DOI: 10.31398/tpjf/31.2.2023-0083

RESEARCH ARTICLE

Quantifying the Current and Future Risk of Invasiveness of the Non-native Fishes in Ramsar-listed Lake Naujan, Philippines

Allan S. Gilles Jr[1,2,*], Jean-Matthew B. Bate[1], Ma. Angela Klarizze H. Solomon[1], Elfritzson M. Peralta[1,2], Richard Thomas B. Pavia Jr[1,2], Lorenzo Vilizzi[2,3]

[1] *Graduate School, University of Santo Tomas, Manila, 1008 Metro Manila, Philippines*
[2] *Department of Biological Sciences, College of Science, Research Center for the Natural and Applied Sciences, University of Santo Tomas, Manila, 1008 Metro Manila, Philippines*
[3] *Department of Ecology and Vertebrate Zoology, Faculty of Biology and Environmental Protection, University of Lodz, 90-237 Lodz, Poland*

ABSTRACT

The number of non-native fish species introduced into the Philippines has steadily increased over the last decades, similar to other Southeast Asian countries. This trend of non-native species introductions is of high concern for the conservation of the native aquatic biota of the country, as invasive fishes are known to be responsible for a wide range of detrimental effects. In this study, the 13 non-native freshwater fish species recently reported for Ramsar-listed Lake Naujan (Province of Oriental Mindoro) were screened for their invasiveness risk under current and predicted climate change scenarios. Of the screened species, 23.1% and 61.5% were ranked as high risk under current and future climate conditions, respectively. The higher-risk species were redbelly tilapia *Coptodon zillii*, Nile tilapia *Oreochromis niloticus*, and guppy *Poecilia reticulata*. These findings indicate a high likelihood that the already threatened aquatic biota of Lake Naujan will be further affected by the presence of the resident non-native fish species in the near future. Recommendations include: (i) implementation of an introduction vector and pathway analysis; (ii) establishment of a comprehensive list or database of potentially invasive or prohibited species; (iii) continuous monitoring and surveillance of fish activities in the lake; and (iv) implementation of a comprehensive, government-led information, education and communication campaign. The outcomes of this study are also meant to serve as a foundation for the development of shared regulations to control the international trade of non-native fish species not only in the Philippines but also among southeast Asian countries.

*Corresponding Author: *asgilles@ust.edu.ph*
Received: *November 11, 2023*
Accepted: *July 15, 2024*

Keywords: *invasive species, risk screening, Aquatic Species Invasiveness Screening Kit (AS-ISK), decision-support tools*

1. INTRODUCTION

Invasive species are known to pose serious threats to native biota, with freshwater ecosystems being especially vulnerable to biological invasions (Andersen et al. 2004; Strayer 2010). The introduction of non-native species, followed by their establishment and spread, can result in substantial impacts once these species become invasive (Copp et al. 2016a). Evaluating these impacts can be problematic due to unpredictability (Strayer 2010). This is because introduced aquatic species can adapt to a niche that differs completely from that occupied in their native range, posing a threat to native species (Gurevitch and Padilla 2004; Cagauan 2007). The deliberate or accidental introduction of invasive fishes is considered one of the most insidious threats to the conservation of aquatic biota worldwide (Kiruba-Sankar et al. 2018), with increased risks of competition for food and space eventually impacting the survival of native fish species. Overall, invasive species can alter the evolution of native species by competition, niche displacement, and predation, eventually leading to their extinction (MacKinnon 2002).

As per other regions worldwide, in Southeast Asia, the number of non-native fish species has steadily increased over the last decades (De Silva 1989; Pallewatta et al. 2003; Welcomme and Vidthayanon 2003), and in the Philippines alone, 159 non-native fishes have been introduced since 1905 (Casal et al. 2007). With freshwater habitats devoid of, or occupied by few, native fish species, the freshwater fish fauna of the Philippine archipelago is depauperate because of the country's biogeography. At the same time, there is currently a dearth of information on the potential of non-native fishes to become invasive in the water bodies of the Philippines. This knowledge gap is further exacerbated by a failure of local government agencies to implement laws on the introduction of non-native species, coupled with an overall unwillingness to interfere with the laws regulating the commerce and trade of these species (Joshi 2006).

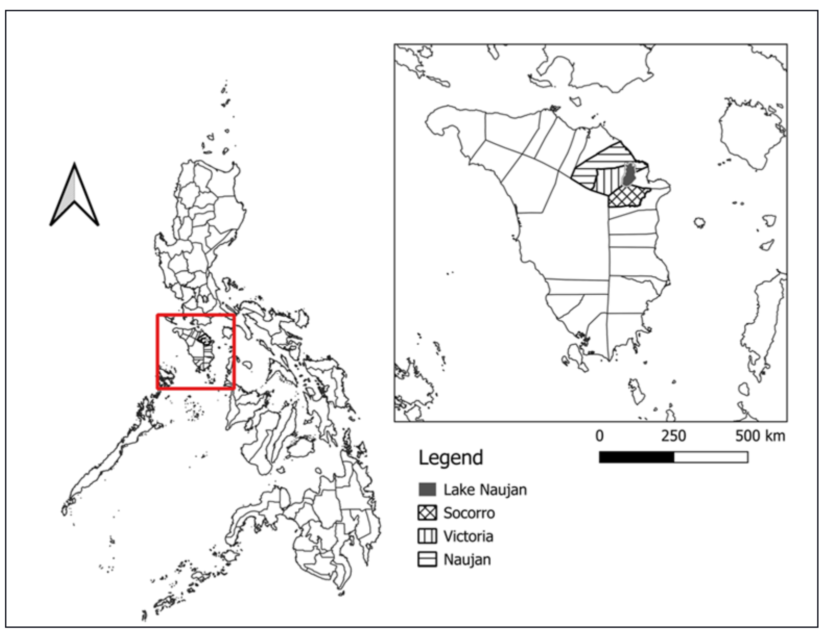
The Philippines possesses more than 100 lakes, which represent over 0.5% (i.e., ≈ 200,000 ha) of the country's surface area (Guerrero 2001; Mercene-Mutia 2001). Among these water bodies is Lake Naujan, the fifth-largest lake in the Philippines. Unlike other major lakes in the country, the aquatic biodiversity of Lake Naujan is poorly studied (Labatos 2012). This may be due to the remoteness of the lake, which is not located within the major island groups of the Philippine archipelago. This study aimed to determine the risk of invasiveness of the non-native fishes in Lake Naujan under current and future climate conditions to fill the knowledge gap. The outcomes of this study are intended to inform the management and conservation of one of the most critically threatened lake ecosystems in the Philippines. The risk screening approach employed in this study is also meant to provide an additional example of its applicability across threatened water bodies of the country (To et al. 2022; Gilles et al. 2023).

2. MATERIALS AND METHODS

2.1 Study area

Lake Naujan is the fifth-largest lake in the Philippines (Figure 1). It is located in the northeastern part of the island of Mindoro in the province of Oriental Mindoro and extends for about 14 km from north to south and 7 km from east to west (13.1727° N, 121.3427° E). The lake, bounded by the four municipalities of Naujan, Pola, Socorro, and Victoria, is fed by numerous mountain streams and springs and drains into the River Butas. Lake Naujan is part of the namesake National Park (21,655 ha), which was established under Proclamation No. 282 (27 March 1956) and later amended by Proclamation No. 335 (25 January 1968). Lake Naujan is recognized as a Ramsar Wetland of International Importance and is part of the East Asian-Australasian Flyway for migratory birds. The lake is rich in nutrients and supports a major fishery of both demersal and pelagic species, with most of the local inhabitants depending on these resources for their livelihood. The marshlands adjacent to the lake are under grass and sedge, and this dense cover serves as a habitat for resident and migratory waterfowl. The presence of wildlife further enhances the value of the lake as a recreational area.

According to available literature, the occurrence of non-native fish species in Lake Naujan has been reported since 1997. In a survey conducted by the Southeast Asian Regional Center for Graduate Study and Research in Agriculture in that year, 14 fish species were reported, of which three were introduced, namely the Philippine catfish ‘hito’ *Clarias batrachus* (Linnaeus, 1758), the Nile tilapia *Oreochromis niloticus* (Linnaeus, 1758), and the snakeskin gourami ‘pla-salit’ *Trichopodus pectoralis* (Regan, 1910). The majority of the native fish species in Lake Naujan are migratory and live primarily in the marine environment but



Map of Lake Naujan, Philippines, the risk assessment area for screening non-native freshwater fishes.

frequently visit freshwater ecosystems to return to the sea by the time they become sexually mature (Labatos 2012). Of these species, 13 are currently recognized as non-native and include, apart from the three species listed above, climbing perch 'puyo' *Anabas testudineus* (Bloch, 1792), goldfish 'tawes' *Carassius auratus* (Linnaeus, 1758), striped snakehead 'dalag' *Channa striata* (Bloch, 1793), redbelly tilapia 'Bruce Lee' *Coptodon zillii* (Gervais, 1848), common carp *Cyprinus carpio* (Linnaeus, 1758), silver perch 'ayungin' *Leiopotherapon plumbeus* (Kner, 1864), guppy 'isdang kanal' *Poecilia reticulata* (Peters, 1859), molly *Poecilia sphenops* (Valenciennes in Cuvier and Valenciennes, 1846), vermiculated sailfin catfish *Pterygoplichthys disjunctivus* (Weber, 1991), and three-spot gourami *Trichopodus trichopterus* (Pallas, 1770).

2.2 Risk screening

All 13 non-native fish species currently present in Lake Naujan (the risk assessment area) were screened for their risk of invasiveness. Risk identification was undertaken using the Aquatic Species Invasiveness Screening Kit v2.3.3 (AS-ISK: Copp et al. 2016b, 2021). This decision-support tool is available for free download (Vilizzi et al. 2021) and offers users 32 languages, including Filipino. The AS-ISK complies with the 'minimum standards' for screening non-native species under EC Regulation No. 1143/2014 on the prevention and management of the introduction and spread of invasivve species. The Philippines government, Bureau of Fisheries and Aquatic Resources, recently adopted the AS-ISK to identify potentially invasive freshwater fish species across the country (Department of Agriculture 2021). The AS-ISK consists of 55 questions, of which 49 comprise the Basic Risk Assessment (BRA) and six comprise the Climate Change Assessment (CCA). The latter section requires the assessor to predict how future predicted climatic conditions will likely affect the BRA concerning risks of introduction, establishment, dispersal, and impact. For the present risk screening, the following studies were consulted for the CCA section: Papa and Briones (2014), Mendoza et al. (2019), and Volta and Jeppesen (2021). All 13 species were screened by the first author of this study jointly with one (six species) or two additional assessors (seven species) involving the second, third, and fourth authors. The joint assessors were selected based on their expert knowledge of the environmental biology of the screened species. Screenings performed by joint assessors have been shown to increase confidence relative to independent screenings by one or more assessors (Vilizzi et al. 2022a).

The standard protocol by Vilizzi et al. (2022a) was followed to achieve a valid screening, whereby the assessor must provide each question with a response, confidence level, and justification (Vilizzi and Piria 2022). This results in two outcome scores: BRA and BRA+CCA. Scores < 1 suggest a 'low risk' of the species being or becoming invasive in the risk assessment area; scores ≥ 1 indicate a 'medium risk' or a 'high risk.' Medium-risk and high-risk species are defined using a calibrated threshold (Vilizzi and Piria 2022; Vilizzi et al. 2022a, 2022b). Given the low sample size (i.e., the total number of species screened) in this study that prevented computation of a calibrated threshold for the risk assessment area (Vilizzi et al. 2022a), the threshold of 34.5 recently identified for Lake Taal in the Philippines (Gilles et al. 2023) was used for the species' risk ranking. The use of this threshold must be considered even more accurate than that of a generalized one for freshwater fishes in tropical climates (Vilizzi et al. 2022a), given the location of lakes Taal and Naujan within the same region (i.e., Philippines). After setting the threshold, evaluation of risk classifications to identify false-positive and false-negative rankings was not applied to the medium-risk species as their further evaluation in a (follow-up) comprehensive risk assessment depends on both policy and management priorities and the availability of financial resources. The risk classification relied on the *a priori* species categorization according (Table 1.)to the standard protocol by Vilizzi et al. (2022a). Permutational ANOVA with normalization of the data was used to test for differences in the confidence factor (CF: Vilizzi et al. 2022a) between the BRA and BRA+CCA. This used a Bray-Curtis dissimilarity measure, 9999 unrestricted permutations of the raw data, and statistical effects evaluated at α = 0.05.

3. RESULTS

Based on the BRA scores (Table 2, Fig. 2a), 3 (23.1%) species were ranked as high risk and 10 (76.9%) as medium risk. Amongst the 10 species categorized *a priori* as invasive, three were high risk, hence true positives (*Coptodon zillii*, *Oreochromis niloticus*, and *Poecilia reticulata*). Of the 10 medium-risk species, three were *a priori* non-invasive (*Anabas testudineus*, *Leiopotherapon plumbeus*, *Trichopodus pectoralis*) and seven invasive (*Carassius auratus*,*Channa striata*, *Clarias batrachus*, *Cyprinus carpio*, *Poecilia sphenops*, *Pterygoplichthys disjunctivus*, and *Trichopodus trichopterus*).

Table 1. Non-native freshwater fish species screened for their risk of invasiveness in Lake Naujan, Philippines. For the *a priori* categorization, the steps of the protocol by Vilizzi et al. (2022a) are indicated: (i) FishBase (www.fishbase.org); (ii) Global Invasive Species Database (GISD: www.iucngisd.org); (iii) European Alien Species Information Network (EASIN: https://easin.jrc.ec.europa.eu/easin); (iv) Google Scholar (GScholar) literature search. N = no impact/threat; Y = impact/threat; '–' = absent; n.a. = not applicable.

		***A priori* categorization**				
Species name	**Common name**	**FishBase**	**GISD**	**EASIN**	**GScholar**	**Outcome**
Anabas testudineus	climbing perch	N	–	–	N	Non-invasive
Carassius auratus	goldfish	Y	Y	Y	n.a.	Invasive
Channa striata	striped snakehead	Y	–	–	n.a.	Invasive
Clarias batrachus	Philippine catfish	Y	Y	Y	n.a.	Invasive
Coptodon zillii	redbelly tilapia	Y	–	N	n.a.	Invasive
Cyprinus carpio	common carp	Y	Y	Y	n.a.	Invasive
Leiopotherapon plumbeus	silver perch	N	–	–	N	Non-invasive
Oreochromis niloticus	Nile tilapia	Y	Y	Y	n.a.	Invasive
Poecilia reticulata	guppy	Y	Y	Y	n.a.	Invasive
Poecilia sphenops	molly	N	–	N	Y	Invasive
Pterygoplichthys disjunctivus	vermiculated sailfin catfish	Y	Y	–	n.a.	Invasive
Trichopodus pectoralis	snakeskin gourami	Y	–	–	N	Invasive
Trichopodus trichopterus	three-spot gourami	N	–	–	N	Non-invasive

Table 2. Risk outcomes for the freshwater fishes screened with the Aquatic Species Invasiveness Screening Kit (AS-ISK) for Lake Naujan. For each species, the following information is provided: *a priori* categorization of invasiveness (N = non-invasive; Y = invasive: see Table 1), Basic Risk Assessment (BRA) and BRA + Climate Change Assessment (BRA+CCA) scores with corresponding risk ranks based on a threshold of 34.5 (after Gilles et al. 2023; M = Medium; H = High), classification (Class: FP = false positive; TP = true positive; '–' = not applicable as medium-risk: see text for details), difference (Delta) between BRA+CCA and BRA scores, and confidence factor (CF). Risk outcomes for the BRA scores: M, with the score within the interval [1, 34.5[; H]34.5, 72[. Risk outcomes for the BRA+CCA scores: M [1, 34.5[; H]34.5, 82[. Note the reverse bracket notation indicating, in all cases, an open interval.

		BRA			**BRA+CCA**				**CF**		
Species name	***A priori***	**Score**	**Rank**	**Class**	**Mean**	**Score**	**Class**	**Delta**	**Total**	**BRA**	**CCA**
Anabas testudineus	N	18.0	M	–	24.0	M	–	6	0.81	0.82	0.71
Carassius auratus	Y	22.5	M	–	28.5	M	–	6	0.81	0.79	1.00
Channa striata	Y	28.0	M	–	36.0	H	TP	8	0.87	0.86	0.96
Clarias batrachus	Y	23.5	M	–	31.5	M	–	8	0.74	0.72	0.92
Coptodon zillii	Y	35.5	H	TP	43.5	H	TP	8	0.82	0.80	1.00
Cyprinus carpio	Y	28.0	M	–	36.0	H	TP	8	0.80	0.78	1.00
Leiopotherapon plumbeus	N	3.0	M	–	11.0	M	–	8	0.69	0.65	1.00
Oreochromis niloticus	Y	42.5	H	TP	48.5	H	TP	6	0.91	0.90	1.00
Poecilia reticulata	Y	37.0	H	TP	45.0	H	TP	8	0.82	0.80	1.00
Poecilia sphenops	Y	31.0	M	–	37.0	H	TP	6	0.79	0.76	1.00
Pterygoplichthys disjunctivus	Y	33.5	M	–	41.5	H	TP	8	0.85	0.83	1.00
Trichopodus pectoralis	Y	14.5	M	–	10.5	M	–	−4	0.82	0.80	1.00
Trichopodus trichopterus	N	27.5	M	–	35.5	H	FP	8	0.73	0.70	0.96

Based on the BRA+CCA scores (Table 2, Fig. 2b), 8 (61.5%) species were ranked as high risk and 5 (38.5%) as medium risk. Amongst the *a priori* invasive species, seven were high risk, hence true positives (same species as for the BRA plus *Channa striata*, *Cyprinus carpio*, *Poecilia sphenops*, and *Pterygoplichthys disjunctivus*); amongst the *a priori* non-invasive species, one was a false positive (*T. trichopterus*). Two of the five medium-risk species were *a priori* non-invasive (*A. testudineus and L. plumbeus*) and three invasive (*Carassius auratus*, *Clarias batrachus*, and *Trichopodus pectoralis*).

The CCA resulted in an increase in the BRA score (cf. BRA+CCA score) for 12 (92.3%) species and a decrease for one (7.7%) (Table 2). Regarding the confidence factor (CF), the mean CF Total was 0.805 ±

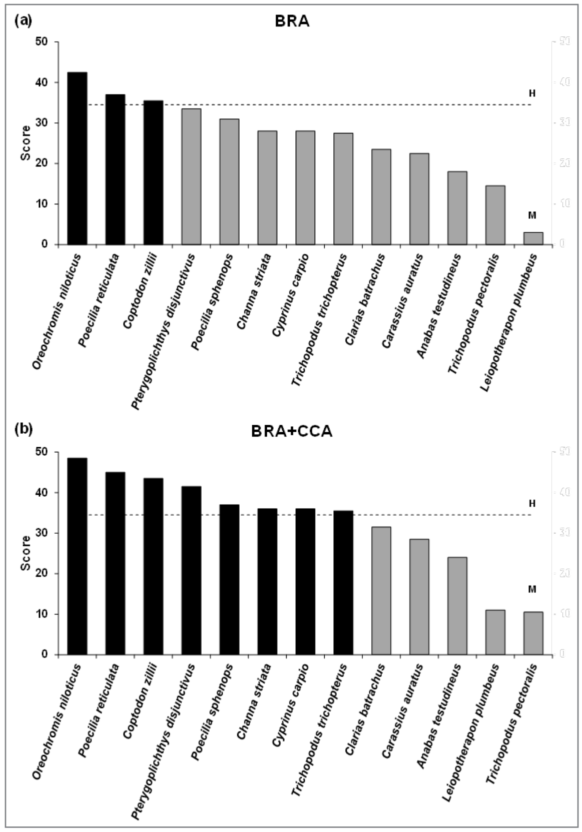


Figure 2. Risk outcome scores for the non-native freshwater fishes screened with the Aquatic Species Invasiveness Screening Kit for Lake Naujan. (a) Basic Risk Assessment (BRA) scores; (b) BRA + Climate Change Assessment (BRA+CCA) scores. Black bars = high-risk species; Gray bars = medium-risk species; Hatched line = high-risk (H) threshold; Dotted line = medium-risk (M) threshold. Thresholds as per Table 1.

0.016 SE, the mean CFBRA 0.785 ± 0.018 SE, and the mean CFCCA0.962 ± 0.023 SE, indicating high confidence in all cases. The mean CFCCA was higher than the mean CFBRA ($F^{\#}_{1,24} = 37.91$, $P^{\#} < 0.001$; # = permutational value). The combined report for the 13 screened species is provided as supplementary material.

4. DISCUSSION

Lake Naujan is a crucial freshwater resource spanning the municipalities of Naujan, Pola, Socorro, and Victoria. As the fifth largest lake in the Philippines, it sustains many fisherfolk who depend on its waters for their livelihood. Despite its designation as Naujan Lake National Park under Republic Act 7586, known as the National Integrated Protected Areas System Act of 1992, and its classification as a 'protected landscape and seascape' by the Department of Environment and Natural Resources Region IV through its Protected Area Suitability Assessment report in 1995, the lake still faces several environmental problems, including the presence of introduced species. This is the reason why this study has evaluated the risk of invasiveness of all recorded introduced non-native fish species in the lake.

Based on the threshold value of 34.5, the present risk screening for Lake Naujan indicated a substantial increase in the number of high-risk non-native fish species under current and predicted climate conditions. This is a warning sign of the high susceptibility of the lake to current invasion by non-native fishes. The three species posing the highest risk of invasiveness under current and predicted climate conditions were *Coptodon zillii*, *Oreochromis niloticus,* and *Poecilia reticulata*. This outcome agrees with a recent screening for the same species in Lake Taal (Gilles et al. 2023). Of note, despite the computation of a risk assessment area-specific threshold being the preferred option, usage of a threshold from a risk assessment area within the same ecoregion (i.e., Lake Taal, in this study) can be regarded as the next most accurate option followed by usage of a generalized threshold (Vilizzi et al. 2022a). This is demonstrated by the reliability of risk outcomes from AS-ISK applications relying on the latter approach (review in

Vilizzi et al. 2024), which is therefore increased by the usage of a threshold from a nearby risk assessment area within the same ecoregion, as achieved in the present study by using for Lake Naujan the threshold for Lake Taal (Gilles et al. 2023).

Coptodon zillii is an economically important fish for aquaculture and the aquarium trade (Dadebo et al. 2014). This species can outcompete other fish species for food, habitat, and nesting sites due to its omnivory and voracious feeding habits (Spataru 1978) and is also known to tolerate a wide range of climatic conditions and salinity levels (Yongo et al. 2023). *Oreochromis niloticus* was introduced in the Philippines in the 1970s for aquaculture purposes, with farming in ponds and cages of this economically valuable species being widespread across the country (Araullo 2001; Rosana et al. 2006; Guerrero 2014; Mutia et al. 2022). This species is one of the most widespread invasive fishes worldwide due to its tolerance of a wide range of environmental conditions coupled with flexible habitat requirements, reproductive strategy, and foraging behavior (Aquilino et al. 2011; Guerrero 2014; Gu et al. 2015). However, in the Philippines, the economic importance of *Oreochromis niloticus* as a food source outweighs its high level of invasiveness, despite its being present in almost all lakes and reservoirs across the country with several documented adverse effects (De Silva et al. 2004; Mutia et al. 2018, 2022). *Poecilia reticulata* is a common species in the aquarium trade that has been introduced in the Philippines as a biomedical measure to control the proliferation of mosquito larvae (Guerrero 2014). The easy establishment of populations of this species can be attributed to its short generation time and viviparous reproductive strategy (Rosenthal et al. 2021), but also to the ability to hybridize with native populations of other species (Sievers et al. 2012). *Poecilia reticulata* can also impact ecosystem services as an ornamental fish due to its capacity to thrive in different water quality conditions (Magurran and Philip 2001). All the above three species are known to tolerate a wide range of water quality conditions and are expected to adapt to changes in climate (Guerrero 2014; Magurran and Philip 2001).

The CCA component of the AS-ISK questionnaire evaluates the potential effects of predicted (future) climate conditions on a taxon's risks of entry, establishment, and dispersal. For some of the species screened in this study, an increase in their risk of invasiveness, as indicated by their risk ranking shifting from medium to high, was observed when accounting for the projected climate conditions for Lake Naujan. This suggests climate change is likely to create conditions even more favorable to several non-native fish species in the risk assessment area (Chan et al. 2019; Mendoza et al. 2019; Gilles et al. 2023). Furthermore, a recent study found that climate change in the Philippines, particularly the expected rise in temperature and altered weather patterns, could significantly increase the risk of non-native fish species becoming invasive in Lake Naujan (Mendoza et al. 2019). The 2017 World Risk Report ranks the Philippines as the third most vulnerable country to climate change (Global Risks Report 2017). Mean temperatures in all areas in the Philippines are expected to rise by 0.9 °C to 1.1 °C in 2020 and by 1.8 °C to 2.2 °C in 2050 (Gilles et al. 2023). The Philippines' vulnerability to climate change makes this especially concerning, as warmer inland waters could become more hospitable to a wider range of invasive fishes.

Amongst the species whose risk rank increased from medium to high after accounting for predicted climate scenarios was *Pterygoplichthys disjunctivus*, which is a popular introduced aquarium fish across the country (Chavez et al. 2006a, 2006b; Hubilla et al. 2007; Rahel and Olden 2008; Guerrero 2014). The high risk of invasiveness of this species under predicted climate conditions is attributed to its tolerance for pollution and low oxygen and salinity levels, feeding behavior, defensive predation through its spiny fins and hard dermal armor, and a reproductive strategy characterized by batch spawning and parental care (Brion et al. 2013; Emiroğlu et al. 2016; Kumar et al. 2018; Chakraborty et al. 2020). In Lake Naujan, *Pterygoplichthys disjunctivus* has also been reported to damage gillnets used by local fishers. Another species whose risk rank increased from medium to high was *Poecilia sphenops*, an ornamental fish whose introduction has resulted from both accidental escapes and intentional releases and is known to represent a potential threat to native fishes (Lee et al. 1991). *Poecilia sphenops* can breed in low and high salinity conditions and survive in clear to turbid or muddy waters (Husna et al. 2014). Despite the lack of records for *Trichopodus trichopterus* being invasive (cf. its classification as a false positive: Table 1), this small and popular ornamental fish native to Southeast Asia has been introduced in at least 17 countries worldwide and is known to colonize easily new aquatic habitats due to its wide environmental tolerance and fast growth rates. The species' ability to tolerate a wide range of temperatures and salinities causes them to compete with native fishes, although it can also positively impact ecosystem services as a food source (Labatos 2012; Mutia et al. 2022).

The five species ranked as medium risk under both current and predicted climate conditions for Lake Naujan were *Anabas testudineus*, *Carassius auratus*, *Clarias batrachus*, *Leiopatherapon plumbeus*, and *Trichopodus pectoralis*. Despite these species being ranked as medium risk, this does not imply that they may not pose any risk at all. For instance, *Carassius auratus*, originally from China, has been widely imported as a pet and ornamental fish worldwide. The species' ability to adapt and thrive under various environmental conditions contributes to its invasiveness in the introduced range. In the Philippines, where *Carassius auratus* are found in several rivers and lakes, including Lake Taal and Laguna de Bay (Mutia et al. 2018; Gilles et al. 2023), impacts include increased turbidity, algal blooms, and competition with native fish species (To et al. 2022; Gilles et al. 2023).

The fisheries office order provided by the Bureau of Fisheries and Aquatic Resources has adopted AS-ISK as the official decision-support tool to conduct risk screenings on non-native aquatic inland water bodies. The outcome of a species-specific screening in terms of its risk ranking allows to inform decision-makers on the management of extant species (i.e., already present in the country) and possible introduction of horizon species (i.e., not currently present in the country). Notably, low-risk species (i.e., with a BRA and BRA+CCA outcome scores less than 1) are considered 'safe' for introduction, whereas medium-risk species are only allowed in reservoirs and land-based aquacultural facilities. Lastly, high-risk species are not allowed into any inland water bodies. According to this study, all species for Lake Naujan were ranked as medium or high risk, with no low-risk species. Following the above guidelines, all high-risk species should not be allowed for further introduction in the risk assessment area, whereas the medium-risk species should be strictly monitored.

4. CONCLUSION

The results of this study are expected to provide valuable insights for policymakers and stakeholders, aiding them in crafting effective policies and guidelines for managing non-native species not only for Lake Naujan but for the entire aquatic ecosystem in the Philippines. Given the high conservation value of Lake Naujan, efforts are needed from stakeholders in the mitigation and prevention of the detrimental impacts caused by the non-native (and invasive) fish species already present, and preventative measures are required to counteract the introduction of any additional non-native species (Dudgeon et al. 2006). This is especially important as the lake is also impacted by a wide range of human-related activities (Labatos 2012). To this end, establishing a comprehensive list and database of potentially invasive and prohibited species would provide accessible and updated information to national and regional policymakers and stakeholders that can contribute to amending and reinforcing non-native species legislation and regulations (Roy et al. 2018).

Overall, this study recommends (i) an introduction vector and pathway analysis to determine the various channels by which non-native species could be introduced into the lake, (ii) the establishment of a comprehensive list or database of potentially invasive or prohibited species, (iii) continuous monitoring and surveillance of fish activities, and (iv) implementation of a comprehensive, government-led Information, Education, and Communication campaign. Given that most invasive non-native fish species pose comparable levels of risk within similar biogeographical regions, further risk screening studies like the present one (To et al. 2022; Gilles et al. 2023) would also serve as a foundation for developing shared regulations to control the international trade of various non-native fish species not only in the Philippines but also among southeast Asian countries (Chan et al. 2019; Wei et al. 2021).

ACKNOWLEDGMENTS

The authors from the Philippines would like to acknowledge the facilities and equipment provided by the University of Santo Tomas Research Center for Natural and Applied Sciences. Special thanks also go to the members of DENR MIMAROPA and NLNP-PAMU, as well as Sir Jomz Fontanilla, for helping secure a Memorandum of Agreement between UST and Lake Naujan. The local fishers of Lake Naujan are also acknowledged for assistance in the field, which made this study possible.

SUPPLEMENTARY MATERIAL

AS-ISK report for the 13 fish species screened for their risk of invasiveness in Lake Naujan. Supplementary file.

AUTHOR CONTRIBUTIONS

Gilles AS: Writing - Original draft preparation, acquisition of data, analysis and interpretation of data, wiring and editing the manuscript for significant intellectual content. **Bate J-MB:** Data curation, Writing - Original draft preparation. **Solomon MAKH:** Data curation. **Pavia RTB:** Writing - Original draft preparation, Writing - Reviewing, and Editing, Supervision. **Peralta EM:** Writing - Reviewing, and Editing. **Vilizzi L:** Writing - Original draft preparation, Writing - Reviewing, and Editing, Software, Validation, Supervision.

CONFLICT OF INTEREST

The authors declare that there are no potential conflicts of interest concerning the research, authorship, and publication of this article.

REFERENCES

Andersen MC, Adams H, Hope B, Powell M. 2004. Risk assessment for invasive species. Risk Anal. 24(4):787–793. https://doi.org/10.1111/j.0272-4332.2004.00478.x

Aquilino SYL, Tango JM, Fontanilla IKC, Pagulayan RC, Basiao ZU, Ong PS, Quilang JP. 2011. DNA barcoding of the ichthyofauna of Taal Lake, Philippines. Molec Ecol Res. 11(4): 612–619. https://doi.org/10.1111/j.1755-0998.2011.03000.x

Araullo DB. 2001. Aquaculture practices and their impact on Philippine lakes. In: Santiago CB, Cuvin-Aralar ML Basiao ZU, editors. Conservation and Ecological Management of Philippine Lakes in Relation to Fisheries and Aquaculture (pp. 25–28). Iloilo: Aquaculture Department, Southeast Asian Fisheries Development Center; Laguna: Philippine Council for Aquatic and Marine Research and Development; Quezon City: Department of Science and Technology; Quezon City: Bureau of Fisheries and Aquatic Resources. http://hdl.handle.net/10862/821

Brion MA, Guillermo JG JR, Uy C, Chavez J, Carandang IV JS. 2013. Salinity tolerance of introduced South American sailfin catfishes (Loricariidae: *Pterygoplichthys* GILL 1858). Philippine J Sci 142(1):13–19. https://philjournalsci.dost.gov.ph/images/pdf/pjs_pdf/vol142no1/pdf/Salinity_Tolerance_of_South_American_catfishes.pdf

Cagauan AG. 2007. Red-bellied pacu in the Philippines. J Environ Sci Manag. 10: 42–47.

Casal CMV, Luna S, Froese R, Bailly N, Atanacio R, Agbayani E. 2007. Alien fish species in the Philippines: pathways, biological characteristics, establishment and invasiveness. J Environ Sci Manag. 10(1):1–9. https://hdl.handle.net/20.500.12348/1628

Chakraborty P, Chakrabarti S, Mukherjee P, Yardi K, Das S. 2020. Notes on the discovery and ecology of the invasive armoured catfish *Pterygoplichthys disjunctivus* (Weber, 1991) and the exotic cichlid *Amphilophus trimaculatus* (Gunther, 1867) from Southern West Bengal, India. Ecological Questions. 31(1):7–13. https://doi.org/10.12775/EQ.2020.001

Chan F, Beatty SJ, Gilles AS Jr, Hill JE, Kozic S, Du L, Morgan DL, Pavia RTB, Therriault TW, Verreycken H, et al. 2019. Leaving the fish bowl: the ornamental trade as a global vector for freshwater fish invasions. Aquatic Ecosys Health Manag. 22:417–439. https://doi.org/10.1080/14634988.2019.1685849

Chavez HM, Casao EA, Villanueva EP, Paras PM, Guinto MC, Mosqueda MB. 2006a. Heavy metal and microbial analyses of janitor fish (*Pterygoplichthys* spp*)* in Laguna de Bay, Philippines. J Environ Sci Manag. 9(2):31–40. https://www.ukdr.uplb.edu.ph/journal-articles/4254

Chavez JM, De La Paz RM, Manohar SK, Pagulayan RC, Carandang VI JR. 2006b. New Philippine record of south american sailfin catfishes (Pisces: Loricariidae). Zootaxa. 1109(1):57–68. https://doi.org/10.11646/zootaxa.1109.1.6

Copp GH, Russell IC, Peeler EJ, Gherardi F, Tricarico E, Macleod A, Cowx IG, Nunn AN, Occhipinti-Ambrogi A, Savini D, Mumford J, Britton JR. 2016a. European Non-native Species in Aquaculture risk analysis scheme–a summary of assessment protocols and decision support tools for use of alien species in aquaculture.

Fish Manag Ecol. 23(1):1–11. https://doi.org/10.1111/fme.12074

Copp GH, Vilizzi L, Tidbury H, Stebbing PD, Tarkan AS, Miossec L, Goulletquer P. 2016b. Development of a generic decision-support tool for identifying potentially invasive aquatic taxa: AS-ISK. Manag Biol Inv. 7(4):343–350. https://doi.org/10.3391/mbi.2016.7.4.04

Copp GH, Vilizzi L, Wei H, Li S, Piria M, Al-Faisal AJ, Almeida D, Atique U, Al-Wazzan Z, Bakiu R, et al. 2021. Speaking their language – development of a multilingual decision-support tool for communicating invasive species risks to decision makers and stakeholders. Environ Model Softw. 135:104900. https://doi.org/10.1016/j.envsoft.2020.104900

Dadebo E, Kebtineh N, Sorsa S, Balkew K. 2014. Food and feeding habits of the red-belly tilapia (*Tilapia zillii* Gervais, 1848) (Pisces: Cichlidae) in Lake Ziway, Ethiopia. Agric Forest Fisher. 3(1):17–23. https://doi.org/10.11648/j.aff.20140301.14

De Silva SS, Subasinghe RP, Bartley DM, Lowther A. 2004. Tilapias as alien aquatics in Asia and the Pacific: a review FAO. Fisheries Technical Paper No. 453.

De Silva SS. 1989. Exotic aquatic organisms in Asia: Proceedings of a workshop on introduction of exotic aquatic organisms in Asia. Manila: Asian Fisheries Society. pp. 154 https://idl-bnc-idrc.dspacedirect.org/bitstream/handle/10625/123/IDL-123.pdf

Department of Agriculture. 2021. Amending FOO 199, Series of 2019: Guidelines on the Implementation of Balik Sigla sa Ilog at Lawa (BASIL) Program on the Conduct of Risk Assessment for Introduction of New Species. Fisheries Office Order 043, Series of 2021. DA-Bureau of Fisheries and Aquatic Resources, Quezon City. 6 pp.

Dudgeon D, Arthington AH, Gessner MO, Kawabata Z-I, Knowler DJ, Lévêque C, Naiman RJ, Prieur-Richard A-H, Soto D, Stiassny MLJ, Sullivan CA. 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. Biol Rev. 81(2):163–182. https://doi.org/10.1017/s1464793105006950

Emiroğlu Ö, Ekmekçi FG, Aksu S, Başkurt S, Atalay MA, Tarkan AS. 2016. Introduction and establishment of tropical ornamental fish, *Pterygoplichthys* spp. (Actinopterygii: Siluriformes: Loricariidae) in hot springs: Aquarium trade as a potential risk for biodiversity in Turkey. Acta Ichthyol Piscat. 46(4):351–356. https://doi.org/10.3750/AIP2016.46.4.07

Gilles AS JR, To DAL, Pavia RTB JR, Vilizzi L, Copp GH. 2023. Risk of invasiveness of non-native fishes can dramatically increase in a changing climate: the case of a tropical caldera lake of conservation value (Lake Taal, Philippines). J of Vertebrate Biology. 73:23032. https://doi.org/10.25225/jvb.23032

Global Risks Report. 2017. 12th Edition is published by the World Economic Forum within the framework of The Global Competitiveness and Risks Team. ISBN: 978-1-944835-07-1

Gu DE, Ma GM, Zhu YJ, Xu M, Luo D, Li YY, Wei H,Mu XD, Luo JR, Hu YC. 2015. The impacts of invasive Nile tilapia (*Oreochromis niloticus*) on the fisheries in the main rivers of Guangdong Province, China. Biochem Syst Ecol. 59:1–7 https://doi.org/10.1016/j.bse.2015.01.004

Guerrero III RD. 2001. Sustainable development of Philippin lake resources: An agenda for research and development, pp. 19-23. In: Santiago CB, Cuvin-Aralar ML, Basiao ZU, editors. Conservation and Ecological Management of Philippine Lakes in Relation to Fisheries and Aquaculture. Iloilo: Southeast Asian Fisheries Development Center, Aquaculture Department; Los Baños, Laguna: Philippine Council for Aquatic and Marine Research and Development; Quezon City: Bureau of Fisheries and Aquatic Resources. 187 pp. http://hdl.handle.net/10862/820

Guerrero III RD. 2014. Impacts of introduced freshwater fishes in the Philippines (1905-2013): A review and recommendations. Philippine J Sci. 143(1):49–59. https://philjournalsci.dost.gov.ph/images/pdf/pjs_ pdf/vol143no1/pdf/impacts_of_introduced_freshwater_fishes_in_the_Phils.pdf

Gurevitch J, Padilla D. 2004. Are invasive species a major cause of extinctions? Trends Ecol Evol. 19(9):470–474. https://doi.org/10.1016/j.tree.2004.07.005

Hubilla M, Kis F, Primavera J. 2007. Janitor fish *Pterygoplichthys disjunctivus* in the Agusan Marsh: a threat to freshwater biodiversity. J Environ Sci Manage. 10(1):10–23. http://hdl.handle.net/10862/3519

Husna WN, Christianus A, Cob ZC, Mazlan AG, Simon KD. 2014. Effects of salinity and water quality parameters on the breeding and larva rearing of black molly *Poecilia sphenops* in laboratory condition. Aquaculture, Aquarium, Conservation & Legislation. 7(1):8–14.

Joshi RC. 2006. Invasive alien species (IAS): concerns and status in the Philippines. Proceedings of the International Workshop on the Development of Database (APASD) for Biological Invasion. FFTC, Taichung, Taiwan, China, pp. 1–23. https://kmadmin.fftc.org.tw/api/backend/articles/82/article-pdf?8d3269d076d70c4f0401344a1c088af4

Kiruba-Sankar R, Praveenraj J, Saravanan K, Kumar KL, Angel JRJ, Velmurugan A, Dam Roy S. 2018. Invasive species in freshwater ecosystems – threats to ecosystem services. In: Sivaperuman C, Velmurugan A, Singh AK, Jaisankar I, editors. Biodiversity and Climate Change Adaptation in Tropical Islands. Elsevier, Academic Press, USA. pp. 257–296. https://doi.org/10.1016/B978-0-12-813064-3.00009-0

Kumar AB, Schofield PJ, Raj S, Satheesh S. 2018. Salinity tolerance of non-native suckermouth armoured catfish (Loricariidae: *Pterygoplichthys* sp) from Kerala, India. Manag Biol Inv. 9(1):49–57. https://doi.org/10.3391/mbi.2018.9.1.05

Labatos BV JR. 2012. Aquatic Vertebrates and Macroinvertebrates of Naujan Lake National Park. pp. 42. https://www.researchgate.net/publication/271763119_Fishes_of_Naujan_Lake_National_Park_Oriental_Mindoro_Philippines

Lee PG, Ng PKL. 1991. The snakehead fishes of the Indo-Malayan Region. Nature Malaysiana. 16:113–129.

Mackinnon JR. 2002. Invasive alien species in Southeast Asia. Asean Biodiversity. 9–11.

Magurran AE, Phillip DA. 2001. Evolutionary implications of large-scale patterns in the ecology of Trinidadian guppies, *Poecilia reticulata*. Biol J Linn Soc. 73(1):1–9. https://doi.org/10.1111/j.1095-8312.2001.tb01342.x

Mendoza M, Dur G, Rosana MR, Santos M, Mutia T, Kawit NS, Ite MO, Villanueva LS, Anneville O, Souissi S, Papa RDS. 2019. Water quality and weather trends preceding fish kill occurrences in Lake Taal (Luzon Is., Philippines) and recommendations on its long-term monitoring. Philippine Science Letters 12(2):147–156. https://scienggj.org/2019/PSL%202019-vol12-no02-p147-156-Papa%20et%20al.pdf

Mercene-Mutia MT. 2001. Assessment of local government's implementation of open access policy in Taal Lake, Philippines: Effects on lake conservation and management. In: Santiago CB, Cuvin-Aralar ML, Basiao ZU, editors. Conservation and Ecological Management of Philippine Lakes in Relation to Fisheries and Aquaculture. Iloilo: Southeast Asian Fisheries Development Center, Aquaculture Department; Los Baños, Laguna: Philippine Council for Aquatic and Marine Research and Development; Quezon City: Bureau of Fisheries and Aquatic Resources. pp. 123–132. https://repository.seafdec.org.ph/bitstream/handle/10862/830/cemplrfa_p123-132.pdf;jsessionid=062BBF507BD01ECB83539BA7BAFE32D9?sequence=1

Mutia MT, Merilles ML, Muyot MC, Tordecilla BD. 2018. Abundance and distribution of *Sardinella tawilis* (Herre, 1927) larvae in Lake Taal, Philippines. Philippine J Fish. 25(2):16–26. https://doi.org/10.31398/tpjf/25.2.2018-0004

Mutia MTM, Magistrado ML, Muyot MC, Alcazar MTM, Tordecilla BD, Garciaa LC, Merilles MLD 2022. Status of Lake Taal fisheries amid volcanic threat and covid 19 pandemic: a preliminary study. Indonesian J Limnol 3(1):1–9. https://doi.org/10.51264/inajl.v3i1.23

Pallewatta N, Reaser JK, Gutierrez AT, editors. 2003. Invasive alien species in South Southeast Asia: national reports & directory of resources. Cape Town: Global Invasive Species Programme. pp. 111 https://www.gisp.org/downloadpubs/SOUTH_AN.PDF

Papa RD, Briones JC. 2014. Climate and human-induced changes to lake ecosystems: what we can learn from monitoring zooplankton ecology. J Environ Sci Manag. 17(1):60–67. https://doi.org/10.47125/jesam/2014_1/07

Rahel F, Olden J. 2008. Assessing the effects of climate change on aquatic invasive species. Conserv Biol. 22(3):521–533. https://doi.org/10.1111/j.1523-1739.2008.00950.x

Rosana MV, Agasen EV, Villanueva LS, Clemente JP JR, Kawit NS, De La Vega JT. 2006. Status and economic impact of *Parachromis maraguensis* in Taal Lake, Philippines. J Environ Sci Manag. 9(2):1–19. https://www.ukdr.uplb.edu.ph/journal-articles/4256

Rosenthal WC, Mcintyre PB, Lisi PJ, Prather RB JR, Moody KN, Blum MJ, Hogan JD, Schoville SD. 2021. Invasion and rapid adaptation of guppies (*Poecilia reticulata*) across the Hawaiian Archipelago. Evol Appl. 14(7):1747–1761. https://doi.org/10.1111/eva.13236

Roy HE, Rabitsch W, Scalera R, Stewart A, Gallardo B, Genovesi P, Essl F, Adriaens T, Bacher S, Booy O, et al. 2018. Developing a framework of minimum standards for the risk assessment of alien species. J Appl Ecol. 55(2):526–538. https://doi.org/10.1111/1365-2664.13025

Sievers C, Willing E-M, Hoffmann M, Dreyer C, Ramnarine I, Magurran A. 2012. Reasons for the invasive success of a guppy (*Poecilia reticulata*) population in Trinidad. PLoS ONE. 7(5):e38404. https://doi.org/10.1371/journal.pone.0038404

Spataru P. 1978. Food and feeding habits of *Tilapia zillii* (Gervais) (Cichlidae) in Lake Kinneret (Israel). Aquaculture. 14(4):327–338. https://doi.org/10.1016/0044-8486(78)90015-7

Strayer DL. 2010. Alien species in fresh waters: ecological effects, interactions with other stressors, and prospects for the future. Freshwat Biol. 55(s1):152–174. https://doi.org/10.1111/j.1365-2427.2009.02380.x

To DAL, Gomez GML, Ramos DRY, Palillo CDY, Go NKC, Gilles AS JR, Briones JCA, Pavia RTB JR. 2022. Invasiveness risk assessment of non-native freshwater fish species (Order: Siluriformes) for Lake Taal, Philippines. Philippine J Sci. 151(3):833–841. https://doi.org/10.56899/151.03.04

Vilizzi L, Copp GH, Hill JE, Adamovich LA, Daniel A, David A, Rigers B, et al. 2021. A global-scale screening of non-native aquatic organisms to identify potentially invasive species under current and future climate conditions. Sci Total Env. 788:147868. https://doi.org/10.1016/j.scitotenv.2021.147868

Vilizzi L, Hill JE, Piria M, Copp GH. 2022a. A protocol for screening potentially invasive non-native species using weed risk assessment-type decision-support tools. Sci Total Env. 832:154966. https://doi.org/10.1016/j.scitotenv.2022.154966

Vilizzi L, Piria M. 2022. Providing scientifically defensible evidence and correct calibrated thresholds for risk screening non-native species with second-generation Weed Risk Assessment-type decision-support tools. Journal of Vertebrate Biology. 71:22047. https://doi.org/10.25225/jvb.22047

Vilizzi L, Piria M, Copp GH. 2022b. Which calibrated threshold is appropriate for ranking non-native species using scores generated by WRA-type screening toolkits that assess risks under both current and future climate conditions? Manag Biol Inv. 13(4):593–608. https://doi.org/10.3391/mbi.2022.13.4.01

Vilizzi L, Piria M, Pietraszewski D, Giannetto D, Flory SL, Herczeg G, Baş Sermenli H, Britvec M, Jukoniene I, Petrulaitis L, et al. 2024. Development and application of a second-generation multilingual tool for invasion risk screening of non-native terrestrial plants. Science Total Environ. 917:170475. https://doi.org/10.1016/j.scitotenv.2024.170475

Volta P, Jeppesen E. 2021. Impacts of human activities and climate change on freshwater fish. Water. 13(21):3068. https://doi.org/10.3390/w13213068

Wei H, Chaichana R, Vilizzi L, Daengchana P, Liu F, Nimtim M, Zhu Y, Li S, Hu Y, Copp GH. 2021. Do non-native ornamental fishes pose a similar level of invasion risk in neighbouring regions of similar current and future climate? Implications for conservation and management. Aquat Conserv. 31(8):2041–2057. https://doi.org/10.1002/aqc.3609

Welcomme RL, Vidthayanon C. 2003. The impacts of introductions and stocking of exotic species in the Mekong Basin and policies for their control (Khmer). MRC Technical Paper No. 9. Phnom Penh: Mekong River Commission. pp. 38. https://doi.org/10.52107/mrc.akbo73

Yongo E, Zhang P, Mutethya E, Zhao T, Guo Z. 2023. The invasion of tilapia in South China freshwater systems: A review. Lakes & Reservoirs: Research & Management. 28(1):e12429. https://doi.org/10.1111/lre.12429