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ASSESSMENT OF TREATMENT OPTIONS FOR MANAGING *FICOPOMATUS ENIGMATICUS* IN THE HAWKE'S BAY REGION

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EXECUTIVE SUMMARY

Ficopomatus enigmaticus Fauvel, 1923 is a sessile serpulid worm that is non-indigenous to New Zealand and has established extensive populations in the Ahuriri Estuary and Clive River near Napier in the Hawke's Bay Region. While these populations have been known to be present since the early 1990s, a recent increase in the regional abundance of *F. enigmaticus* has raised concerns about the integrity of native ecosystems and civic infrastructure required for flood protection.

Hawke's Bay Regional Council (HBRC) engaged the Cawthron Institute to provide advice on the feasibility and potential approaches for managing *F. enigmaticus*. Based on several desktop-based research activities, this report provides:

(i) the identification and systematic assessment of potential approaches to kill or remove *F. enigmaticus* aggregations against an agreed set of feasibility criteria
(ii) a shortlist of approaches deemed suitable for use if HBRC implement a management programme
(iii) recommendations regarding the feasibility of attempted eradication or population control of *F. enigmaticus* in the Hawkes Bay region given its present-day extent and the availability of potential control methods
(iv) recommended actions for HBRC towards decisions around, and implementation of, *F. enigmaticus* interventions.

We identified six physical and two chemical treatment methods as potential candidates for controlling *F. enigmaticus* populations in Hawke's Bay Region. The physical treatment candidates were manual removal, mechanical removal, physical disruption, encapsulation, osmotic stress and thermal stress. The chemical treatment candidates were chlorine and acetic acid. We assessed each potential treatment method against the following criteria: effectiveness, operator safety, biosecurity, regulatory compliance, environmental impacts, quality control and scalability. We also provided some considerations around two further important criteria: cultural acceptance and cost; however, a formal assessment against these criteria can only occur once HBRC has established the objectives and approach of an intervention.

We then subjected the performance (against the assessment criteria) of each treatment method to the 'Treatment Agent Selection Decision Tree', a tool recently developed to assist the Ministry for Primary Industries in making decisions around appropriate treatment approaches in the event of marine pest incursions.

Two methods – encapsulation, and osmotic stress by exposure to hypersaline conditions – were identified as appropriate primary treatments for local eradication attempts across the full range of affected habitat types. Three additional methods – manual removal, mechanical removal and chlorine – were identified as suitable for application during smaller scale population control efforts and / or in particular habitats. While proven to be effective in killing

or removing sessile biofouling organisms, including highly resilient taxa, most of the identified methods will require initial validation of effectiveness for *F. enigmaticus*. Additionally, encapsulation, hypersaline treatment and application of chlorine could kill *F. enigmaticus* in target areas, but these methods will not remove reef structures. To address the physical impacts of reefs and aggregations (e.g. on flushing or sedimentation rates) these approaches would need to be combined with post-treatment removal of reef structures.

Given the relatively restricted abundance and distribution of *F. enigmaticus* in the Hawke's Bay Region compared to overseas populations, we consider regional management of this species feasible. Options range from targeted control of *F. enigmaticus* aggregations in particular areas to attempts at a regional eradication of the species. We advise against the pursuit of attempted eradication unless sufficient levels of commitment, resources and persistence are guaranteed. 'Commitment' here includes the willingness to accept – within reason – the collateral impacts (e.g. on native biota) that some treatment approaches may have in target environments if implemented at the scale required for eradication.

Fundamental decisions around the objectives of *F. enigmaticus* interventions (including whether or not to intervene), and the ability to design a cost-effective, robust operational programme, hinge on several important activities that we recommend HBRC undertake:

- A *delimitation survey* to determine the current distribution of *F. enigmaticus*. Thorough knowledge of the species' regional distribution is essential for guiding final decisions around the feasibility, objectives, resources and operational approaches of potential interventions.
- A *cost-benefit assessment* around *F. enigmaticus* interventions. This will help identify the need for management (versus not acting) and the relative merits of different management options.
- If the decision is to proceed with some form of intervention, the *objectives of this intervention* need to be firmly established. They will heavily influence the choice of treatment method/s, as well as resource requirements, timeframes, operational protocols, interim and long-term goals, and decision-points.
- *Recruitment monitoring* of *F. enigmaticus*, initiated by HBRC in late 2022, should be continued as it helps inform the timing of any future interventions.
- *Dialogue with tangata whenua.* It is important that the use and application of treatments are consistent with Te Ao Māori, tikanga Māori, and the views and values of local iwi and hapū. This dialogue is best commenced during early considerations of a potential management programme; this will ensure tangata whenua values and recommendations can be considered and incorporated into the decision process.
- Once the objectives of a potential intervention have been established, small-scale *pilot trials of envisaged treatment methods* should be carried out to validate

effectiveness and enable the development of operational parameters and protocols for application at the scale of the intervention.

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1. INTRODUCTION

1.1. Background

Ficopomatus enigmaticus Fauvel, 1923 is a sessile serpulid worm that is non-indigenous to New Zealand. It was first discovered in Whangārei Harbour, New Zealand in 1967 and is now established in several North Island harbours and estuaries, including Ahuriri Estuary and Clive River near Napier (Wolf and Floerl 2023). In recent years, Hawke's Bay Regional Council (HBRC) have observed a steep increase in regional populations of *F. enigmaticus*. In particular, the development of substantial worm 'reefs' – which in 2019 amounted to a total of ~6,285 m^2 for the Ahuriri Estuary alone (HBRC aerial survey data) – has raised concerns about the integrity of native ecosystems and civic infrastructure required for flood protection. In 2017/18, HBRC undertook a localised control campaign during which an estimated 600 tonnes of worm reef biomass were removed to re-establish current flow through parts of the estuary. Expansion of reefs appeared to continue despite the removal campaign, although there is some uncertainty regarding their present-day extent and distribution. *Ficopomatus enigmaticus* is listed as an 'Organism or Interest' in HBRC's Regional Pest Management Plan,[1] a category for species that pose a sufficient future risk to warrant being watch-listed for ongoing surveillance or future control opportunities. Organisms of Interest are not accorded pest status, but may be managed through initiatives such as the Ecosystem Prioritisation programme, site-led control and sites of ecological importance.

HBRC has engaged the Cawthron Institute (Cawthron) to provide advice on the feasibility and potential approaches for further efforts for managing *F. enigmaticus* in its jurisdiction. Methods for killing or removing marine pest individuals or populations are only useful if they can be realistically and reliably applied in real-world situations, at relevant scales (square metres to square kilometres), and where the relationship between the overall cost of treatment and the overall benefit of successful treatment (including economic, social, cultural and environmental values) is acceptable (Cahill et al. 2021). Decisions on treatment strategies and protocols for marine pest populations also require clarity regarding the overall objectives of intervention, since some effective treatment approaches may only be appropriate for smaller scale population control and not suited for eradication attempts.

The advice was structured into three project phases and associated reports. In the first phase (Envirolink grant 2219-HBRC261), Cawthron provided recommendations regarding information needs and research activities to inform decisions around pest management for the invasive worm (Floerl and Wolf 2022). The second phase (Envirolink grant 2244-HBRC265) captured current knowledge of the ecology, seasonality, reproduction and recruitment of *F. enigmaticus*, as well as the scale,

[1] Page 23; https://www.hbrc.govt.nz/assets/Document-Library/Plans/Regional-Pest-Management-Strategy/Hawkes-Bay-Regional-Pest-Management-Plan-2018-2038.pdf

timeframes and impacts of invasion or population explosion events, and the methods and outcomes of previous control attempts (Wolf and Floerl 2023).

1.2. Scope of report

This report (Envirolink grant 2303-HBRC266) is the third and final output from the 'advice phase' around *F. enigmaticus* management in the Hawke's Bay Region. Specifically, the report provides:

1. a systematic assessment of potential approaches to kill or remove (treat) invasive marine species populations against an agreed set of feasibility criteria, resulting in a shortlist of approach(es) deemed suitable for use if HBRC implement a management programme
2. recommendations regarding the feasibility of attempted eradication or population control of *F. enigmaticus* in the Napier region given present-day extent and availability of potential control methods
3. priority actions towards the design and implementation of *F. enigmaticus* interventions by HBRC.

Figure 1. Hundreds, possibly thousands, of *Ficopomatus enigmaticus* reefs are established in Ahuriri Estuary. Photo: Hawke's Bay Regional Council, November 2017.

2. CONTROL OR ERADICATION METHODS FOR MARINE NON-INDIGENOUS SPECIES

In this section we describe case studies that employed a range of tools and methods for attempting to control or eradicate populations of marine non-indigenous species. We begin with a description of known case studies for *F. engimaticus* and then cover studies of other marine polychaetes. Finally, we provide examples of other marine taxa that share relevant characteristics with *F. engimaticus*. A summary is provided in Table 1.

2.1. Control of *Ficopomatus enigmaticus*[2]

Over the past 100 years, only a few attempts at eradicating or controlling *F. engimaticus* populations have been made, generally with low overall success. Dixon (1977) described the earliest known case, from Weymouth Harbour, England, where *F. engimaticus* was found to be growing 'in the vicinity' of sluice gates that separated the Weymouth Harbour backwater (marine environment) from the southern end of the adjacent Radipole freshwater lake. An attempt was made to control the incursion via application of anti-fouling paint to worm formations; however, details regarding the size and nature of the treated area, and the type, concentration and active ingredient(s) of the paint, as well as the amount, frequency and duration of its application, were not described. While no quantitative success measures were detailed, the author stated that the localised population was 'controlled' and not reported in subsequent years, indicating that the treatment was possibly successful.

Dixon (1977) also reported a second control attempt from 1973, where chlorine was applied to treat a small population fouling a condenser band-screen at a power station in Tilbury, England. A band-screen is a mesh screen put in place to remove organisms and other debris from cooling water as it flows through into the power station condensers. The size of the population was not reported, but the worms had attained a length of ~30 mm and a density of ~20 individuals per m^2, and were growing in the direction of water flow. Treatment involved the addition of 254 kg of chlorine on a daily basis with a 'residual concentration' (no definition was provided) of 0.5 ppm, but this appeared to have no effect on the worms. However, the lack of information provided about the conditions under which the treatment was applied (e.g. concentration, exposure duration, size and containment conditions of the treated area) makes it impossible to determine whether treatment failure was due to a true lack of efficacy of chlorine against the worms, or whether the type of chlorine and / or the conditions under which it was applied were insufficient for achieving mortality.

[2] Some of the following information was previously reported in Wolf and Floerl (2023), but it has also been included here for completeness.

More recent *F. engimaticus* control efforts have employed physical (manual or mechanical) removal as the primary means of control. Two campaigns were carried out in Argentina in the 1990s and 2000s to reduce the area of established *F. engimaticus* reefs in the Mar Chiquita lagoon (Wolf and Floerl 2023). The first initiative was unsuccessful, as fragments of the worm reef generated from removal subsequently developed into new reefs. The second attempt, a decade later, involved the tourism and recreational fishing industry carving a 310 m path through the matrix of reefs in the lagoon. While this effort resulted in a reduction of the overall population, ongoing removal is required to maintain the path through the matrix.

Physical removal was also employed as the chosen method to reduce the abundance of *F. engimaticus* in the Ahuriri Estuary (Te Whanganui ā Orotū) in Hawke Bay, New Zealand in 2017 and 2018 (Hawke's Bay Today 2017; Hawkes Bay Regional Council 2017; Harper and Ridley 2018). The effort was undertaken due to the worm reefs' perceived restrictive effects on water flow between the upper and lower parts of the estuary. The removal of the worm reefs also formed part of a wider estuary restoration programme led by HBRC in collaboration with Mana Ahuriri Trust. Using a long-reach digger to manually remove the worms, ~600 tonnes of *F. engimaticus* reefs were removed between the upper Ahuriri Estuary and Taipo Stream confluence (pers. comm. 2022, S. Weaver and A. Madarasz-Smith). No post-removal monitoring was undertaken, and the rate of regrowth and recovery of reefs was not quantified. However, the perceived expansion of *F. engimaticus* around the wider Ahuriri Estuary have led HBRC to consider further population management.

In Cape Town, South Africa, manual methods were used to remove *F. engimaticus* in the Zandvlei Estuary in 2015 and 2017. In 2015, 30 m^2 of worm reef was removed by recreational canoeists using spades. This effort was subsequently repeated in 2017 which, while not explicitly stated, was thought to be due to the regrowth of the reefs in the initial removal area (Wolf and Floerl 2023). Following the second attempt, the density and size of the worm populations appeared to decline. However, this population reduction could not be exclusively attributed to the manual removal efforts, as it coincided with a sustained period of drought, during which the temperature and salinity of the surrounding water likely changed.

There are further cases where declines in *F. engimaticus* populations are thought to have occurred as an indirect effect of actions targeting other environmental issues, or independent of human-mediated intervention. In 1952, the sluice gates separating Weymouth Harbour and Radipole Lake were temporarily opened as a means of controlling midge larvae in the lake. This resulted in a consequent increase in the water salinity from freshwater levels to ~20 PSU due to the exchange of water between the Weymouth backwater and the lake. The gates were then reclosed, reducing the salinity back to near freshwater levels (0.1 PSU). Several weeks later, *F. engimaticus* was observed to have proliferated rapidly and extensively across the hard substrata in the lake, with their tubes forming structures up to 15 cm thick. The worms on the freshwater (lake) side perished shortly after, though their tubes persisted for several years, and worms remained on the gates on the harbour backwater side (Tebble 1953; Dittman et al. 2009). *Ficopomatus engimaticus* is known to prefer brackish water environments, with their proliferation thought to occur at the interface between freshwater and saltwater bodies, where salinities lie between ~10 and ~30 PSU (Dittman et al. 2009; Wolf and Floerl 2023). When the gates were opened, water exchange occurred between lake and harbour, and the resulting salinity increase enabled the establishment and growth of *F. engimaticus* within the lake. This process was reversed when the gates were reclosed, resulting in the death of the newly established populations.

In Tunis Lagoon, Tunisia, *F. engimaticus* populations were observed to disappear in response to environmental changes resulting from a concentrated effort to restore the lagoon from a polluted eutrophic state to an oligotrophic state (Diwara et al. 2008). Specifically, the declines are thought to have occurred in response to decreases in water temperature and concentrations of organic matter (*F. engimaticus* reproduction and growth is favoured in warm eutrophic waters), increases in water circulation and depth (*F. engimaticus* prefers confined waters with little to no flow), and the shift from a brackish to marine environment (*F. engimaticus* prefers brackish conditions).

Despite the limited detail and success of previous attempts to control *F. engimaticus* populations, several conclusions can be drawn from these efforts and from observations of natural or indirect population declines. The resulting observations can help inform management of *F. engimaticus* in Ahuriri Estuary and other infested areas of the Hawke's Bay Region:

- Hypo- and hypersaline environments appear to prevent or reduce *F. engimaticus* establishment, growth and survival. Osmotic stress (manipulation of salinity levels), a control tool that has been used for pest incursions elsewhere, should thus be examined as a potential management option.
- *Ficopomatus engimaticus* reefs can reform from residual fragments when these act as nuclei for settlement and reef formation. Ensuring effective containment of biomass material during treatment or removal activities will therefore be important for preventing the persistence and regrowth of populations following management action. Ongoing monitoring, and potentially management, may be required given its propensity for regrowth.
- *Ficopomatus engimaticus* tubes are also able to persist in the absence of live worms for years (e.g. 1952 incursion in Weymouth Habour / Rapidole Lake). Moreover, the tubes could potentially act as nuclei for the formation of new populations in the future. Care must therefore be taken to minimise, if not prevent, the persistence of residual tube structures following treatment.
- Polluted, eutrophic environments facilitate the establishment and growth of *F. engimaticus*, while oligotrophic conditions appear to cause reductions in

abundance. Current or future restoration and pollution mitigation initiatives in the Ahuriri Estuary may thus have beneficial implications for *F. engimaticus* population control, independent of targeted management actions.

2.2. Other marine polychaete species

Beyond *F. engimaticus*, records of successful eradication or control of other marine tube-forming polychaetes are limited. Management attempts appear to be constrained to eradication of the boring sabellid polychaete *Terebrasabella heterouncinata* from a Californian locality in 1996 (Culver and Kuris 2000) and localised management of the Mediterranean fanworm *Sabella spallanzanii* in areas of New Zealand (Fletcher 2014).

Terebrasabella heterouncinata is a sabellid polychaete originating from Namibia and South Africa, which can establish and grow on the shells of abalone and other marine gastropods (snails) with adverse effects on growth, shell formation and integrity, and survival. In 1996, a substantial localised population was found on rocks in the intertidal zone adjacent to a discharge outflow from an abalone culture facility in Cayucos, California (Culver and Kuris 2000). A decision was made to attempt to eradicate the infestation amid concerns about the potential impacts on local native species, particularly the native black turban snail, *Tegula funebralis*. The ensuing campaign primarily involved indirect reduction of target populations through the removal of susceptible host organisms (*T. funebralis* and other animal and shell debris).

The objective was to reduce the host population density to levels at which transmission by *T. heterouncinata* would be insufficient to sustain population persistence. In total, 1.6 million live *T. funebralis*, as well as live individuals and residual shell material of red abalone (*Haliotis rufescens*), brown and Monterey turban snails (*Tegula brunnea* and *T. montereyi*, respectively), and the kelp snail *Norrisia norrisii*, were manually removed (by hand) from a 1500 m^2 area immediately below and south of the abalone facility's discharge outflow. Filtering screens were also installed on the outflow to prevent further discharge of the pest. A mark-recapture study involving the deployment and retrieval of a known number of marked *T. heterouncinata* was also conducted to quantify the rate of new infestations before and after the removal efforts, and it confirmed the success of the eradication. Culver and Kuris (2000) concluded that completely eradicating all *T. heterouncinata* individuals was impossible, as it would have involved the examination and removal of millions of infested snails; however, removing significant numbers of susceptible hosts was an effective means of reducing the prevalence of the worms to biologically undetectable levels, and the reduction appears to have persisted over time.

The Mediterranean fanworm, *Sabella spallanzanii*, is a sessile tube-dwelling marine polychaete, native to the Mediterranean and the Atlantic coast of Europe. The fanworm is invasive in several global regions, including New Zealand. Several removal efforts have been, and continue to be, undertaken in New Zealand, and all have primarily relied on manual removal of worms from target areas (see review by Fletcher 2014). The earliest attempts occurred in 2008 and 2009 in the port of Lyttelton (South Island) and Waitematā Harbour (North Island), respectively. In Lyttelton, intensive diver searches of the entire port habitat resulted in the removal and collection of ~100 worms. Although a few large individuals continued to be detected in the subsequent months, the populations appeared to remain low and there were hopes that, provided removal efforts could be maintained, local elimination could be achieved via Allee effects.[3] However, subsequent detections in 2009 in the outer Lyttelton port area and Waitematā Harbour altered this view. While over 700 worms were removed by divers from port infrastructure and a nearby barge in Waitematā Harbour, subsequent surveillance efforts noted the increasing spread of the worms from the initial site of detection. Consequently, it was deemed that *S. spallanzanii* was unlikely to be eradicated from these two locations, and management efforts at both Lyttelton and the Waitematā Harbour were ceased. The worm has since persisted and undergone further spread in these areas.

In 2012 and 2013, *S. spallanzanii* was detected on the hulls of two fishing boats and two cargo barges moored in Whangārei Harbour and Coromandel Harbour, respectively. The barges featured estimated worm densities of 1000 individuals per m^2. Response efforts targeting the barges involved hand removal by divers and cleaning of the infected vessels, with worms removed from the barge at Coromandel being deposited into a suction hose. While in both cases the vessels were successfully decontaminated, subsequent detections were reported shortly after on built (i.e. wharf piles, pontoons, vessel) and natural substrates at both locations. Low numbers of worms have also been detected on vessel and mooring infrastructure and the adjacent seabed in Nelson, Picton and Tauranga. In most instances these were manually removed via divers or haul-out (of vessels). However, in Nelson, a commercial vessel carrying *S. spallanzanii* was wrapped in plastic ('encapsulated') and treated with 200 L of acetic acid. Nine days after the wrapping and chemical treatment, all worms had been killed (Fletcher 2014).

Overall, manual removal by divers has overwhelmingly been the method of choice for control of invasive *S. spallanzanii* populations, with mixed levels of success. Several aspects of *S. spallanzanii* management can be applied to the current context of controlling *F. engimaticus* in New Zealand:

[3] Allee effects are a density-dependent phenomenon in which population growth or individual components of fitness increase as population density increases. They are named after North American animal ecologist W.C. Allee, who studied the benefits of cooperative behaviour in small populations. The potential for positive density dependence in small populations to increase *extinction risk* has led to keen interest in applications, including conservation and pest control.`

- The sexual maturity of individuals and the timing of their detection appear to influence the degree of success of removal and prevention of further spread. Small, sexually immature populations localised to discrete built structures are more likely to be successfully eradicated than invasions of more expansive natural environments by sexually mature individuals.
- While chemical treatments have been used sparingly in the management of *S. spallanzanii*, where they have been applied they have been largely effective. In addition to the successful encapsulation and chemical treatment method used in the Nelson incursion, a trial by Northland Regional Council showed that encapsulation of vessels of up to 16 m in a specialised pontoon, and subsequent addition of chlorine to the enclosed seawater, resulted in successful and complete elimination of *S. spallazanii* on the vessels. Consequently, chemical treatments still present a potentially viable management option for *S. spallanzanii*, and potentially *F. enigmaticus,* provided the target area can be adequately contained. It is important to note, however, that in contrast to *S. spallanzanii*, *F. enigmaticus* has a fully sealed calcareous tube and a calcareous operculum. Thus for *F. enigmaticus*, the treatment periods and, if necessary, the initial validation phase to assess effectiveness will likely need to be considerably longer.

2.3. Case studies of other relevant taxa

The majority of eradication or control efforts involving invasive or nuisance populations of marine polychaetes have focused on physical disruption or manual and / or mechanical removal of worms or their hosts, with a few isolated cases involving chemical treatment with chlorine, acetic acid or anti-fouling paint. However, there are several additional chemical and physical treatments that have been deployed during control or eradication attempts of sessile marine taxa, including species with similar biological traits to *F. engimaticus* (e.g. hard body structures, ability to seal off from the outside environment, spread exacerbated via fragmentation). The examination of relevant case studies can provide learnings for managing *F. enigmaticus* in the Hawke's Bay Region.

Physical treatments

A notable case of mechanical removal involves the non-indigenous brown mussel *Perna perna* in New Zealand. During the de-fouling of an offshore drilling rig in Tasman Bay in 2007, *P. perna* were discharged onto the soft-sediment seabed below the rig (Hopkins et al. 2011). Dredging operations were initiated to remove the de-fouled material and reduce the mussels to densities that were too low to enable the establishment of a self-sustaining population (see Allee effect mentioned above). A total of 227 dredge tows were carried out over a 2-month period, and ~35 tonnes of dredge spoil was removed from a 12.6-hectare target area encompassing the incursion site. The effort achieved mussel densities substantially lower than those required for successful reproduction (Hopkins et al. 2011).

Success in invasive marine species eradication has also been observed with the application of osmotic stress. In 2002, the aquarium algae *Caulerpa taxifolia* was detected in the West Lakes system in South Australia, an artificial marine lake that can be closed off from the wider marine environment (Walters 2009). As *C. taxifolia* is a marine algae, the decision was made to treat the incursion by reducing the salinity of the water in the system, thereby causing death to the population by osmotic stress. The system was closed off to seawater input, and over a period of 6 months, fresh water was pumped in significant volumes into the lake from a nearby river using a bespoke pumping station. The campaign was successful – the salinity of most parts of the lake system during the eradication period was reduced to 17 ppt, resulting in the death of *C. taxifolia* colonies. Subsequent monitoring of the West Lakes system did not detect any regrowth of the algae.

Thermal stress, the manipulation of ambient temperatures to levels beyond a target species' tolerance range, has also been used to successfully eradicate invasive marine organisms. In 2000, the invasive brown kelp *Undaria pinnatifida* was detected on the hull of a trawler that had sunk at 40 m depth off the Chatham Islands (Wotton et al. 2004). Initially, visible plants were removed by divers, and failed attempts were made to salvage the vessel. Further eradication efforts then involved the continued manual removal of visible plants by divers and heat treatment of areas of the hull. These methods were used to ensure complete removal of the microscopic reproductive life stages of *U. pinnatifida*. Over a period of 4 weeks, heat elements contained in wooden boxes and underwater flame torches were used to treat high-risk areas of the hull. The operation was successful – extensive subsequent monitoring did not detect any further plants on the vessel or in its vicinity.

Encapsulation – the shrouding or smothering of target organisms via a physical barrier – has been widely used in invasive marine organism management. It has proven to be an effective method, particularly when applied in conjunction with chemical treatments because of its ability to isolate target areas and achieve and / or maintain required treatment concentrations. As a standalone treatment, mortality of organisms occurs via the creation of a hypoxic or anoxic environment within the encapsulated area. Encapsulation was used extensively in efforts to eradicate the colonial sea squirt *Didemnum vexillum* in 2003 following its detection and subsequent spread in Shakespeare Bay in the South Island of New Zealand (Coutts and Forrest 2007). Two commercial barges were encapsulated in plastic wrapping, and granulised chlorine was added to the contained water to achieve a concentration of 200 g/m^3. The treatment was successful in killing all *D. vexillum* on both barges. Encapsulation was also used to kill *D. vexillum* on 178 infested wharf piles, with divers wrapping each pile with overlapping layers of plastic wrap secured with tape to create an anoxic environment. This was almost completely effective – *D. vexillum* only remained in areas where the plastic wrap was loose or had been compromised.

A different type of encapsulation – smothering by dredge spoil – was also successfully employed to kill *D. vexillum* in an 80 x 40 m area of flat seabed underneath the initial site of detection in Shakespeare Bay – a heavily infested moored barge (Coutts and Forrest 2007). This method was also used at a nearby sloped site, but it was unsuccessful because the gradient of the sea floor was too steep for the spoil to remain in place. As an alternative, divers covered the affected area of seabed with sheets of small-pore geotextile fabric, which were joined together to smother the colony. However, this effort was also unsuccessful – gaps at the joins between sheets facilitated the continued exchange of water, and thus the persistence of *D. vexillum*.

Further methods employed to treat other infestations of *D. vexillum* in Shakespeare Bay included desiccation and mechanical removal (Coutts and Forrest 2007). Desiccation of populations growing on the hulls of barges was not fully effective, despite the barges being beached for 3 weeks. A custom-built vacuum and filtering system was also unsuccessful at removing *D. vexillum* colonies from the seabed, but it achieved an 80% reduction in fouling biomass on vessel hulls. There were also several other treatments trialled on infested seabed at a small pilot scale, namely lime (calcium hydroxide), concrete powder, hot-water blasting and application of a petrogen torch. While some methods were found to be effective, the overall area of infestation was deemed too large for their deployment at full scale to be economically feasible.

Despite the plethora of methods applied to treat *D. vexillum*, the eradication effort in Shakespeare Bay was ultimately unsuccessful, with the species now being established in the area and wider region. However, this case study illustrates the versatility of encapsulation as a treatment method, and highlights that control efforts in different invaded habitats and environments may require the implementation of multiple treatment methods in order to be successful.

Chemical treatments

Chlorine has the most extensive history of use in the chemical treatment of marine pests. In 2005, it was used to successfully eradicate populations of the invasive algae *Caulerpa taxifolia* from the Agua Lagoon and Huntington Harbour in California (Anderson 2005; Muñoz 2016). Following encapsulation of the colonies using plastic tarps of various sizes weighted down at the edges with bags of gravel, chlorine in the form of liquid sodium hypochlorite and chlorine-releasing tablets was deployed within the encapsulated areas, which ranged in size from 1 to 500 m^2. The treatment was successful – post-treatment surveys did not detect viable colonies at either of the invaded sites, and no plants were detected over the next 2+ years of surveying. Bax et al. (2002) also used chlorine during an attempt to eradicate the invasive black-striped mussel, *Mytilopsis sallei,* from two marinas in Darwin Harbour. The most heavily infested site, Cullen Bay marina, had mussel densities of ~24,000 individuals per m^2 growing on pontoons, pilings, breakwalls and resident vessels. The marina gates were shut to isolate it from the surrounding environment, and 187 tonnes of sodium hypochlorite were added to the marina water. Chlorine alone was unable to achieve mortality of all mussels. Consequently, several tonnes of copper sulphate were added to the marina water as a second treatment chemical. Copper is highly toxic to aquatic organisms and is the one of the primary active ingredients in anti-fouling paint. Four days after deployment of copper sulphate, no live mussels were detected at any of the marina monitoring sites. However, there was extensive collateral mortality of marine invertebrates, algae and fishes. No further mussels were detected during post-eradication monitoring.

2.4. Methods for assessment regarding *Ficopomatus enigmaticus* interventions in the Hawke's Bay Region

Methods assessed in this report

The case studies outlined in sections 2.1, 2.2 and 2.3 highlight several methods as potential candidates for controlling *F. enigmaticus* populations in the Hawke's Bay Region:

Physical treatment candidates:

- Manual removal
- Mechanical removal
- Physical disruption
- Encapsulation (encompasses deoxygenation)
- Osmotic stress
- Thermal stress.

Chemical treatment candidates:

- Chlorine
- Acetic acid.

In Section 4, each candidate method listed above is assessed against a series of criteria to determine its suitability for application during population control initiatives for *F. enigmaticus* in the Hawke's Bay Region.

Methods not considered for assessment

We excluded several treatment options discussed in the sections above (or other resources we consulted) from further assessment based on: (i) their failure to meet key criteria in previous feasibility exercises (Cahill and Floerl 2019; Cahill et al. 2019, 2021), and / or (ii) because we consider them unsuitable or ineffective for management of *F. enigmaticus*:

- *Copper*. Although copper has been shown to be highly effective in killing resilient invasive marine species (e.g. eradication of black-striped mussels in Darwin Harbour), it is also highly toxic to other marine life. Copper is a major legacy contaminant in urban and shipping environments. Several global regions have restricted or banned the use of copper-based anti-fouling coatings to manage local and regional heavy metal pollution.
- *Herbicides*. Herbicides are chemical treatments used to kill plants. There is limited evidence to support their efficacy in the marine environment, and no evidence of their ability to kill or remove animal taxa like *F. enigmaticus*.
- *Trapping*. Baited or un-baited traps have been used to capture mobile invasive species, including the Asian paddle crab (*Charybdis japonica*) in New Zealand However, traps are ineffective for sessile species such as *F. enigmaticus.*
- *Desiccation*. This method involves the exposure of marine organisms to air for extended periods (usually days to weeks) to induce mortality through drying out. Given that many *F. enigmaticus* reefs in the Hawke's Bay Region are intertidal, maintaining complete air exposure for the required durations will not be possible without first removing the worms from the environment. Physical removal is covered as a standalone treatment method.
- *Augmentative biocontrol*. This method enhances the abundance of organisms that act as competitors or predators of invasive target species. An example is the use of native sea urchin / kina (*Evechinus chloroticus*) to graze on juvenile life-history stages of the invasive kelp *Undaria pinnatifida* in Fiordland, New Zealand (Atalah et al. 2013). We are not aware of any predator or competitor species of *F. enigmaticus* that could be present in the Ahuriri Estuary, and there are significant potential risks and implications associated with introducing a novel species to the control area. We do not consider this a viable option at this time.

Additional treatment methods

We identified several additional chemical treatment methods that had no available case studies concerning pest eradication or control; however, these methods have been flagged as potential treatment options for biofouling assemblages or marine pest incursions (Cahill and Floerl 2019; Cahill et al. 2019, 2021).

- Calcium (hydr)oxide
- Bromine
- Ferrate
- Hydrogen peroxide
- Peracetic acid
- Disinfectants
- Descalers.

None of the chemicals listed above are approved for use by the New Zealand Environment Protection Authority (EPA, see Section 3.4), thus we do not consider them viable options for *F. enigmaticus* control in the Hawke's Bay Region in the near future. However, if there is initiative from HBRC and / or other councils, EPA approval may eventually be obtained. We therefore provide a basic assessment of these chemicals in Appendix A1 to enable future consideration by HBRC.

Table 1. Summary of eradication / management attempts of invasive populations of *Ficopomatus enigmaticus,* other species of marine polychaetes and other relevant marine taxa.

Year	Location	Taxon	Species	Scale of invasion	Relevant environmental conditions	Treatment applied	Outcomes	Reference(s)
Ficopomatus enigmaticus								
1937	Weymouth Harbour, England	Marine polychaete	*Ficopomatus enigmaticus*	Small, localised population	Low flow / stagnant water Gates separating marine and freshwater bodies, so no mixing of water of different salinities	**Chemical treatment** (anti-fouling paint)	Population not documented further but considered successful	Dixon 1977
1952	Weymouth Harbour, England	Marine polychaete	*Ficopomatus enigmaticus*	Not specified	Sudden salinity changes (mixing of previously segregated saline and fresh water, then re-segregation of water bodies). Low flow / stagnant water	**No management intervention:** decline due to osmotic stress caused by sudden salinity changes	Mortality of worms on the freshwater lake side (worms on the harbour side remained)	Tebble 1953 Dixon 1977 Dittman et al. 2009
1973	Tilbury Power Station, England	Marine polychaete	*Ficopomatus enigmaticus*	Localised population, exact size not reported. Density of 20 worms/m^2	Distribution of worms limited to the area of the screen submerged in water	**Chemical treatment** (chlorine)	No apparent effect – no observed mortality and population persisted	Dixon 1977
1990s	Mar Chiquita Lagoon, Argentina	Marine polychaete	*Ficopomatus enigmaticus*	Not specified	Shallow (up to 4 m depth) Salt water lagoon, brackish in areas where rivers enter the lake. Multidirectional currents	**Manual removal** (assumed as no tools specified)	Unsuccessful, fragments from removal acted as nuclei for the growth of new reefs	Wolf and Floerl 2023
2000s	Mar Chiquita Lagoon, Argentina	Marine polychaete	*Ficopomatus enigmaticus*	Not specified	Shallow (≤ 4 m depth), salt water lagoon, brackish in areas with multidirectional currents	**Manual removal** (assumed – no tools specified)	Path cleared, but ongoing removal required to keep clear	Wolf and Floerl 2023
2015 & 2017	Zandvlei Estuary, South Africa	Marine polychaete	*Ficopomatus enigmaticus*	Not specified	Sustained period of drought coincided with 2017 removal attempt	**Mechanical removal** (spades)	Area cleared in 2015 regrew, effort repeated in 2017. Population density and size subsequently	Wolf and Floerl 2023

Year	Location	Taxon	Species	Scale of invasion	Relevant environmental conditions	Treatment applied	Outcomes	Reference(s)
							declined, but success confounded by drought	
2017	Ahuriri Estuary, New Zealand	Marine polychaete	*Ficopomatus enigmaticus*	Not specified	Low flow Brackish water Polluted, eutrophic environment	**Manual / mechanical removal** (diggers, suction pumps, hand removal)	Level of success not reported. Reefs suspected to have regrown	Hawke's Bay Today 2017 Hawke's Bay Regional Council 2017 Harper and Ridley 2018
Other marine polychaetes								
1996	Cayucos, California, USA	Marine polychaete	*Terebrasabella heterouncinata*	1500 m^2 area adjacent to abalone facility	N/A	**Manual removal** (worm hosts)	Successful – rate of new infestations and prevalence of worm was reduced to zero	Culver and Kuris 2000
2008	Lyttelton Harbour, New Zealand	Marine polychaete	*Sabella spallanzanii* (Mediterranean fanworm)	Not specified	N/A	**Manual removal** (hand removal by divers)	Initially deemed successful, but new detection in outer harbour subsequently discovered. Now established in Lyttelton	Read et al. 2011 Fletcher 2014
2009	Waitematā Harbour, New Zealand	Marine polychaete	*Sabella spallanzanii* (Mediterranean fanworm)	Not specified	N/A	**Manual removal** (hand removal by divers)	Unsuccessful – worms continued to spread further from the initial incursion site. Now established	Fletcher 2014
2012	Whangārei Harbour, New Zealand	Marine polychaete	*Sabella spallanzanii* (Mediterranean fanworm)	Localised to hulls of two fishing vessels	Initial incursion localised to built structures (i.e. fishing vessels)	**Manual removal** (hand removal by divers)	Unsuccessful – further populations detected, now established in harbour	Fletcher 2014
2013	Coromandel Harbour, New Zealand	Marine polychaete	*Sabella spallanzanii* (Mediterranean fanworm)	"Large" invasion on two barges	Initial incursion localised to built structures (i.e. barges)	**Manual / mechanical removal** (hand removal by divers, vacuum and filter system)	Uncertain – no detections since 2018, but Waikato Regional Council reports that worm is established in harbour and spreading up west coast	Fletcher 2014

Year	Location	Taxon	Species	Scale of invasion	Relevant environmental conditions	Treatment applied	Outcomes	Reference(s)
2013	Nelson, New Zealand	Marine polychaete	*Sabella spallanzanii* (Mediterranean fanworm)	Very localised incursions to cargo vessel and one worm in marina	Incursions limited to built structures (i.e. vessels, wharf piles and docks of marina)	**Not reported** (presumed manual removal. Vessel slipped and cleaned)	Successful – *S. spallanzanii* not currently established in Nelson	Fletcher 2014
2013	Tauranga, New Zealand	Marine polychaete	*Sabella spallanzanii* (Mediterranean fanworm)	Very small (two worms), localised to single vessel	Incursion limited to built structure (vessel)	**Manual removal (**hand removal)	Successful – *S. spallanzanii* not currently established in Tauranga	Fletcher 2014
2014	Nelson, New Zealand	Marine polychaete	*Sabella spallanzanii* (Mediterranean fanworm)	Small, localised to hull of large recreational vessel	Incursion limited to built structure (vessel hull)	**Encapsulation** (wrapping) **and chemical treatment** (acetic acid)	Successful – all worms killed	Fletcher 2014 Morrisey et al. 2016
Other (non-polychaete) relevant marine taxa								
1999	Cullen Bay Marina, Darwin Harbour, Australia	Marine bivalve	*Mytilopsis* sp. (striped mussel)	Densities up to 23,650 individuals/m^2	Marina environment with many built structures, can be locked off from wider seawater environment with gates	**Chemical treatment** (chlorine and copper sulphate)	Chlorine not successful, as not 100% mortality, but copper sulphate successful, as no live mussels detected after application	Bax et al. 2002
1999	Tipperary Waters Estate Marina, Darwin Harbour, Australia	Marine bivalve	*Mytilopsis* sp. (striped mussel)	Localised to the hull of a single yacht. Density of 6 mussels/m^2	Marina environment with many built structures, can be locked off from wider seawater environment with gates	**Chemical treatment** (copper sulphate)	Successful – 100% mortality achieved, no further mussels detected	Bax et al. 2002
2000–2006	Agua Hedionda Lagoon and Huntington Harbour, California, USA	Marine algae	*Caulerpa taxifolia*	Lagoon = > 1000 m^2. Harbour = several small embayments within 4 ha area	Lagoon and harbour both relatively enclosed. High proportion of both sites occupied by built structures (e.g. vessels, wharf piles)	**Encapsulation** (smothering) **and chemical treatment** (chlorine)	Successful – no viable colonies detected at either site in subsequent surveys	Anderson 2005 Muñoz 2016
2002	West Lakes & upper reaches of Port River, South Australia	Marine algae	*Caulerpa taxifolia*	Moderate	Artificial marine lake body, with ability to close off from wider marine environment	**Osmotic stress** (hyposalinity)	Successful – *C. taxifolia* has not been detected in the system since	Walters 2009

Year	Location	Taxon	Species	Scale of invasion	Relevant environmental conditions	Treatment applied	Outcomes	Reference(s)
2000	Hansen Bay, Chatham Islands, New Zealand	Marine algae	*Undaria pinnatifida* (Asian brown kelp)	Localised to the hull of a sunken trawler	Subtidal (20 m depth) open ocean environment, soft-sediment (sandy) habitat	**Manual removal** (hand removal by divers) and **thermal stress** (heat treatment)	Successful – all visible individuals removed and no further plants detected on vessel or on nearby shoreline and wharf structures	Wotton et al. 2004
2003	Shakespeare Bay, New Zealand	Colonial sea squirt	*Didemnum vexillum*	Large – detected at multiple built and natural sites within Shakespeare Bay	Both built and natural environments invaded	**Mechanical removal** (vacuum and filtering), **physical disruption** (water blasting), **desiccation** (beaching), **encapsulation** (wrapping, smothering) and **chemical treatments** (anti-fouling paint, chlorine)	Mixed levels of success across sites and treatment methods	Coutts and Forrest 2007
2007	Tasman Bay, New Zealand	Marine bivalve	*Perna perna* (brown mussel)	Localised to seabed of de-fouling site of drilling rig (~12.6 ha target area)	Natural soft-sediment environment, subtidal – site depth > 40 m	**Mechanical removal** (dredging)	Successful – follow-up monitoring showed densities were more than sufficiently low to prevent population persistence. No further detection	Hopkins et al. 2011

3. CRITERIA FOR ASSESSING THE FEASIBILITY OF POTENTIAL ERADICATION OR CONTROL METHODS

The feasibility of potential methods for treatment and / or removal of *F. enigmaticus* aggregations in the Hawke's Bay Region should be determined by assessing them against key operational criteria. Any method/s used must be effective at killing or removing worms in target habitats and at realistic spatial scales, be safe for operators, comply with regulatory requirements, not result in accidental release or dispersal of target organisms, and not cause unacceptable cultural or environmental impacts. We considered the following criteria to determine the feasibility of potential treatment methods:

- Effectiveness
- Operator safety
- Biosecurity
- Regulatory compliance
- Environmental impacts
- Cultural acceptance
- Quality control
- Scalability
- Cost.

The paragraphs below define each criterion and describe its relevance in the assessment and selection process for eradication and control methods. This section draws heavily on earlier assessments prepared by Cawthron biosecurity scientists (Cahill et al. 2019, 2021; Lovett et al. 2023), which also contain references to the primary literature underpinning many of the statements below.

For simplicity and to avoid repetition, we use the term 'treatment' to describe *any method* that may be used for killing and / or removing worm aggregations within a target area. This includes chemical treatment agents, as well as physical or mechanical methods.

For almost all treatments, the overall success of an eradication or control campaign depends on the ability to detect target individuals within the treatment area. The development of robust detection methods and protocols is therefore critical, particularly for eradication attempts, but this is beyond the scope of this report. Consequently, we do not consider detection in our assessment of methods against the criteria (i) effectiveness and (ii) quality control. These criteria specifically address *the ability of the treatment to kill or remove organisms within aggregations that have been detected,* and *the ability to validate treatment success for organisms subjected to treatment,* respectively.

3.1. Effectiveness

Treatment agents or methods need to be effective against juvenile and adult life stages and during the conditions under which they would be applied in the event of *F. enigmaticus* interventions in the Hawke's Bay Region. These may include intertidal (temporarily exposed) and subtidal (permanently submerged) conditions, and stagnant to moderate flow conditions depending on tides and distance from the sea.

The effectiveness of a treatment or control method can be reported in different ways depending on its mode of action. The 'potency' of biocidal treatments, for example, is usually stated as: (1) a modelled value corresponding to the treatment concentration or intensity lethal to 50% (LC_{50}) or 99% (LC_{99}) of targeted individuals; or (2) the lowest concentration or intensity tested that resulted in 100% mortality of the targeted organisms (Cahill and Floerl 2019). The effectiveness of physical treatments, on the other hand, is often described as the rate at which target organisms have been killed and / or removed following application of the method.

Depending on the method, treatment effectiveness may also depend on the exposure period. This is particularly relevant for situations where treatments need to be administered when targeted pest aggregations are not submerged, and where tidal exposure (to air) periods are shorter than the critical exposure period. Cahill et al. (2019) also mentions the role of 'biofouling load' as an influencing factor. This acknowledges that the effectiveness of a treatment agent delivered at a given concentration or intensity may depend on the number, density or biomass of target organisms per unit area or volume exposed to the treatment agent. An assessment of effectiveness should therefore be based on realistic target organism densities.

We assess the effectiveness of potential treatment methods against two scenarios: (i) attempted eradication, and (ii) population control (reduction / maintenance of local populations to / at a specified abundance or distribution) of *F. enigmaticus*. This approach helps to identify methods that may, for example, not be useful as eradication treatments but that could be feasibly applied to reduce or maintain the abundance of *F. enigmaticus* in particular locations or habitats.

3.2. Operator safety

A treatment agent or method must be safe for handling and implementation by field personnel. Operator safety hazards may include contact with skin or eyes, inhalation of fumes, accidental ingestion, combustion or reaction with other substances, and mechanical injury associated with the treatment agent / system or the operations involved in its delivery. For some chemical treatments, operator safety is dependent on concentration or intensity. For example, concentrated stock solutions of chemical agents can be orders of magnitude more hazardous than the working solutions applied to target populations.

Many operator safety hazards can be managed using established handling procedures (e.g. preventing contact with skin or eyes, secondary containment of stock solutions) and personal protective equipment (PPE; e.g. safety glasses, gloves, covered shoes). Material Safety Data Sheets provide overviews of handling and personal protection requirements for chemical treatment agents. If treatment application requires diving, any safety requirements for treatment agents should not interfere with safe diving practices. Diving operations should follow the Occupational Diving Guidelines developed by Worksafe New Zealand.

3.3. Biosecurity

The aim of population control or eradication is a reduction in, or complete elimination of, target populations, respectively. Some treatment methods may inadvertently exacerbate biosecurity risks, e.g. via escape or dislodgement of viable organisms, or the release of gametes induced by exposure to the treatment agent or method. Depending on the treatment, some risks may be manageable via standardised operational protocols for implementation (e.g. isolation of the treatment area), compliance monitoring and quality control. However, other risks may be difficult to mitigate, in particular when isolation of the treatment area is not possible. Biosecurity risks associated with treatment application need to be considered, including an assessment of their relative magnitude and the potential for mitigation.

3.4. Regulatory compliance

Activities that involve discharges into the marine environment or the removal of marine organisms require resource consent from the relevant local authority, or even a national authority. Discharge can include chemical treatment waste, viable or non-viable biofouling organisms, and water. This criterion addresses regulatory considerations for use of treatments that will or may result in discharges to the environment, and existing or potential mechanisms for approval in New Zealand where relevant. Morrisey (2015) provided a recent overview of consenting requirements for biosecurity treatment agent discharges into New Zealand's marine environment. Such activities must consider several legislative obligations:

- the Resource Management Act 1991 (RMA)
- approval for use by the Environmental Protection Agency
- the New Zealand Coastal Policy Statement
- local body Resource Management Plans.

Most importantly, the use of chemical treatment agents in New Zealand requires EPA approval. The process for new applications is complex and can take months to years. We consider the protracted and uncertain consenting process required for chemical treatments that do not currently have EPA approval not a feasible option for HBRC.

3.5. Environmental impacts

Chemical and non-chemical treatment agents have potential to harm the environment. Some treatments can be isolated from the environment and treatment waste can be collected. However, this will not be possible for all treatments. In addition, accidental spillage of treatment agents or failure of containment systems may occur.

Chemical treatment agents used to kill biofouling organisms are typically non-specific and have potential to harm a wide range of organisms if released into the environment. The quantity of treatment agents released, their persistence in the environment, their potential to bioaccumulate, and their bioavailability to relevant organisms all influence the resulting ecological risk. When some chemicals break down in the environment they form toxic by-products, which in some instances can pose equal or greater ecological risks than the parent compound(s). A commonly cited example is the halogenated by-products formed when halogen-based disinfectants (e.g. chlorine) react with organic compounds to form persistent organic pollutants. Some chemical treatment agents can be neutralised post treatment to reduce ecotoxicological risk (e.g. treating chlorine with sodium thiosulphate; Morrisey et al. 2016).

In comparison, non-chemical treatment agents generally pose fewer ecotoxicological risks. Instead, they either involve removal or destruction of target biomass, or rely on exceeding the tolerance of target organisms to environmental parameters (e.g. temperature, salinity, oxygen). In the latter case, dilution of any associated discharges in the sea can be sufficient to negate ecotoxicological risk.

It is presently unknown whether *F. enigmaticus* reefs in the Hawke's Bay Region serve as habitats or refuges for native species, including valued taonga species. Most of the treatments assessed would likely result in some proportion of mortality of any (native and non-indigenous) organisms associated with targeted worm aggregations, particularly those unable to escape the treatment area. In the absence of knowledge of species that may utilise worm reefs as habitats, we have focused our assessment on the general potential of the methods to impact the environment *beyond* the worm aggregations. If an assessment of the potential habitat role / value of *F. enigmaticus* aggregations, including the species associated with them, is undertaken, our constrained assessment of environmental impact can be revisited and amended accordingly.

3.6. Quality control

Quality control procedures are an essential component of any field operations involved in control or eradication campaigns for marine invasive species. They must ensure that the target treatment concentration (e.g. of a biocide) or intensity threshold (e.g. temperature or salinity) is achieved and maintained for a period known to achieve full mortality. This will require suitable field measurement or assessment systems to be available during treatment delivery. Critical concentrations or intensities required for achieving target species mortality can be identified from case studies (if available) or via pilot experiments. In the case of physical treatments, quality control needs to be able to validate successful removal or killing of target organisms.

3.7. Scalability

Generally, eradication or control attempts for invasive marine organisms take place at the geographical scale of a marina, port, bay or estuary. The affected areas of such locales range in size from one to tens of hectares. Treatment agents, methods and delivery systems need to be feasibly applied at these scales, and at a rate where mortality / removal exceeds population growth. This means that the area that can be treated per unit time is realistic given the total target area. Moreover, the available time, resources, and treatment agent/s or delivery system/s need to be sufficient in terms of quantity to treat the target area.

The treatment agent/s used in a control or eradication attempt also need to be both suitable and effective in terms of their application in the range of habitat types located within the target area. In the case of *F. enigmaticus*, this includes both hard-substrate (rocky reef, bridges, seawalls and other infrastructure) and soft-sediment environments (soft-bottom lagoons / estuaries). It is unlikely that a single-method, silver-bullet approach exists for treating all affected habitats and structures, and an intervention (particularly attempted eradication) may require the use of multiple treatment approaches. Our assessment of scalability primarily focuses on spatial scale, and we separately consider the efficacy for each method across a range of habitats.

3.8. Cost

Depending on the location and spatial extent of an incursion, and the diversity of habitats affected, the direct cost of control or eradication campaigns can be very high, as it includes treatment agent/s, delivery systems, critical materials and infrastructure, personnel, mobilisation, decommissioning, adequate monitoring and, potentially, repeat intervention. These direct costs do not include other types of costs, which may be non-monetary, such as collateral environmental impacts of treatment or the longer-term costs of unsuccessful control or eradication attempts.

It was agreed with HBRC that in our assessment against this criterion we would provide relative indications of direct costs. An assessment of affordability and cost-benefit can then be undertaken by HBRC relative to their level of resourcing and the specific regional values at stake.

3.9. Cultural acceptabilty

The application of treatments to manage pest populations may have impacts on local and / or regional cultural values via direct or indirect impacts on taonga species, the mauri of target environments and the values of tangata whenua as kaitiaki. It is therefore important that potential cultural impacts associated with any treatment or other management activities undertaken to control or remove *F. enigmaticus* populations from the Ahuriri Estuary and wider Hawke's Bay Region are identified, considered and enacted when making decisions about the most appropriate course of action. It is also important that the use of treatments and the nature of their application are consistent with Te Ao Māori, tikanga Māori and the views and values of local iwi and hapū.

We believe that these important considerations are most appropriately addressed through discussion and agreement with affected tangata whenua, rather than evaluated as a criterion in this assessment. Consequently, we have not assessed any of the treatments against cultural values and impacts, and we recommend that HBRC discusses any recommended options from this assessment with local Māori before progressing.

3.10. Deciding on the treatment approach(es) to use

We subject the performance of each treatment method against the criteria above to the 'Treatment Agent Selection Decision Tree' recently developed by Lovett et al. (2023) to assist the Ministry for Primary Industries in making decisions around appropriate treatment approaches in the event of marine pest incursions (Figure 2). This tool lends itself to support the selection of treatment approaches for *F. enigmaticus* populations around the Hawke's Bay Region, and this report represents its first real-world application.

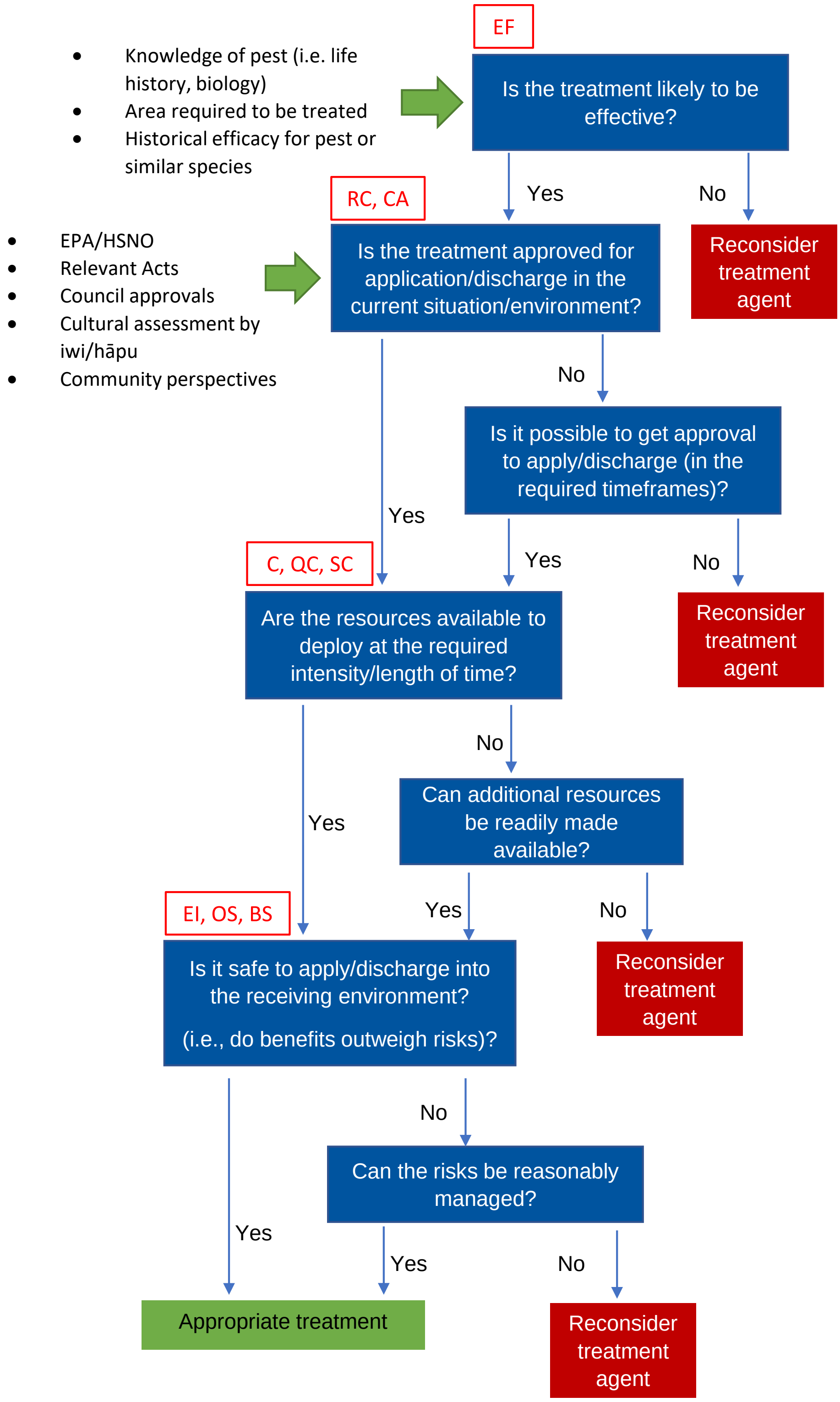

Figure 2. Treatment agent selection decision tree for aquaculture pest treatment and control or eradication or marine pests, proposed by Lovett et al. (2023). Text boxes with red margins indicate where the assessment criteria used in this report apply to the selection and decision process. EF = effectiveness; QC = quality control; SC = scalability; RC = regulatory compliance; CA= cultural acceptability [not assessed]; C = cost [not assessed]; EI = environmental impacts; OS = operator safety; BS = biosecurity.

4. ASSESSMENT OF TREATMENT METHODS

Below we assess each of the candidate treatments identified in Section 2.4 against the criteria defined in Section 3. Our assessment draws heavily on the detailed reviews, expert consultation and consensus discussions undertaken by Cahill and Floerl (2019) and Cahill et al. (2019, 2021), who examined chemical and physical treatment agents for potential application in (i) treatment of biofouling on vessels and submerged infrastructure, and (ii) control and eradication of marine non-indigenous species. These assessments were not species-specific, but aimed at entire biofouling assemblages or commonly encountered non-indigenous taxa. In our assessment, we consider the performance of each candidate method against the various criteria *in the specific context of F. enigmaticus control in the Hawke's Bay Region*. We include references to primary literature only for occasions where information referred to was not included in the sources listed above.

Based on a site visit and communications with HBRC, we infer the following scenario:

> *Ficopomatus enigmaticus* reefs and aggregations currently occur in the Ahuriri Estuary and Clive River, and may also be present in other local water bodies with connection to the sea. In Ahuriri Estuary, *F. enigmaticus* is non-homogenously distributed, occurring from the estuary / river mouth to areas with very low (near-freshwater) salinities, amounting to a linear distance of > 5 km. Within this area, hundreds of worm 'reefs' have formed in soft-sediment environments via 'nuclei' such as rocks or artificial debris (Figure 3). Reefs have attained diameters of > 1 m. Worms also occur on hard substrates, such as natural rock, bridge pilings and revetments along the Clive River, and possibly on flood protection infrastructure in the upper Ahuriri Estuary. Worm aggregations occur both intertidally and subtidally. HBRC has a good understanding of the worm's local distribution preceding the 2023 floods (shape files of aerial imagery indicate ~6,285 m^2 of reefs in Ahuriri Estuary alone), but there is some likelihood that the distribution has changed, and this is yet to be assessed.

For each method, one of the following verdicts is passed against each criterion:

- **Pass:** sufficient evidence that a method meets the criterion. In some instances initial experimental validation is still recommended.
- **Uncertain:** insufficient evidence to make a firm decision, and / or an achievable level of experimentation is required to establish a verdict.
- **Fail:** sufficient evidence that method does not meet criterion, and / or extensive experimentation and resources are required to establish a verdict.

Figure 3. Distribution of *Ficopomatus enigmaticus* in the Ahuriri Estuary in 2019. Map developed by HBRC based on aerial imagery.

4.1. Physical treatments

Physical treatment methods aim to either remove target organisms from the environment or kill them *in situ*. They may be implemented via simple manual processes (e.g. hand-picking) or with the use of motorised or automated delivery systems. Physical treatments rely on a field team's ability to detect and treat all individuals of the target population. For some methods, effective capture and removal of organisms from target habitats is key for mitigating residual biosecurity risks, such as survival of target individuals or release of propagules. Conversely, the success of methods that kill target populations *in situ* (e.g. osmotic stress) is governed by the ability to deliver a lethal level of the treatment agent to all target individuals for the appropriate amount of time. Both capture and delivery can be difficult to achieve, particularly in structurally complex habitats or environments with low visibility. Some physical treatments have non-target effects within the treatment area, but these are generally short- to medium-term effects and need to be carefully weighed against the long-term impacts of established pest populations. Given the potential impacts of *F. enigmaticus* aggregations on flow regimes and flushing of waterways, removal of dead worm biomass post treatment is likely desirable for several methods (encapsulation, osmotic stress and thermal stress).

4.1.1. Manual removal

This approach involves the removal of *F. enigmaticus* individuals and / or aggregations from target areas by hand or via the use of simple tools such as scrapers or shovels. The success of manual removal relies on the ability of field teams to detect sufficient individuals of the target population, depending on the objective of the campaign. Effective removal includes the ability to contain any biomass collected and to dispose of it safely (e.g. via landfill).

Table 2. Method assessment for manual removal.

Criterion	Assessment	Verdict
Effectiveness	Manual removal has been shown to be an effective method for severely diminishing target populations of marine invertebrates and algae at scales of m^2 to ha. However, the challenge for many case studies has been to effectively remove isolated individuals, or small or microscopic life-history stages. Given the relatively small size of *F. enigmaticus* individuals (mm to cm depending on age) and its presence in subtidal areas, there is a significant risk of missing juveniles or small individuals within areas targeted for treatment.	**Eradication: Fail** – high likelihood of incomplete removal. **Population control: Pass** – for readily detectable aggregations in some affected habitats.

Criterion	Assessment	Verdict
Operator safety	Some equipment, such as scrapers, knives or shovels, may pose operator safety risks, particularly when used in combination with diving. However, these risks can usually be managed via appropriate PPE and the implementation of sensible operator protocols and field health and safety procedures.	**Pass** – can be made safe for operators.
Biosecurity	If removal is undertaken during *F. enigmaticus*' reproductive season, there is a risk of release of viable propagules in response to handling and disturbance, particularly when removal is undertaken by divers. Such release can be at least partly mitigated by conducting field operations outside the reproductive season, but the timing is currently unknown. Incomplete removal of all worm biomass, in particular reef / tube material, is known to elevate risk of regrowth, as fragments can act as nuclei for new reefs.	**Uncertain** – complete avoidance of propagule or fragment release has not been documented.
Regulatory compliance	Manual removal of marine pest organisms is widely implemented in New Zealand (e.g. Northland, Bay of Plenty, Marlborough). Regulatory approvals are therefore likely to be readily obtained.	**Pass** – already being implemented in New Zealand, regulatory approvals can be readily obtained.
Environmental impacts	Manual removal does not cause environmental impacts over and above those flagged under the Biosecurity criterion, provided that access to and operations within target areas do not result in damage to other species or habitats (e.g. trampling of seagrass beds), which can largely be mitigated by the personnel undertaking the manual removal being mindful of their surroundings and acting accordingly.	**Pass** – environmental impacts are low / manageable.
Quality control	While removal of sizeable aggregations can be validated, there is a significant risk that small individuals or juvenile worms will be missed. There are no quality control methods available for assessing this, other than repeat 'passes' through the target area, which are subject to the same shortcoming. The literature relating to *F. enigmaticus* and other invasive marine organisms have reported many regrowth events following manual removal, possibly due to non-detection of parts of the target population.	**Fail** – limited ability to monitor and validate completeness of removal operations *in situ*.

Criterion	Assessment	Verdict
Scalability	Manual removal can conceivably be scaled to larger target areas, provided sufficient time and resources (personnel and equipment / infrastructure) are available. Manual removal can be carried out across the range of environments in the Hawke's Bay Region where *F. enigmaticus* is known to occur (e.g. reefs, articifical structures, sandy / muddy estuarine habitats, intertidal and subtidal habitats).	**Pass** – provided sufficient time and resources are available.
Cost	We expect the cost of this method to be relatively high given the labour intensity of manual removal and the spatial distribution of *F. enigmaticus* across a range of intertidal and subtidal habitats.	**High** – considerable operational costs.

4.1.2. Mechanical removal

Mechanical removal is the automated collection and containment of organisms via mechanical means such as dredging, diggers / excavators, suction, robotics or other machinery. It represents an extension of manual removal methods, using equipment to increase the rate and spatial scale of treatment. HBRC has previously used mechanical removal – in the form of a digger and a barge – to control *F. enigmaticus* in parts of the Ahuriri Estuary.

Table 3. Method assessment for mechanical removal

Criterion	Assessment	Verdict
Effectiveness	Different systems may be required for different habitats and substrates. These methods are likely to be relatively effective at removing targeted aggregations and reefs, but there is a risk of incomplete removal from complex surfaces such as reefs or bridge pilings. Like manual removal, mechanical approaches require detection of small aggregations, isolated individuals, or small or microscopic life-history stages. This is particularly challenging in subtidal areas, and there is a significant risk of missing small individuals or aggregations of *F. enigmaticus* in target areas.	**Eradication: Fail** – high likelihood of incomplete removal. **Population control: Pass** – for readily detectable aggregations in some affected habitats.
Operator safety	Some equipment, namely heavy or electronic machinery, may pose operator safety risks, especially when used in combination with diving. However, these risks can usually be managed via appropriate PPE and the implementation of sensible operator protocols and field health and safety procedures.	**Pass** – can be made safe for operators.

Criterion	Assessment	Verdict
Biosecurity	If removal is undertaken during *F. enigmaticus*' reproductive season there is a risk of release of viable propagules in response to handling and disturbance. Such release can be mitigated, at least in part, by conducting field operations outside the reproductive season, but the timing is currently unknown. Incomplete removal of all worm biomass, including in particular reef / tube material, is known to elevate risk of regrowth when fragments act as nuclei for new reefs in otherwise soft-substrate environments.	**Uncertain** – complete avoidance of propagule or fragment release has yet to be documented.
Regulatory compliance	Mechanical removal of biofouling material from vessel hulls is already implemented in parts of New Zealand (e.g. Marlborough). Regulatory approvals are therefore likely to be readily obtained.	**Pass** – already being implemented in New Zealand, regulatory approvals can be readily obtained.
Environmental impacts	Mechanical removal will likely require specialised equipment and infrastructure to be transported to target areas. This may risk disturbance and damage to other species or habitats (e.g. trampling or vehicle access on seagrass beds), but such risks can be anticipated and adequately managed.	**Pass** – environmental impacts are manageable.
Quality control	While removal of sizeable aggregations can be validated, there is a significant risk that small individuals or juvenile woms will be missed. There are no quality control methods available for assessing this, other than repeat 'passes' through the target area, which are subject to the same shortcoming. The literature relating to *F. enigmaticus* and other invasive marine organisms have reported many regrowth events following mechanical removal, possibly due to non-detection of parts of the target population or incomplete recovery of residual material.	**Fail** – limited ability to monitor and validate completeness of removal operations *in situ*.
Scalability	Mechanical removal can conceivably be scaled to larger target areas provided sufficient time and resources (personnel and equipment / infrastructure) are available. Mechanical removal can be carried out across the range of environments in the Hawke's Bay Region where *F. enigmaticus* is known to occur (e.g. reefs, articifical structures, sandy / muddy estuarine habitats, intertidal and subtidal habitats).	**Pass** – provided sufficient time and resources are available.

Criterion	Assessment	Verdict
Cost	We expect the cost of this method to be relatively high given the need to develop bespoke tools or adapt existing tools for removal of *F. enigmaticus* in different target habitats. In addition, there are complex logistics involved in transporting and operating the necessary equipment in these areas, and in the spatial distribution of *F. enigmaticus* across habitats.	**High** – considerable operational costs.

4.1.3. Physical disruption

Physical disruption involves *in situ* killing of target organisms via crushing or otherwise damaging them to render them non-viable. The most common methods of physical disruption have been water blasting and variations of mechanical brushing (both of which have aspects that cross over with mechanical removal), although there is also precedence for simple approaches, such as destroying target organisms (e.g. oysters in South Australia) with hammers and other basic tools. The key difference between physical disruption and manual and mechanical removal methods is that the residual material is left *in situ* following disruption activities.

Table 4. Method assessment for physical disruption.

Criterion	Assessment	Verdict
Effectiveness	Most physical disruption methods used for biosecurity interventions have achieved only partial mortality of target organisms. As for manual and mechanical removal, physical disruption requires effective detection of small individuals or life-history stages within and around aggregations targeted for treatment. There is a significant risk of missing some of these individuals and life-history stages. Since there is no removal of biomass following physical disruption and the method can facilitate fragmentation, there is also the risk that viable individuals / fragments will be left behind and regrow into new populations.	**Eradication: Fail** – likelihood of incomplete mortality and of missing individuals and small aggregations. **Population control: Fail** – benefits questionable if biomass not removed.
Operator safety	Some equipment, namely heavy or electronic machinery, may pose operator safety risks, particularly when used in combination with diving. However, these risks can usually be managed via appropriate PPE and implementation of sensible operator protocols and field health and safety procedures.	**Pass** – can be made safe for operators.

Criterion	Assessment	Verdict
Biosecurity	If treatment is undertaken during *F. enigmaticus*' reproductive season there is a risk of release of viable propagules in response to disturbance caused by treatment. Such release can be mitigated, at least in part, by conducting field operations outside the reproductive season, but the timing is currently unknown. Additionally, physical disruption without subsequent removal of treated worm biomass may result in the persistence of potentially viable fragments, which can then act as nuclei for new reefs.	**Fail** – treated material left behind can facilitate regrowth of worm aggregations.
Regulatory compliance	Physical disruption involves methods similar to those used for mechanical removal of biofouling material from vessel or infrastructure in some areas of New Zealand. Since no material is removed or discharged via this activity, regulatory approval is unlikely to be a hurdle.	**Pass** – regulatory approvals can be readily obtained.
Environmental impacts	Physical disruption may require specialised equipment and infrastructure to be transported to target areas. This may risk disturbance and damage to other species or habitats (e.g. trampling or vehicle access), but such risks can be anticipated and adequately managed.	**Pass** – environmental impacts are manageable.
Quality control	Physical disruption methods can be tested and validated via pilot studies involving realistic aggregations of *F. enigmaticus*. Additional *in situ* quality control is possible via examination of treated worms in random samples. However, this does not address the issue of operators missing small individuals or life-history stages of *F. enigmaticus* within the target area.	**Fail** – limited ability to monitor and validate completeness of removal operations *in situ*.
Scalability	Physical disruption can conceivably be scaled to larger target areas provided sufficient time and resources (personnel and equipment / infrastructure) are available. Physical disruption can be carried out across the range of environments in the Hawke's Bay Region where *F. enigmaticus* is known to occur (e.g. reefs, articifical structures, sandy / muddy estuarine habitats, intertidal and subtidal habitats).	**Pass** – provided sufficient time and resources are available.
Cost	Physical disruption is likely to require personnel and infrastructure resources comparable to those required for manual or mechanical removal. However, it does not require capture and disposal of treated worm biomass. We therefore expect the cost of this method to be moderate.	**Moderate** – moderate operational costs.

4.1.4. Encapsulation (deoxygenation)

Encapsulation generally involves wrapping, covering or smothering pest organisms on target substrates or habitats. The resulting reduction or elimination of water exchange causes mortality via reduction of dissolved oxygen to below respiratory requirements (i.e. creation of anoxic or hypoxic conditions), generation of toxic chemical species (e.g. hydrogen sulphide) and / or prevention of feeding. Encapsulation has previously been applied to vessel hulls and submerged static infrastructure (e.g. pilings and pontoons). It usually involves wrapping target surfaces with plastic foil or smothering by dredge spoil or other organic material, but any material that creates an impermeable barrier between the target area and the surrounding environment could be considered (e.g. fast-setting cement / plaster). Many organisms can tolerate hypoxic (low dissolved oxygen) or even anoxic (zero oxygen) conditions for extended periods of time, particularly those able to seal themselves off from the environment via protective structures such as tubes, shells and opercula. Extensive treatment times may therefore be required for encapsulation methods to be successful, but these can be reduced via the addition of oxygen scavenging agents (e.g. sodium sulphite or sodium dithionite) or other chemicals to the encapsulated area.

Table 5. Method assessment for encapsulation.

Criterion	**Assessment**	**Verdict**
Effectiveness	Encapsulation of non-complex surfaces, such as vessels and pontoons, has successfully killed a wide range of biofouling taxa. Complete mortality is likely to be achieved if *F. enigmaticus* aggregations can be effectively isolated from the ambient environment and for a sufficient period. Existing reviews suggest that incubation periods of at least 14 days are required to kill complex and diverse biofouling assemblages via encapsulation and without the use of additives. Required treatment times may therefore be extensive, particularly since *F. enigmaticus* is enclosed in a protective calcareous tube and can seal itself off from the wider environment.	**Eradication: Pass** – provided worm aggregations can be effectively encapsulated for periods sufficient to cause mortality. **Population control: Pass** – provided worm aggregations can be effectively encapsulated for periods sufficient to cause mortality.
Operator safety	Encapsulation only poses safety risks if oxygen scavenging or other chemicals are added, but these can be mitigated via appropriate PPE and the implementation of sensible operational procedures and field health and safety protocols.	**Pass** – can be made safe for operators.

Criterion	Assessment	Verdict
Biosecurity	Applying some encapsulation methods (e.g. smothering by organic material) can result in the dislodgement of viable target organisms or the release of propagules in response to disturbance. Nonetheless, these risks are likely to be lower than manual / mechanical removal and physical disruption since, by the nature of encapsulation, the target area will be at least partially contained. Breaches in wrapping-based encapsulation systems caused by sharp worm tubes and reefs may also occur during treatment, potentially resulting in the release of viable organisms or propagules. However, these risks can to some extent be mitigated via the application of treatment outside *F. enigmaticus* reproductive season, monitoring and timely repairs, and the use of robust materials and validated methods that prevent dislodgement of worms and damage to encapsulation systems.	**Pass** – biosecurity risks can be managed.
Regulatory compliance	Most forms of encapsulation are unlikely to require regulatory approvals unless an oxygen scavenging or other chemical agent is used in conjunction, but discharge consents may be required if dredge spoil or other organic materials are used (i.e. smothering).	**Pass** – regulatory approval either able to be obtained or not required.
Environmental impacts	Encapsulation will require specialised equipment, infrastructure and / or material to be transported to target areas. This may risk disturbance and damage to other species or habitats (e.g. trampling or vehicle access), but such risks can be anticipated and adequately managed. Encapsulation of reefs via smothering by dredge spoil or other organic material may have collateral environmental effects (e.g. smothering of other organisms in the target area or immediate surrounding area); however, these effects are likely to be short-lived and can be mitigated with the use of appropriate containment.	**Pass** – environmental impacts are manageable.
Quality control	Water quality parameters (e.g. dissolved oxygen levels) can be used as proxies for treatment effectiveness and effective thresholds can be determined via pilot trials. *In situ* quality control is achievable via installation of cabled dissolved oxygen probes or loggers in treatment areas.	**Pass** – able to be readily monitored *in situ*.

Criterion	Assessment	Verdict
Scalability	Encapsulation can be scaled to larger target areas provided sufficient time and resources (personnel and equipment / infrastructure / materials) are available. Encapsulation can be carried out across the range of environments in the Hawke's Bay Region where *F. enigmaticus* is known to occur (e.g. reefs, articifical structures, sandy / muddy estuarine habitats, intertidal and subtidal habitats). Different encapsulation approaches may be required for treating different habitats or structures.	**Pass** – provided sufficient time and resources are available.
Cost	Overall costs will depend on the form(s) applied, but encapsulation will require considerable personnel and materials for containment, treatment delivery and monitoring, and subsequent recovery of encapsulation equipment. We therefore expect the cost of this method to be relatively high.	**High** – considerable operational costs.

4.1.5. Osmotic stress

Osmotic stress involves exposing target organisms to salinity conditions either above or below their lethal limits. Sodium chloride is the primary contributor to the salinity of seawater, and it is also a crucial constituent of biological extracellular fluids. Most organisms have a fine osmotic balance, and upsetting this balance can lead to cell damage and death. Most marine organisms are vulnerable to hypo- (i.e. fresh water) and hypersaline (i.e. brine) conditions, and both approaches have been used during previous attempts to control marine invasive species populations.

Table 6. Method assessment for osmotic stress.

Criterion	Assessment	Verdict
Effectiveness	Experimental exposure to brine (60–300 ppt) or fresh water has been observed to cause partial or complete mortality in a wide range of biofouling taxa. Invasive *F. enigmaticus* populations have been observed to recede dramatically following naturally mediated substantial increases or declines in salinity. The salinity tolerance range of *F. enigmaticus* is reported to be ~10–30 PSU, therefore exposure to salinity conditions outside this range may be effective. Short (seconds) to moderate (hours) exposure to brine or fresh water was observed to have no effect on shelled organisms such as mussels and oysters, thus extensive treatment times may be required.	**Eradication: Pass** – but requires preliminary experimental evaluations of efficacy against *F. engimaticus*. **Population control: Pass** – but requires preliminary experimental evaluations of efficacy against *F. engimaticus*.
Operator safety	No significant operator hazards. Sodium chloride is a potential eye irritant, but this risk can be mitigated via appropriate PPE and the implementation of sensible operational procedures and field health and safety protocols.	**Pass** – safe for operators.
Biosecurity	Osmotic stress will not cause dislodgement or fragmentation of worms, but it may trigger spawning. This can be readily mitigated via treatment application outside of *F. enigmaticus*' reproductive season and via adequate containment of treated areas.	**Pass** – biosecurity risks can be managed.
Regulatory compliance	Regulatory approvals are likely to be readily obtained. Consents to discharge fresh water, brine or salt into the marine environment are regularly granted in New Zealand (e.g. *Caulerpa brachypus* control trials at Great Barrier Island), and guidelines for discharges from desalination plants have been developed overseas.	**Pass –** regulatory approvals can be readily obtained.
Environmental impacts	Sodium chloride is a primary constituent of seawater and poses minimal overall concern to the marine environment. Any effects of hypo- or hypersaline treatments are likely to be localised and short-term. Osmotic shock treatment will require specialised equipment and infrastructure to be transported to target areas. While this may risk disturbance and damage to other species or habitats (e.g. trampling or vehicle access), such risks can be anticipated and adequately managed.	**Pass** – environmental impacts are manageable.

Criterion	Assessment	Verdict
Quality control	Salinity parameters can be used as proxies for treatment effectiveness, and effective thresholds can be determined via pilot trials. *In situ* quality control is achievable via installation of salinity probes or loggers in treatment areas.	**Pass** – able to be readily monitored *in situ*.
Scalability	Hypersaline treatment via deposition of bulk salt onto target aggregations can likely be scaled to larger target areas provided sufficient time and resources (personnel and equipment / infrastructure / materials) are available. However, delivery of salt or brine and maintenance of critical concentrations to complex environments, particularly built vertical structures, has not previously been attempted and may pose logistical challenges. Hyposaline treatments have only been used for environments that were able to be fully isolated from marine water sources. Given the general nature (i.e. estuarine, geographically isolated) of the invaded areas in the Hawke's Bay Region, achieving and maintaining hyposaline conditions via addition of fresh water poses significant logistical challenges, and thus it is not considered feasible.	**Pass** – hypersaline treatment for flat or 'horizontal' habitats is achievable. **Uncertain** – hypersaline treatment for complex and vertical structures) may present logistical challenges. **Fail** – logistical challenges associated with hyposaline treatment insurmountable.
Cost	Similar to encapsulation, osmotic stress will require considerable personnel and materials for containment, treatment delivery and monitoring, and subsequent recovery of encapsulation equipment. An additional consideration is the likely large volumes of salt required to achieve hypersaline conditions. We therefore expect the cost of this method to be relatively high – comparable to encapsulation but higher due to the added cost of salt.	**High –** considerable operational costs.

4.1.6. Thermal stress

Treatments using thermal stress work by either elevating or reducing ambient temperature beyond the lethal thermal limits of target organisms. Biosecurity operations have mostly utilised hyperthermic (heat) treatments to date, typically in the form of heated water but also via steam or blow torches. Hypothermic (cold) treatments have been trialled to kill shellfish aquaculture pests and decontaminate equipment using supercooled brine or via freezing. Similar to osmotic stress, containment is an important requirement for maintaining target temperatures that achieve mortality. This is particularly challenging *in situ* due to the large volumes involved and high thermal conductivity of seawater.

Table 7. Method assessment for thermal stress.

Criterion	Assessment	Verdict
Effectiveness	While not previously trialled on *F. enigmaticus*, exposure to a water temperature of 60 °C for 60 minutes has been shown to kill all biofouling taxa, even resilient organisms such as oysters. Mortality has also been achieved by exposure to higher temperatures for shorter periods. Exposure to supercooled brine (-12 to -16 °C) effectively killed well-protected taxa such as oysters and barnacles.	**Eradication: Pass** – effective for even resilient taxa, but preliminary experimental evaluations of efficacy against *F. engimaticus* required. **Population control: Pass** – effective for even resilient taxa, but preliminary experimental evaluations of efficacy against *F. engimaticus* required.
Operator safety	Water temperatures above 65 °C can cause instantaneous burn injuries, but this risk can be mitigated via appropriate PPE and the implementation of sensible operational procedures and field health and safety protocols.	**Pass** – can be made safe for operators.
Biosecurity	Thermal stress will not cause dislodgement or fragmentation of worms, but it may trigger spawning. This can be readily mitigated via treatment application outside of *F. enigmaticus*' reproductive season and via adequate containment of treated areas.	**Pass** – biosecurity risks can be managed.
Regulatory compliance	Under the Resource Management Act 1991, regional councils are required to apply water quality classifications to their coastal marine area. It is specified that discharges in some classes shall not change the temperature of the water by more than 3 °C after reasonable mixing. However, many regional Coastal Plans have provisions exempting some discharges of water contaminated with heat alone, with controls on allowable temperature change in the receiving environment. Required regulatory approvals are therefore likely to be readily obtained.	**Pass –** regulatory approvals can be readily obtained.

Criterion	Assessment	Verdict
Environmental impacts	Discharging large quantities of heated water could harm organisms in the surrounding environment, but rapid mixing and adequate containment should effectively avoid impacts. Effects can also be mitigated by allowing treatment units to cool prior to removing containment systems.	**Pass** – environmental impacts are manageable.
Quality control	Thermal parameters (i.e. temperature) can be used as proxies for treatment effectiveness, and effective thresholds can be determined via pilot trials. *In situ* quality control is achievable via installation of thermal probes or loggers in treatment areas.	**Pass** – able to be readily monitored *in situ*.
Scalability	While not impossible, it is unlikely that heated or cooled water can be feasibly delivered to hundreds of local reefs and aggregations, and that target thermal conditions be sustained for the extensive treatment periods that are likely required.	**Fail** –delivery and maintenance of required thermal thresholds for treatment timeframes unlikely to be logistically feasible.
Cost	Use of thermal stress to control *F. enigmaticus* aggregations will require considerable personnel, heating or cooling infrastructure, and materials for treatment delivery, including encapsulation systems. Post-treatment recovery of encapsulation and treatment equipment will incur further costs. We therefore expect the cost of this method to be very high.	**Very high** – significant operational costs.

4.2. Chemical treatments

Chemical treatments are agents capable of killing marine organisms or otherwise rendering them non-viable due to their biocidal properties. Efficacy of chemical treatments relies heavily on achieving and maintaining effective concentrations within the target area for relevant durations, therefore reliable containment is crucial to success. Containment also provides a means of mitigating collateral effects of chemical treatments on the marine environment, and it is a requirement for legistative approvals around the use of treatment chemicals.

Given the perceived impacts of *F. enigmaticus* aggregations on flow regimes and flushing of waterways, removal of dead worm biomass post treatment is likely desirable for at least some areas. In such situations, the use of chemicals is best done in conjunction with manual / mechanical removal techniques.

4.2.1. Chlorine

Chlorine is the most frequently used chemical in the eradication and management of marine organisms, and it has previously been used successfully in the control of invasive populations of several species, including the marine polychaete *S. spallanzanii*. Chlorine is available in several forms, including chlorine dioxide (industrial water disinfectant), sodium hypochlorite (active ingredient in household bleach), and dichloroisocyanurate and trichloroisocyanuric acids (pool chlorine). While the composition and behaviour may vary between forms, its primary mechanism of action is the same – oxidative stress via free available chlorine (FAC).

Table 8. Method assessment for chlorine.

Criterion	Assessment	Verdict
Effectiveness	Chlorine has been shown to be effective in real-world and lab-based trials on a range of biofouling species and other invasive populations of marine organisms, including marine polychaetes (*Sabella spallazanii*), sea squirts and mussels. Effective concentrations vary widely across species (6–20,000 ppm FAC), but required exposure times tend to decrease with increasing concentration. Dichloroisocyanurate dihydride (dichlor) and trichloroisocyanuric acid (trichlor) are recommended as most appropriate for marine biosecurity use. While the use of chlorine to treat *F. enigmaticus* was previously reported to be unsuccessful (Dixon 1977), there was insufficient information to provide any level of confidence that chlorine is ineffective on *F. enigmaticus*.	**Eradication: Pass** – effective for even resilient taxa, but preliminary experimental evaluations of efficacy against *F. engimaticus* required. **Population control: Pass** – effective for even resilient taxa, but preliminary experimental evaluations of efficacy against *F. engimaticus* required.
Operator safety	Some safety risks exist, which vary depending on the form of chlorine used. Chlorine dioxide is not recommended due to risk of serious harm upon inhalation. However, other forms of chlorine are commonly used in industrial and household settings, and the risks can be mitigated via appropriate PPE and the implementation of sensible operational procedures and field health and safety protocols.	**Pass** – can be made safe for operators.
Biosecurity	Application of chlorine should not cause dislodgement or fragmentation of worms, but it may trigger spawning. This can be readily mitigated via treatment application outside of *F. enigmaticus*' reproductive season and via adequate containment of treated areas.	**Pass** – biosecurity risks can be managed.

Criterion	Assessment	Verdict
Regulatory compliance	There is blanket approval for chlorine application for biosecurity use in New Zealand through the Environmental Protection Authority (EPA), provided that applicable conditions are met: • Apply in containment to encapsulated vessel hulls and surfaces by wrapping, or by isolation of internal seawater plumbing of vessels. • Any residual active ingredient may be neutralised with sodium thiosulphate. • Notify the EPA of intention and provide contact details of a representative and standard operating procedure.	**Pass** – regulatory approvals likely able to be obtained.
Environmental impacts	Overall environmental risk is low. While some by-products can persist in the marine environment, chlorine rapidly degrades in seawater (chlorine dioxide has the longest half-life of the various forms, but this is still < 96 hours), and residual amounts can be neutralised with sodium thiosulphate. Chlorine can corrode some types of metals (e.g. stainless steel); however, this generally occurs during long periods of exposure (i.e. weeks to months), which would exceed the required treatment timeframes.	**Pass** – environmental impacts are low / manageable.
Quality control	Concentrations (using FAC as a proxy) can be monitored relatively easily *in situ* using chlorine test strips, colorimetric test-kits and amperometric sensors.	**Pass** – able to be readily monitored *in situ*.
Scalability	Treatment of *F. enigmaticus* aggregations with chlorine will require secure containment in order to be effective. This may be difficult to achieve given the large scale of the infestation, particularly for reefs occupying subtidal areas and structurally complex habitats. Consequently, while chlorine is likely to be a suitable treatment for some areas / habitats (e.g. discrete built structures such as wharf piles), it cannot feasibly be used to treat the total area of *F. engimaticus* infestation. However, a current research project is developing and evaluating larger scale chlorine treatments for control or eradication of marine pests. Results from this research may elevate the scalability of treatment approaches using chlorine. See Section 5. As chlorine is readily available, product availability is unlikely to be a limiting factor.	**Fail** – containment and treatment delivery not feasible for all infested habitats or treatment of the entire target area.

Criterion	Assessment	Verdict
Cost	Although chlorine is relatively inexpensive (e.g. dichlor ~NZ$10 per kg), significant volumes may be required, as well as considerable personnel, infrastructure and materials for containment and treatment delivery, and recovery of containment and treatment equipment. We therefore expect the cost of this method to be relatively high.	**High** – considerable operational costs.

4.2.2. Acetic acid

Acetic acid is a naturally occurring weak acid that partially dissociates in seawater to confer biocidal activity via pH reduction and acetate ion bioactivity. While it is commonly recognised as the primary ingredient in household vinegar, acetic acid is produced synthetically for a range of purposes and has previously been used successfully for the treatment of a range of marine biofouling organisms, including algae, bivalves and sea squirts.

Table 9. Method assessment for acetic acid.

Criterion	Assessment	Verdict
Effectiveness	Acetic acid has been shown to be effective against a range of marine organisms (e.g. colonial and solitary sea squirts, algae, and resilient taxa such as bivalves) at 50 ppt (5%, equivalent concentration to household vinegar) over minutes to hours. Immersion is recommended, as spraying was not found to be 100% effective.	**Eradication: Pass –** effective for even resilient taxa, but preliminary experimental evaluations of efficacy against *F. engimaticus* required. **Population control: Pass** – effective for even resilient taxa, but preliminary experimental evaluations of efficacy against *F. engimaticus* required.

Criterion	**Assessment**	**Verdict**
Operator safety	Poses some operator safety hazards where concentration exceeds that of household vinegar (5%). However, working concentrations are likely to be within this range, and risks can be further mitigated via appropriate PPE and the implementation of sensible operational procedures and field health and safety protocols.	**Pass** – can be made safe for operators.
Biosecurity	Application of acetic acid should not cause dislodgement or fragmentation of worms, but it may trigger spawning. This can be readily mitigated via treatment application outside of *F. enigmaticus*' reproductive season and via adequate containment of treated areas.	**Pass** – biosecurity risks can be managed.
Regulatory compliance	EPA has not yet approved the use of acetic acid as a treatment tool. However, permission has previously been granted for discharge associated with *offshore* oil and gas activities and certain conditions (e.g. specified maximum dosage rates, concentrations, timing and duration of application). It has also been used in emergency biosecurity scenarios (treatment of high-risk biofouling on vessel hulls). Extensive use for pest treatment will require EPA approval. While this may well be achieved, the application and approval process will likely take time and render acetic acid a non-viable option at this point in time.	**Fail** – until regulatory approval has been obtained.
Environmental impacts	Overall environmental risk low. While acetic acid presents some environmental hazards, these are likely to be low at recommended treatment concentrations (i.e. 5%) and are able to be mitigated with containment of the treated area. Acetic acid rapidly degrades in the natural environment and is not known to bioaccumulate. Neutralisation of residual chemicals can be achieved with addition of a base (e.g. sodium hydroxide) prior to discharge into the wider marine environment (i.e. removal of containment structures).	**Pass** – environmental impacts are low / manageable.
Quality control	Reliable monitoring of concentrations on site can be achieved through available field-implementable colorimetric titration and micro-flow refractometer systems. Experienced personnel may be required to carry out this method, as it involves multiple titration steps and the end points can be subjective. Reliable real-time monitoring tools are not available, but pH has previously been used as a proxy.	**Pass** – reliable *in situ* monitoring tools available, although specialist expertise may be required.

Criterion	Assessment	Verdict
Scalability	Scalability is largely contingent upon the ability to contain the target areas. Given the large spatial scale of the *F. enigmaticus* populations established in the Hawke's Bay Region, this may be difficult to achieve, particularly for reefs occupying subtidal areas and complex habitats. Consequently, while acetic acid is likely to be a suitable treatment for some areas / habitats that can realistically be isolated and contained (e.g. discrete built structures such as wharf piles), it cannot feasibly be used to treat the total area of *F. engimaticus* infestation. As stock solutions are readily available and generally highly concentrated (e.g. 80%) compared to what is required (5%), product availability is unlikely to be a limiting factor.	**Fail** – containment and treatment delivery not feasible for all infested habitats or treatment of the entire target area.
Cost	Although acetic acid is cheap (~NZ$2 per litre for 80% concentration), considerable personnel, infrastructure and materials are required for containment and treatment delivery, and recovery of containment and treatment equipment. We therefore expect the cost of this method to be relatively high.	**High** – considerable operational costs.

An overview of the assessments above is provided in Table 10. Refer to Appendix A1 for additional chemical treatment agents that may be have some potential for *F. enigmaticus* control but are yet to be approved by the EPA.

Table 10. Summary of assessment of treatment methods for *Ficopomatus enigmaticus* infestations against suitability criteria. Green, orange and red shading denote Pass, Uncertain and Fail statuses of treatments against the assessment criteria, respectively, and correspond to the detail presented in Sections 4.1 and 4.2. If combinations of treatments are used in an intervention (e.g. osmotic stress treatment followed by post-treatment removal of reef structures), the cost will likely be additive.

Treatment	Effectiveness		Operator Safety	Biosecurity	Regulatory Compliance	Environmental Impacts	Quality Control	Scalability	Cost
Physical methods	**Eradic.**	**Contr.**							
Manual removal	[red]	[green]	[green]	[orange]	[green]	[green]	[red]	[green]	High
Mechanical removal	[red]	[green]	[green]	[orange]	[green]	[green]	[red]	[green]	High
Disruption	[red]	[red]	[green]	[red]	[green]	[green]	[red]	[green]	Moderate
Encapsulation	[green]	[green]	[green]	[green]	[green]	[green]	[green]	[green]	High
Osmotic stress	[green]	[green]	[green]	[green]	[green]	[green]	[green]	[green] [orange] [red]	High
Thermal stress	[green]	[green]	[green]	[green]	[green]	[green]	[green]	[red]	Very high
Chemical methods									
Chlorine	[green]	[green]	[green]	[green]	[green]	[green]	[green]	[red]	High
Acetic acid	[green]	[green]	[green]	[green]	[red]	[green]	[green]	[red]	High

4.3. Assessment results and treatment selection

Evaluating the assessment of treatment methods in Sections 4.1 and 4.2 using the treatment decision tool proposed by Lovett et al. (2023) yields some clear indications of the relative suitability of different methods for interventions against *F. enigmaticus*. Two methods – encapsulation and osmotic stress by exposure to hypersaline conditions – were identified as appropriate primary treatments for local eradication attempts, and three additional methods – manual removal, mechanical removal and chlorine – were identified as suitable for smaller scale population control efforts or application in particular habitats.

Encapsulation and exposure to hypersaline conditions (osmotic shock) are the only treatment agents currently available for *F. enigmaticus* treatment that would be suitable at scale and across the range of affected habitats (Table 11). These include both intertidal and subtidal soft-sediment habitats, rocky reefs and built vertical structures (e.g. wharf piles). Encapsulation can be achieved via a range of approaches, such as sealing off target aggregations with tarpaulins, plastic wrapping or mats, or smothering them with dredge spoil or other material. In the case of the Ahuriri Estuary, where there are hundreds of distinct *F. enigmaticus* reefs distributed across both soft-sediment and hard substrates, we recommend that simple, cost-effective approaches are identified or developed that enable rapid deployment of encapsulation and / or hypersaline treatments, as well as cost-effective coverage of infested areas.

Previous attempts at managing *F. enigmaticus* using manual and mechanical removal have resulted in regrowth or recolonisation of treated populations due to the presence of residual material left behind following treatment. If either of these options are selected for implementation in specific habitats, a removal strategy should be employed that minimises the chance of material being inadvertently left behind. This will likely maximise the effectiveness and longevity of the treatment. Application of chlorine would require containment for compliance with EPA approval conditions, and to ensure that effective concentrations are maintained. While many forms of chlorine are available for use, in the current context, the use of chlorine tablets may be the most appropriate approach, as they can act over a sustained period of time and are more easily contained and applied than other forms, particularly given the types of affected environments in the Hawke's Bay Region.

While proven to be effective in killing or removing sessile biofouling organisms, most of the identified methods will require initial validation of effectiveness for *F. enigmaticus* (Table 11). Additionally, encapsulation, hypersaline treatment and application of chlorine will kill *F. enigmaticus* in target areas but not remove reef structures. To address the physical impacts of reefs and aggregations (e.g. on flushing or sedimentation rates), these approaches would need to be combined with post-treatment removal of reef structures.

Physical disruption, thermal stress and acetic acid are not recommended as treatment methods because they have failed the assessment and selection process due to a lack of effectiveness, scalability and regulatory approval (Table 10; Table 11).

Our assessment provides an initial indication of potentially suitable treatment options for eradication or population control attempts. However, final selection of the most appropriate method(s), and the development of an effective implementation strategy, can only occur once HBRC has established the objectives of intended interventions around *F. enigmaticus* in the Hawke's Bay Region. Considerations and suggestions regarding this are provided in Section 5.

Table 11. Application of decision framework (Lovett et al. 2023) to the treatment methods assessed and for use during attempted eradication ('Erad.') or population control ('Con.') of *Ficopomatus enigmaticus*. The decision process is 'vertical' (top to bottom) and discontinued once a treatment method has failed a critical decision step. The assessment criteria 'cost' and 'cultural acceptability' were not considered in this table but should be included in HBRC's final decision process. Decision stages where treatment options failed are indicated via red 'stop signs', and square brackets denote the assessment criteria associated with that decision. EF = effectiveness; SC = scalability; RC = regulatory compliance.

Decision step	**Manual removal**		**Mechanical removal**		**Physical disruption**		**Encapsulation**		**Osmotic stress (hypersaline)**		**Thermal stress**		**Chlorine**		**Acetic acid**	
	Erad.	Con.	Erad.	Con.	Erad.	Con.	Erad.	Con.	Erad.	Con.	Erad.	Con.	Erad.	Con.	Erad.	Con.
1. Treatment likely to be effective?	⛔ [EF]	✓	⛔ [EF]	✓	⛔ [EF]	⛔ [EF]	✓	✓	✓ [2]	✓ [2]	✓ [2]	✓ [2]	✓ [2]	✓ [2]	✓ [2]	✓ [2]
2. Treatment approved for application / discharge in current situation / environment?		✓		✓			✓	✓	✓	✓			✓	✓	⛔ [RC]	⛔ [RC]
3. Resources available for deployment at required intensity / time?		✓		✓			✓	✓	✓	✓	⛔ [SC]	⛔ [SC]	⛔ [SC]	✓		
4. Safe to apply / discharge treatment into receiving env.?		✓		✓			✓	✓	✓	✓				✓		
Suitable as eradication or control tool? [1]	No	**Yes**	No	**Yes**	No	No	**Yes**	**Yes**	**Yes**	**Yes**	No	No	No	**Yes**	No	No
Suitability for habitat types																
– Soft-sediment		Yes		Yes			Yes	Yes	Yes	Yes				Yes		
– Rocky reef		Yes		Yes			Yes	Yes	Yes	Yes				Yes		
– Built vertical structures		Yes		Yes			Yes	Yes	No	No				Yes		
– Intertidal		Yes		Yes			Yes	Yes	Yes	Yes				Yes		
– Subtidal		Yes		Yes			Yes	Yes	Yes	Yes				Yes		

[1]Use as control tool includes acceptance of potential residual biosecurity risks and / or that periodic re-treatment is required to maintain population at desired abundance or distribution. [2] Initial experimentation required to validate effectiveness against *F. enigmaticus*.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. *Ficopomatus enigmaticus* management in the Hawke's Bay Region

Given the relatively restricted abundance and distribution of *F. enigmaticus* in the Hawke's Bay Region compared to overseas populations (Wolf and Floerl 2023), we consider regional management of this species feasible.[4] Options range from targeted control of *F. enigmaticus* aggregations in particular areas (e.g. maintenance of reef structures to ensure sufficient water exchange into and out of Ahuriri Estuary; limitation of biomass build-up on pumping stations or other critical civic infrastructure) to attempts at eradication of the species from the region. Population control is certainly a viable option for *F. enigmaticus*, and our assessment has identified several suitable treatment approaches that, if implemented using appropriate protocols and tactics, would likely be successful at maintaining target abundance and / or distribution of the species in the Hawke's Bay Region. However, attempting local eradication requires careful consideration. While there are many examples of failed eradication attempts of marine non-indigenous species, there are also several success stories (Section 2; see Lovett et al. 2023 and examples therein).

Our assessment has identified treatment methods that would be suitable, and these options could potentially be up-scaled and / or used in combination to cover the range of currently infested habitats. Given commitment, sufficient resources and persistence, eradication of *F. enigmaticus* from the Hawke's Bay Region may be achievable. However, without these three key elements, attempts at eradication should not be pursued. In this context, 'commitment' includes the willingness to accept – within reason – the collateral impacts that some treatment approaches may have in target environments if implemented at the scale required for eradication, particularly if these impacts are unlikely to persist in the longer term. Examples of such collateral impacts may be the mortality of native species within the treatment area, and the associated impacts on cultural values, recreational use and other important aspects. The acceptability of such impacts will be context dependent, but acceptance will likely be higher for scenarios where common, widely occurring native species are affected (and eventual recolonisation / recovery is likely), and lower for scenarios where taonga, rare or endangered species are involved. However, these potential effects need to be considered against the the continued proliferation and associated impacts of *F. enigmatus* in the region.

[4] This assumes that the species' distribution and abundance have not vastly increased since the last survey in 2019.

5.2. Recommended actions for HBRC

The fundamental decisions around the objectives of *F. enigmaticus* interventions (including whether or not to intervene), and the ability to design a cost-effective, robust operational programme, hinge on several important activities that we recommend HBRC undertake:

A. Establish current distribution

The most recent assessment of *F. enigmaticus'* distribution in the Hawke's Bay Region is an aerial survey undertaken in 2019. Since then, one-off control operations have removed worm reefs from some areas, and catastrophic flooding and sedimentation has recently occurred as a result of cyclone Gabrielle. The current distribution of the species may therefore differ considerably from that observed during the 2019 survey. We recommend that HBRC undertake a carefully designed delimitation survey to determine the current distribution of *F. enigmaticus*. Incomplete knowledge of *F. enigmaticus'* distribution has the potential to compromise any eradication attempts that may be undertaken. Thorough knowledge of the species' regional distribution is essential for guiding final decisions regarding the feasibility, objectives, resources and operational approaches of potential interventions.

B. Cost-benefit analysis

Applying treatments for control or eradication will require significant investment and may pose collateral risks to the environment (e.g. mortality of native biota), economic activities (e.g. local tourism activities), social values (e.g. temporary closure of recreational fisheries), cultural values (e.g. impacts on taonga species and Te Ao Māori) and human health. However, the benefits of successful eradication or control (e.g. preservation or recovery of environmental, cultural or economic values; protection of critical civic infrastructure; public trust in biosecurity system performance) have the potential to outweigh these costs. Knowledge of the likely magnitude and timeline of the overall costs of an intervention (direct costs plus collateral impacts) can be weighed against the estimated benefits of successful eradication or control initiatives to inform decision-making. Environmental, social and cultural values are usually non-monetary and hence difficult to measure. However, proven economic approaches exist to enable useful cost-benefit assessments around biosecurity measures. We recommend that HBRC undertake a cost-benefit assessment of *F. enigmaticus* interventions. This will help identify the need for management (versus not acting) and the relative merits of the different management options.

C. Establish the management objectives

If HBRC decide to proceed with some form of intervention to manage populations of *F. enigmaticus*, the objectives of this intervention need to be firmly established. This is important for several reasons. First, the objectives will influence the choice of treatment method/s. For example, some treatment methods, such as manual or mechanical removal, are unsuitable for attempting eradication of *F. enigmaticus* due to incomplete effectiveness and the risks of spreading propagules or reef biomass (Section 4.1; Table 10). However, use of these methods is entirely appropriate for population control, where periodic re-treatment of areas is expected, and accidental propagule release poses no risk over and above reproductive activity of the adjacent unmanaged population. Similarly, if the objective of control operations is to reduce the physical impacts of reef structures (e.g. to maintain flushing rates and prevent sedimentation in particular areas of Ahuriri Estuary), then a treatment method/s would need to be selected that results in the reduction or absence of reef structures post treatment. Second, other crucial aspects of any proposed management action – such as resource requirements, timeframes of control and monitoring activities, operational protocols, interim and long-term goals and decision-points – will also be contingent upon the overarching intervention objectives.

D. Continue recruitment monitoring

In late 2022, HBRC initiated recruitment monitoring of *F. enigmaticus.* This activity should be continued, as it helps inform the timing of future interventions. Eradication or control operations undertaken outside periods of reproductive activity will likely minimise the risk of propagule release in response to disturbance.

E. Dialogue with tangata whenua

It is important that the use and application of treatments are consistent with Te Ao Māori, tikanga Māori and the views and values of local iwi and hapū. We recommend that a dialogue with affected tangata whenua is best commenced during early considerations regarding a management programme to ensure their values and recommendations can be incorporated into the decision process.

F. Development and / or small-scale trials of treatment methods

Once the objectives of a potential intervention have been established, small-scale pilot trials of envisaged treatment methods should be carried out to validate effectiveness and enable (i) the choice of treatment method(s) that may be applied to target habitats during the intervention, and (ii) the development of operational parameters and protocols for application at the scale of the intervention. Examples of potentially relevant trials and their objectives are provided below:

- *Encapsulation*. Identification and evaluation of efficient and cost-effective encapsulation techniques for worm aggregations in affected habitats. Options include spraying aggregations with quick-set plaster, cement or other material, smothering them with sand or dredge spoil, or application of other barriers that isolate target aggregations from oxygenated water and food sources (e.g. plastic wrapping, tarpaulins, mats).
- *Hypersaline treatment (osmotic stress)*. Evaluation of quantity / concentration and treatment duration of salt or saline solution required to achieve mortality. Trial of delivery (including containment) and monitoring approaches that

reliably achieve and maintain lethal treatment concentrations and exposure periods.

- *Chlorine*. Evaluation of the form (tablets, powder, liquid concentrate), quantity / concentration and treatment duration of chlorine required to achieve mortality. Method for effective isolation of treatment areas must be compliant with EPA permit requirements. Note that research commissioned by the Ministry for Primary Industries is underway (2023/24) that will trial larger scale application of chlorine treatments for marine pest control in a boating marina. This research will examine the use of sediment curtains[5] as barriers to isolate larger treatment areas (tens of metres) from surrounding environments. Depending on results, this may change the present status of chlorine treatment as a small-scale tool.
- *Manual and / or mechanical removal*. Trial of methodologies for different habitats (e.g. removal of reefs from bridge pilings versus removal of reefs from the estuary sea floor). Quantification of removal efficiency, rate of fragment loss, and avenues for minimising both.

[5] A sediment curtain (also known as a turbidity curtain or silt screen) is either a permeable or impervious structure that sits suspended in the water column to contain water-bourne sediment arising from construction, dredging or other activities that disturb the sea floor. The presence of the curtain allows suspended sediment to settle and within a defined area and avoid dispersion.

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APPENDICES

A1. ADDITIONAL CHEMICAL TREATMENT AGENTS

The following treatment agents were identified as potential treatment options for biofouling assemblages or marine pest incursions in earlier studies (Cahill and Floerl 2019; Cahill et al. 2019, 2021). The EPA has not approved use of these chemicals in New Zealand, thus they were omitted from formal consideration in this project. A basic description of each agent and notes relating to the feasibility criteria are provided below and are available to inform decisions regarding future permit applications. Details and literature sources are provided in the resources cited above. If the intervention objectives include amelioration of *F. enigmaticus'* impacts on flushing and / or sedimentation rates, manual or mechanical removal of residual reef structures will also be required post treatment.

Calcium (hydr)oxide

Calcium oxide and calcium hydroxide are two forms of a group of basic calcium-based compounds collectively known as 'lime'. Calcium oxide ('quicklime') is known to be more reactive than calcium hydroxide ('hydrated lime'); however, many available formulations contain both compounds, which generally exist in powdered form. While frequently used in industrial settings as pH-buffering agents, limes have also been used as a general disinfectant in aquaculture and for the management of problematic populations of marine organisms, such as predatory sea stars and urchin barrens. The primary mechanism of action is biocidal by increased pH, though physical action by smothering may also occur and further contribute to efficacy.

Table A1. Method assessment for calcium (hydr)oxide.

Criterion	**Assessment**	**Notes / considerations**
Effectiveness	Incomplete mortality of target organisms has been observed during application in biosecurity response scenarios, with some studies assessing it as the least effective chemical option. However, lime can act as a physical clogging agent as well as a biocidal treatment for filter-feeding invertebrates, which may confer increased efficacy when applied to *F. enigmaticus* populations.	Likely an effective treatment agent, but requires preliminary experimental evaluations of efficacy against *F. engimaticus*.
Operator safety	While some operator safety risks exist (i.e. skin corrosion, serious eye damage), these can be mitigated via appropriate PPE and the implementation of sensible operational procedures and field health and safety protocols.	Can be made safe for operators.

Criterion	Assessment	Notes / considerations
Biosecurity	Application of lime should not cause dislodgement or fragmentation of worms, but it may trigger spawning. This can be readily mitigated via treatment application outside of *F. enigmaticus*' reproductive season and adequate containment of treated areas.	Biosecurity risks can be managed.
Regulatory compliance	May be viewed favourably by regulators (EPA, HBRC) for use compared to other chemicals due to its natural geological origin, previous approval for use in the marine environment, and benign end products. However, approvals dependent on required discharge volumes and concentration.	No existing approval for use.
Environmental impacts	Environmental impacts are considered low. Lime is a natural geological substance, and the commercially available forms (hydrated and quick lime) have undergone minimal processing. All end products produced upon reaction with seawater are benign and abundant in the marine environment, and lime rapidly degrades in seawater (< 5 hour half-life). While smothering of non-target taxa may occur, these effects are likely to be short-lived and can be minimised by encapsulation of treatment areas.	Environmental impacts are low / manageable.
Quality control	The ability to achieve target dosages and monitor concentrations is dependent on the type of lime used and the form in which it is applied (i.e. dissolved or powder). Powder may be more difficult to apply in even quantities given its propensity to dissipate upon release into water, but overdosing may be an effective mitigation to ensure target concentrations are reached. Measurement options are complex and not well developed, but photographic methods may be used to provide a visual proxy for the amount applied.	*In situ* monitoring tools available, though some development may be required to ensure reliability.
Scalability	Scalability is largely contingent upon the ability to contain the target areas, although perhaps to a lesser extent for lime than other chemicals in natural (i.e. non-built) environments due to the natural occurrence of lime and its ability to act as a clogging agent. However, containment will be required for application of treatment to built and vertical structures; however, lime may not be suitable for application to these environments because of its tendency to readily fall out of suspension. This will be difficult to overcome logistically without the use of significant volumes of lime to “fill up” isolated vertical surfaces.	Containment and treatment delivery likely not feasible for all infested habitats.

Criterion	Assessment	Notes / considerations
	As lime is readily available and regularly used at industrial scales, product availability is unlikely to be a limiting factor.	
Cost	The cost of lime is low and comparable to acetic acid, with 20–25 kg bags retailing for NZ$20–$30 (~$1 per kg) and readily available from farm supply and home improvement stores. Considerable personnel, infrastructure and materials will likely be required for containment and treatment delivery, as well as recovery of containment and treatment equipment. However the cost may be less than other comparable chemical treatments (e.g. acetic acid) due to lower containment requirements in some target habitats. We therefore expect the cost of this method to be moderate-high.	Moderate operational costs.

Bromine

Bromine, typically administered as sodium bromide or bromine chloride salts, is a commonly used alternative to chlorine for swimming pool disinfection. While it does not appear to have been used in the context of managing marine non-indigeous species populations, it has been used successfully as an anti-foulant for industrial cooling systems and as a disinfectant for ballast water pre-discharge. Bromine has similar properties to chlorine, but it is more temperature and pH stable, and has been reported to be two to five times more toxic in tests on several freshwater species.

Table A2. Method assessment for bromine.

Criterion	Assessment	Notes / considerations
Effectiveness	No information is available on the effectiveness of bromine for management of invasive populations of marine organisms; however, it has similar biocidal properties to chlorine (with added stability under various environmental conditions) and is therefore likely to be similarly effective. Toxicity in freshwater species has been reported to be two to five times more potent than chlorine. It has been effectively used as an anti-foulant on industrial cooling systems and as a ballast water disinfectant.	Likely an effective treatment agent, but requires preliminary experimental evaluations of efficacy against *F. engimaticus*.

Criterion	Assessment	Notes / considerations
Operator safety	Similar safety concerns to chlorine because of common biological properties. Risk of death on inhalation; however, this and other risks can be mitigated via appropriate PPE and the implementation of sensible operational procedures and field health and safety protocols.	Can be made safe for operators.
Biosecurity	Application of bromine should not cause dislodgement or fragmentation of worms, but it may trigger spawning. This can be readily mitigated via treatment application outside of *F. enigmaticus*' reproductive season and adequate containment of treated areas.	Biosecurity risks can be managed.
Regulatory compliance	Currently there is no consent to discharge bromine into the marine environment in New Zealand. Bromine has similar properties to chlorine, which has blanket approval, but it may be looked upon less favourably due to longer persistence in the environment. Obtaining approval depends to a large extent on required volumes and concentration.	No existing approval for use.
Environmental impacts	Similar environmental concerns as chlorine – breaks down in seawater, although less rapidly than chlorine, and reactions in seawater can produce organic pollutants that persist in the marine environment. However, environmental impacts are still anticipated to be low and can be managed via containment. Bromine can corrode some types of metals (e.g. stainless steel); however, this generally occurs during long periods of exposure (i.e. weeks to months), which would likely greatly exceed the required treatment timeframes.	Environmental impacts are low / manageable.
Quality control	Containment will be important to ensure achievement and maintenance of effective concentrations. Point monitoring is easily achieved in the field using portable colourimeter, but methods for real-time monitoring are not available.	Reliable *in situ* monitoring tools available.
Scalability	Treatment of *F. enigmaticus* aggregations with bromine will require secure containment in order to be effective. This may be difficult to achieve given the large scale of the infestation, particularly for reefs occupying subtidal areas and structurally complex habitats. Consequently, while bromine is likely to be a suitable treatment for some areas / habitats that can realistically be isolated and contained (e.g. discrete built structures such as wharf piles), it cannot feasibly be used to treat the total area of *F. engimaticus* infestation. As bromine is readily available, product availability is unlikely to be a limiting factor.	Containment and treatment delivery not feasible for all infested habitats.

Criterion	Assessment	Notes / considerations
Cost	More expensive than chlorine (~NZ$30 per kg), but effective doses are likely to be lower. Significant volumes may be required, as well as considerable personnel, infrastructure and materials for containment and treatment delivery, and recovery of containment and treatment equipment. We therefore expect the cost of this method to be high.	Considerable operational costs.

Ferrate

Ferrate is an oxidant derived from substances such as potassium ferrate, which is widely used as a wastewater treatment. While it has not yet been used for the management of marine organisms, it is considered a stronger oxidiser than chlorine and therefore has the potential to have similar biocidal effects.

Table A3. Method assessment for ferrate.

Criterion	Assessment	Notes / considerations
Effectiveness	Ferrate has the potential to be effective, but it is not yet proven for management of marine species. Therefore, it would likely require significant preliminary experimental investigation with *F. enigmaticus* to determine appropriate dosages and treatment conditions.	Would likely require significant preliminary experimental evaluations of efficacy against *F. engimaticus*.
Operator safety	There are some safety concerns associated with combustibility of solid potassium ferrate (parent compound) and potential irritant properties, but these risks can be mitigated via appropriate PPE and the implementation of sensible operational procedures and field health and safety protocols.	Can be made safe for operators.
Biosecurity	Application of ferrate should not cause dislodgement or fragmentation of worms, but it may trigger spawning. This can be readily mitigated via treatment application outside of *F. enigmaticus*' reproductive season and adequate containment of treated areas.	Biosecurity risks can be managed.

Criterion	**Assessment**	**Notes / considerations**
Regulatory compliance	Currently there is no precedent for discharge into marine environments in New Zealand. Since it is widely used in wastewater treatment and considered to pose low environmental risk, ferrate may be looked upon favourably by regulators, but approval depends to a large extent on required volumes and concentration.	No existing approval for use.
Environmental impacts	Environmental impacts are considered low – ferrate rapidly degrades in seawater (within hours to days) to benign end products (iron oxides) – and can be managed through adequate containment.	Environmental impacts are low / manageable.
Quality control	Known to be reactive with organic matter and therefore susceptible to rapid depletion during treatment, but this could be managed with appropriate containment and overdosing and / or repeat dosing throughout the treatment period. Monitoring concentrations requires specialist procedures that are not readily implementable in the field.	*In situ* monitoring options not available.
Scalability	Treatment of *F. enigmaticus* aggregations with ferrate will require secure containment in order to be effective. This may be difficult to achieve given the large scale of the infestation, particularly for reefs occupying subtidal areas and structurally complex habitats. Cost is an additional limitation to the scalability of ferrate, as it is very expensive (see Cost). Consequently, while ferrate is likely to be a suitable treatment for some areas / habitats that can realistically be isolated and contained (e.g. discrete built structures such as wharf piles), it cannot feasibly be used to treat the total area of *F. engimaticus* infestation.	Significant cost limitations, and containment and treatment delivery not feasible for all infested habitats.
Cost	Potassium ferrate retails at ~NZ$100 per kg, which is several orders of magnitude higher than other candidate chemicals. For example, the required dosage would be similar to chlorine, but the cost would be 10-fold higher. Ferrate can be produced directly on site (rather than using potassium ferrate), but this process is complex and requires specialist chemicals and equipment, which are likely to be expensive. In addition, there are other costs associated with containment and deployment, as well as recovery of containment and treatment equipment, which would likely be considerable. We therefore anticipate the cost to be very high.	Significant operational costs.

Hydrogen peroxide

Hydrogen peroxide is another oxidant that is typically available in aqueous form for bleaching and disinfection in both industrial and household settings. Although it has not been tested widely on marine taxa, it has been shown to be effective in the control of bivalves.

Table A4. Method assessment for hydrogen peroxide.

Criterion	Assessment	Notes / considerations
Effectiveness	Hydrogen peroxide has been shown to be effective when applied to adult bivalves; for example, striped zebra mussel (90% mortality after 21 days exposure to 5.4 mg per L, 100% mortality after 3 days exposure at 40 mg per L) and Asian clams (death after 14 days exposure at 40 mg per L). However, it has not been tested on other marine taxa.	Likely effective, but requires preliminary experimental evaluations of efficacy against *F. engimaticus*.
Operator safety	There are some safety concerns associated with corrosive properties at high concentrations, but required working concentrations are low and risks can be mitigated via appropriate PPE and the implementation of sensible operational procedures and field health and safety protocols.	Can be made safe for operators.
Biosecurity	Application of hydrogen peroxide should not cause dislodgement or fragmentation of worms, but it may trigger spawning. This can be readily mitigated via treatment application outside of *F. enigmaticus*' reproductive season and adequate containment of treated areas.	Biosecurity risks can be managed.
Regulatory compliance	Currently there is no precedent for discharge into marine environment in New Zealand. Regulators may consider hydrogen peroxide favourably compared to some other chemical options because of its low environmental impacts, benign end products and rapid degradation in seawater, but approval depends to a large extent on required discharge volumes and concentration.	No existing approval for use.
Environmental impacts	Environmental impacts considered low – hydrogen peroxide is toxic to the aquatic environment, but this can be managed with appropriate containment of target areas. It also readily degrades in seawater to benign end products (oxygen and hydrogen), so long-term impacts are likely negligible.	Environmental impacts are low / manageable.

Criterion	Assessment	Notes / considerations
Quality control	Long exposure times required for efficacy may be difficult to maintain given its tendency to rapidly degrade in seawater; however, this may be able to be overcome with secure containment and overdosing and / or repeat dosing. While real-time monitoring is not available, point monitoring can be achieved *in situ* using portable colourimeters.	Reliable *in situ* monitoring tools available.
Scalability	Treatment of *F. enigmaticus* aggregations with hydrogen peroxide will require secure containment in order to be effective. This may be difficult to achieve given the large scale of the infestation, particularly for reefs occupying subtidal areas and structurally complex habitats. Consequently, while hydrogen peroxide is likely to be a suitable treatment for some areas / habitats that can realistically be isolated and contained (e.g. discrete built structures such as wharf piles), it cannot feasibly be used to treat the total area of *F. engimaticus* infestation. As hydrogen peroxide is readily available and frequently used at an industrial scale, product availability is unlikely to be a limiting factor.	Containment and treatment delivery not feasible for all infested habitats or treatment of the entire target area.
Cost	Cost comparable to chlorine (~NZ$10 per L of 35% concentration). Significant volumes may be required, as well as considerable personnel, infrastructure and materials for containment and treatment delivery, and recovery of containment and treatment equipment. We therefore expect the cost of this method to be high.	Considerable operational costs.

Peracetic acid

Peracetic acid is a general disinfectant typically used in food processing and wastewater facilities. While not tested widely on marine taxa, it reacts in water to produce the biocidal agents hydrogen peroxide and acetic. Consequently, it can be expected to have an equally or even higher efficacy than either of the derived substances applied alone.

Table A5. Method assessment for peracetic acid.

Criterion	**Assessment**	**Notes / considerations**
Effectiveness	Peracetic acid has not been tested widely for management of marine organisms, but it is being increasingly used for biofouling control in industrial cooling systems and has been shown to be effective against mussel embryos (15 min exposure at 5 mg per L concentration). It is generally considered a fast-acting and effective biocidal agent given its dual action acetic acid-hydrogen peroxide derivatives, but targeted experimentation will be required to determine its efficacy for management of *F. enigmaticus.*	Likely effective, but requires preliminary experimental evaluations of efficacy against *F. engimaticus*.
Operator safety	There are some safety concerns associated with corrosive and irritant properties, but required working concentrations are low and risks can be mitigated via appropriate PPE and the implementation of sensible operational procedures and field health and safety protocols.	Can be made safe for operators.
Biosecurity	Application of peracetic acid should not cause dislodgement or fragmentation of worms, but it may trigger spawning. This can be readily mitigated via treatment application outside of *F. enigmaticus*' reproductive season and adequate containment of treated areas.	Biosecurity risks can be managed.
Regulatory compliance	Currently there is no precedent for discharge into marine environments in New Zealand. Regulators may consider peracetic acid favourably compared to some other chemical options because of its low environmental impacts, benign end products and low persistence in aquatic environments, but approval depends to a large extent on volume and concentration of discharge.	No existing approval for use.
Environmental impacts	Environmental impacts considered low – peracetic acid readily reacts with organic matter and the reaction produces acetic acid and hydrogen peroxide, which are readily degradable in the aquatic environment, produce benign end products, and can be readily neutralised. Containment will ensure that treatment is constrained within the target area, thus minimising the risk of collateral non-target effects on the wider environment.	Environmental impacts are low / manageable.
Quality control	Reacts readily with organic matter, so containment will be important for achieving and maintaining required treatment concentrations, and over- and / or repeat dosing may be needed. While real-time monitoring tools are not available, concentrations can be point monitored *in situ* using portable colourimetry devices.	Reliable *in situ* monitoring tools available.

Criterion	Assessment	Notes / considerations
Scalability	Treatment of *F. enigmaticus* aggregations with peracetic acid will require secure containment in order to be effective. This may be difficult to achieve given the large scale of the infestation, particularly for reefs occupying subtidal areas and structurally complex habitats. Consequently, while peracetic acid is likely to be a suitable treatment for some areas / habitats that can realistically be isolated and contained (e.g. discrete built structures such as wharf piles), it cannot feasibly be used to treat the total area of *F. engimaticus* infestation. As peracetic acid is readily available and frequently used at an industrial scale, product availability is unlikely to be a limiting factor.	Containment and treatment delivery not feasible for all infested habitats or treatment of the entire target area.
Cost	Cost comparable to acetic acid (~NZ$5 per L for 85% concentration). Significant volumes may be required, as well as considerable personnel, infrastructure and materials for containment and treatment delivery, and recovery of containment and treatment equipment. We therefore expect the cost of this method to be high.	Considerable operational costs.

Disinfectants

Disinfectants comprise a range of chemicals used to kill micro-organisms on surfaces or in water. This includes the aquatic disinfectant Virkon® Aquatic, which has been specifically developed for the treatment of aquatic pathogens in aquaculture and contains potassium hydrogen peroxymonosulphate as the primary active ingredient. Many other disinfectants contain quartenary ammonium compounds (QACs) as the active ingredient. While there are many different specific types of disinfectants, for the purposes of efficiency, we have assessed these compounds as a collective.

Table A6. Method assessment for desinfectants.

Criterion	Assessment	Notes / considerations
Effectiveness	Exposure times for disinfectants are relatively short (seconds to 24 hours), although efficacy is variable and / or not fully elucidated for many products, including Virkon® Aquatic. Some products have at least partial efficacy against mussels, oysters, snails and sea squirts, but incomplete mortality has been shown in some cases, and efficacy can change with size of target organisms and dosage. When tested in the field, 5% Quatsan for 24 hours was found to kill all mussels of certain sizes, but smaller individuals and those exposed to lower doses survived. Repeat dosing may therefore be required. The product Conquest was not effective against mussels in the field, but 1, 5 and 10% doses for 14 hour exposures in the lab were found to kill 100% of blue mussels. Dosing rates (concentration and time) have also not been fully elucidated for some disinfectants. Since these compounds have not been tested on marine taxa beyond bilvalves, additional experimentation for efficacy against *F. enigmaticus* and required dosages would be needed.	Would require significant preliminary experimental evaluations of efficacy against *F. engimaticus*.
Operator safety	There are some safety concerns associated with swallowing, skin corrosion and burns, and eye damage, but risks can be mitigated via appropriate PPE and the implementation of sensible operational procedures and field health and safety protocols.	Can be made safe for operators.
Biosecurity	Application of disinfectants should not cause dislodgement or fragmentation of worms, but it may trigger spawning. This can be readily mitigated via treatment application outside of *F. enigmaticus*' reproductive season and adequate containment of treated areas.	Biosecurity risks can be managed.
Regulatory compliance	Currently there is no precedent for discharge into marine environments in NZ. Moreover, there is a lack of knowledge regarding potential environmental risks (see Environmental impacts), which will likely make this option less favourable to regulators compared to other options where the potential impacts are known.	No existing approval for use.

Criterion	**Assessment**	**Notes / considerations**
Environmental impacts	Environmental impacts and behaviour and fate of chemicals upon reaction in aquatic environment are not clear. There is concern that some products will have adverse impacts on environment given their high toxicity to aquatic life. While containment of target areas may help to mitigate the risk, alternative chemical options that pose a lower known environmental risk would be viewed more favourably.	Environmental impacts unclear and potentially adverse.
Quality control	As with any chemical, containment will be required to ensure target treatment concentrations are achieved and maintained. Determination of concentrations requires specialist methods (i.e. mass spectrometry) and associated equipment, and these are not field-implementable, so will not be able to measure concentrations in real-time or on site in all locations. While visual and / or portable colorimetric assessments of colour can be used as a proxy for concentrations of disinfectants containing pigment indicators, e.g. Virkon®, these would be difficult to implement given the water clarity of the Hawke's Bay Region and the lighting difficulties likely associated with containment measures.	*In situ* monitoring options not available.
Scalability	Treatment of *F. enigmaticus* aggregations with disinfectants will require secure containment in order to be effective. This may be difficult to achieve given the large scale of the infestation, particularly for reefs occupying subtidal areas and structurally complex habitats. Consequently, while disinfectants may be suitable for treatment of some areas / habitats that can realistically be isolated and contained (e.g. discrete built structures such as wharf piles), they cannot feasibly be used to treat the total area of *F. engimaticus* infestation. As disinfectants are readily available and frequently used at an industrial scale, product availability is unlikely to be a limiting factor.	Containment and treatment delivery not feasible for all infested habitats.
Cost	While disinfectants are relatively cheap and comparable to some other chemicals at ~NZ$10 per L, the cost to achieve required concentrations is likely to be much higher (~NZ$500 to treat an area with 1000 L). Additional costs are associated with containment of the target areas and treatment deployment, as well as recovery of containment and treatment equipment. We therefore expect the cost of this method to be high-very high.	Considerable operational costs.

Descalers

Similar to disinfectants, descalers encompass a range of products that are primarily used for removing hard chemical deposits – 'scale' – from household and industrial surfaces, particularly pipework. They are typically acidic in nature, with formulations generally containing phosphoric acid, sulfamic acid, hydrochloric acid, or an acid blend as the primary active ingredients. While many descaling products are currently available, we have focused our assessment on those that have been deemed most effective for the treatment of marine organisms in a biosecurity context, and for which sufficient information exists to make assessment worthwhile: Descalex® (sulfamic acid as active ingredient) and Rydlyme® (hydrochloric acid as active ingredient), both of which are used to manage biofouling in vessel internal niche areas.

Table A7. Method assessment for descalers.

Criterion	**Assessment**	**Notes / considerations**
Effectiveness	Both Descalex® and Rydlyme® have been successfully used to treat marine biofouling organisms, including in seawater systems of vessels, within ~48 hours. For example, mortality across a range of biofouling taxa was observed when Descalex® was applied in a recirculating system over 10 hours at ~10% concentration (40 °C fresh water), while mussel weight was reduced by 92% after 12 hours when they were exposed to ≥ 25% Rydlyme®, and after 48 hours at 12.5% concentration. A special type of Rydlyme® (Rydlyme Marine®) has also been developed to specifically target the removal of biofouling, e.g. barnacles on vessels. These formulations are specifically designed for dissolving hard chemical deposits such as calcium, and therefore they may be particularly effective for *F. enigmaticus*, as reefs are mostly comprised of calcium carbonate.	Likely effective, but requires preliminary experimental evaluations of efficacy against *F. engimaticus*.
Operator safety	There are a range of safety concerns associated with both descaler formulations, predominantly because they contain strong acids. While these risks can largely be mitigated for Rydlyme® via appropriate PPE and the implementation of sensible operational procedures and field health and safety protocols, Descalex® reacts to form potentially hazardous gases, including carbon dioxide and hydrogen. Consequently, preparation should not occur in confined space, and handling, preparation and deployment will require experienced operators.	Rydlyme® can likely be made safe for operators. Descalex® requires experienced operators and particular conditions for safe handling and deployment.

Criterion	Assessment	Notes / considerations
Biosecurity	Application of descalers should not cause dislodgement or fragmentation of worms, but it may trigger spawning. This can be readily mitigated via treatment application outside of *F. enigmaticus*' reproductive season and adequate containment of treated areas.	Biosecurity risks can be managed.
Regulatory compliance	Currently no precedent for discharge into marine environment in New Zealand. Both formulations are considered fully biodegradable, but may not be favourably looked upon by regulators due to lack of knowledge of environmental effects (see Environmental impacts).	No existing approval for use. Regulators unlikely to approve due to lack of knowledge of potential environmental impacts.
Environmental impacts	While acids in both formulations can be easily neutralised and are reported to be readily biodegradable, the environmental impacts and behaviour and fate of chemicals upon reaction in aquatic environment are not clear due to formulations containing proprietary ingredients. Some by-products may also persist in the aquatic environment. While containment of target areas may help to mitigate the risk, alternative chemical options that pose a lower known environmental risk are likely to be more favourable.	Environmental impacts unclear and may be adverse.
Quality control	As with any chemical, containment will be required to ensure target treatment concentrations are achieved and maintained. Descalex® is incompatible with some metals, but Rydlyme® is reported to be generally compatible. Both formulations will be neutralised by reaction with calcareous organisms and other matter, thus over- and / or repeat dosing will likely be required given *F. enigmaticus* reefs are comprised of ~80% calcium carbonate. Only indirect monitoring options using pH as a proxy (e.g. pH indicator strips, portable pH meter) are available, but these are recommended as being suitable.	Reliable *in situ* monitoring tools available, although indirect.

Criterion	Assessment	Notes / considerations
Scalability	Treatment of *F. enigmaticus* aggregations with descalers will require secure containment in order to be effective. This may be difficult to achieve given the large scale of the infestation, particularly for reefs occupying subtidal areas and structurally complex habitats. Consequently, while descalers may be suitable for treatment of some areas / habitats that can realistically be isolated and contained (e.g. discrete built structures such as wharf piles), they cannot feasibly be used to treat the total area of *F. engimaticus* infestation. As descalers are readily available and frequently used at an industrial scale, product availability is unlikely to be a limiting factor.	Containment and treatment delivery not feasible for all infested habitats.
Cost	Rydlyme® is available in New Zealand at a cost of ~NZ$25–$50 per L (NZ$521.80 for 20 L or $180.67 for 3.78 L). This is comparably expensive to other treatments, without taking into account the additional necessary costs associated with containment, deployment and monitoring, and recovery of containment and treatment equipment. Descalex® is available in New Zealand in small amounts (~5 L) from online industrial chemical supply stores. Commercial volumes (25 kg drums) need to be sourced from overseas, but cost is not reported on retailer websites. Additional costs are associated with containment of the target areas and treatment deployment, and recovery of containment and treatment equipment. We expect the cost of this method to be very high.	**Very high –** significant operational costs.