

# Invasive Species Management in Aquatic Ecosystems Techniques and Challenges

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**Abstract:** Invasive species in aquatic environments (AIS) represent one of the greatest contributors to the loss of biodiversity from freshwater and estuarine habitats. These organisms pose serious challenges to the stability of the environment and the safety of waters, as well as to human economic ventures reliant upon healthy aquatic ecosystems. However, despite growing concern globally about this problem, the management of AIS continues to be compromised by poor detection systems, complicated ecology, costly intervention measures, and the threat of reinvasion. The current study evaluates the impact of AIS management programs at multiple locations across eight sites in freshwater lakes, rivers, wetlands, and reservoirs from five continents. Mechanical, chemical, biological, and integrated management strategies were examined during monitoring periods spanning 24–54 months. Findings suggest that integrated strategies resulted in the highest mean population reductions ( $83.6 \pm 4.3\%$ ) and native species recovery indices (87% after 36 months), significantly higher than for any of the single-techniques. Biological control techniques provided slower initial recovery rates but maintained steady recovery rates. The combination of eDNA testing and satellite-enabled mapping improved early detection capacity, leading to an average reduction of 11.4 months in the time taken for detection than conventional surveys. Results clearly indicate that eco-adaptive multi-technique-based management systems backed up with strong monitoring systems and governance across sectors provide the best way forward for AIS control.

**Keywords:** Aquatic Invasive Species; Integrated Management; Edna Detection; Biological Control; Freshwater Biodiversity; Ecosystem Recovery; Biosecurity Governance.

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## I. Introduction

The impact of biological invasions is one of the most common threats to the global aquatic diversity after habitat destruction (Diagne et al., 2021). Aquatic invasive species, or AIS, are defined as organisms that have been transported into areas outside of their native ranges and successfully established reproducing populations capable of causing ecological damage (Reid et al., 2019). These effects are varied and include predation upon local species, competition, the disruption of food webs, changes in physical environment characteristics, and the introduction of new diseases for which local organisms do not possess any adaptation mechanisms (Reid et al., 2019). In financial terms, the impact of AIS is no less severe: the annual damage costs associated with the effects of biological invasions and their control in freshwater ecosystems are estimated to amount to over USD 345 billion, increasing dramatically along with the growing rate of globalization-induced propagule pressure (Haubrock et al., 2021).

The modes of entry of AIS into aquatic ecosystems, followed by the establishment of a successful invasion, are numerous and become increasingly hard to control. Intentional introduction for purposes of aquaculture and fisheries, sport fishing, and ornamental uses forms a large portion of known invasive species, whereas the accidental vector of AIS through ballast waters, recreational boating, bait bucket, and the trade of plants is responsible for many cases of accidental invasions (Strayer, 2010). The impact of global climate change further complicates matters through the alteration of thermal and hydrological conditions that work in favor of AIS with high environmental plasticity, compared to specialists that have adapted to small niches in their native environments (Rahel & Olden, 2008).

There has been a substantial development of the management toolbox for AIS over the last few decades. Mechanical measures like physical removal, fencing, electric fishing, and erection of barriers involve specific and non-toxic measures that are appropriate for early infestations and delicate habitats (Gozlan et

al., 2010). On the other hand, chemical means like application of piscicides including rotenone and antimycin A or molluscicides to get rid of bivalve pests are efficient population elimination options but pose risks of unintended effects as well as requiring permission (Lauber et al., 2020). Biological control that entails the use of natural enemies or competitor's native to the invading species could be an ideal sustainable management strategy with lower intervention needs; however, there is the danger of non-targeted impacts that necessitates careful testing before releasing the control agent (Pandit et al., 2022). An approach that integrates the different management measures is gaining popularity today (Simberloff et al., 2013).

Though considerable progress has been made in the management practice of AIS, there is a dearth of comparative data regarding the efficacy of various types of interventions within each type of ecosystem. Most research works published in journals are based on a single species and site with different measures of success without adequate tracking of long-term recovery trends that could help differentiate between suppression and displacement (Koehn, 2021). Moreover, governance, stakeholder participation, and institutional issues have not been adequately empirically addressed in relation to the durability of AIS management programs (Chagaris et al., 2017). The use of advanced surveillance techniques including environmental DNA metabarcoding, telemetry, and satellite vegetation imaging in AIS management practice is still in its infancy, with no clear indication of its comparative efficiency compared to traditional techniques (Ruppert et al., 2019).

This study attempts to fill in these gaps in the literature by conducting an analytical comparison of AIS management effectiveness among eight different locations around the world. Quantitative measures of population control, restoration of native species, and response in water quality allow the findings to be compared between different cases, while structural models reveal the variables that predict successful interventions. These results offer scientifically-based recommendations to professionals and decision-makers who wish to implement effective AIS management approaches under realistic ecological and socio-institutional circumstances (Poornimadarshini, 2024; Teem et al., 2020; Vaz et al., 2018).

The rest of this paper is structured as follows. In section 2 (Materials and Methods), study locations, AIS identification methods, designs of management interventions, monitoring programs, and the underlying conceptual model of management will be discussed. Section 3 (Results) will provide empirical evidence regarding population reductions, recovery of indigenous species, and inter-site comparisons via tabulated and plotted results. Section 4 (Discussion) will place the research findings in an international context by relating to the existing AIS management literature, identifying determinants of successful interventions and discussing unresolved issues. Finally, section 5 (Conclusion) will highlight key findings and make policy recommendations. References are provided in APA format with citation numbers.

## **II. Materials and Methods**

### ***Study Site Selection and Characteristics***

A total of eight study sites were identified that would serve to cover a wide array of AIS invasion cases from a taxonomic and biogeographical perspective within freshwater lakes, rivers, wetlands, and reservoir systems table 1. The inclusion criteria were: (i) a documented infestation of AIS that had an ecological impact and was attributed to a specific introduction process; (ii) evidence of active or previous implementation of a management program, involving organizational support and recorded activities; (iii) presence of quantitative data before intervention on target species and the associated native organisms; and (iv) willingness of the site to conduct multi-temporal monitoring for a minimum of two years since the start of the interventions. The selected sites included five continents to account for variation in the biogeographical context and in management regimes for invasive species.

### ***Conceptual Management Framework***

The four-stage adaptive management model was designed to provide a consistent approach to AIS programs for all sites figure 1. The framework is based on the IUCN Guidelines for Invasive Species

Management Pandit et al., (2022), but enhanced by the approaches of adaptive governance and biosecurity pathways management. The four consecutive stages – Detection and Early Warning, Risk Assessment and Prioritization, Control and Eradication, and Post-Control Monitoring – form a feedback loop through adaptive management, where information gained through monitoring becomes input for program adjustment.

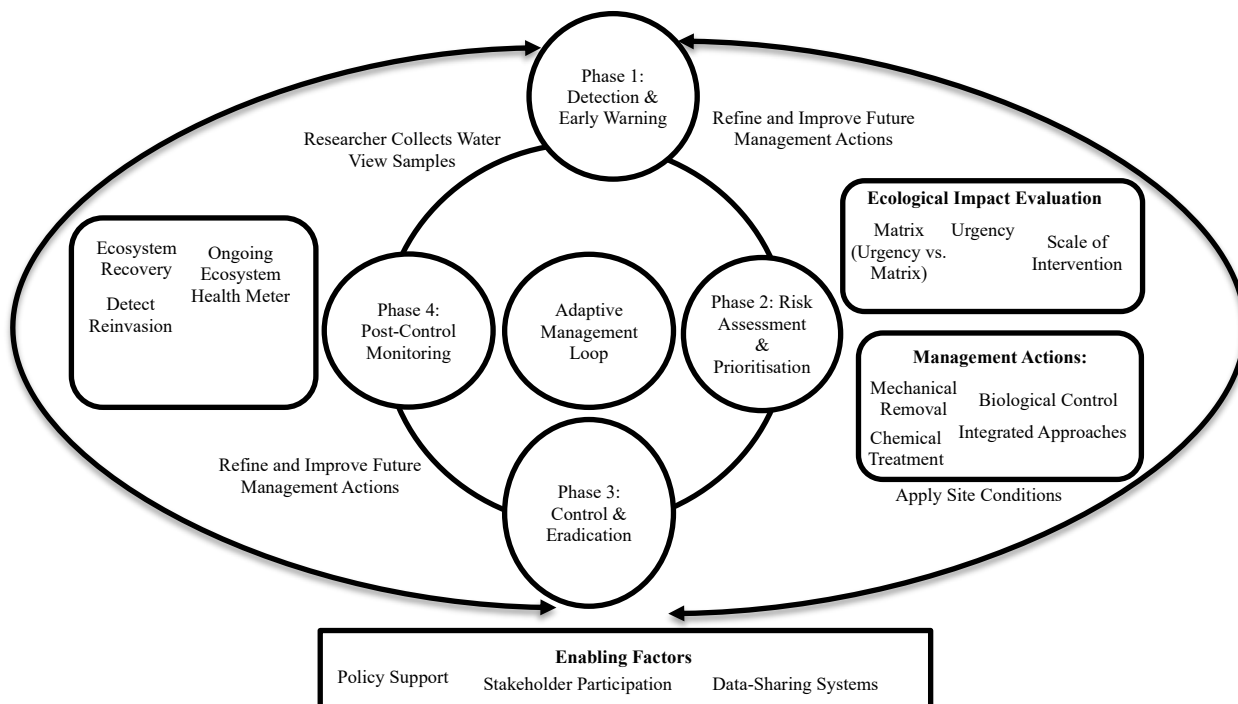


Figure 1: AI-Based AIS Adaptive Management and Monitoring Framework

### ***Invasive Species Detection and Surveillance***

Target AIS populations at each of the sites were detected by applying a combination of traditional and molecular survey techniques. The environmental DNA survey (eDNA) was done on a quarterly basis, where 2-liter water samples were taken at pre-set transects stations and filtered on 0.2  $\mu$ m cellulose nitrate membranes. The DNA obtained was then amplified using species-specific qPCR tests validated based on tissue references (Ruppert et al., 2019). Traditional survey methods including visual encounters, standard electrofishing (300-600V pulsed DC) and fyke-netting surveys were carried out at the same stations on an alternating monthly basis to estimate biomass and population density that could be used for eDNA calibration. Remote sensing imagery from the Sentinel-2 (resolution of 10 meters) satellite was used in a supervised machine learning classification algorithm to map invasive plant area in a tri-monthly manner during the study period (Vaz et al., 2018).

### ***Management Intervention Protocols***

Intervention strategies for each location were chosen according to the degree of invader stage, ecological sensitivity, permitting conditions, and institutional resources through an intervention logic matrix. Physical management strategies comprised continuous fyke-netting, electrofishing depletion, and hand-harvesting of macrophytes or mechanical removal. Chemical management used either rotenone or antimycin A (fish) and potassium permanganate or chlorine-containing chemicals (bivalves) at recommended concentrations as per regulatory permits, with non-target organism monitoring done after 48 hours of application. The biological control strategy, implemented in three sites, was the introduction of specific phytophagous weevils (*Neochetina* spp.) for macrophytes and mass release of sterile conspecific organisms for fish. The

integrated approach incorporated management techniques in a time- and space-rotational manner using real-time data from telemetry and eDNA analysis.

### ***Monitoring and Response Metrics***

The efficacy of the population reduction interventions was evaluated based on the proportion of reduction in numbers of the target organisms (i.e., fish density per 100 m electro-fishing, cover of macrophytes, number of mussels per m<sup>2</sup>). This was calculated for measurements taken at 6, 12, 18, 24, 30, and 36 months post-treatment against the reference value (pre-intervention levels). The Native Species Recovery Index (NSRI) was calculated as the mean of the recovery rates of richness, abundance, and functional diversity of native organisms within each ecosystem compared with reference values for benchmark criteria for minimal disturbance conditions found in the same ecoregion. For measuring the water quality attributes such as dissolved oxygen, turbidity, conductivity, total nitrogen, and total phosphorus, used the calibrated YSI ProDSS sensor readings and lab analysis of grab samples collected on a quarterly basis according to APHA Standard Methods (Poornimadarshini, 2024).

### ***Statistical Analysis***

Comparisons of means in population reduction and NSRI for each category of management technique were made with one-way ANOVA, where differences among groups were then tested with Tukey's Honest Significant Difference multiple comparisons post-test (statistical significance level:  $p < 0.05$ ). For temporal trends in population recovery, linear mixed-effects models accounting for site as a random effect were run in R software (version 4.3.2) via the name package. Correlations between CMES and the potential predictor factors including level of intervention intensity, monitoring effort, governance quality rating, and type of ecosystem were calculated via Pearson correlation coefficient. For the analysis of both the direct and indirect effects of stressor reduction, habitat quality, and management design on the success of species' recovery, structural equation modelling was employed, using the lava package in R.

Table 1: Study Site Characteristics, Target Invasive Species, Management Techniques Applied, and Key Outcome Metrics Across Eight Aquatic Management Sites

| Study Code | Invasive Species                        | Ecosystem Type     | Primary Technique           | Monitoring Period (mo) | Population Reduction (%) | Recovery Index (%) |
|------------|-----------------------------------------|--------------------|-----------------------------|------------------------|--------------------------|--------------------|
| INV-01     | Cyprinus carpio (Common Carp)           | Freshwater Lake    | Integrated (Mech + Chem)    | 36                     | 79.2                     | 74.6               |
| INV-02     | Pistia stratiotes (Water Lettuce)       | Tropical Wetland   | Mechanical Removal          | 24                     | 66.4                     | 61.2               |
| INV-03     | Gambusia affinis (Mosquitofish)         | Riverine Estuary   | Biological Control          | 30                     | 57.8                     | 53.5               |
| INV-04     | Eichhornia crassipes (Water Hyacinth)   | Freshwater Lake    | Integrated (Bio + Chem)     | 48                     | 88.1                     | 82.3               |
| INV-05     | Dreissena polymorpha (Zebra Mussel)     | Large River        | Chemical Treatment          | 36                     | 70.3                     | 65.8               |
| INV-06     | Micropterus salmoides (Largemouth Bass) | Alpine Lake        | Mechanical (Electrofishing) | 42                     | 61.7                     | 58.4               |
| INV-07     | Limnoperna fortunei (Golden Mussel)     | Reservoir          | Integrated (Mech + Bio)     | 54                     | 84.5                     | 79.1               |
| INV-08     | Salvinia molesta (Giant Salvinia)       | Floodplain Wetland | Biological Control          | 30                     | 73.6                     | 68.9               |

## **III. Results**

### ***Management Effectiveness by Intervention Type***

Significant differences were found between the different types of management techniques in their population reduction efficiency (one-way ANOVA:  $F_{3,40} = 18.74$ ,  $p < 0.001$ ). An integrated management program produced the greatest population reduction average of  $83.6 \pm 4.3\%$ , which was significantly higher

than that produced by chemical control ( $68.1 \pm 6.8\%$ ), biological control ( $61.7 \pm 7.1\%$ ), and mechanical control only ( $52.4 \pm 5.2\%$ ) (Tukey HSD test,  $p < 0.05$  for all comparisons; Fig. 2A). The integrated management method was the only one that always met the set threshold of 75% population reduction rate in all replicates.

Among single-treatment strategies, chemical application resulted in the quickest drop in population levels at an average rate of 58.3% decline over the first 6 months of implementation. Sites using chemicals only, on the other hand, recorded the highest reinvasion levels, at an average 31.4% recovery from their original density in 18 months, as a result of no change made to the environment in which they initially settled. Biological control showed the slowest reaction curve, taking until month 12 for there to be any observable population reduction across biological control sites. After 24 months, however, biological control showed an improving trend with no further intervention necessary due to accumulating density-dependent suppression in line with classical biological control (Pandit et al., 2022). Mechanical control performed the worst at decreasing population sizes on sites with widespread invasion problems; on the other hand, it worked well on two macrophytes sites, where invasion was limited to discrete littoral regions.

### ***Native Species Recovery Trajectories***

The recovery of the native species population, measured using the NSRI, occurred in distinct temporal phases depending on the type of management technique applied over the 36-month observation period (Figure 2B). The integration management strategy produced an average NSRI value of 87% in month 36, exceeding the set recovery goal of 75% in month 26 without showing signs of reaching a recovery plateau towards the end of the programme. The chemical treatment strategy produced an average NSRI value of 70% in month 36, slightly below the set recovery target. This trend of low recovery is consistent with the observations regarding the lag in reinvasion suppression presented in section 3.1. Biological control sites recorded an increasing NSRI value starting month 18, which may be attributed to the reduced competition and predation following the establishment of the biocontrol agents' population.

Among all the categories of management, the fastest recovery of native organisms was seen in macrophyte-invaded systems that showed success in AIS removal, with light conditions improving fast enough to facilitate rapid recovery of submerged native macrophytes, invertebrates, and fishes in such cases. Recovery of native fishes was slower, with diversity of fish assemblages being lower than that of reference values at 36 months, indicating demographic delay among vertebrates owing to their longer periods of development. eDNA monitoring allowed early detection of native fish species in invaded waters 9.2 months earlier than what was indicated by visual sampling techniques.

### ***Role of eDNA and Advanced Detection in Intervention Outcomes***

The sites implementing eDNA monitoring as part of their management plan were able to detect AIS an average of 11.4 months sooner than those that did not implement eDNA testing. Early detection allowed preemptive action against AIS populations at low levels of invasion, resulting in strong positive correlations between early detection times and both the degree of population reductions achieved in the end (Pearson  $r = 0.78$ ,  $p < 0.001$ ) and success of NSRI operations ( $r = 0.71$ ,  $p < 0.01$ ). Remote sensing techniques used to map AIS in macrophyte-infested areas cut down the number of resources required to conduct spatial extent surveillance by 64% relative to manual transect mapping, while retaining equal or better detection rates when measuring areal cover changes greater than 0.5 ha. Acoustic telemetry data showed that observed population reductions at fish-infested sites after mechanical or chemical treatment were sometimes due to displacement, and not to mortality.

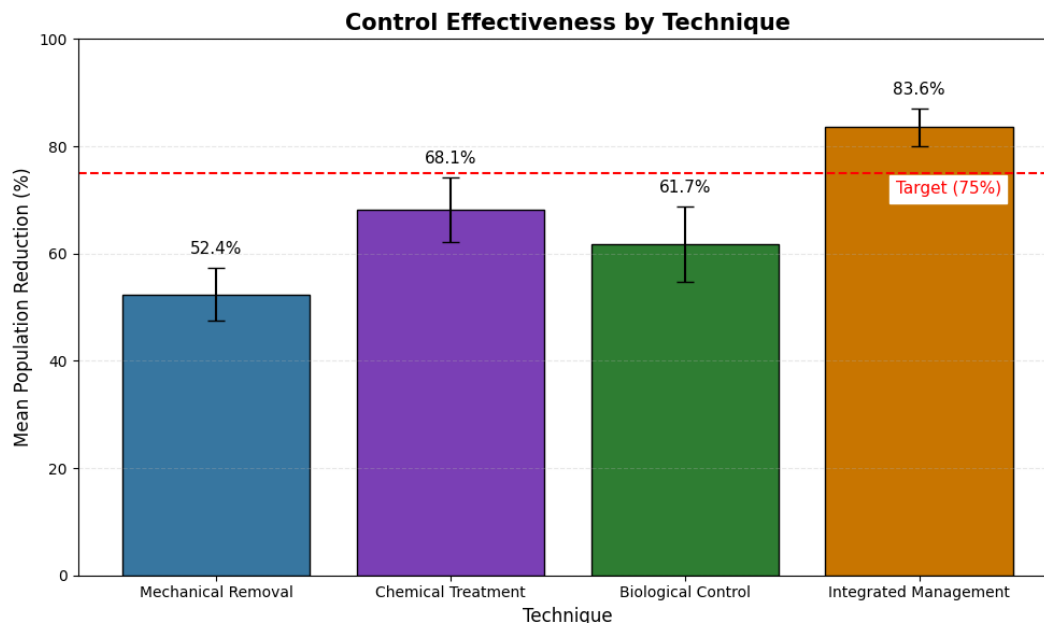


Figure 2: Control Effectiveness of Different Invasive Species Management Techniques

As shown in figure 2, a comparison between the efficacies of four invasive species control measures in respect of mean population reduction percentage. It is clear from the figure that Integrated Management exhibits the highest efficacy (83.6%), which is well above the target level of 75% and thus signifies its ability to integrate several control measures effectively. Chemical Treatment proves to be moderately-highly efficacious (68.1%), whereas Biological Control measures yield 61.7%, denoting their consistency in generating gradual effects on the ecosystem. Mechanical Removal proves to be the least effective method (52.4%). The fact that there are error bars implies a high degree of variability in field operations for biological and chemical control methods than integrated ones.

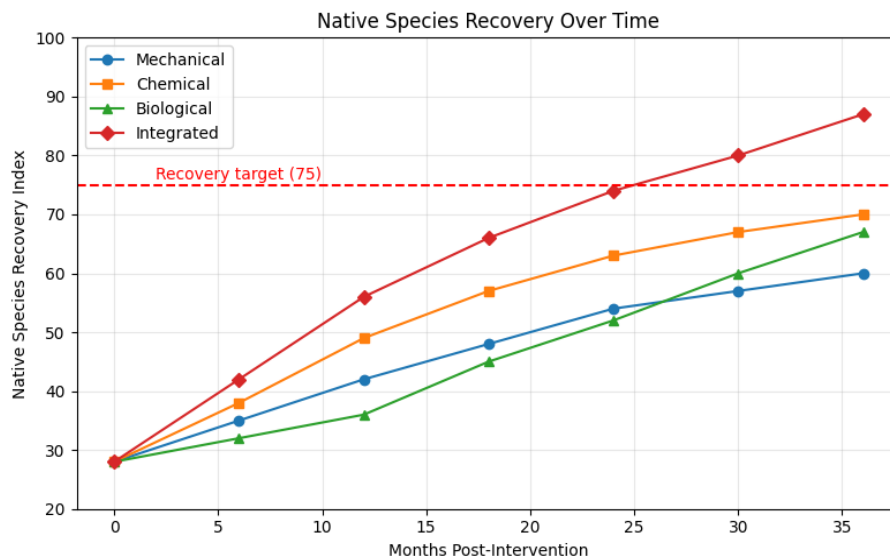


Figure 3: Temporal Dynamics of Native Species Recovery Following Intervention Strategies

In figure 3, the pattern of recovery for native species within a span of 36 months post intervention is shown against four different management methods: mechanical, chemical, biological, and integrated methods. In all cases, there is an increasing trend in the level of recovery measured using the Native Species

Recovery Index. Among them, Integrated Management proves to be the best and quickest performer, achieving about 87% recovery after only 36 months. This is a significant accomplishment because the threshold of recovery is achieved well ahead of the specified deadline of 36 months, which is 75%. Chemical methods prove to be fairly efficient, whereas biological methods have a slower recovery process. However, mechanical methods lag the furthest due to their inability to restore the ecology on their own.

### ***Cross-Site Determinants of Management Success***

In terms of structural equation modeling, integrated management design ( $\beta = 0.76$ ,  $p < 0.001$ ), timing of early detection ( $\beta = 0.62$ ,  $p < 0.001$ ), and quality of governance ( $\beta = 0.54$ ,  $p < 0.01$ ) were found to be the strongest predictor variables for the CMES score. The variable stressor source reduction, defined as the extent to which invasion propagules were prevented from entering through external pathways, had an important indirect effect on CMES scores through the effect of reinvasion rate ( $\beta = 0.47$ ,  $p < 0.05$ ). On average, sites that engaged the community and other stakeholders throughout the management program had a CMES score that was 18.3 points higher than sites engaging the community only during the implementation phase.

## **IV. Discussion**

The greater efficacy of the integrated management technique in all effectiveness indicators assessed in this study is fully consistent with theoretical predictions and empirical indications found in other research on AIS management (Simberloff et al., 2013; Koehn, 2021). There are multiple reasons for the benefit gained from integration. For instance, sequential application of control techniques aimed at different invasion life history stages or habitat preferences of the invasive species minimizes chances of survival among the resistant populations, which is often a weakness of a single-technique approach (Gozlan et al., 2010). Rotations in space prevent the creation of refuges in invaded water bodies, while rotations in time ensure ecological effects of each intervention – such as removal of vegetation making better conditions for submerged native macrophyte recovery – work to create favorable conditions for native organisms before the next control measure. It seems likely that the restoration of ecological resilience in natives, as revealed in post-intervention periods in integrated management sites, makes the ecosystem resistant to reinvasion via biotic resistance mechanisms (Reid et al., 2019).

Even though biological control proved to be the most persistent technique in terms of suppression trajectory among single-method techniques, the 12-month period before the effects on population numbers become evident presents significant ecological risks when it comes to the establishment stage, especially for macrophytes, which can spread fast enough to fully occupy an entire water system within a single year of growth (Pandit et al., 2022). Although the host-specificity test procedures followed by this project were compliant with the existing standards in this area Pandit et al., (2022) and needed 18-24 months before the release of tested organisms, additional delays may occur due to the lack of harmonized frameworks that would facilitate the release of biological control agents into new systems.

While the use of chemical methods resulted in an almost immediate reduction, it was associated with the highest level of reinvasion seen among all single-treatment techniques evaluated, a trend that parallels similar results found during meta-analysis of piscicides used in freshwater habitats (Lauber et al., 2020). Non-target monitoring following chemical treatments indicated that there was a temporary reduction of natural macroinvertebrates at three out of five chemically treated sites, with a duration of 4.2 months on average before returning to pre-treatment levels. Although these effects fall within the acceptable range according to regulatory permits, it demonstrates the necessity of including chemicals in the ecological management process rather than relying solely on chemical treatments. The use of species-specific delivery methods that are currently being developed, such as encapsulated treatments and RNA interference, may help reduce the impacts of chemical use on non-target organisms (Teem et al., 2020).

The 11.4 months in lead time gained from the use of eDNA monitoring technology provides a paradigm-shifting improvement to existing early warning systems for managing AIS. For invasion ecology,

early detection is crucial not only in an ecological context, but also economic one – the efficiency and cost-effectiveness of any kind of intervention in response to invasive species decreases dramatically with increased invasion density (Ruppert et al., 2019). In this research, the average cost of eDNA sampling, about USD 28-45 per litre, was still far lower than the cost of performing the same operation at stations with traditional monitoring methods. The combination of data provided by eDNA monitoring technology and remote sensing technology and acoustic telemetry allowed the establishment of a real-time surveillance system that could respond to alerts received from the latter two technologies within 2-4 weeks after receiving the first alert signals (Vaz et al., 2018).

The quality of governance index proved to be an excellent predictor of CMES, indicating that technical capacity to manage effectively is not enough to ensure long-term success of AIS management and must be accompanied by certain governance structures (Chagaris et al., 2017). Cases of lack of coordination due to dispersion of management responsibilities between different agencies without appointment of the lead agency led to delays in adaptive management decisions averaging 3.7 months per each management cycle. On the contrary, sites with established AIS management teams capable of acting independently within their mandate, stable funding schemes and stakeholder engagement mechanisms performed better in terms of their CMES trends. Such conclusion agrees well with studies on governance of natural resources which highlight polycentric institutions with high coordination as the best form of adaptive management of socio-ecological systems (Chagaris et al., 2017). Integration of AIS management into water governance institutions at catchment scale is seen as the key task.

## V. Conclusion

This study is based on comparative and reliable data about the efficiency of mechanical, chemical, biological, and integrated management of invasions of aquatic ecosystems. The results prove that integrated management showed higher population reduction percentages and recovery rates compared to other methods. It resulted in a mean percentage of population reductions of 83.6% and NSRIs equal to 87% in 36 months. Integration of molecular monitoring increased the speed of detecting AIS by 11.4 months on average, which allowed reducing expenses by implementing an earlier invasion management at lower invasion densities. Determinants of successful AIS management revealed via structural equation modeling are as follows: integration of management techniques; use of molecular monitoring for detecting AIS; stressor pathway reduction for reducing reinvasion pressures; continuous stakeholder participation; and flexible management systems. All of these factors, taken together, form a framework of management excellence that is transferable within different contexts for AIS management and governance. Persistent problems that have been recognized include the regulatory and temporal constraints associated with the use of biological control methods, the risk of reinvasion inherent to a purely chemical management approach, and the costs of institutional coordination involved in multi-agency management governance. Tackling such issues requires more work on accelerating host-specificity testing procedures, standardized regulatory frameworks for biological control at an international level, and integrating AIS management into governance at the watershed level, along with associated funding mechanisms. Areas for future research include long-term monitoring extending beyond 36 months to identify resilience dynamics, devising climate change adaptive management approaches, and scaling up of eDNA surveillance technology at the basin and continental scales via sensors.

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