Unnes Journal of Public Health 15 (1) (2026)

Unnes Journal of Public Health

http://journal.unnes.ac.id/journals/ujph

Osmoregulatory Pattern and Larval Density of *Culex* spp. in Coastal Aquatic Ecosystem: Implications for Vector Control Strategies in Lymphatic Filariasis Elimination

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Article Info

Article History:
Submitted April 20, 2025
Revised February 26, 2026
Accepted March 30, 2026

Keywords:
culex larvae; osmoregulatory pattern; tidal flooding; vector control; lymphatic filariasis

DOI
https://doi.org/10.15294/ujph.v15i1.23743

Abstract

Lymphatic filariasis in coastal regions is prone to transmission due to the environmental factors that enable the reproduction of *Culex* spp. Therefore, this study aims to examine the relationship between *Culex* spp. larval osmoregulation patterns with coastal ecosystem properties, and the impact on the larval density and control of vectors. Sampling was conducted in the field across different aquatic environments. Larval density was quantified, and environmental salinity was measured with a refractometer, while larval hemolymph and water osmolarity were analyzed using an automatic osmometer. The results showed that larvae demonstrated different osmoregulatory patterns, including iso-osmotic, iso-hyperosmotic, and iso-hypoosmotic. Significant differences in larval densities were observed among these patterns, with the highest density found in iso-hyperosmotic conditions (p=0.034), typically in low-salinity waters (0–1‰). Field analysis also showed that areas affected by occasional tidal flooding had significantly higher larval densities compared to unaffected areas (p=0.008). Multivariate analysis indicated that larval iso-hyperosmotic conditions, occasional tidal flooding, and damaged mangrove collectively increased larval density (p<0.0001). Therefore, effective *Culex* spp. larvae control in coastal regions should focus on micro-hydrological management through the elimination of unintended puddles and habitat modification, such as mosquito ditching, to support the sustainability of lymphatic filariasis elimination.

INTRODUCTION

Lymphatic filariasis is one of the global public health problems targeted to be eliminated by World Health Organization (WHO) in 2030. To achieve this goal, WHO has instructed the endemic countries to execute a mass drug administration (MDA) program in affected areas. However, the outcomes of this program vary across different countries. WHO reported that as of 2024, aproximately 39 countries are still in the process of eliminating lymphatic filariasis with MDA, including Indonesia, Philipine, Malaysia, Myanmar, India, Nepal, Madagascar, Mozambique, Zimbabwe, Congo, Angola, Tanzania, Liberia, Sudan, Ethiopia, Chad, Ghana, and others (Local Burden of Disease 2019 Neglected Tropical Diseases Collaborators, 2020; WHO, 2025).

The pre-TAS (Preliminary Transmission Assessment Survey) is conducted to evaluate the transmission risk after implementing MDA. After passing pre-TAS, an endemic area still has to be evaluated through the Transmission Assess-

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pISSN 2252-6781
eSSN 2548-7604

ment Survey (TAS) at TAS-1, TAS-2, and TAS-3, where MDA is no longer executed. In Indonesia, several areas have failed at least once at pre-TAS, TAS-1, TAS-2, or TAS-3 evaluation, necessitating the re-implementation of MDA. Some of these areas include Pekalongan City, Ambon City, Bangka Selatan Regency, Tanjung Jabung Timur Regency, Jayapura City, Sorong City, and others, with the majority located in coastal areas. These coastal areas in tropical regions have unique problems in the form of tidal flooding that is difficult to handle, resulting in poor sanitation and serving as suitable breeding sites for disease vectors. Consequently, sanitation-based and vector-borne diseases are often concentrated in coastal areas, including lymphatic filariasis (Chaiphongpachara & Sumruayphol, 2017).

Failure in TAS-1, TAS-2, or TAS-3 may be associated with unoptimal vector control (Burkot et al., 2006; Moustafa et al., 2017). When society discontinues MDA, the microfilarial worm transmitted by various mosquitoes would have a higher potential to spread infection. *Culex spp.* are widely recognized as vectors of various pathogens, posing significant public health concerns in tropical and subtropical regions. In Indonesia, *Culex spp.* contributes to transmitting lymphatic filariasis (WHO, 2020). Although traditional mosquito control has focused on targeting adult stages, which directly transmit pathogens, increasing evidence suggests intervening at the larval stage offers a strategic advantage (WHO, 2017).

Mosquito larvae live in water, making it easier to control than adults, which are highly mobile and can easily escape. A previous study by Siwiendrayanti et al. (2020) showed that the use of anti-mosquito repellents does not significantly prevent filariasis infection in Pekalongan City, Indonesia. Controlling mosquito larvae prevents the life cycle from progressing, thereby stopping the spread of diseases, making it a preventive method. In general, larvae are also more susceptible to environmental changes and chemical interventions, allowing for reduced insecticide use and lowering the risk of resistance commonly observed in adult mosquitoes. Larval habitats are usually easy to locate, which makes it possible to use specific ecological or biological control methods. Therefore, focusing on larval-stage interventions offers a more sustainable, cost-effective, and environmentally friendly method of vector control (Djerdj, Hackenberger, Klanjšček, & Hackenberger, 2023; Okumu et al., 2025; Shapiro, Murdock, Jacobs, Thomas, & Thomas, 2016).

The osmoregulatory pattern of *Culex spp.* larvae is crucial in understanding the adaptability to various environmental conditions, which can inform vector control strategies. Osmoregulation is a form of homeostasis system carried out by an organism to maintain internal structure and conditions, enabling normal physiological activities. In general, *Culex* larvae thrive in different aquatic habitats, including polluted and stagnant water with rich organic matter. This adaptability is partly due to the osmoregulatory capabilities, which enhance survival in environments with varying salinity, pH, and other physicochemical parameters (Bhuiyan & Saha, 2024).

Coastal areas are increasingly affected by changes due to human activities and rising salt levels resulting from climate change. These conditions facilitate the growth of *Culex* larvae (Röthig et al., 2023). Coastal environments are characterized by fluctuating salinity due to tidal influences, requiring larvae to develop specific physiological adaptations to survive and reproduce (Balasubramanian et al., 2019; Ma et al., 2016).

Although extensive studies have been conducted on controlling adult mosquitoes, the larval stages, especially in coastal habitats, remain underexplored in vector management strategies. Examining the osmoregulatory pattern used by *Culex* larvae in these environments is important not only to understand ecological plasticity but also to guide specific control interventions. Therefore, this study aimed to explore the osmoregulatory pattern and larval density of *Culex spp*. larvae in coastal freshwater environments, providing critical insights into the effectiveness and environmental sustainability of vector control.

This study was conducted on the north coast of Central Java in Brebes Regency, Central Java, Indonesia. Brebes Regency is a lymphatic filariasis endemic area and is currently undergoing the completion of the TAS series. The primary vector in this region, similar to other areas on Java Island, is *Culex quinquefasciatus*. The densities of the mangrove vary in Brebes Regency, and consequently lead to different tidal flooding and salinity. These environmental variations provide an ideal setting to investigate differences in larval density and osmoregulatory responses of *Culex* larvae across diverse coastal ecosystem.

METHODS

Data were collected in January 2024, across 32 locations in various coastal aquatic ecosystem in Brebes Regency during the day. *Culex* larvae were observed and distinguished by behavioral patterns, including rest positioning and movement within the water column, which differ from those of other mosquito genera. Surface water was sampled by picking larvae with a 350 mL dipper and volumetrically estimated. Larval density at every site was estimated as a mean count of collected dips of ten consecutive dips. Indonesian Health Ministry Regulation No. 2 of 2023 defines the national vector control regulation as high densities when more than 20 larvae are obtained per dip. Environmental salinity was measured in situ using a portable refractometer. Salinity at 0-5‰ was classified as fresh water, 6-18‰ indicates brackish water, and >18‰ represents saline water. Water stream conditions were divided into two categories, namely flowing and stagnant.

For osmoregulation analysis, larval specimens and the habitat water samples were transferred into microtubes using micropipettes and immediately frozen. Samples were subsequently frozen to preserve the larval physiological state and maintain osmoregulatory status, as observed in the field, during transport to the Fisheries and Marine Science Laboratory at Diponegoro University. Freezing was crucial to ensure the larval stage remained unaltered during transport, preventing any metabolic or developmental shifts that might influence the osmolarity analysis. Osmoregulatory patterns were measured using the Automatic Osmometer Roebling.

The result of osmoregulatory pattern analysis would be categorized as iso-osmotic, iso-hypoosmotic, or iso-hyperosmotic. An iso-osmotic regulation is characterized by the equality of the osmotic pressure of body fluids and that of the surrounding water. Conversely, an iso-hypoosmotic regulation occurs when the osmotic pressure of body fluids is lower than that of the surrounding water, resulting in a potential net water influx into the body. An iso-hyperosmotic regulation is defined by a scenario where the osmotic pressure of body fluids surpasses that of the surrounding water. Tidal flood frequencies were identified by interviewing surrounding communities, classified as consistently, occasionally, or never. Mangrove density data were provided by the environment and forestry office of Central Java Province, derived from the newest data in the National Mangrove Map 2021, which categorized the mangrove density as "intact" (≥50% or ≥1,000 trees/Ha) and "damaged" (<50% or <1,000 trees/Ha).

Statistical tests were performed with the SPSS program. Normality and homogeneity tests using the Shapiro–Wilk test indicated the need for a non-parametric test. Kruskal-Wallis test with alpha level of 0.05 was employed to determine whether there were statistically significant differences in *Culex* larval density based on osmoregulatory patterns and mangrove densities. Meanwhile, a Mann-Whitney test with an alpha level of 0.05 was performed to identify larval density differences based on tidal flood frequencies, types of salinity, and streaming categories. Multivariate analysis was also conducted using Generalized Linear Models (GLM) with a Log link function and Gamma distribution to identify the most dominant variables influencing the density of *Culex* spp. larvae. The selection of this model is based on the characteristics of larval density data, which are positive continuous and not normally distributed, by including categorical independent variables with a p-value <0.25 in the previous bivariate test.

RESULT AND DISCUSSION

Osmoregulation refers to the physiological process that maintains the balance of water and ions in an organism despite changes in environmental salinity. The process plays a crucial role in the survival of the mosquito larvae, especially those that live in salty water bodies. These larvae are usually hyposmotic (with a lower internal solute concentration than that of the environment) or iso-osmotic/iso-hyperosmotic, depending on the salinity of the habitat. The principal organs engaged in the process of osmoregulation include anal papillae, midgut, malpighian tubules, and rectum. The anal papillae are important in the absorption of ions during hyposmotic conditions, while the malpighian tubules and rectum control the excretion and reabsorption of salts and water. The osmoregulation process ensures that larvae absorb the necessary ions, including sodium (Na^+) and chloride (Cl^-), while losing unneeded salt or water to keep the internal balance. Failure to ensure that this process works correctly leads to larvae being dehydrated or ionically imbalanced, potentially causing damage to cells or even death. Larvae have an impressive ability to adapt to different environments. These organisms balance internal conditions by using various methods. In brackish water, larvae rely on hypoosmotic regulation, while under more extreme conditions, iso-osmotic or iso-hyperosmotic strategies are used (Bradley, Strange, & Philips, 1984). This flexibility demonstrates the ability of larvae to adapt to changing situations. For example, *Culex* larvae can stand various ranges of salinity and pH. The larvae of *Culex quinquefasciatus* were found in an aquatic environment with a neutral pH and salinity ranging from 4.3-18.8 ‰. This tolerance, rarely found in other species, enables survival in polluted, brackish, and low-oxygen water, contributing to the widespread distribution (Cavalca et al., 2021; Kinga et al., 2022; Kudom, 2015).

Table 1 shows that among 32 larvae samples, 6 (18.75%) demonstrated iso-hypoosmotic regulation, 3 (9.38%) isosmotic regulation, and 23 (71.89%) iso-hyperosmotic regulation. The isosmotic and iso-hyperosmotic patterns existed in salinity ranging from 0-1‰, while the iso-hypoosmotic pattern existed in salinity of 0-14‰. Only the isosmotic pattern was consistently associated with normal larval densities (below 20 larvae/dip), while high larval densities (≥20 larvae/dip) were present in the iso-hypoosmotic and iso-hyperosmotic patterns. These patterns support the ability of *Culex* larvae to thrive in brackish aquatic environments (Balasubramanian et al., 2019).

Mosquito larvae have unique mechanisms to regulate body fluids in response to varying salt levels in the environment. In freshwater, characterized by low salinity and resulting in iso-hyperosmotic regulation, the larvae absorb essential ions, such as sodium (Na^+) and chloride (Cl^-), through structures called anal papillae, while preventing excessive water influx that could disrupt cellular integrity. Under moderately salty water (isosmotic regulation), larvae maintain internal balance with reduced active ion transport, thereby conserving energy. In systems with a high degree of salinity, which leads to iso-hypoosmotic regulation, the larvae are confronted with the problem of increased extrinsic salt concentration compared to intrinsic concentration. The response is to minimize water loss and the consumption of additional salts by reducing the level of permeability on the surfaces, as well as through rectal and anal systems that actively excrete excess salt. Additionally, the larvae adjust the concentration of certain substances within cells to maintain size and function. Organic substances, such as amino acids, also help maintain this balance. Overall, these processes require careful adjustments of ion transporters and enzymes, allowing the larvae to survive in various salt levels found in estuaries and oceans (Bradley et al., 1984).

Table 2 shows a significant difference in larval density among iso-hypoosmotic, iso-osmotic, and iso-hyperosmotic regulations, where iso-hyperosmotic regulation had the highest mean in larval density (p=0.034). As shown in Table 3, larvae tend to have the highest density in iso-hyperosmotic conditions (p=0.0001) when analyzed simultaneously with tidal flood frequency and mangrove density. Iso-hyperosmotic regulation indicates that the hemolymph pressure/osmolarity of the larvae is higher compared to the medium, but the difference is relatively small (approaching iso-osmotic). This condition is typical of freshwater to very low-salinity waters (≈ 0–1‰), where the larvae act as weak hyperosmoregulators. Therefore, the result showing that iso-hyperosmosis occurs at 0–1‰ is physiologically consistent for *Culex*, strongly associated with freshwater habitats (Nurjazuli & Santjaka, 2020).

At a salinity of 0–1‰, the osmotic gradient exists but is not extreme. Activities that occur in this condition include pumping ions (Na^+/K^+-ATPase) in the anal gills and intestinal epithelium, as well as excess water excretion through the malpighian tubules. It operates efficiently with low energy costs, and by implication, metabolic energy can be directed toward growth, molting, and survivability, rather than maintaining osmotic balance. This directly enhances larval survival, which is reflected in higher densities. Therefore, a salinity of 0–1‰ is considered the physiological optimum zone for *Culex spp.* larvae. Under this zone condition, the mortality of the larvae would be very low, allowing efficient processing of energy from nutrients and optimal growth to reach the adult phase in a shorter time. The salinity levels ecologically represent rainwater puddles, sewerage canals, abandoned freshwater-dominated fishponds, coastal swamps with minimal marine intrusion, and temporary water bodies after rainfall. At a salinity of 0–1‰, *Culex* often outcompetes other genera, such as certain *Anopheles* species or *Aedes* species, which have more volatile habitats. Selection pressure from salinity is virtually absent, hence, the primary limiting factors are nutrients, predation, and pool stability. This explains why maximum densities occur in the salinity range. Coastal environments with near-zero salinity are not "safe zones," but rather pose a high risk for *Culex* breeding. In the context of lymphatic filariasis, habitats within the 0–1‰ range should be treated as priority habitats for control, not simply transitional habitats (Balasubramanian et al., 2019).

Although freshwater (salinity of 0–5‰) is normally the ideal habitat for *Culex* larvae, Table 1 shows that high larval density was also observed at a salinity of 14‰ with iso-hypoosmotic regulation. At salinities up to ±14‰, hemolymph becomes relatively hypo-osmotic compared to the medium (iso-hyposmosis). However, the ion regulation system (anal gills, rectal epithelium, malpighian tubules) is still able to adapt by increasing ion reabsorption, decreasing ion excretion, and modifying epithelial permeability. Survivability remains maintained, although not as optimally compared to iso-hyperosmotic and iso-osmotic regulations (Durant & Donini, 2024).

Table 1. Characteristics of larval aquatic habitats and osmoregulatory patterns

Sample code	Aquatic environment type	Mangrove density type	Tidal flood frequency	Stream	Salinity (‰)	Osmolarity (mOsm/I H_2O)		Osmotic activity (mOsm/I H_2O)	Osmoregulatory pattern	Larval density
						Haemolymph	Media			
BAP-87	Puddle	Damaged	Occasionally	Stagnant	14	399	403	4	Iso-hypoosmotic	*27.8
BAP-117	Puddle	Intact	Never	Stagnant	14	399	401	2	Iso-hypoosmotic	2.3
BAP-96	Sewerage	Damaged	Occasionally	Stagnant	0	20	18	2	Iso-hyperosmotic	*37.5
BAP-97	Sewerage	Damaged	Occasionally	Stagnant	0	20	18	2	Iso-hyperosmotic	*45.0
BAP-98	Sewerage	Damaged	Occasionally	Stagnant	0	20	19	1	Iso-hyperosmotic	9.0
BAP-60	Sewerage	Non-mangrove	Never	Stagnant	0	21	20	1	Iso-hyperosmotic	11.3
BAP-61	Sewerage	Non-mangrove	Never	Stagnant	0	21	19	2	Iso-hyperosmotic	0.2
BAP-39	Sewerage	Non-mangrove	Never	Stagnant	0	20	18	2	Iso-hyperosmotic	*30.0
BAP-40	Sewerage	Non-mangrove	Never	Stagnant	0	21	19	2	Iso-hyperosmotic	*52.5
BAP-42	Sewerage	Non-mangrove	Never	Stagnant	0	20	18	2	Iso-hyperosmotic	12.8
BAP-45	Sewerage	Non-mangrove	Never	Stagnant	0	21	19	2	Iso-hyperosmotic	5.3
BAP-46	Sewerage	Non-mangrove	Never	Stagnant	0	21	19	2	Iso-hyperosmotic	*67.5
BAP-49	Sewerage	Non-mangrove	Occasionally	Stagnant	0	21	20	1	Iso-hyperosmotic	*37.5
BAP-52	Sewerage	Non-mangrove	Occasionally	Flowing	0	21	19	2	Iso-hyperosmotic	*48.8
BAP-68	Sewerage	Non-mangrove	Never	Stagnant	0	21	20	1	Iso-hyperosmotic	*22.5
BAP-70	Sewerage	Non-mangrove	Never	Flowing	1	29	29	0	Isosmotic	3.0
BAP-71	Sewerage	Non-mangrove	Never	Stagnant	1	29	29	0	Isosmotic	15.0
BAP-72	Sewerage	Non-mangrove	Never	Stagnant	2	30	33	3	Iso-hypoosmotic	7.5
BAP-75	Sewerage	Non-mangrove	Never	Stagnant	0	19	19	0	Isosmotic	15.0
BAP-128	Puddle	Damaged	Never	Stagnant	5	140	144	4	Iso-hypoosmotic	4.2
BAP-131	Sewerage	Damaged	Never	Stagnant	0	21	19	2	Iso-hyperosmotic	4.1
BAP-77	Sewerage	Non-mangrove	Never	Stagnant	0	21	20	1	Iso-hyperosmotic	15.0
BAP-78	Sewerage	Non-mangrove	Never	Stagnant	0	21	20	1	Iso-hyperosmotic	5.3
BAP-83	Sewerage	Non-mangrove	Never	Stagnant	0	21	19	2	Iso-hyperosmotic	4.8
BAP-84	Sewerage	Non-mangrove	Never	Stagnant	0	21	20	1	Iso-hyperosmotic	7.5
BAP-16	Sewerage	Non-mangrove	Never	Stagnant	0	21	20	1	Iso-hyperosmotic	*22.5

Sample code	Aquatic environment type	Mangrove density type	Tidal flood frequency	Stream	Salinity (‰)	Osmolarity (mOsm/I H_2O)		Osmotic activity (mOsm/I H_2O)	Osmoregulatory pattern	Larval density
						Haemolymph	Media			
BAP-18	Sewerage	Non-mangrove	Never	Stagnant	0	21	19	2	Iso-hyperosmotic	15.0
BAP-22	Sewerage	Non-mangrove	Never	Flowing	0	21	20	1	Iso-hyperosmotic	12.3
BAP-27	Sewerage	Non-mangrove	Never	Stagnant	0	21	20	1	Iso-hyperosmotic	5.3
BAP-30	Riverbank	Non-mangrove	Never	Stagnant	1	25	29	4	Iso-hyperosmotic	0.2
BAP-35	Sewerage	Non-mangrove	Never	Stagnant	2	49	52	3	Iso-hypoosmotic	0.9
BAP-11	Puddle	Intact	Never	Stagnant	9	249	259	10	Iso-hypoosmotic	1.8

*) High larval dencity (≥20 larvae/dip)

Table 2. Differential test of larval density in various osmoregulatory patterns and environmental characteristics

Variables	n	Mean	Med.	Min.	Max.	St. Dev.	p
Osmoregulatory patterns							
Iso-hyposmotic	7	6.386	2.30	0.2	27.8	9.7525	
Isosmotic	3	11.000	15.00	3.0	15.0	6.9282	#0.034
Iso-hyperosmotic	22	21.441	13.90	0.2	67.5	18.8787	
Tidal flood frequency							
Occasionally	6	34.267	37.50	9.0	48.8	14.335	*0.008
Never	26	13.223	7.50	0.2	67.5	15.8675	
Mangrove density type							
Non-mangrove	2	2.05	2.05	1.8	2.3	0.3536	
Damaged	6	21.267	18.40	4.1	45.0	17.9216	#0.162
Intact	24	17.404	12.55	0.2	67.5	17.8344	
Salinity							
6-18‰ (Brakishwater)	3	10.633	2.30	1.8	27.8	14.8689	*0.349
0-5‰ (Freshwater)	29	17.845	12.30	0.2	67.5	17.8258	
Stream							
Stagnant	29	16.734	11.30	0.2	67.5	17.1655	*0.821
Flowing	3	21.367	12.30	3.0	48.8	24.2087	

#Kruskal-Wallis *Mann-Whitney

Table 3. Multivariate test of larval density in various necessary variables

Variables	B		p	Exp(B) Lower	95% CI Upper	
Osmoregulatory Patterns						
Iso-hyposmotic	-10.671		0.000	2.321E-5	8.474E-6	6.359E-5
Isosmotic	-6.501	0.000	0.000	0.002	0.000	0.005
Iso-hyperosmotic	0		.	1	.	.
Tidal Flood Frequency						
Occasionally	24.592	0.000	0.000	4.789E10	1.557E10	1.472E11
Never	0		.	1	.	.
Mangrove density type						
Damaged	-9.072		0.000	0.000	3.645E-5	0.000
Intact	-4.781	0.000	0.000	0.008	0.002	0.045
Non-mangrove	0		.	1	.	.

Culex larvae are not purely stenohaline, rather, many species show weak to moderate euryhalinity. In this condition, high larval densities do not always equate to the most efficient physiological conditions. In mild to moderate iso-hypoosmosis, growth rates may be slower, larval development time is prolonged, and mortality increases slightly, but larvae survive and accumulate in the habitat. Therefore, in laboratory snapshots, this appears as a relatively high density, resulting from accumulation over time, not an optimum effect (Siwiendrayanti et al., 2017, 2021).

At salinities of 5–14‰, the surviving individuals are a subset of larvae with better osmoregulatory capacity, and physiological filtration occurs, not total extinction. In other words, the relatively high densities reflect population adaptation, not a universal preference of all larvae (Kengne et al., 2019). The ecological significance of 0–14‰ iso-hypoosmosis in coastal landscapes is that the coastal transition zone serves as a secondary habitat (Boerlijst et al., 2024). Salinity levels of 0–14 ‰ reflect tidal marshes, ponds with episodic marine intrusion, small estuaries, and brackish pools after high tide or during the dry season. This habitat is not the core habitat of *Culex*, but rather a secondary region that remains productive, especially when freshwater habitats are disturbed. The persistence of *Culex* larvae in these 14‰ secondary habitats suggests a potential 'residual transmission' risk that is often overlooked by standard larval source management (LSM) protocols, primarily targeting freshwater bodies (Kengne et al., 2019).

Salinities of 5-14 ‰ do not represent a superior physiological condition, but it is a survival strategy. Under these conditions, iso-hypoosmotic regulation enables *Culex* larvae to survive in mild brackish water but at an increased physiological cost. This reflects a trade-off, namely, reduced energy efficiency in exchange for expanded ecological tolerance. A significant conceptual interpretation of this study is that the salinity gradient generates two distinct ecological regimes, namely an optimum regime (iso-hyperosmosis, 0-1‰) where larval densities are greatest, and efficiency is optimum, as well as an adaptive tolerance regime (iso-hypoosmosis, up to ±14‰) where larval densities remain significant, although under sub-optimum conditions. From a vector control perspective, increasing salinity does not necessarily eliminate *Culex*, rather, it shifts the population from an optimal to a tolerance zone. This implies that salinity-driven environmental responses will have to surpass tolerance, or other constraining factors, including drainage, predators, and hydrological changes (Saward-Arav et al., 2016; Bartlow et al., 2019).

Beyond the above discussion, the comparative test of the larval densities at various salinities had discrete results. In this study, *Culex* larvae were only detected in fresh and brackish water with a salinity of 0-14‰. The analysis results in Table 2 show that the salinity of fresh and brackish water is not significantly related to the density of *Culex* larvae. The absence of a significant correlation suggests that absolute salinity as a dichotomous categorical variable is not a dominant factor in the formation of larval habitats in the coastal ecosystem. This result does not necessarily imply that the biological role of salinity is not critical, but only suggests the categorical approach is not very sensitive to represent the adaptive osmoregulatory systems of larvae according to physiological tolerance limits. Many *Culex* species have osmoregulatory abilities to ensure internal balancing at low to intermediate salinities. Therefore, the variation between fresh and low brackish water does not necessarily translate into statistically significant variation in larval density. The outcomes are in line with the laboratory test results in this experiment, showing that *Culex* larvae can develop optimally when in iso-hyperosmotic and, to a certain degree, iso-hypoosmotic salinity of up to about 14‰. This implies that freshwater and saline waters in the field environment are most probably within the physiological range capable of promoting larval survival and development.

The absence of correlation between salinity and larval density implies that environmental processes have a stronger impact than real salinity levels. Salinity change caused by episodic tidal flooding, the salty water mixing with the inland water, and changing rapidly of post-inundation osmotic conditions can also generate environmental stages more definitive in larval development than the constant salinity status. This is in line with the results where frequency of tidal floods and larval density were significantly correlated, suggesting that hydrological and osmotic processes are the more important determinants in the coastal ecosystem. In terms of public health, the results indicate that a salinity-based regional classification, only separating fresh and brackish waters, cannot be used to determine the risk of vectors. This approach may overlook microhabitats with optimal osmotic conditions for *Culex* larvae, which temporarily arise in response to environmental fluctuations. Therefore, vector surveillance and control strategies in coastal areas need to shift from a focus on salinity categories to a more dynamic understanding of hydrological changes, pond retention, and microhabitat osmotic conditions that directly influence larval densities (Walton et al., 2016)

In the study field, no area was consistently affected by tidal flooding. Instead, locations were categorized as either occasionally inundated by tidal flooding or never affected. Table 2 shows a significant difference in larval density between these categories, with higher mean densities observed in areas experiencing occasional tidal flooding (p=0.008). Areas with occasional tidal flood have an average larval density of 32.4, while those that are never flooded by tidal flooding have an average larval density of 13.2. This implies that larval densities in areas frequently affected by tidal flooding are approximately 2.5 times higher. As also shown in Table 3, areas with tidal flooding occasionally tend to have a significantly higher larval density ($p < 0.0001$) than those that have never been affected. This indicates that the ponds provide optimal breeding sites for larvae. From a public health perspective, this demonstrates an environment with a significantly greater vector risk (Kurucz et al., 2016).

An important question arising from these results is why areas that are occasionally flooded by tidal flooding are actually more productive for larvae. Episodic tidal flooding creates iso-hyperosmotic post-inundation conditions. Tidal flooding is not always synonymous with permanent high salinity. Importantly, seawater enters during inundation and subsequently mixes with rainwater and inland freshwater as it recedes, leading to rapid dilution. Consequently, post-tidal flood habitats often demonstrate 0–2 ‰ salinity. This falls precisely within the iso-hyperosmotic zone identified in this study as the region of highest larval density. In other words, episodic tidal flooding is a natural mechanism that accidentally produces an optimal habitat for *Culex* larvae. It can also be assumed that tidal flooding increases the availability of nutrients and organic matter due to the transfer of fine sediment, dissolved organic matter, and coastal domestic waste. After the inundation settles, microalgae and bacteria increase, and larval food sources become abundant. This is crucial because high nutrient levels compensate for mild osmotic stress, especially during the transient iso-hypoosmosis phase. The outcome is that larval density increases not only because water is present, but also due to improvement in habitat quality.

Another explanation for why the density of larvae is higher at tidal flood locations is that episodic tidal flooding creates new habitats that are less prone to predators. Areas that never experience tidal flooding typically have more stable aquatic communities, allowing larval predators (small fish and invertebrates) to become more established. Conversely, areas that occasionally experience tidal flooding often experience a "reset" of habitat, allowing mosquito larvae, with the rapid life cycle, to thrive and survive before predators have time to recover. This is the classic concept of colonizer advantage, closely related to disease ecology. Another question that also arises is why areas that never experience tidal flooding actually have lower larval densities. Ecological stability does not necessarily translate to high vector risk. Although salinity in these areas remains low and physiologically favorable, other factors, such as increased water flow, reduced pooling, stable predator populations, and lower post-inundation nutrient inputs, may limit larval development (Cuthbert et al., 2019). The frequency of episodic tidal flooding functions as a risk amplifier for the development of *Culex* larvae.

Tidal flooding causes salinity fluctuations, which lead to a post-inundation iso-hyperosmosis phase and provide an opportunity for larvae to survive optimally, resulting in high larval densities. This phenomenon does not increase larval density directly, but through the creation of an optimum physiological window for larvae. The results suggest that areas occasionally experiencing tidal flooding should be prioritized for larval surveillance, even when not permanently inundated. Environmental risk indicators should not simply reflect "whether or not flooding has occurred," but also consider the frequency and episodic nature. In the context of lymphatic filariasis elimination, areas that occasionally experience tidal flooding have the potential to become sources of residual transmission (Saward-Arav et al., 2016).

Table 2 shows that there was no significant correlation between mangrove density (non-mangroves, damaged, and intact mangroves) and *Culex* larval density. However, the multivariate analysis results in Table 3 indicate a significant correlation with $p<0.0001$. The greatest density of the larvae was observed in non-mangrove regions (as a reference). This observation shows that the establishment of mangroves as the structural component of the coastal ecosystem is not a direct predictor of the development of mosquito larval habitats. Instead, the dynamic environmental factors, especially hydrology and water osmotic conditions, appear to have a significantly stronger influence. Mangroves are a complicated transitional terrestrial-marine system. Although the mosquito larvae do not directly interact with the mangrove vegetation structure, the survival cycle solely relies on the presence of aquatic microhabitats such as shallow puddles, ditches, pools of runoff, and other stagnant water bodies. Therefore, the use of the mangrove density to determine the vegetation cover does not necessarily reflect the physical and chemical state of the waters within which the larvae are growing. The salinity, the stability of the puddles, the retention time of water, and the presence of dissolved organic matter are some of the key variables that are not directly captured in the mangrove density indicators. Moreover, the effects of mangroves on larval habitat are indirect and mediated by other environmental factors.

Mangroves are able to alter water run-off, sluggish drainage, as well as determine sediment and organic substance buildup. However, when these mediating variables, including salinity and tidal frequency of flood, are highly connected to the larval density, then the impact of mangroves as an independent variable becomes statistically smaller. In this context, mangroves are used as a situational qualifier rather than a direct influence on the dynamics of mosquito larvae population. The heterogeneity of mangrove ecological functions due to the condition can also explain these results. Mangroves in good condition generally have more active tidal connectivity and a diverse aquatic predator community, potentially suppressing larval survival (Cuthbert et al., 2019). On the other hand, mangled or bare mangroves tend to have stagnant water bodies either due to hydrological degradation or human activities, which, in fact, may favor larval growth. These opposing effects potentially result in a statistically insignificant net effect when analyzed solely by mangrove density category.

From an osmoregulatory physiology perspective, *Culex* larvae respond directly to the water osmotic gradient, not to the presence of vegetation. Previous results in this study indicate that larvae develop optimally under iso-hyperosmotic and, to some extent, iso-hypoosmotic conditions at low to medium salinity levels. Larvae can survive and develop provided these osmotic conditions are met, regardless of the presence or absence of mangroves. This further confirms that mangroves do not directly determine whether a habitat is within the optimal physiological range for larvae. An important implication of these results is the need to correct simplifying assumptions about the relationship between mangroves and vector risk. In coastal policy and management practices, mangrove rehabilitation is often implicitly perceived as an intervention that will also reduce the risk of vector-borne diseases. This study indicates that without specific hydrological and watershed management, mangroves alone are insufficient to control mosquito larval densities. Therefore, vector control strategies in coastal ecosystem need to prioritize the management of water dynamics, salinity fluctuations, and aquatic microhabitat characteristics, with mangroves positioned as part of the ecosystem context, not the sole solution. Previous studies reported that mangrove density contributes to mosquito density and biting pattern, making restoration an important supporting intervention (Claflin & Webb, 2017; Ismail et al., 2018).

The analysis results in Table 2 show that there was no relationship between stream conditions (flowing and stagnant) and the density of *Culex* larvae. This finding is ecologically and physiologically plausible, particularly in dynamic coastal environments. Although stagnant waters are traditionally considered more conducive to the larval development of mosquitoes, this dichotomy is overly simplistic to be used in the context of coastal environments influenced by tides, tidal flooding, and irregular hydrological processes. In this context, flowing and stagnant may be transient in coastal ecosystem. Many water bodies that appear to be continuously flowing contain localized zones where flow is minimal or absent, such as channel margins, shallow depressions, or sediment-rich areas. These microhabitats are biologically pertinent to the *Culex* larvae and not the macroflow conditions experienced in the field. Consequently, there is no significant correlation between binary flow classifications and the various habitats inhabited by larvae.

The capability of the *Culex* larvae to survive weak to intermittent flow conditions implies that water flow is not a key limiting factor, provided it does not lead to extreme mechanical disturbance. Light tidal currents may also help in mixing water and distributing nutrients in coastal areas without necessarily washing away larvae. Therefore, even stagnant or flowing waters may offer rather stable microclimate conditions, which would allow the larvae to develop, provided the flow is not too strong or permanent. The weak correlation between flow conditions and larval density also needs to be realized in combination with other results, especially the influence of salinity and tidal flooding. Episodic tidal flooding can create stagnant pools following water recession, even when the original water source was flowing. This implies that post-flow and water retention processes are greater determinants of larval occurrence compared to the flow condition during observation. In other words, larvae adapt to the end-of-life conditions of the microhabitat, and not to the initial flow properties. From a public health perspective, these findings have important implications. Vector control strategies should not assume that flowing water bodies are free from mosquito breeding. Waterways, drainage channels, and tidal canals remain potential larval habitats, especially in the presence of slow-flowing sections, sedimentation, or post-flood puddles. Instead of classifying flows, surveillance and intervention approaches aiming at reducing the occurrence of high-risk microhabitats in water systems should be applied (Rochlin & Morris, 2017).

In general, the results suggest that the density of *Culex* larvae in coastal ecosystem is not conditioned by one environmental factor, but the dynamic interplay of hydrological conditions and physiological adaptation of the larvae to the changes in the environment. A laboratory osmoregulation test has shown that *Culex* larvae tolerate a wide range of low to moderate salinity changes, with the greatest densities being found in iso-hyperosmotic conditions and sustained survival under mild iso-hypoosmotic conditions. This observation explains why structural and static variables, such as salinity category (freshwater and brackish water), mangrove density, and water flow conditions, did not show any significant relationships with larval density during field analyses because all these conditions were within the physiological window, promoting larval development. Contrastingly, episodic tidal flooding frequency was determined to be greatly associated with larval density, and this implies that hydrological processes, such as salinity changes, development of post-receding pools, elevated nutrients, and lowered predator pressure, are significantly more critical in developing optimal larval habitats than fixed environmental attributes. The results confirm that dynamic, temporal processes of the environment, rather than traditional ecological groups, affect the risk of *Culex* larval development in coastal environments. Effective vector control strategies should therefore focus on managing environmental processes that prevent the formation of optimal physiological conditions for larvae, rather than solely modifying structural habitat characteristics (Rochlin & Morris, 2017; Saward-Arav et al., 2016).

The results indicate that control of *Culex* larval vectors in coastal ecosystem can no longer be based on a static approach relying on single environmental categories such as water salinity, flow conditions, or mangrove density. The insignificant relationship between these variables and larval density, when interpreted in an integrated manner with the results of osmoregulation tests and tidal flood frequency analysis, indicates that the risk of larval reproduction is determined more by temporal and micro-spatial environmental dynamics. Therefore, effective vector control strategies in coastal areas need to be directed at managing environmental processes capable of preventing the creation of optimal physiological conditions for larvae, rather than simply the structural characteristics of the habitat. The primary implication is the need to prioritize larval control during the post-tidal flood phase, when temporary ponds form and iso-hyperosmotic conditions that support the highest larval densities.

Rapid interventions during this period, before the larval development cycle reaches an advanced stage, have a greater control impact than routine calendar-based approaches. Therefore, mapping post-tidal pond microhabitats and scheduling interventions adaptive to tidal flood events are key components of larval control strategies in coastal areas. The absence of correlation between the flow conditions and salinity categories with larval density confirms that micro-hydrologic management, specifically water retention and post-flow stagnation, is more relevant than macro-flow classification or water type. The control measures must revolve around minor environmental changes, including bettering micro-drainage, alleviating anthropogenic depressions, as well as management of recurring puddles caused by high tides or after rainfall events. This method is consistent with the properties of *Culex* larvae, exploiting the stationary microhabitats even in water bodies that otherwise appear to be in motion.

In the context of the mangrove ecosystem, the lack of a direct relationship between mangrove density and larval density indicates that mangrove rehabilitation cannot be an independent control measure of vectors. It is important to view mangroves as supporting factors that can enhance natural control by promoting the presence of tidal connectivity and predators, although functionality is greatly contingent on hydrological management (Cuthbert et al., 2019). Therefore, integrating mangrove with inundation management is a more realistic and evidence-based approach. This study emphasizes the need for a paradigm shift in vector control within coastal areas, from an environmental category-based approach to one grounded in the dynamics of ecosystem processes. An adaptive, temporary, microhabitat-focused *Culex* larval control strategy following tidal flooding is not only more consistent with the physiological and ecological results but also more relevant to supporting lymphatic filariasis elimination efforts in dynamic coastal areas (Rochlin & Morris, 2017). This description is presented in Table 4.

Environmental or habitat modification is a viable control strategy in coastal areas. The use of larvicides and natural predators is either impossible or difficult. This approach does not target the ecological problem roots, has a high risk of resistance, and is less in line with ecosystem-based control. Similarly, the deployment of natural predators is challenging because most larval habitats consist of unintended puddles, drainage channels, or sewage systems. Establishing predator populations would require the creation and maintenance of suitable habitats, which may not be feasible in such unstable and artificial environments. Consequently, it is impractical to rely on predator-based control in these settings. Given the constraints, priority should be given to the reduction or elimination of unintended puddles and the implementation of mosquito ditching strategies. Table 4 shows the comparison of these approaches in terms of funding, technology, suitability to Indonesia natural environment, and sustainability (Cuthbert et al., 2019; Saward-Arav et al., 2016).

Although *Culex* larvae have the ability to survive in various conditions supported by the osmoregulatory systems, survival remains dependent on the availability of water to complete the life cycle. Therefore, eliminating standing water would disrupt temporary habitats that are stable enough for larval development. Unintended puddles in coastal areas are formed by remaining undried tidal floods and rainwater. In general, land areas can be raised to allow excess tidal floodwater and rainwater to fill drainage canals. However, adequate drainage systems must be en-

Table 4. Summary of Results, Implications, Solution Concepts, and Control Strategies for *Culex* Larvae in Coastal Ecosystem

Study Results	Implications	Solution Concepts	Control Strategies
Culex larvae showed the highest density under iso-hyperosmosis conditions and still survived under mild iso-hypoosmosis.	Larvae have a wide osmoregulatory tolerance; low to medium salinities are within the optimum physiological window.	The focus of intervention is on microhabitats that are temporarily at optimum osmotic conditions, not on water type.	
The frequency of tidal flooding is significantly related to larval density.	Episodic tidal flooding acts as a risk amplifier through the formation of post-ebb inundation and osmotic fluctuations.	Time-targeted control of larvae immediately after a tidal flood event	
Mangrove density (non-mangrove, damaged, intact) is not significantly related to larval density in bivariate analysis, but is significantly related in multivariate analysis.	Mangroves are not a direct determinant; their effects are mediated by hydrology and predators.	Integration of mangrove rehabilitation with hydrological management; mangroves should not be the sole control strategy.	Reduction/elimination of unintended puddles. *Culex* larvae can survive in a variety of habitats, but the essential requirement is the presence of water.
There was no significant relationship between salinity category (freshwater and brackish water) and larval density.	Salinity classification is too crude and does not reflect the osmotic dynamics relevant to larvae.	Reorientation of surveillance from salinity categories towards monitoring of micro-salinity fluctuations and changes	Mosquito ditching. A way to control mosquito breeding in wetlands by drying them to disturb larval optimum and tolerance zones.
There was no significant relationship between flow conditions (flowing and stagnant) and larval density.	Larvae utilize microhabitats with slow flow or post-flow puddles.	Management of water retention and micro-stagnation (micro-drainage, basin elimination)	
The combination of static variables does not adequately explain larval density.	Vector risks are determined by dynamic and temporal environmental processes.	Process-based larval control approach	
Temporary post-tide flooding escapes routine control.	Potential sources of residual transmission	Adaptive larval surveillance and risk-based selective interventions	
Larvae are able to develop in various coastal environmental conditions.	Zone-based control is ineffective	Location and time-specific microhabitat control strategies	

sured. Mangrove ecosystem rehabilitation can be implemented as a supporting effort, considering that good mangrove ecosystem has the capacity to reduce the severity of tidal flooding. Reduced frequency of tidal flooding will certainly decrease the number and extent of unintended puddles, suggesting an effective method of habitat removal (Nagy et al., 2022; Nurjazuli & Santjaka, 2020).

The concept of mosquito ditching refers to impairing the optimum physiological conditions of the larvae by disrupting hydrological stability. *Culex* larvae are pushed out of the optimum zone and simultaneously prevented from adapting stably within the tolerance zone. This implies that the modification is directed not at killing larvae directly, but rather increasing the cumulative physiological burden, disrupting the stability of the habitat, and the continuity of the life cycle. Based on the results, *Culex* larvae tolerate static salinity levels of 5–14 ‰, but rapid and unpredictable fluctuations are not well tolerated. Therefore, interventions can be directed at opening and closing water systems (simple sluice gates) in coastal channels, with a periodicity of short brackish/seawater intrusion phases followed by rapid drying or water replacement phases. The fluctuations impose physiological stress, forcing larvae to expend energy on osmoregulatory adaptation rather than growth and development. This reduces molting success and delays or prevents pupation, thereby interrupting the life cycle. In the United States, particularly along the East and Gulf coasts, mosquito ditching techniques have been used since the early 20th century as part of control efforts in salt marshes and coastal wetlands. These drainage initiatives were implemented to diminish the breeding of mosquito larvae, connect surface depressions to more profound waterways, amplify access by natural larval predators, and decrease the quantity of pools that might potentially include mosquito larvae (Saward-Arav et al., 2016). The method is referred to as Open Marsh Water Management (OMWM), which is used in numerous coastal areas in the United States and other countries with similar wetland environments (Dale et al., 2021). OMWM continues to be refined to balance vector control objectives with ecological conservation considerations.

From a funding perspective, eliminating unintended puddles for implementation in Indonesia is a low-to-medium cost intervention that does not require high technology. It can be implemented using routine budgets such as the Regional Revenue and Expenditure Budget (*APBD)*, Village Funds *(Dana Desa*), and environmental sanitation programs. The approach is also compatible with cross-sectoral programs from the environment office, health office, as well as the Public Works and Public Housing sector (*PUPR*). Activities can be implemented through microtopographic planning, repairing small channels, and closing artificial cavities. The funding required is generally less expensive than repeated chemical interventions (larvicides). The elimination of unintended puddles is very feasible in terms of funding, especially for gradual implementation and based on priority areas. Meanwhile, implementing mosquito ditching requires an initial investment for surveying and construction, but the costs are only a one-time expense. Periodic maintenance costs are also required, and can be combined with drainage, flood control, or coastal rehabilitation projects. Overall, mosquito ditching is financially feasible when positioned as a light environmental infrastructure project, rather than a pure health program.

In terms of technical complexity, neither unintended puddle elimination nor mosquito ditching requires sophisticated technology. Both methods can be implemented with simple civil engineering skills and basic ecohydrology knowledge, often with the involvement of local labor. The key factors include microhabitat-based planning and an understanding of local tidal dynamics to produce a system truly suited to each region. Technology is not the key problem, but specific design and location. In terms of institutional readiness, Indonesia already has experi-

Table 5. The comparison between eliminating unintended puddles and mosquito ditching in terms of funding, technology, suitability to Indonesia's natural environment, sustainability, and ecological risks

Aspect	Eliminating unintended puddles	Mosquito ditching
Funding	Very feasible	Fiseable
Technology	Simple	Simple-Medium
Suitability for Indonesia's natural environment	Very suitable	Suitable (with adaptation)
Sustainability	High	High (when maintained well)
Ecological risks	Low	Low-Medium (requires local design precision)

ence in micro-drainage, canal normalization, as well as coastal and mangrove management programs. The missing element is integrating vector control objectives into technical planning and strengthening intersectoral coordination (Rochlin & Morris, 2017; Talukdar et al., 2023).

In general, the implementation of eliminating unintended puddles and mosquito ditching is in accordance with Indonesia natural conditions, including daily tides, periodic tidal flooding, high sedimentation, and intense rainfall. These conditions enhance the applicability of puddle elimination and support mosquito ditching as an adaptive strategy to improve water redistribution. However, the ditching must be carefully implemented to avoid interfering with the activity of the crucial ecosystem (mangroves and nursery grounds). Structures should follow natural hydrological patterns rather than rigid linear configurations. This approach is particularly appropriate in the Indonesian context, where *Culex* larvae demonstrate high tolerance to variations in salinity and water flow, making single-factor control strategies ineffective. Consequently, physical habitat modification is considered the most rational intervention (Rulli et al., 2025).

From an ecological perspective, the methods do not form biological resistance nor pollute the environment, while promoting ecosystem functionality in combination with mangroves. Effective ditching enhances water connectivity, and eliminating unwanted puddles disrupts mosquitoes habitat, and preserves the ecosystem. Both methods are better than the long-lasting chemical techniques. Socially and institutionally, the community can easily comprehend this activity, as the usefulness is apparent (water retention is prevented) and can be incorporated into the local culture of village cooperation *(gotong royong)*. The potential challenges include regular maintenance, yearly budget stability, and local governmental dedication. Sustainability is high when the methods are institutionalized as part of coastal governance, not a temporary project.

Effective vector control in coastal areas cannot rely on a single environmental factor or intervention. Instead, it must be grounded in micro-hydrological management that reduces the presence and persistence of stagnant water. In the Indonesian context, eliminating unintended puddles and mosquito ditching is not only feasible but also rational and sustainable. These strategies should be framed as environmentally based structural interventions, designed according to local microhabitat characteristics and coastal dynamics, integrated with mangrove restoration as an ecological buffer, and institutionalized across sectors and over time. Further studies are needed to further explore the technical implementation of flood control and mosquito ditching in Indonesia.

This study has several limitations stemming from natural variations that are difficult to control and comprehensively measure. The limitations include seasonal variations, identification of *Culex* larval species, variations in water conditions, and geographic region. This study was conducted during a specific time period (January 2024), which coincided with the rainy season in Indonesia. Therefore, salinity fluctuations and more extreme tidal frequencies during the dry season may result in different osmoregulatory dynamics in *Culex* larvae. Larval identification was carried out morphologically to distinguish the *Culex* genus from other genera. Although *Culex quinquefasciatus* is known to be the main vector in the study area, future use of molecular identification would be very useful for mapping variations in osmoregulatory ability at a more species-specific level. This study focused on the relationship between salinity, osmolarity, and larval density. However, other environmental factors, such as organic matter load (BOD/COD), the presence of natural predators, or interspecific competition, that can also affect habitat productivity, were not analyzed in depth. The results provide a specific overview of the coastal characteristics of Brebes Regency with the particular mangrove forest conditions. Consequently, caution should be exercised when generalizing the results to coastal areas with significantly different topographic characteristics or vegetation structures. These limitations are expected to serve as a reference for future studies to obtain more in-depth results.

CONCLUSION

In conclusion, this study demonstrates that *Culex* larval density in coastal ecosystem is not determined by a single environmental factor, but rather by the interaction between the physiological ability to adapt to osmotic changes and hydrological dynamics. Osmoregulation test results show that *Culex* larvae have a wide tolerance to salinity variations. Consequently, variables such as salinity, flow conditions, and mangrove density are not significantly related to larval density in the field. In contrast, tidal flood frequency is significantly related to larval density. This emphasizes the importance of the presence and duration of unintended puddles as key factors influencing the formation of ideal *Culex* larval habitats. The results indicate that vector control in coastal areas needs to be directed at micro-hydrological management through the elimination of unintended puddles and habitat modifications such as mosquito ditching. Mangrove ecosystem restoration remains important as a supporting intervention to strengthen ecosystem stability. In the context of lymphatic filariasis elimination, particularly in the Pre-TAS and TAS phases, this environmentally based larval control approach plays a crucial role in reducing residual vector density. These strategies help reduce the risk of residual transmission in dynamic coastal areas vulnerable to tidal flooding.

ACKNOWLEDGEMENT

The authors are grateful to the Brebes Regency Health Office, the regional government of Brebes Regency, and the Environment and Forestry Office of Central Java Province for the invaluable support in providing the necessary data and granting permission for data collection. Appreciation also goes to the Fisheries and Marine Science Laboratory at Diponegoro University for the hospitality and assistance during osmoregulatory measurements.

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