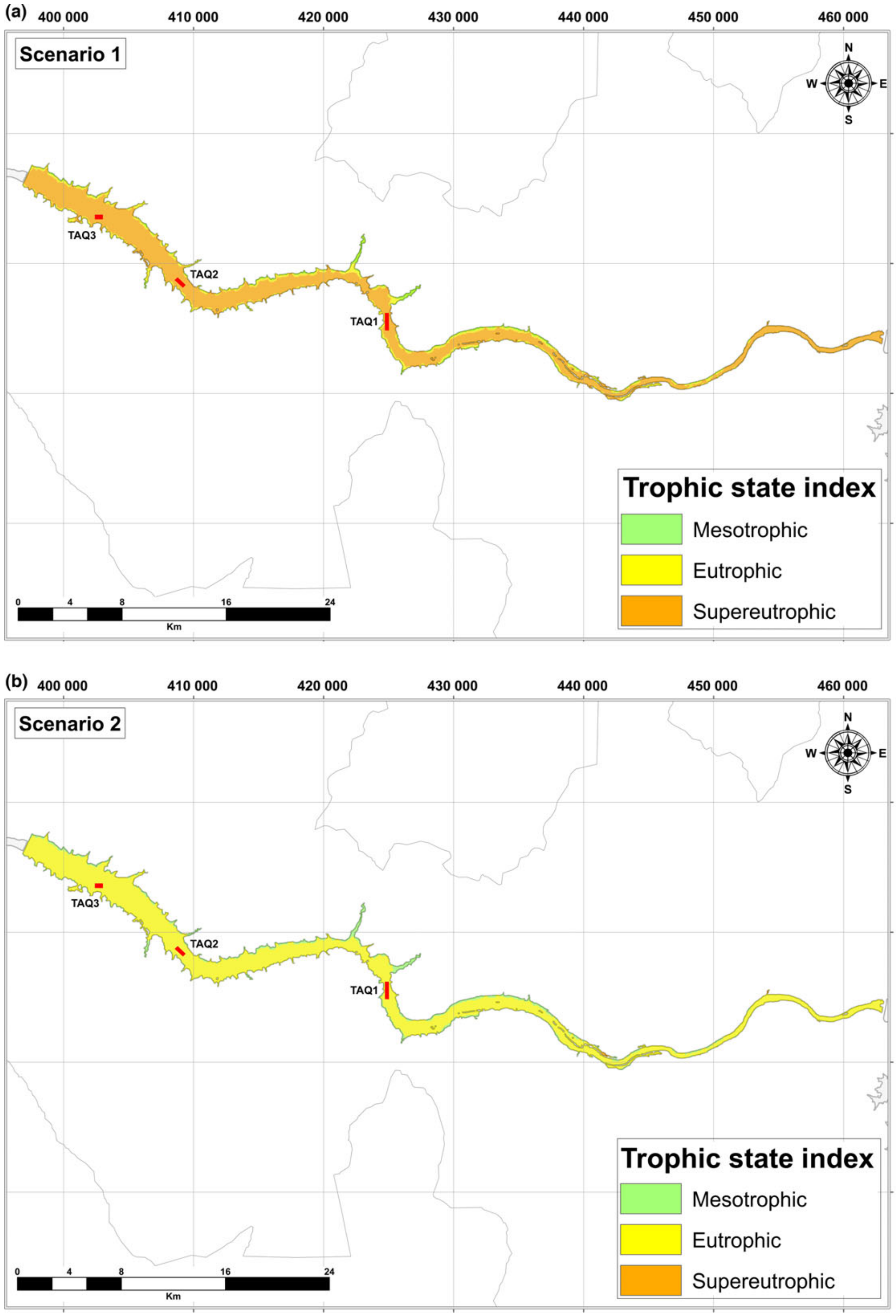

Figure 8 Graphical representation of the trophic state index simulated for scenarios 1 and 2 along the length of the Taquaruçu reservoir. The aquaculture parks proposed for each scenario are marked in red. [Colour figure can be viewed at wileyonlinelibrary.com].

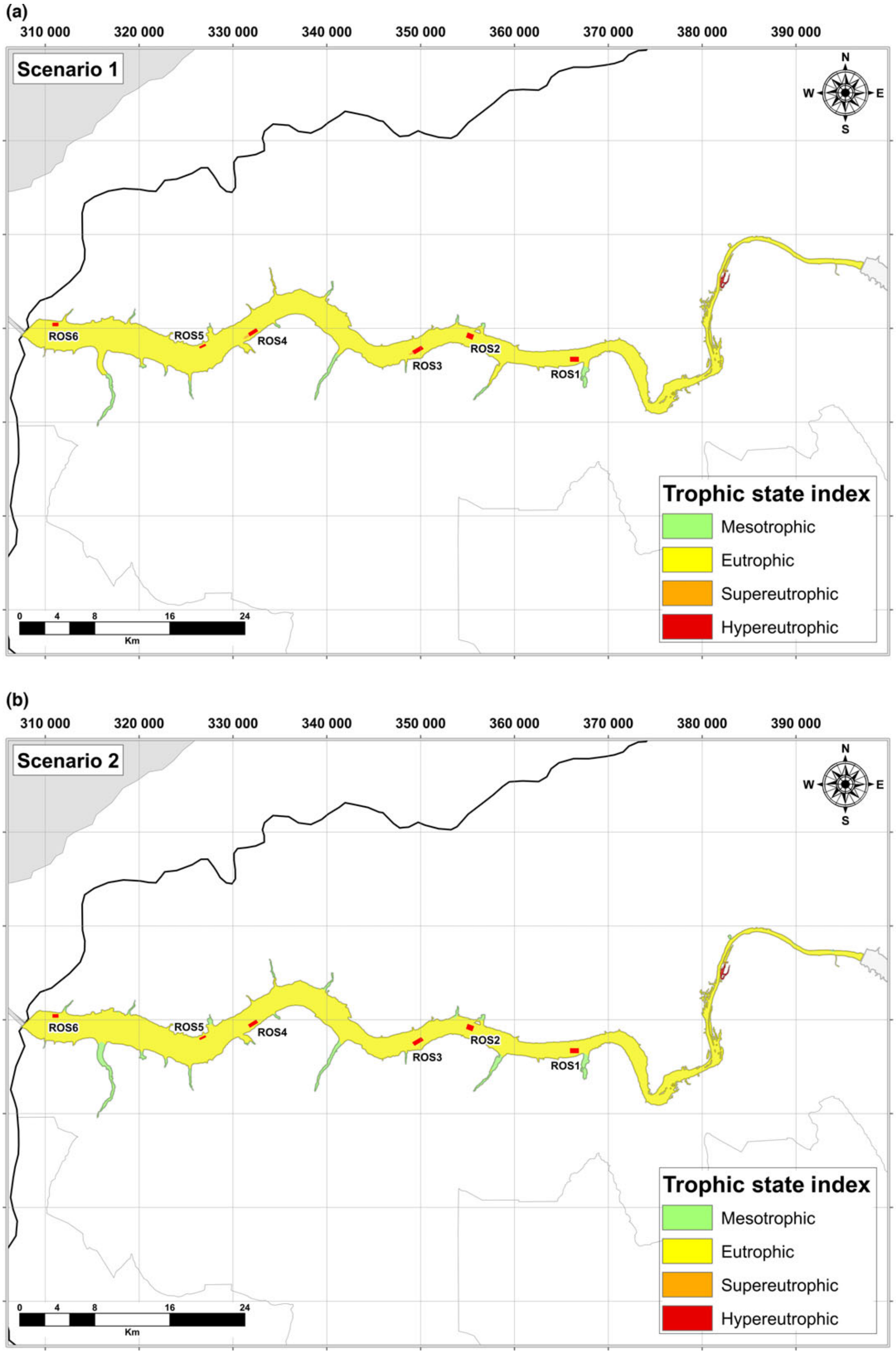

Figure 9 Graphical representation of the trophic state index simulated for scenarios 1 and 2 along the length of the Rosana reservoir. The aquaculture parks proposed for each scenario are marked in red. [Colour figure can be viewed at wileyonlinelibrary.com].

study. However, based on the results of the water quality prognosis, a high potential for trophic state changes was observed in all of the reservoirs when their occupancy models were based on scenario 1.

According to the simulation, the nutrient loads generated in this scenario would cause most of the reservoirs to be classified as eutrophic. Considering the entire combined surface of the eight reservoirs, approximately 75% of the area would be classified as eutrophic, supereutrophic and even hypereutrophic. Four reservoirs (Canoas 2, Canoas 1, Taquaruçu and Rosana) would run the risk of becoming completely eutrophic, and nearly the entire length of the last two reservoirs of the cascade (Taquaruçu and Rosana) would be classified as supereutrophic. This trend can be explained by the high nutrient loads that would be supplied by the upstream reservoirs, especially those with a higher volume of water, and this effect has been extensively reported in studies on pollutant loads in rivers with artificial reservoirs arranged in cascade, which occurs in the Paranapanema River (Ouyang, Hao, Song & Zhang 2011; Xin, Yin & Wang 2012; Nikanorov & Khoruzhaya 2014).

In scenario 2, the trophic state of the studied reservoirs would be similar to that reported in the scientific literature and previously assessed. However, in certain regions that are close to potential aquaculture parks and have deficient circulation or shallow water levels, localized risks of eutrophication would occur in areas accounting for less than 30% of the total area of the reservoirs. However, Taquaruçu and Rosana would still run the risk of becoming eutrophic because of inputs from the Capivara reservoir, which confirms the 'cascade effect' of effluent loads from upstream reservoirs to those close to the river mouth and presents a scenario similar to that of scenario 1.

The modelling results only indicate trends related to what would happen if the proposed parks are implemented according to the simulated scales and conditions. However, mathematical modelling involves uncertainty; therefore, the results presented here cannot be considered as immutable or even unconditional truths (Bastin, Cornford, Jones, Heuvelink, Pebesma, Stasch, Nativi, Mazzetti & Williams 2013). The reliability of the models largely depends on continuous environmental monitoring of the target water bodies to provide detailed information for dynamic calibration and constant validation of the models (Krapivin, Varotsos & Soldatov 2015).

Thus, it is recommended that the aquaculture parks should be effectively defined and implemented by applying an integrated methodology that involves performing preliminary studies to diagnose the initial conditions of the water bodies, simulating scenarios involving zootechnical indices of the fish farming activity and loads released into the aquatic ecosystems, and performing continuous monitoring of the water quality after implementing the enterprises to assess the actual behaviour of the environment rather than relying on predictions. Thus, aquaculture parks with higher environmental safety may be implemented, and the degree of occupancy in the reservoirs may be gradually increased through the continued monitoring of the environment.

Based on these assumptions and the conservative parameters employed in the present study, it is recommended that the establishment of definitive borders, park licensing and bidding for the aquaculture sites should be performed with extreme caution in all of the analysed reservoirs. In addition, more careful occupancy must be implemented in the last three reservoirs of the Paranapanema channel to ensure that the water quality standards suggested by environmental legislation and sustainability of the enterprises are maintained.

Acknowledgments

We thank the GIA staff for providing access to the information about fish farming in the Paranapanema region, which was indispensable for the completion of this study. We also thank the National Council for Scientific and Technological Development (CNPq) for granting funding to Antonio Ostrensky.

References

Arrow K., Bolin B., Costanza R., Dasgupta P., Folke C., Holling C.S., Jansson B.-O., Levin S., Mäler K.-G., Perrings C. & Pimentel D. (1995) Economic growth, carrying capacity, and the environment. *Ecological Economics* **15**, 91–95.

Bastin L., Cornford D., Jones R., Heuvelink G.B.M., Pebesma E., Stasch C., Nativi S., Mazzetti P. & Williams M. (2013) Managing uncertainty in integrated environmental modelling: the UncertWeb framework. *Environmental Modelling & Software* **39**, 116–134.

Beveridge M.C.M. (1996) *Cage Aquaculture*. Fishing News Books Ltd., Londres, UK.

Beveridge M.C.M. & Phillips M.J. (1993) Environmental impact of tropical inland aquaculture. In: *Environment and Aquaculture in Developing Countries* (ed. by R.S.V. Pullin, H. Rosenthal & J.L. Maclaen), pp. 213–236. International Center for Living Aquatic Resources Management, Manila, Philippines.

Bolte J., Nath S. & Ernst D. (2000) Development of decision support tools for aquaculture: the POND experience. *Aquacultural Engineering* **23**, 103–119.

Brazil (2004) *Instrução Normativa Interministerial n° 6, de 31 de maio de 2004. Normas complementares para a autorização de uso dos espaços físicos em corpos d'água de domínio da União para fins de aquicultura*. Ministério da Pesca e Aquicultura/Ministério do Meio Ambiente, Brasília, Brazil.

Brazil (2005) *Instrução Normativa Interministerial n° 7, de 28 de abril de 2005. Diretrizes para implantação dos parques e áreas aquicolas*. Ministério do Meio Ambiente/Secretária Especial de Aquicultura e Pesca, Brasília, Brazil.

Brazil (2013) Manual de procedimentos técnicos e administrativos de outorga de direito de uso de recursos hídricos. Agência Nacional de Águas, Brasília, Brazil.

Bueno G.W., Ostrensky A., Canzi C., de Matos F.T. & Roubach R. (2013) Implementation of aquaculture parks in Federal Government waters in Brazil. *Reviews in Aquaculture* **5**, 1–12.

Byron C.J. & Costa-Pierce B.A. (2013) Carrying capacity tools for use in the implementation of an ecosystems approach to aquaculture. In: *Site selection and Carrying Capacities for Inland and Coastal Aquaculture* (ed. by L.G. Ross, T.C. Telfer, L. Falconer, D. Soto & J. Aguilar-Manjarrez), pp. 87–102. Food and Agriculture Organization of the United Nations, Stirling, UK.

Cunha D.G.F., Calijuri M.d.C. & Lamparelli M.C. (2013) A trophic state index for tropical/subtropical reservoirs. *Ecological Engineering* **60**, 126–134.

Dillon P.J. & Rigler F.H. (1974) A test of a simple nutrient budget model predicting the phosphorus concentration in lake water. *Journal of the Fisheries Research Board of Canada* **31**, 1771–1778.

FAO (2013) *Site selection and Carrying Capacities for Inland and Coastal Aquaculture*. Food and Agriculture Organization of the United Nations, Fisheries and Aquaculture Department, Roma, Italy.

Felisberto S.A. & Rodrigues L. (2005) Periphytic community of reservoirs cascade in the Paranapanema river, Brazil. *Acta Scientiarum Biological Sciences* **27**, 215–223.

Ganguly D., Patra S., Muduli P.R., Vardhan K.V., Abhilash R.K., Robin R.S. & Subramanian B.R. (2015) Influence of nutrient input on the trophic state of a tropical brackish water lagoon. *Journal of Earth System Science* **124**, 1005–1017.

Granada L., Sousa N., Lopes S. & Lemos M.F.L. (2015) Is integrated multitrophic aquaculture the solution to the sectors' major challenges? – a review. *Reviews in Aquaculture*. doi:10.1111/raq.12093.

Jorcin A. & Nogueira M. (2008) Benthic macroinvertebrates in the Paranapanema reservoir cascade (southeast Brazil). *Brazilian Journal of Biology* **68**, 1013–1024.

Kautsky N., Berg H., Folke C., Larsson J. & Troell M. (1997) Ecological footprint for assessment of resource use and development limitations in shrimp and tilapia aquaculture. *Aquaculture Research* **28**, 753–766.

Krapivin V.F., Varotsos C.A. & Soldatov V.Y. (2015) Information-Modeling Technology for the Environmental Monitoring. *New Ecoinformatics Tools in Environmental Science: Applications and Decision-making*, pp. 1–118. Springer International Publishing, Cham, Switzerland.

Montanhini Neto R. & Ostrensky A. (2013) Nutrient load estimation in the waste of Nile tilapia *Oreochromis niloticus* (L.) reared in cages in tropical climate conditions. *Aquaculture Research* **46**, 1309–1322.

Montanhini Neto R. & Ostrensky A. (2015) Evaluation of commercial feeds intended for the Brazilian production of Nile tilapia (*Oreochromis niloticus* L.): nutritional and environmental implications. *Aquaculture Nutrition* **21**, 311–320.

Montanhini Neto R., Nocko H. & Ostrensky A. (2015) Environmental characterization and impacts of fish farming in the cascade reservoirs of the Paranapanema River, Brazil. *Aquaculture Environment Interaction* **6**, 255–272.

Nikanorov A.M. & Khoruzhaya T.A. (2014) Intra-water-body processes in large reservoirs of southern Russia (pollution, eutrophication, toxification). *Geography and Natural Resources* **35**, 135–142.

Nogueira M.G. & Jorcin A. (2006) Contaminação dos sedimentos na bacia hidrográfica do Rio Paranapanema (SE, Brasil) por pesticidas sintéticos e metais e sua relação com os processos de eutrofização. In: *Eutrofização na América do Sul: Causas, Consequências e Tecnologias Para Gerenciamento e Controle* (ed. by J.G. Tundisi, T. Matsumura-Tundisi & C.S. Galli), pp. 103–118. IIE/DMD Propaganda e Marketing, São Carlos, Brazil.

Nogueira M.G., Jorcin A., Vianna N.C. & Britto Y.C.T. (2006) Reservatórios em cascata e os efeitos na limnologia e organização das comunidades bióticas (fitoplâncton, zooplâncton e zoobentos): um estudo de caso no Rio Paranapanema (SP/PR). In: *Ecologia de Reservatórios: Impactos Potenciais, Ações de Manejo e Sistemas em Cascata* (ed. by M.G. Nogueira, R. Henry & A. Jorcin), pp. 83–126. Rima, São Carlos, Brazil.

Ouyang W., Hao F., Song K. & Zhang X. (2011) Cascade dam-induced hydrological disturbance and environmental impact in the upper stream of the Yellow River. *Water Resources Management* **25**, 913–927.

Pagioro T.A., Velho L.F.M., Lansac-Tôha F.A., Pereira D.G. & Nakamura A.K.S. (2005) Influência do grau de trofia sobre os padrões de abundância de bactérias e protozoários planctônicos em reservatórios do Estado do Paraná. In: *Biocenoses em Reservatórios: Padrões Espaciais e Temporais* (ed. by L. Rodrigues, S.M. Thomaz, A.A. Agostinho & L.C. Gomes), pp. 47–56. Rima, São Carlos, Brazil.

Pittroff W. & Pedersen E.K. (2001) *Ecological Modelling*. John Wiley & Sons, Londres, UK.

Stagnitti F. (1997) A decision support tool for aquaculture. *Environmental Modelling & Software* **12**, 229–236.

Xin X., Yin W. & Wang M. (2012) Reservoir operation schemes for water pollution accidents in Yangtze River. *Water Science and Engineering* **5**, 59–66.