

<https://doi.org/10.1590/2318-0331.272220210124>

Population growth of the golden mussel (*L. fortunei*) in hydroelectric power plants: a study via mathematical and computational modeling

*Crescimento populacional do mexilhão dourado (*L. fortunei*) em reservatórios de hidroelétricas: um estudo via modelagem matemática e computacional*

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Received: November 09, 2021 - Revised: January 24, 2022 - Accepted: January 26, 2022

ABSTRACT

Golden mussel is an invasive species in Brazil which impacts local environments, dislocating native species and altering microecological conditions as well as affecting hydroelectric power plants and water treatment systems. The objective of this research is to establish a method that is both effective and efficient to quantify the population of the Golden mussel in hydroelectric power plant reservoirs, with a focus on population control measures. A two-dimensional mathematical model was developed combining hydrodynamics and populational dynamics to simulate the distribution of mussels in a reservoir. The results showed that dam's region was progressively infested, and after 18 months of simulation it has reached around 80% of its carrying capacity. The method proved to be satisfactory and the generated map of cluster locations for the golden mussel corresponds to field observations. Furthermore, the result of the algae density simulation matched chlorophyll-a density map obtained from satellite images. The methodology can be further applied to new areas and could be expanded to predict population variations in order to guide environmental measures for preservation and recovery of impacted reservoirs, presenting another tool for hydroelectric operators who can use information together with field inspections to plan maintenance intervals before infestation damages equipment.

Keywords: Populational dynamics; Mathematical modeling; Bioinvasion; Diffusion-advection-reaction equations; Plant operation.

RESUMO

O Mexilhão dourado é uma espécie invasora no Brasil que causa impactos ambientais, remove espécies nativas e modifica condições microecológicas, além de afetar hidroelétricas e sistemas de tratamento de água. O objetivo deste estudo é estabelecer um método que seja ao mesmo tempo eficaz e eficiente para quantificação da população do mexilhão dourado em reservatórios de hidrelétricas, visando o controle populacional do animal. Um modelo matemático bidimensional foi desenvolvido combinando hidrodinâmica e dinâmica populacional para simular a distribuição de mexilhões em um reservatório. Os resultados mostraram que a região da barragem foi progressivamente infestada por mexilhões, e depois de 18 meses de simulação alcançou 80% da sua capacidade suporte. O método se mostrou satisfatório e o mapa de localização dos agrupamentos de mexilhões corresponde a observações *in situ*. Além disso, o resultado da simulação da densidade das algas correspondeu ao mapa de densidade de clorofila obtido por imagens de satélite. A metodologia pode ser aplicada a novas áreas e deve ser expandida para prever variações populacionais, servindo para guiar medidas de preservação ambiental e de recuperação de reservatórios impactados, apresentando uma ferramenta alternativa para os operadores hidrelétricos, que podem utilizar as informações junto as inspeções locais no planejamento dos intervalos de manutenção antes que a infestação danifique os equipamentos.

Palavras-chave: Dinâmica populacional; Modelagem matemática; Bioinvasão; Equações de difusão-advecção-reação; Operação de reservatórios.



INTRODUCTION

The *Limnoperna fortunei* (Dunker, 1857) is a small freshwater bivalve mollusk, commonly known as the golden mussel due to its yellowish shell. This is a filter feeding species with a capacity to filter more than its own weight in microalgae per hour (Sylvester et al., 2005). The animal has external reproduction, liberating gametes in the water which then produce planktonic larvae that can be carried by water currents for up to 10-20 days (Cataldo et al., 2005). After this period, the mussel will go through recruitment in which the larvae will seek a proper substrate for attachment and will form a byssus for permanent fixation on the selected spot.

The golden mussel is originally from China and was artificially introduced in South America in the 1990s, in the Rio da Prata basin and, in a short time, traveled more than 5,000 km across the continent. Today it is found in Argentina, Uruguay and Brazil, including the South of the country, the Pantanal and even the São Francisco River (Boltovskoy et al., 2006).

The presence of this invasive animal has become an immense environmental problem in Brazil. The Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA) classifies the golden mussel as one of the three priority invasive species for control, since the overpopulation of this animal can cause serious issues for the native fauna (Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis, 2019). With its high tolerance to different environments and relying on human assistance in its transport, this species is a threat even to the Amazonian aquatic ecosystems, which hold the largest, and still unknown, aquatic biodiversity in the world.

The areas invaded by the mussel undergo significant modifications. The filtration of water by the bivalve may cause reduction in the supply of nutrients and in the availability of microalgae used as food by native animals as has been observed with the zebra mussel invasion (Karatayev et al., 1997). This mollusk can reach densities of 200,000 individuals/m², especially in environment already affected by human activity such as hydroelectric power plant (HPP) reservoirs. In these areas, the animals can block the grids, pipes and heat exchangers, a particularly favored spot where the temperature contributes to the reproduction and growth of the bivalve (Silva et al., 2016). Thus, the presence of high mollusk densities in pipelines is related to hydraulic head losses, as shown by Simeão et al. (2011). In addition, it causes more frequent and prolonged maintenance stops, which represent economic losses and risks for hydroelectric generation in the country with total expenditures in Brazil on monitoring and maintenance between US \$ 6.9 - 8 million. This information was provided by the companies that finance the Golden Mussel Project (CTG Brasil, SPIC Brasil and Tijoa Energia).

One of the challenges faced in the management of the golden mussel is the very assessment of the severity of infestation in areas that are very vast and often difficult to reach. Currently, the most used method to quantify population size of benthic fauna involves manual counting of individuals (Bodkin et al., 2016; Carey et al., 2019; Pestana et al., 2010; Xu et al., 2015b). This approach, in addition to being slow and laborious, is not usually applied to animals with population sizes in the order of magnitude of the golden mussel, which can reach trillions of individuals in a single hydroelectric reservoir. Emerging methods

using statistical or molecular analysis techniques to estimate the abundance of organisms have already been successfully applied in determining the population size of other animals (Burguera & Oliver, 2016; Pie et al., 2017; Xia et al., 2017; Oliveira Junior et al., 2018; Iwai et al., 2019).

The present study is a qualitative analysis aiming at simulating the beginning of the golden mussel infestation. Through computational simulation it is possible to analyze the infestation of the golden mussel in a reservoir with different simulation scenarios, reducing costs, and facilitating its operation as a methodology that could be easily replicated in different locations. The numerical modeling technique has been successfully applied in many studies, whether for hydrodynamic analysis in rivers and lakes (Fan et al., 2021; Zhang et al., 2020) or even to represent coastal environments (Gireli et al., 2017; Harari & Camargo, 1998; Baptistelli, 2008; Roversi et al., 2016) in conjunction with ecological models (Ganju et al., 2016; Liu et al., 2021; Wang et al., 2008).

MATERIAL AND METHODS

Study area

The research was carried on the Três Irmãos HPP reservoir, located in the Tietê river basin, near the municipalities of Pereira Barreto (SP) and Andradina (SP) (see Figure 1). The stretch of the dam considered consists of about one third of the total flooded area of the reservoir and was chosen because it is the stretch where the dam of the hydroelectric is located and the region with the greatest availability of physical data obtained in the field. A simplified two-dimensional outline of the region was established with about 156 km² (25 km by 14 km, approximately).

In situ analyses

In November 2020, the right margin of the Tietê River from the Pereira Barreto Channel until the Três Irmãos HPP was visually inspected for a general overview of the mussel distribution on the reservoir and evaluation of the severity of the infestation in the area. From this inspection, three points of higher concentration were selected for further sampling: along the right margin near the Três Irmãos HPP, along both margins of the Pereira Barreto Channel and near the Pereira Barreto dock. On the Pereira Barreto dock however, while the animals were still abundant, they were dead and covered by an unidentified substance. This collection point was removed from the analysis and 12 samples were obtained in the other two locations. All the samples were weighted with digital scale and manually counted for estimation of biomass and population density. From each location, 100 random animals were selected, measured and weighted individually for an estimate of average body mass. Abiotic data was also obtained in each location: temperature (*T*), dissolved oxygen (*O*₂), pH, electric conductivity (*EC*), total dissolved solids (*TDS*), and salinity. Abiotic information as well as average abundance and weight on Table 1 below.

Additional environmental data on chlorophyll-a density and distribution and water surface temperature (WST) was obtained

Table 1. Biotic and abiotic information on the golden mussel on collection points in the Três Irmãos HPP.

Location (see Figure 1)	Coordinates	Abundance	Weight (g)	T(°C)	O ₂ [diss]	pH	EC	TDS	Salinity
Três Irmãos HPP (P1)	20°39'17.592" S; 51°18'20.094" W	3598	1732	30.0	8.8	8.8	253	162	0.08
Pereira Barreto Channel (P2)	20°36'47.286" S; 51°4'35.544" W	1325	562.5	27.6	8.4	8.2	227	148	0.07
Pereira Barreto Dock (P3)	20°38'40.872" S; 51°5'56.508 W	360	216	28.4	9.4	8.5	185	120	0.06

Note: EC = electric conductivity; TDS = total dissolved solids.

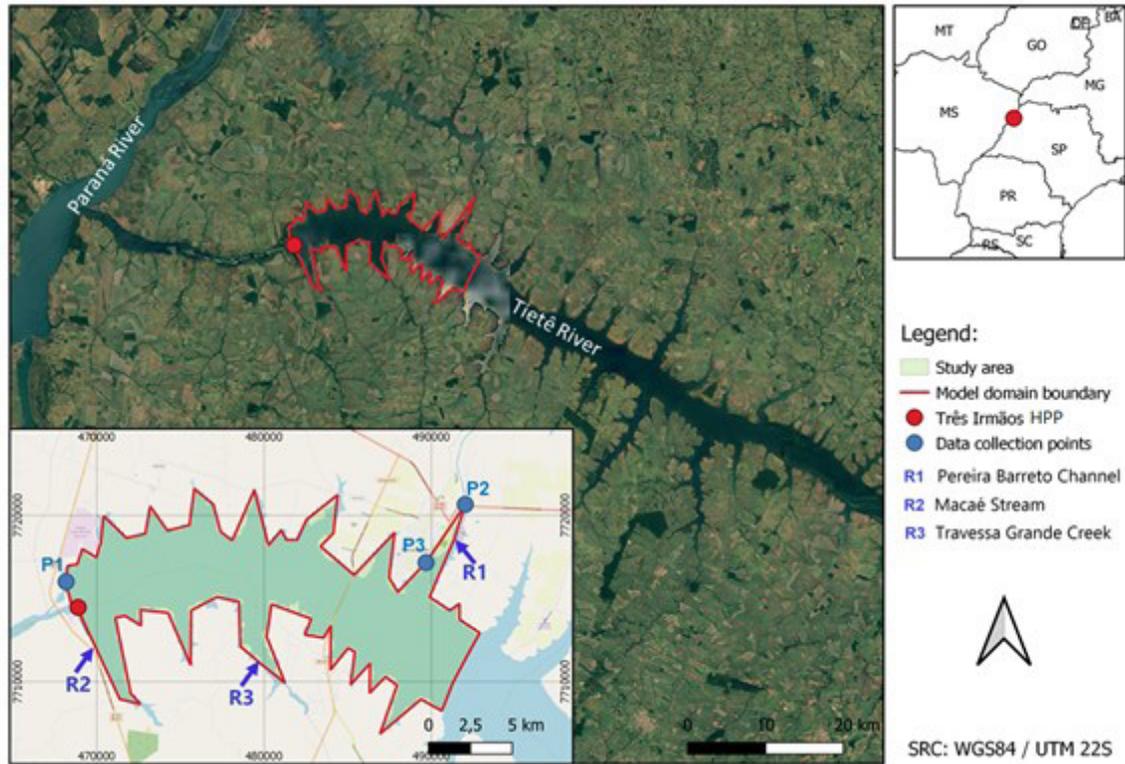


Figure 1. Study area. In detail, the region of the dam of the Três Irmãos hydroelectric power plant. Adapted from Google Earth©.

from satellite images for comparison and for definition of annual averages in each location to be used as a baseline. The selected images from the satellite Landsat 8 produced between 2013-2021 were processed according to methodology described in the Appendix A. The average yearly variation was plotted on the graphs on Figure 2.

Note that Figure 2a does not present significant seasonal variation in chlorophyll-a density, since chlorophyll-a density can be directly related with algae density (Basak et al., 2021), no significant variation in algae density was considered. In addition, Figure 2b also does not present significant variation in water superficial temperatures. Thus, seasonality effects were not considered for the development of this model. In addition, Figure 3 presents the chlorophyll-a density in the region.

Proposed population modeling

For the region considered Ω the laminar flow model (Donea & Huerta, 2003) will be used to provide the velocity field in the

reservoir $V(x,t)$, where t is time. Note that Figure 4 represents the velocity field, which was normalized for best visualization. In addition, the highest velocity (1.2 m/s) is found near point 14 (dam). The velocity field was used in conjunction with a population growth model that considers adult mussels, larvae and algae, its main source of food, which will be described below.

The two-dimensional simulation of the distribution of mussels in the reservoir is performed based on the following mathematical model proposed, where L , M and A represent the populations of Larvae, adult Mussels and Algae, respectively:

$$\frac{\partial L}{\partial t} = r_1 M \left(1 - \frac{L}{k_L}\right) - b_1 L - \lambda L + D_L \nabla^2 L - V \cdot \nabla L \quad (1)$$

$$\frac{\partial M}{\partial t} = \lambda L \left(\frac{A^2}{c_1^2 + A^2}\right) \left(1 - \frac{M}{k_M}\right) - b_2 M + D_M \nabla^2 M \quad (2)$$

$$\frac{\partial A}{\partial t} = r_2 A \left(1 - \frac{A}{k_A}\right) - b_3 \left(\frac{A^2}{c_2^2 + A^2}\right) M + D_A \nabla^2 A - V \cdot \nabla A, \quad (3)$$

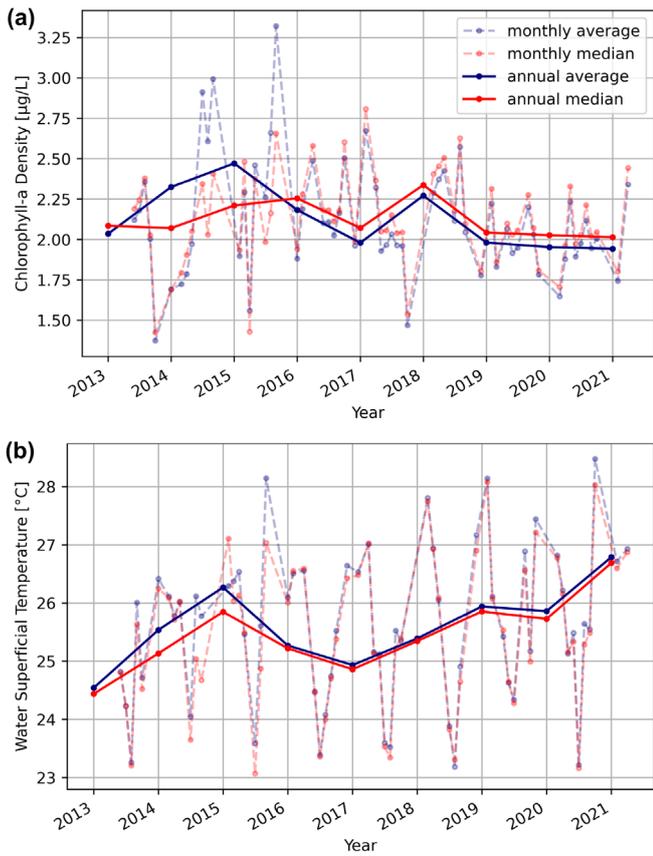


Figure 2. (a) Average and median values of Chl-a density (µg/L); (b) Average and median values of WST (°C) for the Três Irmãos HPP reservoir between 2013 and 2021.

subject to initial values: $L(0) = L_0$, $M(0) = M_0$ and $A(0) = A_0$.

The first equation admits that the growth of larvae is related to adult mussel population, due to external reproduction (Cataldo & Boltovskoy, 2000). Besides, the logistical growth function (Murray, 2007) that depends on an intrinsic growth rate of the larvae population, r_L , and the carrying capacity for the larvae population, k_L , which is the limit of individuals of a particular species (density) that the environment can sustain due to limiting factors (Edelstein-Keshet, 2005). In addition, the losses of larvae are understood as mortality in a rate of b_1 , and the maturation, which represents the larvae that successfully turns into adult golden mussel in a rate of λ . Finally, to model the spatial propagation in a certain domain, a diffusion parcel and an advection term due to the suspension of larvae in the water column (Cataldo & Boltovskoy, 2000) were considered, being V the velocity field and D_L the diffusion coefficient of larvae.

For the second equation of our model (adult mussel equation), we admit that mussel growth depends on the larvae maturation and algae availability, as we interpret algae as the golden mussel's main source of food as some studies indicated was the case for the zebra mussel (Karatayev et al., 1997). Accordingly, we associated mussel population growth directly with mature larvae and a function related to algae predation. The equation also highlights the logistical growth rate, as some studies suggest (van de Koppel et al., 2005; Zhou et al., 2021), being k_M the carrying capacity for the golden mussel, c_1 the half saturation constant for the adults, and b_2 the mortality rate due to fish predation. Furthermore, a diffusion term is considered, admitting D_M as a measure of mussel motility caused by their pedal locomotion mechanism and its concomitant byssal thread deployment (Wang et al., 2009 apud Cangelosi et al., 2015).

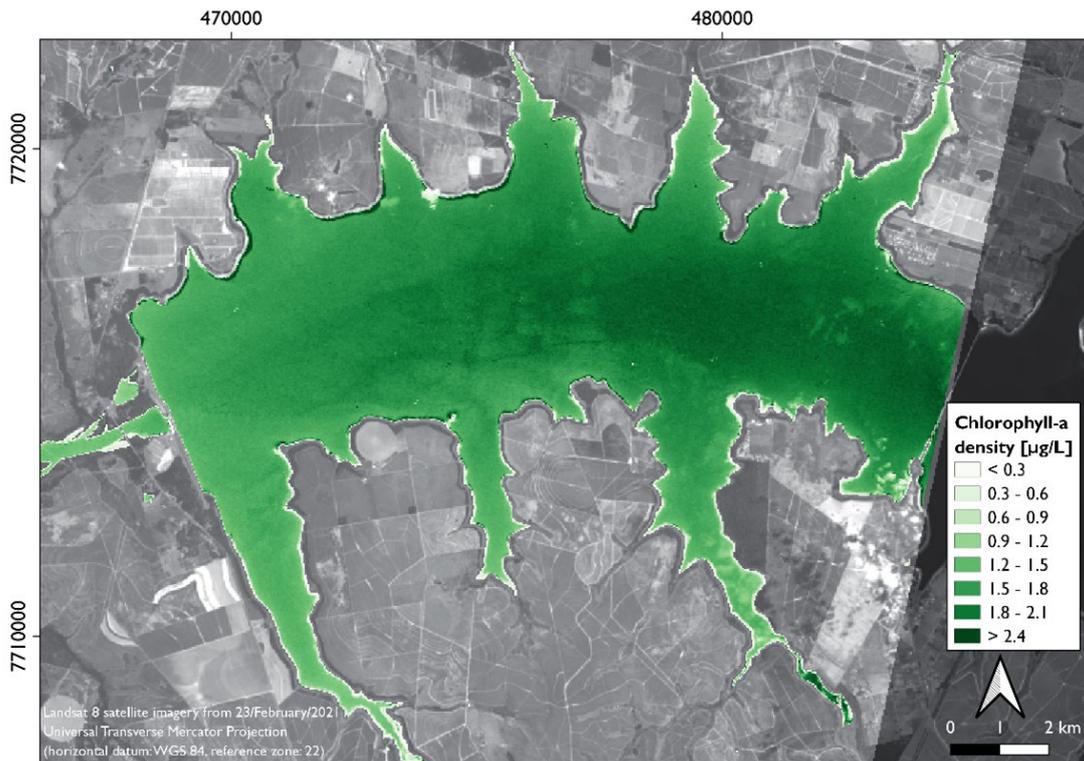


Figure 3. Chlorophyll-a density map.

For the last equation, the variation in algae population can be directly modelled assuming an r_2 growth rate and the logistical growth limited by a carrying capacity for algae, k_A . Besides, the terms of diffusion and advection were considered, with D_A being the diffusion coefficient of algae and b_3 its mortality due to predation by golden mussels. For a better understanding of the model dynamics see Figure 5, which presents the compartment diagram.

The system of equations is solved numerically by the finite element method (Johnson, 1987). A computational code was developed for this purpose to enable the analysis of different simulation scenarios, as will be seen ahead.

Simulations

In order to obtain the numerical solution of the model, a spatial discretization was performed using the Finite Elements Method – FEM – with linear elements (Johnson, 1987) and Crank-Nicholson method (LeVeque, 2007) for time discretization. The discretization led to a nonlinear algebraic system that was solved by a Predictor-Corrector method at every step of time (Douglas Junior et al., 1979). From the study area, 2731 triangular elements were used, and a constant flow inlet through the Tietê river was assumed (0.1 m/s and 0.05 m/s in sectors A and B). The values of the physical parameters used are shown in Table 2.

We must highlight that most of the parameters involved had to be inferred by the authors, based on in situ analysis (see page 6). Also, the proliferation of the invader is directly related to human activity (Ricciardi, 1998), so we assumed a small uniform presence of larvae population throughout the study region, $L(0) = 0.019 \text{ g/l}$, and for the adult mussel, we considered $M(0) = 100 \text{ g/m}^2$ uniformly along the contour of the region. However, sector A and B received as initial condition $M(0) = 50 \text{ g/m}^2$, since a smaller amount better represents these particular regions, as they receive influx from small streams currently free of the mussel infestation. The algae population received $A(0) = 0.001 \text{ g/l}$ as initial condition evenly distributed throughout the reservoir, similarly to the initial conditions for larvae.

In addition, it was admitted that the larvae mortality rate, b_1 , assumes a different value for a specific normalized velocity range. Therefore, for the normalized range of 0.03 m/s to 0.15 m/s we considered $b_1 = 0.45$, which corresponds around 0.1 m/s to 0.5 m/s in non-normalized values (Xu et al., 2015a). These values represent colonization velocity.

Finally, as the objective of this work was to study the beginning of infestation, the simulation assumed a period of 540 days, seasonal climatic effects were not considered as well as reservoir depth, and we worked with 0.4 days of time step.

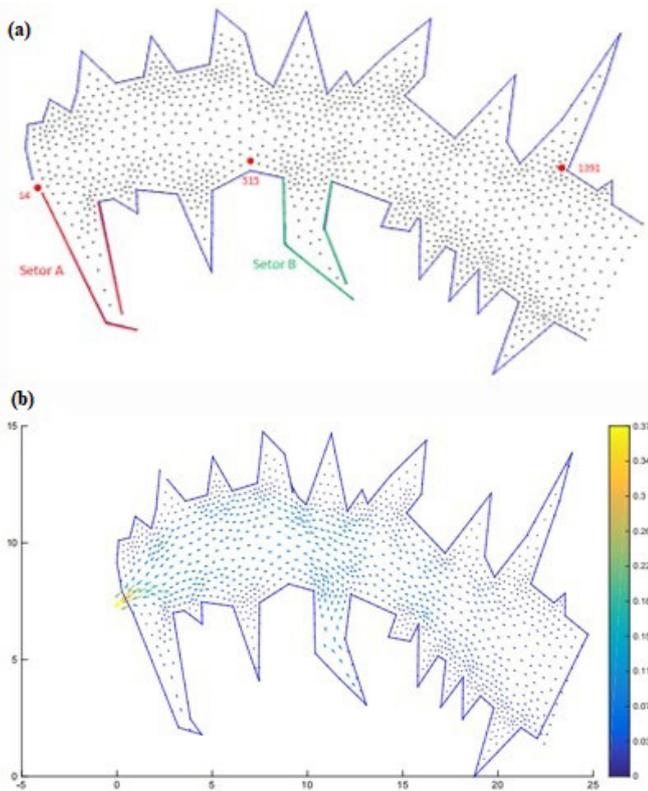


Figure 4. (a) Finite element mesh and observation points; (b) Normalized velocity field.

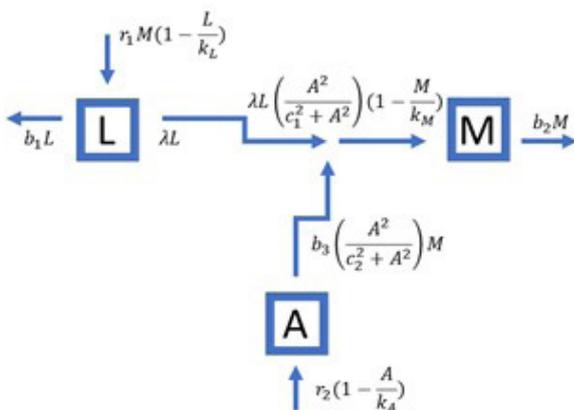


Figure 5. Compartment layout diagram.

Table 2. Parameters used in the simulations.

Parameter	Values	Units	Reference
D_A	1.2	m^2 / day	Cangelosi et al. (2015)
D_M	0.0012	m^2 / day	Montesor (2014)
D_L	0.012	m^2 / day	van de Koppel et al. (2005)
b_1	0.015*	day^{-1}	Inferred
b_2	0.01	day^{-1}	Inferred
b_3	0.0002	$\text{m}^{-1} \text{day}^{-1}$	Inferred
λ	0.03	day^{-1}	Inferred
r_1	0.07	$\text{m}^{-1} \text{day}^{-1}$	Inferred
r_2	0.12	day^{-1}	Inferred
K_L	20	g/l	Inferred
K_M	1732	g/m^2	Inferred
K_A	0.01	g/l	Inferred
c_1	0.001	g/l	Inferred
c_2	0.001	g/l	Inferred

RESULTS

The qualitative analysis of the results, which can be seen in Figures 6 to 8, that show the evolution of the densities of algae, with 180, 360 and 540 days of analysis, respectively.

From the observation of the Figures 6 to 8, the algae population after 540 days is smaller at the edges due to the high

concentration of adult mussels. Besides, it is noted that the highest concentration of algae is in sector B possibly due the low density of mussels, as larvae sink or are carried away by the flow in that region (Chou, 1999). Figures 9 to 11 show the evolution of the densities of larvae of the golden mussel, with 180, 360 and 540 days of analysis, respectively.

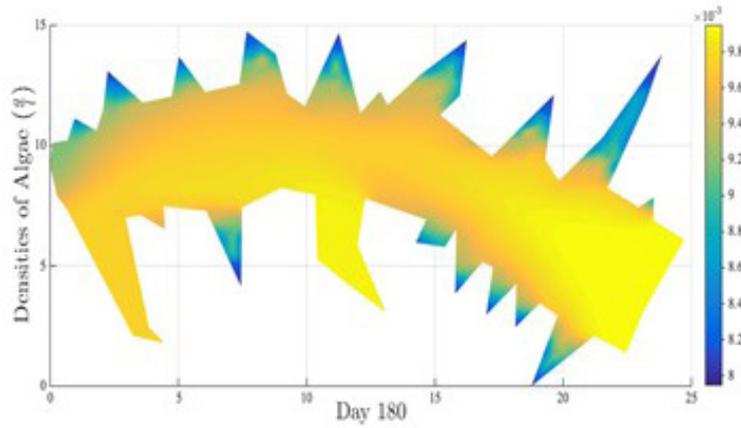


Figure 6. Densities of algae with 180 days of analysis.

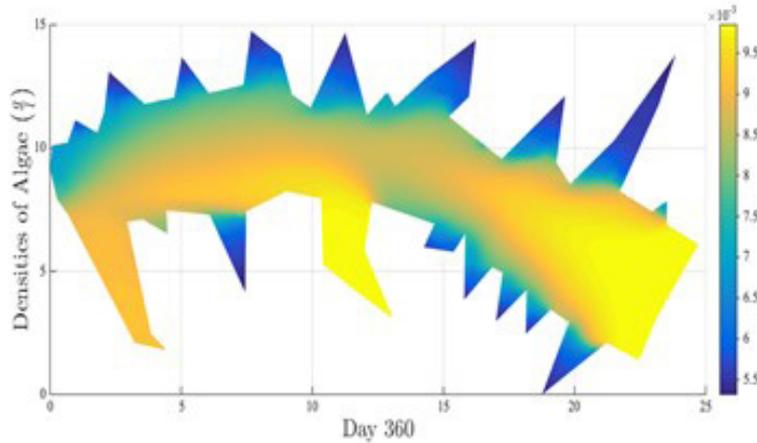


Figure 7. Densities of algae with 360 days of analysis.

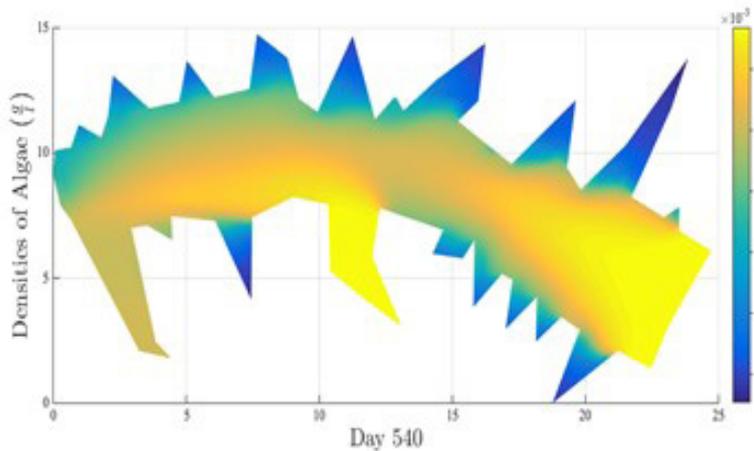


Figure 8. Densities of algae with 540 days of analysis.

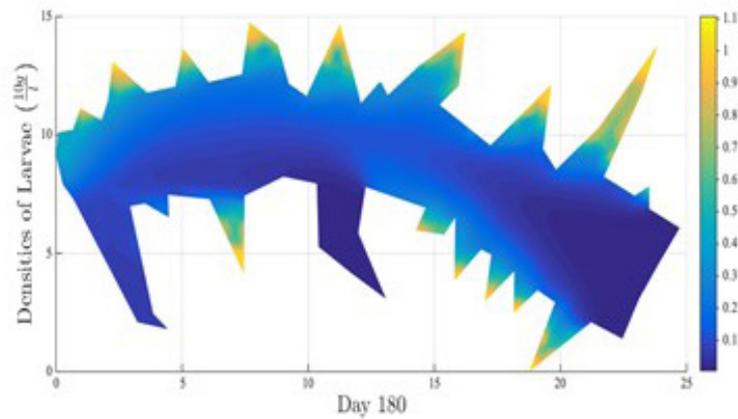


Figure 9. Densities of larvae with 180 days of analysis.

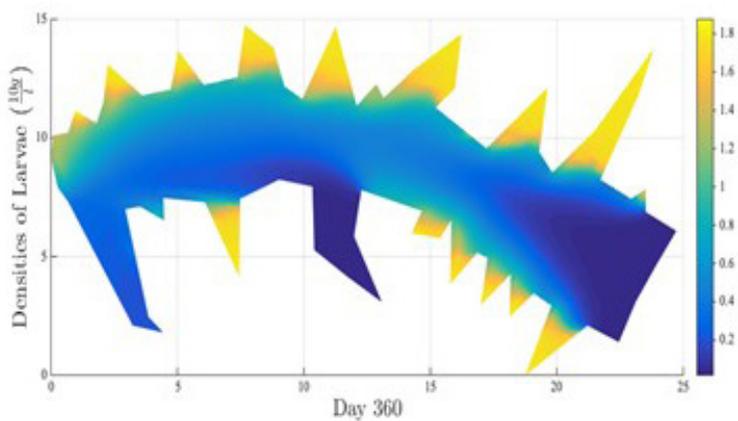


Figure 10. Densities of larvae with 360 days of analysis.

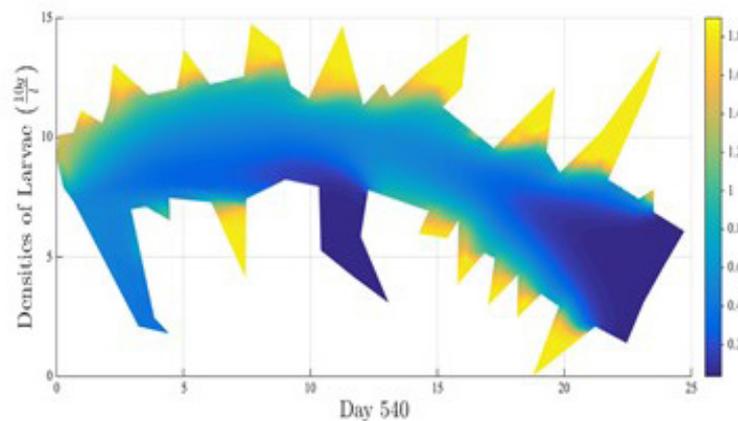


Figure 11. Densities of larvae with 540 days of analysis.

Note that the concentration of golden mussel larvae presents a pattern of high densities in low velocity regions ($< 0.1 m/s$). It is important to emphasize that the larvae must first reach a given region to initiate the settlement and development of into the adult mussel, as they are carried by the flow. Consequently, after one year of simulation (see Figure 10) it is possible to see a significant concentration of larvae at the dam region, not visible on the result

of the six months simulation (see Figure 9). Figures 12 to 14 show the evolution of the densities of golden mussel, with 180, 360 and 540 days of analysis, respectively.

Analyzing Figures 12 to 14 comparatively, it is possible to observe that the reservoir has a large population of adult mussels with 360 days of simulation, particularly on the borders with special accumulation in the region of the dam. The result of

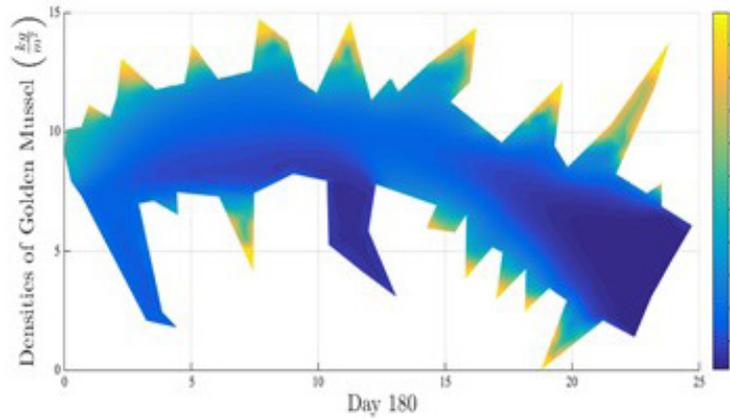


Figure 12. Densities of golden mussel with 180 days of analysis.

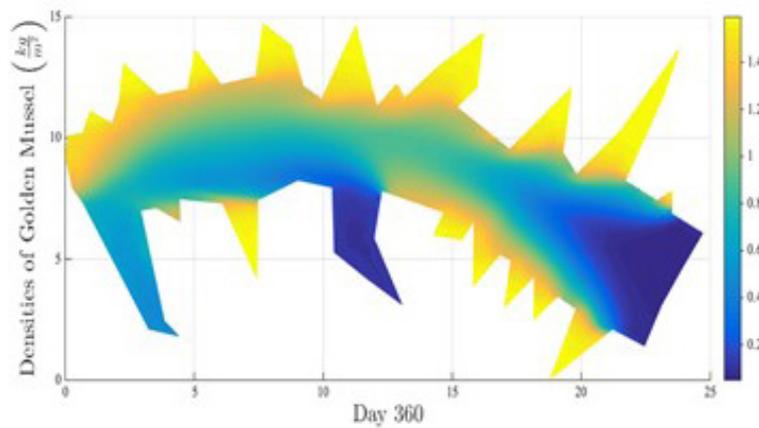


Figure 13. Densities of golden mussel with 360 days of analysis.

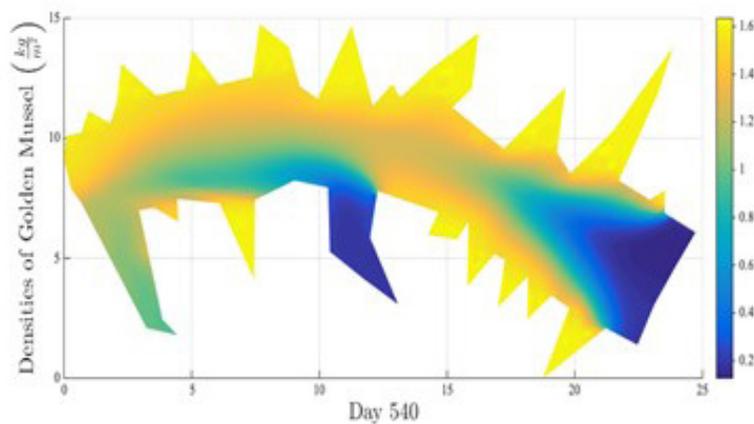


Figure 14. Densities of Golden Mussel with 540 Days of Analysis.

the simulation for 540 days shows that, in fact, the adult mussel population reaches levels close to the environment limit, i.e., carrying capacity, which is around $1.7 \text{ kg} / \text{m}^2$.

Through this methodology, it is also possible to choose specific nodes of the finite element mesh used in the simulation to observe in detail the temporal evolution of the reservoir populations. Figure 4 illustrates the choice of observation points

and their spatial correspondence with the geometry adopted for the study area. Figures 15 to 17 illustrate the temporal evolution of populations at specific points in the Tres Irmãos reservoir that correspond to nodes of the finite element mesh (see Figure 4): close to the dam (node 14), midpoint of the reservoir on the left margin (node 515) and the entrance to the Pereira Barreto Channel (node 1391), respectively.

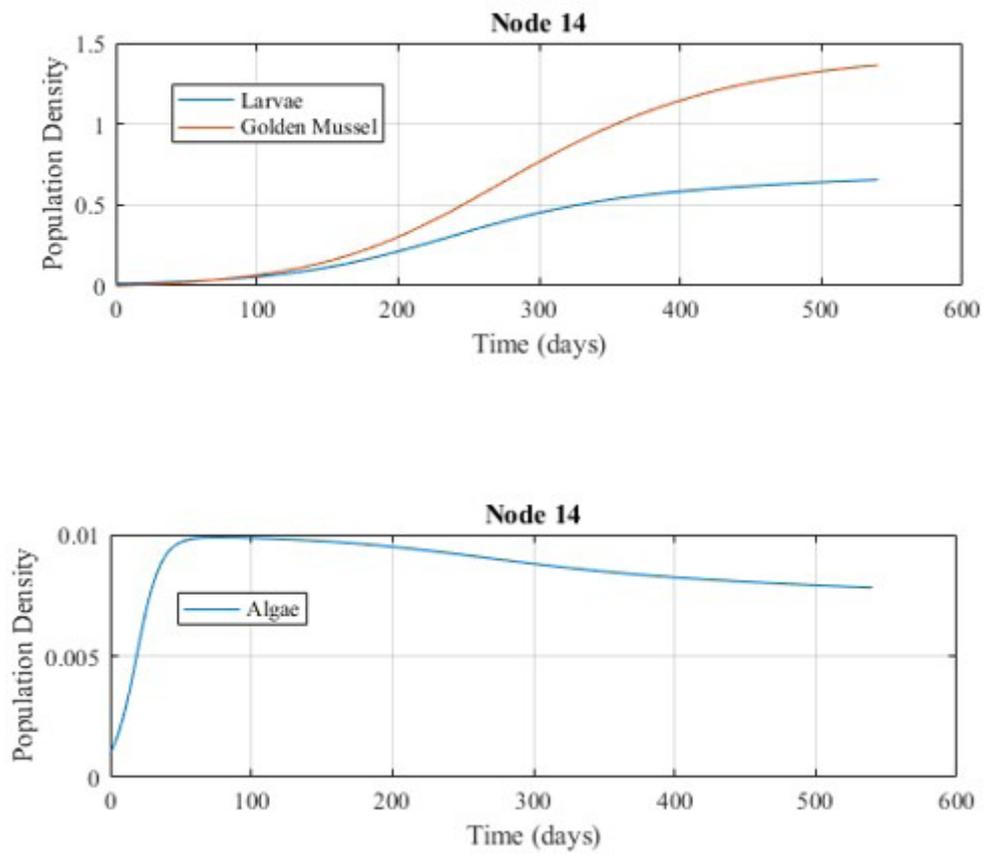


Figure 15. Temporal evolution of populations at node 14, located in the dam.

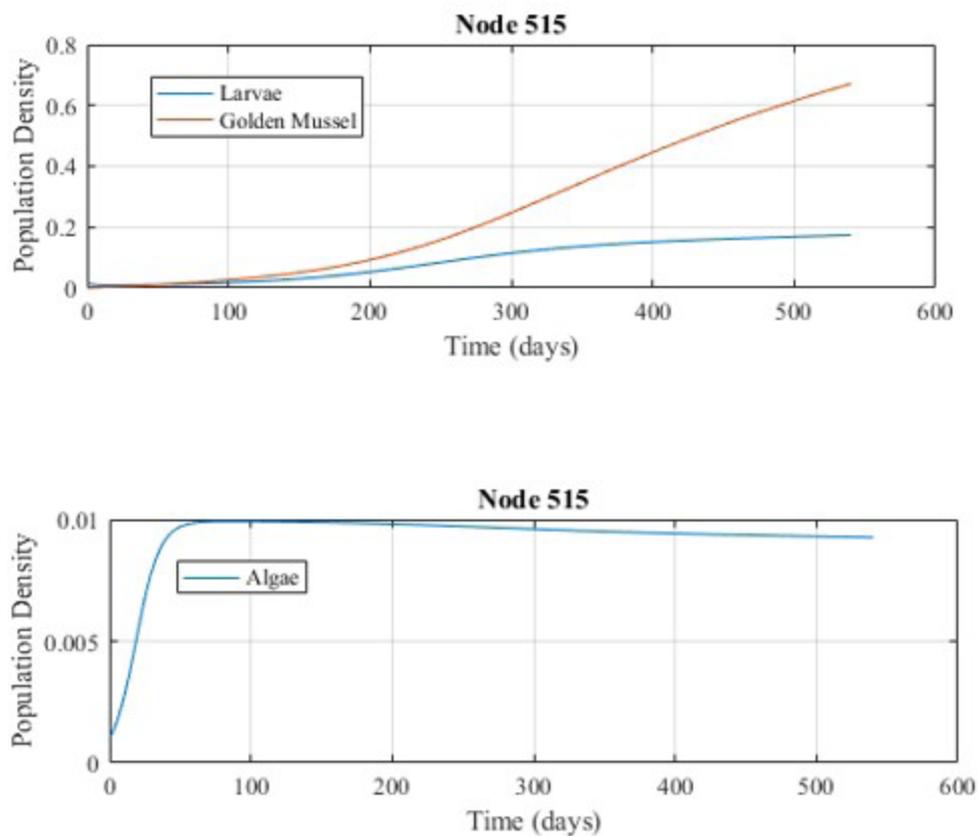


Figure 16. Temporal evolution of populations at node 515, in the margin of sector B.

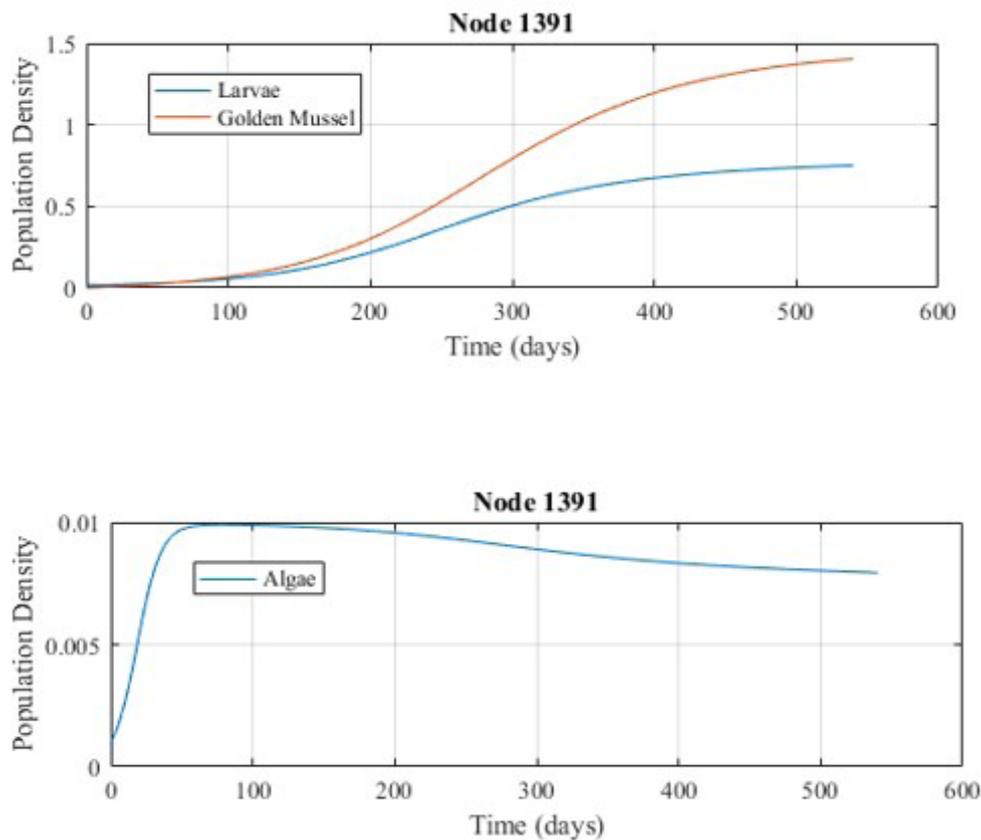


Figure 17. Temporal evolution of populations at node 1391, in the entrance of Pereira Barreto. Channel.

From Figure 15, it is possible to observe that the region of the dam was progressively infested by mussels and that after 18 months of simulation it has reached around 80% of its carrying capacity. It can be said that this is a region with such a high concentration of the species will require special attention since there are protection grids where mussels tend to accumulate. From the simulation, it can be inferred that the grids should undergo maintenance/cleaning approximately 1 year after the start of the infestation. The analysis of Figure 16 shows that although it is an accumulation point, it is not as worrying as the dam region, reaching about half of the mussel carrying capacity in 18 months of simulation. Figure 17 illustrates that the region close to the entrance to the Pereira Barreto Channel is an important accumulation point as well. As the channel is lined with concrete, it is possible that the large concentration in the region makes the channel a nursery for the species, even contributing to the infestation of other areas due to the natural hydrodynamics of the region.

The complete simulation for 540 days can be found at: <https://www.youtube.com/watch?v=WtUPcrQinp4>

CONCLUSIONS

The results have been promising and match with the field observations, as can be seen in Figure 3, which presents the chlorophyll-a density in the region. Note that the chlorophyll-a density map resembles the zones highlighted by the algae numerical result shown in Figure 8 (Basak et al., 2021).

Although the results obtained qualitatively converge with real life observations, it is important to emphasize that for a more assertive quantitative analysis, it is necessary to obtain more field data. Accordingly, more collection points and a longer time series of data would be needed.

The methodology can be used to forecast infestation of other reservoirs and to assist in scheduling of periodic cleaning/maintenance of the affected structures, such as hydroelectric protection grids. Furthermore, the results illustrated by Figure 15, which corresponds the region next to the dam, indicate fast evolution of populational density of adult mussels. Thus, this result is presented as another tool for hydroelectric operators who can use the information together with field inspections to contribute to plan maintenance intervals before the mussel infestation can cause damage to the equipment. Additionally, visual inspections of the HPP structures are costly and considered an operational risk for the workers, therefore companies in the area (CTG Brasil, SPIC Brasil and Tijoá Energia) can benefit from the development of tools to manage the golden mussel situation while preserving the safety of the employees and reducing costs.

The mathematical model has proven to be effective and efficient, with a great potential to improve current methods of quantification and become an important tool in the management of the golden mussel. Finally, the method can be adapted to generate maps of distribution of mussel density in other location which face similar difficulties.

Future developments

This is an ongoing project and the mathematical tools developed here are currently being tested in new areas. The main goal of the project is to combat the golden mussel and recover impacted environments. As such the method presented here will be useful in measuring current infestations and forecasting different infestation scenarios.

ACKNOWLEDGEMENTS

Research carried out within the scope of the project “Biotechnology for Golden Mussel Control in Brazil” (PD-10381-0419/2019) with funding from CTG Brasil, SPIC Brasil and Tijoá Energia, within the Research & Development Program of ANEEL. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

REFERENCES

- Baptistelli, S. C. (2008). *Análise crítica da utilização de modelagem matemática na avaliação da dispersão de efluentes leves no litoral da Baixada Santista (Estado de São Paulo)* (Tese de doutorado). Escola Politécnica, Universidade de São Paulo, São Paulo. <http://dx.doi.org/10.11606/T.3.2008.tde-24112008-150611>.
- Basak, R., Wahid, K. A., & Dinh, A. (2021). Estimation of the chlorophyll: a concentration of algae species using electrical impedance spectroscopy. *Water*, *13*(9), 1223. <http://dx.doi.org/10.3390/w13091223>.
- Bodkin, J. L., Dean, T. A., Coletti, H. A., & Ballachey, B. E. (2016). *Mussel bed sampling: standard operating procedure, v. 1.2, Southwest Alaska Network* (Natural Resource Report NPS/SWAN/NRR—2016/1175). Fort Collins: National Park Service.
- Boltovskoy, D., Correa, N., Cataldo, D., & Sylvester, F. (2006). Dispersion and Ecological Impact of the Invasive Freshwater Bivalve *Limnoperna fortunei* in the Río de la Plata Watershed and Beyond. *Biological Invasions*, *8*(4), 947-963. <http://dx.doi.org/10.1007/s10530-005-5107-z>.
- Burguera, A., & Oliver, G. (2016). High-resolution underwater mapping using side-scan sonar. *PLoS One*, *11*(1), e0146396. PMID:26821379. <http://dx.doi.org/10.1371/journal.pone.0146396>.
- Cangelosi, R. A., Wollkind, D. J., Kealy-Dichone, B. J., & Chaiya, I. (2015). Nonlinear stability analyses of Turing patterns for a mussel-algae model. *Journal of Mathematical Biology*, *70*(6), 1249-1294. PMID:24832542. <http://dx.doi.org/10.1007/s00285-014-0794-7>.
- Carey, C. S., Jones, J. W., Butler, R. S., Kelly, M. J., & Hallerman, E. M. (2019). A comparison of systematic quadrat and capture-mark-recapture sampling designs for assessing freshwater mussel populations. *Diversity*, *11*(8), 127. <http://dx.doi.org/10.3390/d11080127>.
- Cataldo, D., & Boltovskoy, D. (2000). Yearly reproductive activity of *Limnoperna fortunei* (Bivalvia) as inferred from the occurrence of its larvae in the plankton of the lower Paraná River and the Río de la Plata estuary (Argentina). *Aquatic Ecology*, *34*(3), 307-317. <http://dx.doi.org/10.1023/A:1009983920942>.
- Cataldo, D., Boltovskoy, D., Hermosa, J., & Canzi, C. (2005). Temperature-dependent rates of larval development in *Limnoperna Fortunei* (Bivalvia: mytilidae). *The Journal of Molluscan Studies*, *71*(1), 41-46. <http://dx.doi.org/10.1093/mollus/eyi005>.
- Chou, C. L. (1999). *Potential biofouling strategies against blue mussel (Mytilus edulis), infestation in a cooling water system*. Dartmouth: Department of Fisheries & Oceans, Science Branch, Marine Environmental Sciences Division, Bedford Institute of Oceanography.
- Donea, J., & Huerta, A. (2003). *Finite element methods for flow problems*. Chichester: John Wiley & Sons. <http://dx.doi.org/10.1002/0470013826>.
- Douglas Junior, J., Dupont, T., & Ewing, R. E. (1979). Incomplete iteration for time-stepping a Galerkin method for a quasilinear parabolic problem. *SIAM Journal on Numerical Analysis*, *16*(3), 503-522. <http://dx.doi.org/10.1137/0716039>.
- Edelstein-Keshet, L. (2005). *Mathematical models in biology*. Philadelphia: Society for Industrial and Applied Mathematics. <http://dx.doi.org/10.1137/1.9780898719147>.
- Fan, F. M., Siqueira, V. A., Fleischmann, A. S., Brêda, J. P. F., Paiva, C. D., Pontes, P. R. M., & Collischonn, W. (2021). On the discretization of river networks for large scale hydrologic-hydrodynamic models. *Revista Brasileira de Recursos Hídricos*, *26*, e5. <http://dx.doi.org/10.1590/2318-0331.262120200070>.
- Ganju, N. K., Brush, M. J., Rashleigh, B., Aretxabaleta, A. L., Del Barrio, P., Grear, J. S., Harris, L. A., Lake, S. J., McCardell, G., O'Donnell, J., Ralston, D. K., Signell, R. P., Testa, J. M., & Vaudrey, J. M. (2016). Progress and challenges in coupled hydrodynamic-ecological estuarine modeling. *Estuaries and Coasts*, *39*(2), 311-332. PMID:27721675. <http://dx.doi.org/10.1007/s12237-015-0011-y>.
- Gireli, T. Z., Souza, C. M. M. A., Nobre, L. B., & Garcia, P. D. (2017). The efficiency of curved jetties in Bay of Santos – SP: numerical modeling. *Revista Brasileira de Recursos Hídricos*, *22*(0), e5. <http://dx.doi.org/10.1590/2318-0331.011716092>.
- Harari, J., & Camargo, R. (1998). Modelagem numérica da região costeira de Santos (SP): circulação de maré. *Revista Brasileira de Oceanografia*, *46*(2), 135-156. <http://dx.doi.org/10.1590/S1413-77391998000200004>.
- Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis – IBAMA. (2019). Retrieved in 2021, March 3, from <https://www.ibama.gov.br/especies-exoticas-invasoras/sobras-especies-exoticas-invasoras#sobre-especies-exoticas-invasoras>
- Iwai, N., Yasumiba, K., & Takahara, T. (2019). Efficacy of environmental DNA to detect and quantify stream tadpoles

- of *Odorrana splendida*. *Royal Society Open Science*, 6(1), 181798. PMID:30800406. <http://dx.doi.org/10.1098/rsos.181798>.
- Johnson, C. (1987). *Numerical solution of partial differential equations by the finite element method*. Cambridge University Press, Cambridge.
- Karatayev, A., Burlakova, L., & Padilla, D. (1997). The Effects of *Dreissena polymorpha* (Pallas) Invasion on aquatic communities in Eastern Europe. *Journal of Shellfish Research*, 16, 187-203.
- LeVeque, R. J. (2007). *Finite difference methods for ordinary and partial differential equations: steady-state and time-dependent problems* (Vol. 98). Philadelphia: SIAM. <http://dx.doi.org/10.1137/1.9780898717839>.
- Liu, W. C., Liu, H. M., & Yam, R. S. W. (2021). A three-dimensional coupled hydrodynamic: ecological modeling to assess the planktonic biomass in a subalpine lake. *Sustainability*, 13(22), 12377. <http://dx.doi.org/10.3390/su132212377>.
- Mishra, S., & Mishra, D. (2012). Normalized difference chlorophyll index: a novel model for remote estimation of chlorophyll-a concentration in turbid productive waters. *Remote Sensing of Environment*, 117, 394-406. <http://dx.doi.org/10.1016/j.rse.2011.10.016>.
- Montresor, L. C. (2014). *Implicações ecotoxicológicas do controle químico de *Limnoperna fortunei* (Dunker, 1857) (Bivalvia: Mytilidae)* (Tese de doutorado). Universidade Federal de Minas Gerais, Belo Horizonte.
- Murray, D. (2007). *Mathematical biology: I, an introduction*. New York: Springer Science & Business Media.
- Oliveira Junior, R. B., Paula, R. S., Diniz, V. S. R., Carvalho, M. D., & Cardoso, A. V. (2018). RFLP pattern determination for the invasive bivalves *Limnoperna fortunei* (Dunker, 1857) and *Corbicula fluminea* (Muller, 1774). *Ambiente e Água*, 13(3), 1-2. <http://dx.doi.org/10.4136/ambi-agua.2172>.
- Page, B. P., Olmanson, L. G., & Mishra, D. R. (2019). A harmonized image processing workflow using Sentinel-2/MSI and Landsat-8/OLI for mapping water clarity in optically variable lake systems. *Remote Sensing of Environment*, 231, 111284. <http://dx.doi.org/10.1016/j.rse.2019.111284>.
- Pestana, D., Ostrensky, A., Tschá, M. K., & Boeger, W. A. (2010). Prospecção do molusco invasor *Limnoperna fortunei* (Dunker, 1857) nos principais corpos hídricos do estado do Paraná, Brasil. *Papéis Avulsos de Zoologia*, 50(34), 553-559. <http://dx.doi.org/10.1590/S0031-10492010003400001>.
- Pie, M. R., Ströher, P. R., Agostinis, A. O., Belmonte-Lopes, R., Tadra-Sfeir, M. Z., & Ostrensky, A. (2017). Development of a real-time PCR assay for the detection of the golden mussel (*Limnoperna fortunei*, Mytilidae) in environmental samples. *Anais da Academia Brasileira de Ciências*, 89(2), 1041-1045. PMID:28640350. <http://dx.doi.org/10.1590/0001-3765201720160723>.
- Ricciardi, A. (1998). Global range expansion of the Asian mussel *Limnoperna fortunei* (Mytilidae): another fouling threat to freshwater systems. *Biofouling*, 13(2), 97-106. <http://dx.doi.org/10.1080/08927019809378374>.
- Roversi, F., Rosman, P. C. C., & Harari, J. (2016). Análise das trajetórias das águas continentais afluentes ao sistema Estuarino de Santos. *Revista Brasileira de Recursos Hídricos*, 21(1), 242-250. <http://dx.doi.org/10.21168/rbrh.v21n1.p242-250>.
- SERVIR. (2021). Retrieved in 2021, November 9, from <https://github.com/SERVIR/water-quality-gee>
- Silva, F. A., Barbosa, N. P. U., Paula, R. S., Carvalho, V. A., Corrêa, A., Cardoso, A. V., & de Carvalho, M. D. (2016). Mexilhão-Dourado no Brasil: detecção de um perigoso invasor. *Ciência Hoje*, 338(57), 38-42. Retrieved in 2021, June 18, from https://www.cbeih.org/wp-content/uploads/2019/09/silva_2016.pdf
- Simeão, C. M. G., Resende, M. F., & Martinez, C. B. (2011). Variação das características hidráulicas em condutos forçados operando sob condições de infestação por *Limnoperna fortunei*. *Revista Brasileira de Recursos Hídricos*, 16(2), 13-24. <http://dx.doi.org/10.21168/rbrh.v16n2.p13-24>.
- Sylvester, F., Dorado, J., Boltovskoy, D., Juarez, A., & Cataldo, D. (2005). Filtration rates of the invasive pest bivalve *Limnoperna fortunei* as a function of size and temperature. *Hydrobiologia*, 534, 71-80. <http://dx.doi.org/10.1007/s10750-004-1322-3>.
- U.S. Geological Survey – USGS. (2021). *Using the USGS Landsat Level-1 Data Product*. Retrieved in 2021, June 18, from <https://www.usgs.gov/core-science-systems/nli/landsat/using-usgs-landsat-level-1-data-product>
- van de Koppel, J., Rietkerk, M., Dankers, N., & Herman, P. M. J. (2005). Scale-dependent feedback and regular spatial patterns in young mussel beds. *American Naturalist*, 165(3), E66-E77. PMID:15729660. <http://dx.doi.org/10.1086/428362>.
- Wang, H., Huang, W., Harwell, M. A., Edmiston, L., Johnson, E., Hsieh, P., Milla, K., Christensen, J., Stewart, J., & Liu, X. (2008). Modeling oyster growth rate by coupling oyster population and hydrodynamic models for Apalachicola Bay, Florida, USA. *Ecological Modelling*, 211(1-2), 77-89. <http://dx.doi.org/10.1016/j.ecolmodel.2007.08.018>.
- Wang, R.-H., Liu, Q.-X., Sun, G.-Q., Jin, Z., & van de Koppel, J. (2009). Nonlinear dynamic and pattern bifurcation in a model for spatial patterns in young mussel beds. *Journal of the Royal Society, Interface*, 6(37), 705-718. PMID:18986965. <http://dx.doi.org/10.1098/rsif.2008.0439>.
- Xia, Z., Zhan, A., Gao, Y., Zhang, L., Haffner, G. D., & MacIsaac, H. J. (2017). Early detection of a highly invasive bivalve based on environmental DNA (eDNA). *Biological Invasions*, 20(2), 437-447. <http://dx.doi.org/10.1007/s10530-017-1545-7>.
- Xu, M., Darrigran, G., Wang, Z., Zhao, N., Lin, C. C., & Pan, B. (2015a). Experimental study on control of *Limnoperna fortunei*

biofouling in water transfer tunnels. *Journal of Hydro-environment Research*, 9(2), 248-258. <http://dx.doi.org/10.1016/j.jher.2014.06.006>.

Xu, M., Wang, Z., Zhao, N., & Pan, B. (2015b). Growth, reproduction, and attachment of the golden mussel (*Limnoperna fortunei*) in water diversion projects. *Acta Ecologica Sinica*, 35(4), 70-75. <http://dx.doi.org/10.1016/j.chnaes.2015.06.006>.

Zhang, C., Wang, L., Zhu, H., & Tang, H. (2020). Integrated hydrodynamic model for simulation of river-lake-sluice interactions. *Applied Mathematical Modelling*, 83, 90-106. <http://dx.doi.org/10.1016/j.apm.2020.02.019>.

Zhou, D., Liu, M., Qi, K., & Liu, Z. (2021). Long-time behaviors of two stochastic mussel-algae models. *Mathematical Biosciences and Engineering*, 18(6), 8392-8414. PMID:34814305. <http://dx.doi.org/10.3934/mbe.2021416>.

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Editor-in-Chief: Adilson Pinheiro

Associated Editor: Iran Eduardo Lima Neto

APPENDIX A. ADDITIONAL ENVIRONMENTAL DATA.

Satellite imagery processing

Additional environmental data on chlorophyll-a (Chl-a) density and water surface temperature (WST) spatial and temporal distribution was obtained from satellite imagery. This dataset was used for comparison and for definition of annual averages in each location to be used as a baseline in the model computation. The selected images from the satellite Landsat 8 produced between 2013-2021 (Figure 18a) were processed at Google Earth Engine (GEE) platform, modifying the scripts idealized by Page et al. (2019) and available at SERVIR (2021) repository. At first, the Landsat 8 Tier 1 collection was imported, totalizing 84 scenes (path/row 223/74) for the period between 2013 April and 2021 May, with scene cloud percentage less than 10%. Secondly, the delimitation of the reservoir was done using the SWIR 1 band. After that, the atmospheric correction was performed using the Modified Atmospheric correction for INland waters (MAIN), developed by Page et al. (2019). Lastly, the Chl-a, in $\mu\text{g/L}$, and WST, in $^{\circ}\text{C}$, were computed (Table 3). Average and median monthly and yearly variations were also calculated (Figure 2).

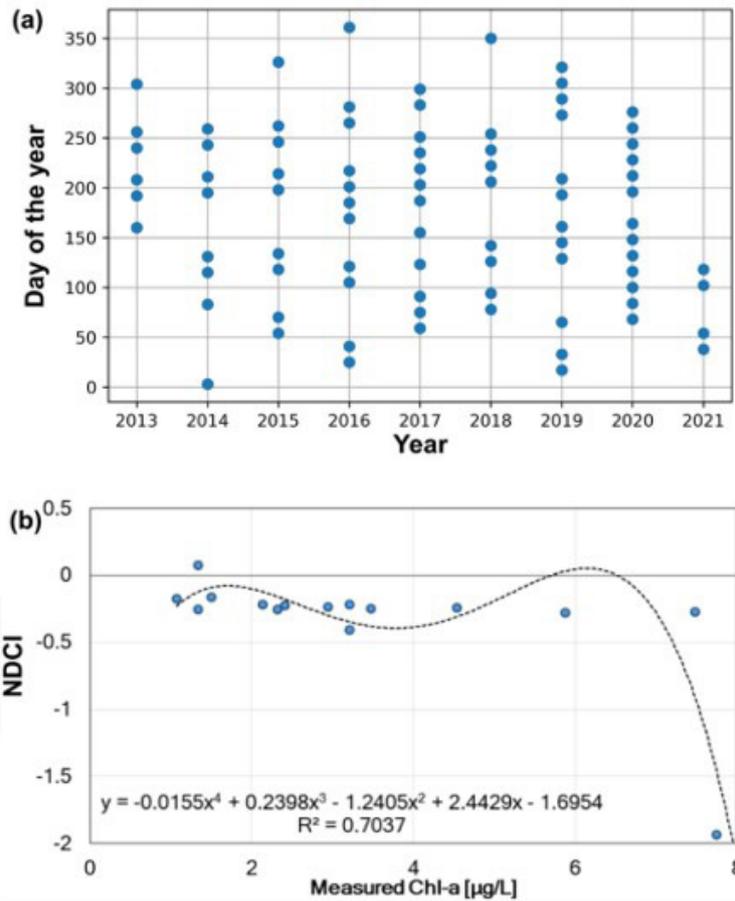


Figure 18. (a) Temporal distribution of Landsat 8 imagery used in this work; (b) Comparison between the NDCI and the Chl-a density measured by CETESB in the Tres Irmãos HPP reservoir.

Table 3. Bio-optical parameters computed from satellite images.

Parameter	Formula	Reference
Chlorophyll-a (<i>chl-a</i>)	$NDCI = \frac{R_{rs}(655) - R_{rs}(560)}{R_{rs}(655) + R_{rs}(560)}$ $chl_a = -1.6954 + 2.4429 \times NDCI - 1.2405 \times [NDCI]^2 + 0.239 \times [NDCI]^3 - 0.0155 \times [NDCI]^4$	Mishra & Mishra (2012) This paper
Water Surface Temperature (WTS)	$L_l = M_L Q_{cal} + A_L$ $WTS_{WC} = (K_2 / \ln(K_1 / L_l + 1)) - 273.15$ $WTS = (0.7745 \times T_{SC}) + 9.6502$	U.S. Geological Survey (2021)

Note: *NDCI* = Normalized Difference Chlorophyll-a Index; R_n = remote sensing

Chl-a formula calibration

So that the Chl-a density values could be compared to values close to reality, a calibration was carried out from a water quality monitoring point carried out by São Paulo State Environmental Company (CETESB) at the 'Tres Irmãos' reservoir (20°39'35"S and 51°26'41"W). Correlation was made between the NDCI and the values measured by CETESB (Figure 18b). The equation for determining the density of chl-a was fitted to a fourth-degree polynomial (Table 3), presenting an R2 of 0.70.

Values extraction to the points of the grid

The values of Chl-a (in g/L) and WST (in °C), for scenes taken between the years 2013 and 2021, were extracted for each point of the sampling grid, using the GEE platform.