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Dynamic Analysis of the Predator-Prey Model on the Decline of the Bonylip Barb Fish Population in Rawa Pening Lake, Central Java, Indonesia

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ABSTRACT

This research aims to model the population dynamics of the Bonylip Barb Fish (Osteochilus vittatus Valenciennes) and predator fish in Rawa Pening Lake using the Lotka-Volterra predator-prey mathematical model. The purpose of this study is to understand the interaction between the Bonylip Barb Fish and predator fish, as well as to determine the equilibrium points and the stability of the populations of both species. The methods used include constructing the mathematical model, determining equilibrium points, linearizing the model, analyzing the stability of the equilibrium points, and performing numerical simulations using Google Colab. The results show that the predator-prey mathematical model is effective in describing the interaction between the Bonylip Barb Fish and predator fish in Rawa Pening Lake. The equilibrium points obtained are T_1 when both populations are extinct, T_2 when the predator population is extinct, T_3 when the prey population is extinct, and T_4 when both populations interact, showing system stability with damped oscillations. This means that the populations of both species will oscillate around the equilibrium point, but disturbances from equilibrium will decrease over time. This indicates that the population system of the Bonylip Barb Fish and predator fish in Rawa Pening Lake has long-term stability. This research provides important contributions to the management and conservation of the Rawa Pening Lake ecosystem by providing a better understanding of the population dynamics of the Bonylip Barb Fish in the lake.

1. Introduction

Bonylip Barb Fish (Osteochilus Vittatus Valenciennes) is one of the endemic fish species originating from Rawa Pening [1]. Over time, it is known that the population of Bonylip Barb Fish continues to decline every year. According to research conducted by Yanto, the results of surveys conducted on fishermen in various places show that catching Bonylip Barb Fish is increasingly difficult, so it can be concluded that the number of Bonylip Barb Fish has decreased by more than ten percent [2]. According to information from the Semarang Regency Fisheries Service, the decline in the population of Bonylip Barb Fish is caused by predation activities by predatory fish against

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Bonylip Barb Fish species [3]. The decline in the population of Bonylip Barb Fish raises concerns about the potential scarcity and even extinction of Bonylip Barb Fish .

This decline has become a serious concern for interested parties, especially the Fisheries Service and local communities, as it can have a major impact on ecosystem balance and the sustainability of fisheries resources. One scientific approach that can be used to understand the population dynamics of Bonylip Barb Fish is through the analysis of Predator-Prey models. This model helps identify the complex relationship between predator fish and prey fish, and how ecological and environmental factors can affect the population dynamics of both.

The Predator-Prey model based on the Lotka-Volterra model is one of the most popular models in ecological mathematics [4]. According to Luckinbill [5] considered a prey - predator population model and showed that prey and predator populations can live together for a long period of time when the frequency of contact between the two is reduced [5].

Some previous research shows that there have been various studies analyzing the Predator-prey model in aquatic ecosystems. The first research conducted by Resmi *et al*., [6] entitled "Optimal Control of Water Hyacinth Population Growth with Grass Carp and Harvesting". This research focuses on optimal control of water hyacinth populations using grass carp and harvesting methods using the Predator-Prey model with the Holling type III response function [6] . The second research conducted by Ilmiawan *et al*., [7] entitled "Analysis of Water Hyacinth Predator-Prey Model with Grass Carp and Harvesting". This research focuses on analyzing the population of water hyacinth with grass carp and harvesting using the holling type II function [7].

The third research conducted by Wijayanto *et al*., [8] entitled "The Predator-Prey Model On Squids And Anchovies Fisheries In Jepara District, Central Java, Indonesia". This study examines the Predator-Prey model on anchovies and squid fisheries in Jepara. This study provides insight into the Predator-Prey dynamics in the context of anchovy and squid fisheries [8]. The fourth research conducted by Pratiwi *et al*., [9] entitled "Analysis of Predator-Prey Mathematical Models of Fisheries in Polluted Aquatic Ecosystems". This research focuses on analyzing the Predator-Prey mathematical model in polluted aquatic ecosystems using the Lotka-Volterra model [9]. Finally, the fifth research conducted by Zhuraedah *et al*., 2022 entitled "Predator - Prey Modeling Case Study: Spiny Starfish (Acanthaster Planci) and Coral Reefs". This research examines the Lotka Volterra Predator-Prey model in the population of spiny starfish and coral reefs [10].

Based on these five researchers, the author wants to build a Lotka Volterra predator-prey model and then analyze the stability of the model and conduct numerical simulations to see the condition of the two populations based on the stability point. The author assumes the model occurs in the population of Bonylip Barb Fish and predator fish. Based on information, Bonylip Barb Fish is one of the animals whose population is currently decreasing.

By analyzing the dynamics of the Predator-Prey model on the decline of the Bonylip Barb Fish population in Lake Rawa Pening, it is expected to find deep insights into changes in interactions between species and environmental factors that play an important role. This research will not only provide a better scientific understanding of changes in the ecosystem and fish populations in the lake, but can also help design appropriate and sustainable conservation policies.

2. Methodology

The type of research used is literature study and quantitative analysis. This research also uses a quantitative approach through dynamic analysis of Predator-Prey mathematical models. The variables used in this study are the population of Bonylip Barb Fish as prey (W) and the population of Predator fish (P). The parameters used in this study include the intrinsic growth rate parameter for

Bonylip Barb Fish (α), natural mortality of Bonylip Barb Fish (μ), consumption rate of Predator fish (β), interaction rate of Bonylip Barb Fish and Predators (δ), natural mortality of Predator fish (γ) and competition between Predators (π). The stages carried out in this study, namely: (1) determine the problem that causes the population of Bonylip Barb Fish to decline, (2) determine the variables for both species, (3) make assumptions for both species by adding parameters, (4) create a predator-prey mathematical model, (5) determine and analyze the equilibrium point, (6) perform numerical simulations using Google colab, (7) draw conclusions.

3. Results

3.1 Predator-Prey Model Construction

In this section, the predator-prey model is constructed based on the research variables and parameters using the Lotka-Volterra predator-prey model.

a. Population growth of Bonylip Barb Fish (prey)

The population density of yellow perch is represented as W at time t. The prey population grows logistically $\alpha W\left(1-\frac{W}{K}\right)$ where α is the intrinsic growth rate of yellow perch, and assumes the absence of predator fish and the existence of an environmental capacity limit K. The growth rate of yellow perch decreases under two assumptions. The first assumption is that Bonylip Barb Fish decline due to natural mortality μ and the second assumption is that Bonylip Barb Fish decline due to predation by predatory fish β. So that the population growth rate of Bonylip Barb Fish can be written as follows:

$$\frac{\partial W}{\partial t}=\alpha W\left(1-\frac{W}{K}\right)-\mu W-\beta WP \tag{1}$$

b. Population growth of predatory fish (predator)

The population density of yellow perch is represented as P at time t. The growth rate of the predator fish population follows that of the Bonylip Barb Fish population δ. The growth rate of predator fish will decrease under two assumptions. The first assumption is that predator fish will decrease due to starvation causing natural mortality γ and the second assumption is due to competition between predators π. So the growth rate of predator fish can be written as follows:

$$\frac{\partial P}{\partial t}=\delta WP-\gamma P-\pi P^2 \tag{2}$$

c. Predator-prey Model Construction Results

Based on the assumptions described above, and referring to equations (1) and (2), the interaction model between Bonylip Barb Fish and predatory fish is obtained as follows:

$$\begin{aligned}\frac{\partial W}{\partial t}&=\alpha W\left(1-\frac{W}{K}\right)-\mu W-\beta WP\\ \frac{\partial P}{\partial t}&=\delta WP-\gamma P-\pi P^2\end{aligned} \tag{3}$$

3.2 Determination of Equilibrium Point

The equilibrium point in the system of equations (3) can be obtained by making the right-hand side of each equation equal to zero, then:

$$\left[\alpha-\frac{\alpha W}{K}-\mu-\beta P\right]W=0$$
$$[\delta W-\gamma-\pi P]\ P\ =0$$

As a result, the following equilibrium points are obtained:

a. Point $T_1 = (0,0)$. This equilibrium point indicates that in this condition there is no population of Bonylip Barb Fish and predator fish or the point where both populations are extinct in Rawa Pening lake.
b. Point $T_2 = \left(\frac{K(\alpha-\mu)}{\alpha}, 0\right)$. This equilibrium point means that if the Predator fish population becomes extinct, the Bonylip Barb Fish population will experience a significant increase. Without Predator fish preying on the Bonylip Barb Fish, the Bonylip Barb Fish population can grow rapidly due to the lack of predation pressure.
c. Point $T_3 = \left(0, -\frac{\gamma}{\pi}\right)$. This equilibrium point is negative, so it does not meet the population requirement. Where the population must be positive.
d. Point $T_4 = \left(\frac{K(\alpha\pi+\beta\gamma-\mu\pi)}{\delta K\beta+\alpha\pi}, \frac{\delta K\alpha-\delta K\mu-\alpha\gamma}{\delta K\beta+\alpha\pi}\right)$. This equilibrium point reflects a dynamic equilibrium where the interaction between Bonylip Barb Fish and predatory fish, along with environmental factors such as birth rate, natural mortality, and inter-species interactions, regulates the population of both in the long run.

3.3 Analysis of Equilibrium Point Stability

The predator-prey model in the system of equations (3) is a system of non-linear differential equations, so to determine the stability of the system, a linearization process is required. The linearization process is done using the Jacobian matrix as follows:

$$J = \begin{bmatrix} \alpha - 2\frac{\alpha}{K}W - \mu - \beta P & -\beta W \\ \delta P & \delta W - \gamma - 2P\pi \end{bmatrix} \tag{4}$$

By substituting the equilibrium points into the jacobian matrix, the eigenvalue of the determinant of the jacobian matrix is obtained, so that :

a. Stability analysis of point $T_1 = (0,0)$.
The jacobian matrix of the equilibrium point of extinction of the population of Bonylip Barb Fish and Predator fish $T_1 = (0,0)$ is

$$J(T_1) = \begin{pmatrix} \alpha - \mu & 0 \\ 0 & -\gamma \end{pmatrix} \tag{5}$$

Furthermore, the characteristic equation of the Jacobian matrix $J(T_1)$with $det(J(T_1) - \lambda I) = 0$ can be formed, namely:

$$(\alpha - \mu - \lambda)(-\gamma - \lambda) = 0$$

The eigenvalues of the matrix $J(T_1)$ are $\lambda_1 = \alpha - \mu$ and $\lambda_2 = -\gamma$. This shows that the equilibrium point $\dot{W}_1, \dot{P}_1$ will be stable if $\alpha - \mu > 0$ and $\gamma > 0$.

b. Stability analysis of point $T_2 = \left(\frac{K(\alpha-\mu)}{\alpha}, 0\right)$
The jacobian matrix of the extinction equilibrium point of the Bonylip Barb Fish and Predator fish population $T_2 = \left(\frac{K(\alpha-\mu)}{\alpha}, 0\right)$ is

$$J(T_2) = \begin{pmatrix} -\alpha + \mu & \dfrac{\beta K\mu - \alpha\beta K}{\alpha} \\ 0 & \dfrac{\alpha K\delta - K\delta\mu - \alpha\gamma}{\alpha} \end{pmatrix} \tag{6}$$

Furthermore, the characteristic equation of the jacobian matrix $J(T_2)$ with $det(J(T_2) - \lambda I) = 0$ can be formed, namely:

$$(-\alpha+\mu-\lambda)\left(\frac{\alpha K\delta-K\delta\mu-\alpha\gamma}{\alpha}-\lambda\right)=0$$

The eigenvalues of the matrix $J(T_2)$ are $\lambda_1=-\alpha+\mu$ and $\lambda_2=\frac{\alpha K\delta-K\delta\mu-\alpha\gamma}{\alpha}$. This shows that the equilibrium point $\dot{\mathrm{W}}_2, \dot{\mathrm{P}}_2$ will be stable $\mu<\alpha$ and $\frac{\alpha K\delta-K\delta\mu-\alpha\gamma}{\alpha}<0$.

c. Stability analysis of point $T_3=\left(0,-\frac{\gamma}{\pi}\right)$

The jacobian matrix of the extinction equilibrium point of Bonylip Barb Fish and Predator fish population $T_3=\left(0,-\frac{\gamma}{\pi}\right)$ is

$$J(T_3)=\begin{pmatrix}\alpha+\dfrac{\beta\gamma}{\pi}-\mu & 0\\ -\dfrac{\delta\gamma}{\pi} & \gamma\end{pmatrix} \tag{7}$$

Furthermore, the characteristic equation of the jacobian matrix $J(T_3)$ with $det(J(T_3)-\lambda I)=0$ can be formed, namely:

$$\left(\alpha+\frac{\beta\gamma}{\pi}-\mu-\lambda\right)(\gamma-\lambda)=0$$

The eigenvalues of matrix $J(T_3)$ are $\lambda_1=\alpha+\frac{\beta\gamma}{\pi}-\mu$ and $\lambda_2=\gamma$. This shows that the equilibrium point $\dot{\mathrm{W}}_3, \dot{\mathrm{P}}_3$ will be stable if $\alpha+\frac{\beta\gamma}{\pi}<\mu$ and $\gamma<0$.

d. Stability analysis of point $T_4=\left(\frac{K(\alpha\pi+\beta\gamma-\mu\pi)}{\delta K\beta+\alpha\pi},\frac{\delta K\alpha-\delta K\mu-\alpha\gamma}{\delta K\beta+\alpha\pi}\right)$

The jacobian matrix of the extinction equilibrium point of Bonylip Barb Fish and Predator fish population $T_4=\left(\frac{K(\alpha\pi+\beta\gamma-\mu\pi)}{\delta K\beta+\alpha\pi},\frac{\delta K\alpha-\delta K\mu-\alpha\gamma}{\delta K\beta+\alpha\pi}\right)$ is

$$JT_4=\begin{pmatrix}\dfrac{\alpha(-\alpha\pi-\beta\gamma-\mu\pi)}{\delta K\beta+\alpha\pi} & \dfrac{K\beta(-\alpha\pi-\beta\gamma+\mu\pi)}{\delta K\beta+\alpha\pi}\\ \dfrac{\delta(K\alpha\delta-K\delta\mu-\alpha\gamma)}{K\beta S+\alpha\pi} & \dfrac{\pi(-K\alpha\delta+K\delta\mu+\alpha\gamma)}{K\beta S+\alpha\pi}\end{pmatrix} \tag{8}$$

The above matrix can be written as

$$JT_4\begin{pmatrix}a_{11} & a_{12}\\ a_{21} & a_{22}\end{pmatrix}=0 \tag{9}$$

With

$$a_{11}=\frac{\alpha(-\alpha\pi-\beta\gamma-\mu\pi)}{\delta K\beta+\alpha\pi}$$

$$a_{12}=\frac{K\beta(-\alpha\pi-\beta\gamma+\mu\pi)}{\delta K\beta+\alpha\pi}$$

$$a_{21}=\frac{\delta(K\alpha\delta-K\delta\mu-\alpha\gamma)}{K\beta S+\alpha\pi}$$

$$a_{22}=\frac{\pi(-K\alpha\delta+K\delta\mu+\alpha\gamma)}{K\beta S+\alpha\pi}$$

Furthermore, the characteristic equation of the jacobian matrix $J(T_4)$ with $det(J(T_4)-\lambda I)=0$ can be formed, namely:

$$\lambda^2-(a_{11}+a_{22})\lambda+(a_{11}a_{22}-a_{12}a_{21})=0$$

Because the above form is a quadratic characteristic equation in this case the ABC formula is needed to solve it, so the eigenvalues of the matrix J $J(T_4)$ are obtained

$$\lambda_1 = \frac{(a_{11}+a_{22}) - \sqrt{(a_{11}+a_{22})^2 - 4(a_{11}a_{22} - a_{12}a_{21})}}{2}$$

$$\lambda_2 = \frac{(a_{11}+a_{22}) + \sqrt{(a_{11}+a_{22})^2 - 4(a_{11}a_{22} - a_{12}a_{21})}}{2}$$

This shows that the equilibrium point $\dot{W}_4, \dot{P}_4$will be stable if $trace(J) < 0$ and $Det(J) < 0$.

3.4 Numerical Simulation

Numerical simulations are applied to check for consistency with the analytical results that have been obtained. This simulation is run using Google Colab, which will display a visualization of the dynamics of the Predator-Prey model between the Bonylip Barb Fish and Predator fish populations. Some parameters are referenced based on journal references. Parameter values will be adjusted following the equilibrium points presented in table 1 as follows.

Table 1
Parameter value

Parameter	Simulation 1	Simulation 2	Simulation 3	Reference
α	0.01	4.0	3.5	Assumption
K	70	70	70	Ilmiawan *et al.*, [7]
μ	1.78	1.78	1.78	Kumarawati
β	0.02	0.02	0.95	Assumption
δ	0.01	0.08	0.4	Assumption
γ	0.70	0.70	0.70	Kumawati and Djumanto [1]
π	0.05	0.01	0.012	Assumption

a. First Simulation

Based on the assumptions of the value (K) = 70, the value (μ) = 1.78, the value (γ) = 0.70, the value (α) = 0.01, the value (β) = 0.02, the value (π) = 0.05 and the value (δ) = 0.01. the graph of the population dynamics of Bonylip Barb Fish and Predator fish over time from the equilibrium point T_1 will be displayed as follows:

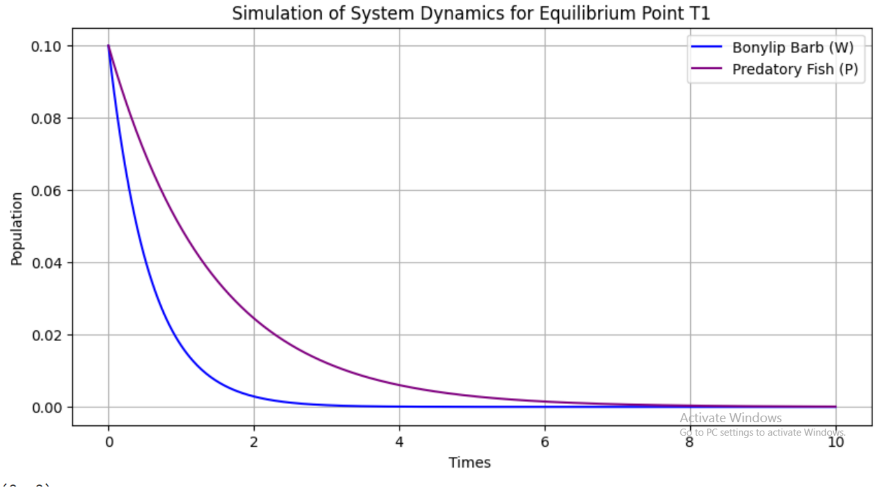

Fig. 1. Simulation of dynamic system for equilibrium point T_1

Based on the eigenvalues obtained for the equilibrium point T_1 with coordinates $(W_1, P_1) = (0, 0)$ two eigenvalues are $\lambda_1 = \alpha - \mu$ $atau$ $\lambda_2 = -\gamma$. If using the parameters from table 1, namely (α) = 0.01, the value of μ = 1.78 and the value of γ = 0.70, the results of the two eigenvalues are as follows:

$$\lambda_1 = \alpha - \mu = 0.01 - 1.78 = -1.77$$
$$\lambda_2 = -\gamma = -0.70$$

Since both eigenvalues ($\lambda_1 = -1.77$ dan $\lambda_2 = -0.70$) are negative, it can be concluded that the equilibrium point T_1 is Asymptotically Stable. This shows that the population of Bonylip Barb Fish and Predator fish will remain at the equilibrium point T_1 or return to the equilibrium point T_1 if there is a small disturbance in the ecosystem.

b. Second Simulation

Based on the assumptions of the value of (K) = 70, the value of (μ) = 1.78, the value of (γ) = 0.70, the value of (α) = 4.0, the value of (β) = 0.02, the value of (π) = 0.01 and the value of (δ) = 0.08, the graph of the population dynamics of Bonylip Barb Fish and Predator fish over time from equilibrium T_2 will be displayed. Predator over time from the equilibrium point T_2 will be displayed as follows:

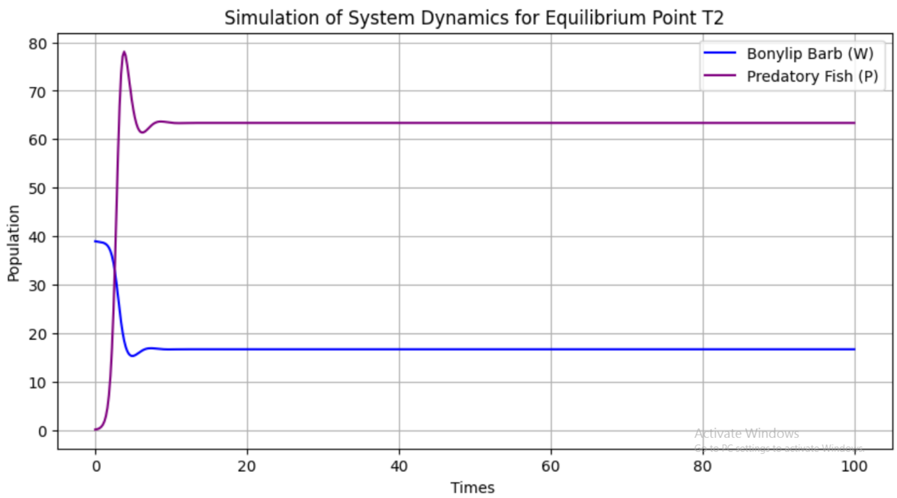

Fig. 2. Simulation of dynamic system for equilibrium point T_2

Based on the eigenvalues obtained for the equilibrium point T_2 with coordinates $(W_2, 0) = \left(\frac{K(\alpha-\mu)}{\alpha}, 0\right)$ two eigenvalues are obtained, namely $\lambda_1 = -\alpha + \mu$ $atau$ $\lambda_1 = \frac{\alpha K\delta - K\delta\mu - \alpha\gamma}{\alpha}$. If using the parameters from table 1, namely (α) = 4.0, value (δ) = 0.08, value (K) = 70, value (μ) = 1.78 and value (γ) = 0.70, then the results of the two eigenvalues are as follows:

$$\lambda_1 = -\alpha + \mu = -4.0 + 1.78 = -2.22$$
$$\lambda_2 = \frac{\alpha K\delta - K\delta\mu - \alpha\gamma}{\alpha}$$
$$= \frac{(4.0)(70)(0.08) - (70)(0.08)(1.78) - (4.0)(0.70)}{(4.0)}$$
$$= 2{,}408$$

Since both eigenvalues $\lambda_1 = -2.22$ are negative and $\lambda_2 = 2.408$ is positive, it can be concluded that the equilibrium point T_2 is a Saddle point. The equilibrium between these two populations is unstable. The Bonylip Barb Fish population will tend to move away from this equilibrium point with little disturbance from Predators, indicating long term instability. A Predator fish population starting from zero shows no significant change, but a potential increase in Predators would cause a large change in the Bonylip Barb Fish population.

c. Third Simulation

Based on the assumptions of the value (K) = 70, the value (μ) = 1.78, the value (γ) = 0.70, the value (α) = 3.5, the value (β) = 0.95, the value (π) = 0.012 and the value (δ) = 0.4, the graph of the population dynamics of Bonylip Barb Fish and Predator fish over time from the equilibrium point T_4 will be displayed as follows:

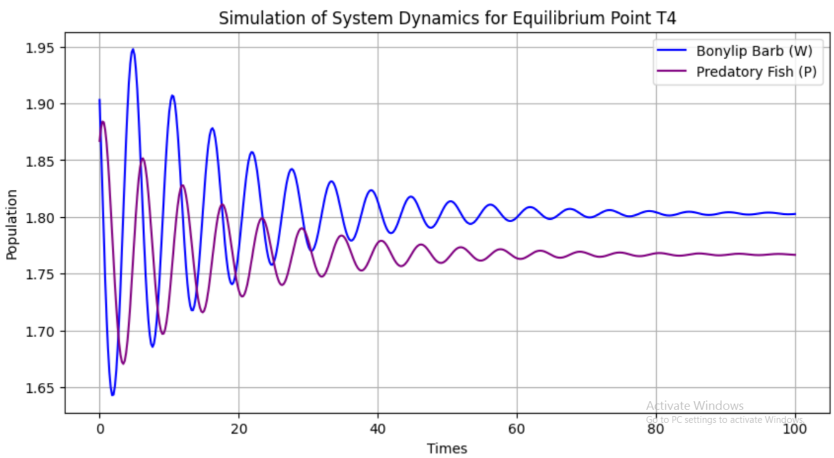

Fig. 3. Simulation of dynamic system for equilibrium point T_4

Based on the eigenvalues obtained for equilibrium point T_4 with coordinates $(W_4, P_4) = \left(\frac{K(\alpha\pi+\beta\gamma-\mu\pi)}{\delta K\beta+\alpha\pi}, \frac{\delta K\alpha-\delta K\mu-\alpha\gamma}{\delta K\beta+\alpha\pi}\right)$, two eigenvalues are obtained, namely

$$\lambda_1 = \frac{(a_{11}+a_{22})-\sqrt{(a_{11}+a_{22})^2-4(a_{11}a_{22}-a_{12}a_{21})}}{2} \; atau \; \lambda_2 = \frac{(a_{11}+a_{22})+\sqrt{(a_{11}+a_{22})^2-4(a_{11}a_{22}-a_{12}a_{21})}}{2}$$

then the result of the two eigenvalues is as follows:

$$\lambda_1, \lambda_2 = \frac{(a_{11}+a_{22}) \pm \sqrt{(a_{11}+a_{22})^2 - 4(a_{11}a_{22} - a_{12}a_{21})}}{2}$$

By substituting the matrix elements into the eigenvalues above, the eigenvalues are obtained as follows:

$$\lambda_1 = -0.05815 - 1.0831i$$
$$\lambda_2 = -0.05815 + 1.0831i$$

Because both eigenvalues $\lambda_1 = -0.05815 - 1.0831i$ and $\lambda_1 = -0.05815 + 1.0831i$ are negative. This shows that the equilibrium point T_4 is stable. The presence of the imaginary component $\pm 1.0831i$ indicates that the population will oscillate. However, this oscillation will be dampened due to the negative component.

Simulations show that the population system of Bonylip Barb Fish and Predator fish has a stable equilibrium point with damped oscillations. The populations of both species oscillate around the equilibrium point, and the disturbance from the equilibrium will decrease over time, indicating the long-term stability of the system.

4. Conclusions

The dynamics of the Predator-prey relationship model showed that the interaction between Predator fish and Bonylip Barb Fish played a significant role in the decline of the Bonylip Barb Fish population. Predation by Predator fish is the main factor causing this decline. The construction of the mathematical model used in this study is a modified Lotka-Volterra Predator-prey model on the decline in the Bonylip Barb Fish population in Lake Rawa Pening as follows:

$$\frac{\partial W}{\partial t} = \alpha W\left(1 - \frac{W}{K}\right) - \mu W - \beta WP$$
$$\frac{\partial P}{\partial t} = \delta WP - \gamma P - \pi P^2$$

Based on the model, four stability points are obtained, namely $T_1(0,0)$ when both populations are extinct, $T_2\left(\frac{K(\alpha-\mu)}{\alpha}, 0\right)$ when the Predator Fish population is extinct, $T_3\left(0, -\frac{\gamma}{\pi}\right)$ when the Wader Fish population is extinct and $T_4\left(\frac{K(\alpha\pi+\beta\gamma-\mu\pi)}{\delta K\beta+\alpha\pi}, \frac{\delta K\alpha-\delta K\mu-\alpha\gamma}{\delta K\beta+\alpha\pi}\right)$when the two populations interact. The stability point T_3does not meet the population requirement, because the population cannot be negative.

Analysis of the dynamics of the Predator-prey model provides important insights into effective conservation strategies. There are three simulations that can describe the interaction of the two populations according to the equilibrium point obtained. In the first simulation when the equilibrium point $T_1(0,0)$ the eigenvalues obtained from the parameter assumption results are$\lambda_1 = -1.77$ dan $\lambda_2 = -0.70$. In the second simulation when the equilibrium point $T_2\left(\frac{K(\alpha-\mu)}{\alpha}, 0\right)$obtained eigenvalues from the results of parameter assumptions $\lambda_1 = -2.22$dan $\lambda_2 = 2.408$. In the third simulation when the equilibrium point $T_4\left(\frac{K(\alpha\pi+\beta\gamma-\mu\pi)}{\delta K\beta+\alpha\pi}, \frac{\delta K\alpha-\delta K\mu-\alpha\gamma}{\delta K\beta+\alpha\pi}\right)$ obtained eigenvalues from the parameter results are $\lambda_1 = -0.05815 - 1.0831i$ and $\lambda_1 = -0.05815 + 1.0831i$

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