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| United States Army Corps of Engineers |
| How does management impact the spread of dreissenid mussels across the Western United States: A Case Study (DRAFT) |
| Engineer Research and Development Center – Environmental Laboratory |

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# Introduction

Aquatic, invasive species are a global issue impacting natural and manmade resources, human health, recreational opportunities, and other ecosystem services (Gurevitch and Padilla, 2004; Gallardo et al., 2015). Aquatic invaders cost $345 billion USD annually in damages and control (Cuthbert et al., 2021) and will continue to increase cost as global connectivity increases while reducing barriers that limit the species ranges (Vander Zanden and Olden, 2008; Higgins and Vander Zanden, 2010; Havel et al., 2015). Mollusks account for 62% of the total annual cost of US aquatic invasive species (Cuthbert et al., 2021). While over 80 species of mollusks have been introduced to the US, the dreissenid mussel, quagga mussel (*Dreissena rostriformis bugensis*) and zebra mussel (*Dreissena polymorph*), attribute to the most damage and cost (OTA, 1993; Pimental et al., 2005; Mei et al., 2016).

Once invasive species are established, eradication can be difficult, if not impossible. This makes it critical to develop approaches that can accurately forecast future dispersal (Potapov et al., 2009; Leung et al., 2006; Muirhead and MacIsaac, 2011). Despite investment in various efforts (Pimental et al., 2005; Stewart-Koster et al., 2015; Simberloff, 2020), management and eradication successes have been lacking among aquative invasives (Higgins and Vander Zanden, 2010; Moorhouse and Macdonald, 2015; Simberloff, 2020). Management is needed to not only decrease the density of this species in a waterbody, but also to potentially decrease the number of mussels that are being transported via boating vessels.

Aquatic species are often introduced to new waterbodies by boater transportation (Asheton et al., 2014, Havel et al., 2015). While transport risks can be hard to predict among vessels and boaters (Rothlisberger et al., 2010; Ferrario et al., 2016; Robertson et al., 2020), human behavior and paths between waterbodies can be projected (Fischer et al., 2021), which is where the use of a gravity model becomes important. Gravity models mirror Newtonian laws in that the attractions between two objects is modeled as proportional to masses and distance. Since relatively few lakes serve as an invasion source to infect other lakes (Muirhead & Macisaac, 2005), modelers can constrain or integrate gravity models to improve transport projections among lakes that vary in size, distance, and attraction features that affect boater traffic (Padilla et al., 1996; Schneider et al. 1998; Bossenbroek et al., 2001 & 2007; Leung et al., 2006; Robertson et al., 2020; Fischer et al., 2020).

Carrillo et al. (2023) discussed the base model for the case study that this paper will discuss. The objective of this case study was to build upon the model Carrillo et al. (2023) developed and add a management constraint to project the decrease in dreissenid mussel spread by observing three different management scenarios.

# Materials & Methods

## Study system

Data incorporated into this model comes from 402 freshwater inland lakes in the Western US and 11 of which were confirmed to have been infested with quagga mussels between 2011 and 2019. These lakes vary in size, management initiatives, and distance to cities. The Bureau of Reclamation (Reclamation) oversees these waterbodies and managers at each lake collect annual plankton tow samples for early detection or population monitoring for the dreissenid mussels. Cross polarized light microscopy is used to determine veliger presence/absence. The results from the microscopy are confirmed via genetic sequencint (Reclamation, 2020). Mean water quality values, such as calcium and pH levels, were gathered from various agencies throughout the Western United States (Reclamation or other state agencies).

## Study Species

Dreissenid mussels were introduced to the US in the late 1980’s – early 1990’s via ship ballast (Mills et al., 1996; Hebert et al., 1989; May and Marsden, 1992). Since their arrival, they have spread to other waterbodies largely by small recreational boats (Ferrario et al., 2016; Cole et al., 2019; Robertson et al., 2020). Since they have a biphasic life cycle, the free-swimming planktonic veliger allows them to discretely travel on boats and boating material (Johnson et al., 2001). When they reach the settling stage of their life cycle, they will attach to any hard surface, including the shells of native mussels, which leads to competition for both the environmental niche as well as physical habitat space of natives (Benson et al., 2022). Adults can attach to boats and survive up to a month out of water (Rothlisberger et al,. 2010; Collas et al., 2018; Benson et al., 2022).

## Management study

While it is important for waterbody managers to know when dreissenid mussels could potentially be introduced, it is equally important to provide these managers with sufficient options and in turn, success rates, of different management scenarios that could be implemented. There have been different types of management routes aimed at dreissenid mussels, but because of the high rate of reproduction, lakes may need to incorporate multiple management options. Many options are applied directly to the lake, while others are applied to recreational vehicles (Aldridge et al., 2006; Molloy et al,. 2013). A common boater targeting option is a cleaning station, where boats are required to clean their boats to wash off any potential mussels that could have attached to the boat while in the lake. Cleaning stations have been effective, but not every boater is going to comply to the cleaning process, so having lake targeted management can be a more effective step towards decreasing mussel density. Lake targeted management options include potassium chloride/potassium hydroxide, lake drawdown, and others; although some of these options are not conducive due to their potential harmful effects on waterbodies and species living there (Murawski, 2016). Theseaffect mussels by either becoming incorporated to their food chain and killing them, or by exposing them to direct sunlight and causing them to die off. This type of management needs to be incorporated because if the density of mussels in a lake can be decreased, then the number of mussels being transported by boats would in theory be decreased also. To date, gravity models that incorporate multiple different management options has not been achieved. Cleaning stations have been the only thing to be incorporated to this type of model (Robertson et al., 2021).

### Lake Options

#### Potassium Toxicity

Dreissenid mussels are highly effective feeders, so creating management options that can be tailored to this feeding is showing to be a popular management technique. Potassium salt toxicity in bivalves was first discovered when it was used to target the invasive Asian Clam (Anderson 1976). Potassium chloride and potassium phosphate have been shown to destroy the gill epithelium of the mussel, which leads to asphyxiation (Fischer et al., 1991; O’Donnell et al., 1996; Wildridge et al., 1998). Aldridge et al (2006) created a microcapsule, call the BioBullet, containing potassium chloride that has been engineered for dreissenid mussel ingestion as well as being dissolvable to decrease potential ingestion of non-target organisms. Potassium chloride has also shown to be extremely affective, resulting in the only documented case of successful open-water treatment and eradication of a dreissenid population from Millbrook Quarry in Virginia (Fernald & Watson 2005, 2013).

#### Lake Drawdown

Air exposure studies have shown that extreme temperatures greatly decrease the mortality time for mussels (Payne, 1992; McMahon et al., 1993; Ricciardi et al., 1995a; Ussery et al., 1998). Several studies found that extreme temperatures (both elevated temperatures and temperatures below 0° Celsius) greatly decreased the mortality time compared with the normal temperature range for mussels (Payne, 1992; Ricciardi et al., 1995a; Ussery et al., 1998). Relative humidity where mussels are emersed also plays an important role in the mortality rate. Mussels in environments with higher relative humidity showed longer survival times in above freezing temperatures (McMahon et al., 1993).

A recent data analysis conducted by Yarnell et al, (2021) indicates that there is a correlation between frequency and duration of lake drawdowns in conjunction with the presence of dreissenid mussels. A sample size of 42 lakes were placed in three categories as either (a) established, (b) suspect, and (c) negative. These categories were determined by the presence or absence of dreissenid mussels during lake sampling protocols that the Bureau of Reclamation follows (Standard Operating Procedure: Field Sampling Methods for Invasive Mussel Early Detection, 2020). These categories resulted in six established lakes, twelve suspect lakes, and twenty-four negative lakes. After conducting a series of statistical analysis to compare the different categories based on frequency and duration of drawdown events, the results indicated that reservoirs with established mussel infestations generally had more frequent and shorter duration events than the suspect or negative reservoirs.

#### Copper

While copper compounds have shown to be toxic to dreissenid mussels, they are also toxic to a wide variety of species. Further studies have developed a more targeted approach to dreissenid mussel mortality (Bloodsworth, 2015; Lund et al., 2018). Although these results are moving towards more eradication, copper treatments have only been tested in small portions of lakes and have not resulted in full eradication (Dupuy, 2015; Lund et al., 2018; Olson, 2018).

#### Chlorine

Oxidation methods using a variety of chlorine compounds have been shown to be effective at killing dreissenid mussels (Klerks & Fraleigh, 1991; Van Benschoten et al., 1995; Brady et al., 1996; Matisoff et al., 1996; Rajagopal et al., 2002). Chlorination has long been used for water treatment due to its success in controlling mussel populations, but it may not be appropriate for open-water use.

#### Zequanox

Zequanox is a biopesticide that has been designed to specifically target dreissenid mussels. It is derived from a strain of naturally occurring microbe bacterium that is found in soils and waters around the globe (Molloy & Mayer, 2007; Molloy et al., 2013b). studies indicate that mortality is achieved by degragind the stomach and digestive glands of the mussels (Molloy et al., 2013c).

#### Electric Current and Electric Fields

Alternating current (AC) and direct current (DC) electrical fields have been shown to reduce mussel settlement or increase mortality (Fears & Mackie, 1995; Fears & Mackie, 1997; Luoma et al., 2017), but it is not known whether these approaches would reduce downstream settlement (Smythe & Miller, 2003). Pulse-power exposis water passing between electrodes to an electrical current; however, it produces higher energy fields than AC and DC techniques (Smythe & Dardeau, 1999; Smythe & Miller, 2003).

#### Predators

A wide variety of fish species have been observed as preying upon dreissenid mussels in Eastern Europe, Western Europe, and North America (Molloy et al., 1997; Bartsch et al., 2005; Bowers & Szalay, 2007; Karo & Thomas, 2014). Lab studies have shown that the round goby can consume up to 100 mussels per day, depending upon the size of the mussel (Ghedotti et al., 1995). A field study on Lake Dardanelle in Arkansas resulted in 17 different fish species that preyed upon zebra mussels between 1996-1999 (Magoulick & Lewis, 2002).

### Boater Options

#### Cleaning Stations

Recreational boaters unintentionally transport mussel larvae via infested boat and fishing components (Johnson et al., 2001) and adult mussels that are attached to hulls. Cleaning stations have been used to help curb overland spread of dreissenid mussels across the United States. Hydro-blasting and abrasive blasting are used to remove mussels from small-diameter areas of a boat that could otherwise go undetected (Chakraborti, 2013). While this management option is one of the easier options ot achieve, boaters vary in their compliance to aid in reducing spread (Rothlisberger et al., 2010; Ferrario et al., 2016; Roberson et al., 2020), which can make it difficult to properly model.

#### Coatings

Due to the nature of overland mussel dispersal via hard substrate attachment, significant effort has been focused on developing materials and coatings that can resist or repel mussel settlement and attachment (Wells & Sytsma, 2009; Skaja, 2010, 2015). Traditional anti-fouling coats rely on an incorporation of metals that leach from the surface and inhibit the settlement and attachment of organisms (Gross, 1994; Race & Kelly, 1994; Dormon et al., 1996; Kobak et al., 2002; Wells & Sytsma, 2009; Skaja, 2010, 2014a, 2015). Naturally occurring and synthetic organic compounds have also been evaluated as biocides that could be incorporated to reduce fouling (Cope et al., 1997; Diers et al., 2006; Angarana, 2007; Skaja, 2011; Ram et al., 2012).

“Foul-release” coatings have been developed as an approach to deter mussels from attaching to hard substrates. These formulations do not leach biocides. Instead, they have inherent surface characteristics that reduce the strength of adhesion to organisms. This adhesion reduction causes the organisms ot be dislodges by water flow over the surface of the hard substrates.

### Chosen Options

While important to the eradication/decrease of mussel populations, some of these management options are not conducive to the model in its current form due to the ability to accurately determine the extent of mussel impact. Foul-release coatings have two major impediments to a more widespread adoption: durability of these materials (Mortensen, 2013; Skaja, 2015) and its incombatability with coal tar enamel coating that is currently present on many infrastructure surfaces (Tordonato, 2011; Skaja, 2015). Copper options have been shown to be successful in small portions of a waterbody, but have not been scaled up to test an entire waterbody.

Potassium chloride/potassium hydroxide (i.e., BioBullet), lake drawdown, and cleaning stations were chosen as the management options to be represented in this model due to their extent of research, safety for the environment, and level of success.

# Model Description

## general overview

The original model simulates annual inter-lake boater movement, the likelihood of each boat carrying dreissenids, those mussels that survive both transport and the new lake, and how many arriving infested boats change the infestation rate of a lake. The model is coded in Netlogo© v6.1.1, an open-source multi-agent platform (Wilensky and Rand, 2015). The model domain is a spatially explicit grid composed of two sub-models: (1) a constrained gravity model that simulates boater movement and (2) a habitat suitability model. The model equations are modified from Bossenbroek et al, (2001, 2007) and Robertson et al. (2020). The input is a georeferenced shapefile of waterbodies which was imported into the model using the Netlogo© GIS extension. This shapefile contains the following lake attributes: waterbody name, dreissenid presence (Y/N), mean values for habitat suitability parameters (water pH and calcium (Ca) levels), boater density, surface area (m2), and XY centroid coordinates. The timestep in this model is considered an annual boating season with the assumption that boats return to their point of origin at the end of each time step.

## Constrained gravity sub-model

The constrained gravity model used modifies the approach used by Bossenbroek et al. (2007) which simulates the number of boats moving among lakes within a spatial domain where the number of boaters moving from lake *I*  to *j* per timestep (*Tij*) is calculated as:

(1)

Where *Oi* represents the density of boats traveling from watershed *i*, *Wi* represents watershed *j* attractiveness, *Cij*  represents the distance between wtaersheds, *α* represents a distance-decay coefficient (i.e., the distance that boats travel from their origin lake (Roberson et al., 2020)) , and *Ai* is a balancing factor. In a constrained gravity model, a smaller α represents a strong deterrent to interaction, while a larger α represents a weak deterrent to interaction. For this model, we used a constant α of 2.2 as determined by Roberson et al. (2020) from hindcasting to yield the best model fit. The balancing factor (*Ai*) ensures that all boats leaving lake *i* arrive at some lake *j*:

(2)

Where N is the total number of destinations (*j*) within the model domain.

Total boats associated with each lake *i* (*Oi*) is estimated as

*Oi = bPi* (3)

Where *b* is a constant (0.0362) that represents the per capita rate of boat ownership for the US (Statista, 2020) and *P* is the adult population within each US county in the model domain (US Census Bureau, 2019; ESRI, 2020). The number of boats per lake were sub-divided into two groups, infested boats (*Zi*) and uninfested boats (*Ui*). The number of boats in each groups are calculated as

*Zi* = *xOi* (4)

*Ui* = *Oi* – *Zi* (5)

Where *x* is a user-defined variable that represents the proportion of boats in lake *i* that are infested with dreissenid mussels.

Lake attractiveness (*W*) is based on the waterbody’s surface area (Bossenbroek et al., 2007; Rothlisberger et al., 2010). Larger waterbodies are considered to be more attractive due to increased recreational and other opportunities increasing the likelihood that a boater will travel to that lake.

Boater threshold is a user-defined variable that determined the number of infested boats that are required to arrive at a lake before that lake has the potential to become infested. In the model runs presented here, the baseline or null threshold value was set to 100.

Overland travel distance can be model constrained via a spatial buffer between lakes. This constraint is a user-defined pairwise Euclidian distance between lakes (*Cij*) and is calculated as:

(6)

Where X and Y are the respective X and Y coordinates of the centroid of each lake. The buffer limits the boater movements between lakes. It was implemented because boater surveys indicate that prople travel ≤ 31 miles on average per boating trip (Padilla et al., 1996; Buchan and Padilla, 1999; Cole et al., 2019). For buffer implemented scenarios, boats could not travel further than the buffer distance (e.g., a 50 mile buffer (Fig 1)). Buffered lakes that did not have any additional lakes within their respective buffer zones (i.e., were isolated within the buffer) were removed from the analysis. Distances in Netlogo are relative to the GIS source data and the number of cells in the Netlogo domain. In this model, a distance of 0.01 Netlogo units translates to ~1 mile in reality.

## Habitat suitability index sub-model

Habitat suitability index (HSI) models result in a value of score based on the geometric mean of all limiting variables (Roloff and Kernohan, 1999). The index in this model is based on mean pH and Ca levels per lake as the most limiting factors that affect veliger survival (Hincks and Mackie, 1997; Whittier et al., 2008). HSI score is calculated based on pH and Ca ranges as they affect known *D. bugensis* establishment and survival (Figure 2, Table 1). The HSI scores were formulated as a step function with linear approximations between steps. The pH and Ca values used in this model were gathered by Reclamation from multiple years of water quality testing using standard sampling protocols (Reclamation, 2020). In order to calculate the HSI for the lakes, the average pH and Ca were calculated for each lake and input into the model. The levels that are suitable for survival are based on dreissenid veligers as opposed to developed mussels because we assume mature mussels would only exist of they could initially survive as veligers. The model is intended to forecase the movement of both dreissenid species; however, *D. bugensis* has a wider range of acceptable habitat conditions than *D. polymorpha*. By focusing on *D. bungensis* for HSI calculations (Table 1), the model is more conservative because it is more likely to over forecast invasions than under forecast (Whittier et al., 2008; Sepulveda et al., 2012). The HSI calculation is expressed as a geometric mean:

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|  | (7) |

Where *xm* represents the individual habitat suitability score for variable *m* (calculated from Table 1), and *k* represents the number of environmental parameters. Following Robertson et al. (2020), waterbodies with an HSI score ≥ 0.8 were ‘high’, scores ≤ 0.4 were ‘low’, and scores between these values were potentially suitable and treated probabilistically based on a logistic function. Twenty-seven of the 402 lakes were missing a water quality parameter (17 Ca and 10 pH), so the HSI for these lakes were based on one limiting factor.

## management sub-models

### BioBullet

Calculations for application of the BioBullet is determined using lab study results indicated in Aldridge et al. (2005).

# General Freshwater Mussel Habitat Model

# Model Evaluation

# Model Considerations

# Modifying Parameters for Specific Guilds

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