New Zealand Mud snail Invasions in Lake Tahoe - Technical Science Advisory Committee

Memorandum to Managers

Submitted to

Dan Segan, Chief Science and Policy Officer
Tahoe Regional Planning Agency

From

Committee Members:
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We thank Dr. Adam Sepulveda (USGS) and Seth Jones (Marina Taxonomic Services, Ltd.) for their contributions in developing this memorandum.

October 12, 2023

Questions presented in a charge written to the Technical Science Advisory Committee on October 6, 2023 that will be addressed in this memorandum:

- How would you approach assessment of the extent and severity of the infestation?
- What options are available to eradicate, contain, control, or manage the infestation?
- What is the likely impact of the infestation and how could you assess the impacts (if any) from snails to the ecosystems in the Lake Tahoe basin?

Responses to more detailed questions requested by the management team are in the Supplementary Section.

How would you approach assessment of the extent and severity of the infestation?

Specific: Provide an overall assessment of the current infestation in the context of what is known about past mudsnail invasions and life history.

New Zealand mud snails (NZMS) are a global invader with a suite of life history characteristics that facilitate their ability to colonize and establish in freshwater and estuarine ecosystems. In the US, populations of NZMS range in adult length from 4-6 mm. The shell color is variable, but is commonly observed to be very dark brown to light gray-brown. Reproduction in the US is believed to be entirely asexual, with parthenogenetic females producing between 170-230 offspring per year in a reproductive season that spans (but is not limited to) spring and summer. Females are reproductively viable as early as three months of age. This asexual reproduction means there is very low genetic diversity among populations in the US. In addition the species is known to survive across a wide range of salinities, calcium concentrations, and temperatures (Loo et al. 2007). Very little is known about the lifespan of the NZMS. A synthesis of NZMS life history information can be found in Geist et al. (2022). Many invaded systems experience very high densities (300,000 to 800,000 individuals per m^2). NZMS are highly mobile, and can actively move downstream and upstream in flowing waters. The snails are also known to 'hitchhike' on plants, mobile birds and human equipment (boats, construction gear and fishing equipment). The species is a nocturnal grazer of plants, algae, and diatoms.

New Zealand mud snails have established in 39 countries across 5 continents (Geist et al. 2022). The first US Geological Survey (USGS) records of NZMS establishment occurred in Idaho's Snake River in 1987. In the following 35 years, NZMS were found in the Great Lakes region and throughout the Mountain West (Figure 1). Established populations of NZMS currently exist elsewhere in California and Nevada. Populations of NZMS near Lake Tahoe are found in the Truckee River, NV (2008) and Mono Lake, CA (2004). Forecasts of US habitat suitability identified the Western US was suitable for NZMS establishment as early as 2007 (Loo et al. 2007). The *National Management and Control Plan for the New Zealand Mudsnail (Potamopyrgus antipodarum)* was initiated in 2003 and published in 2007 (NZMS MCWG), with a further update forthcoming.

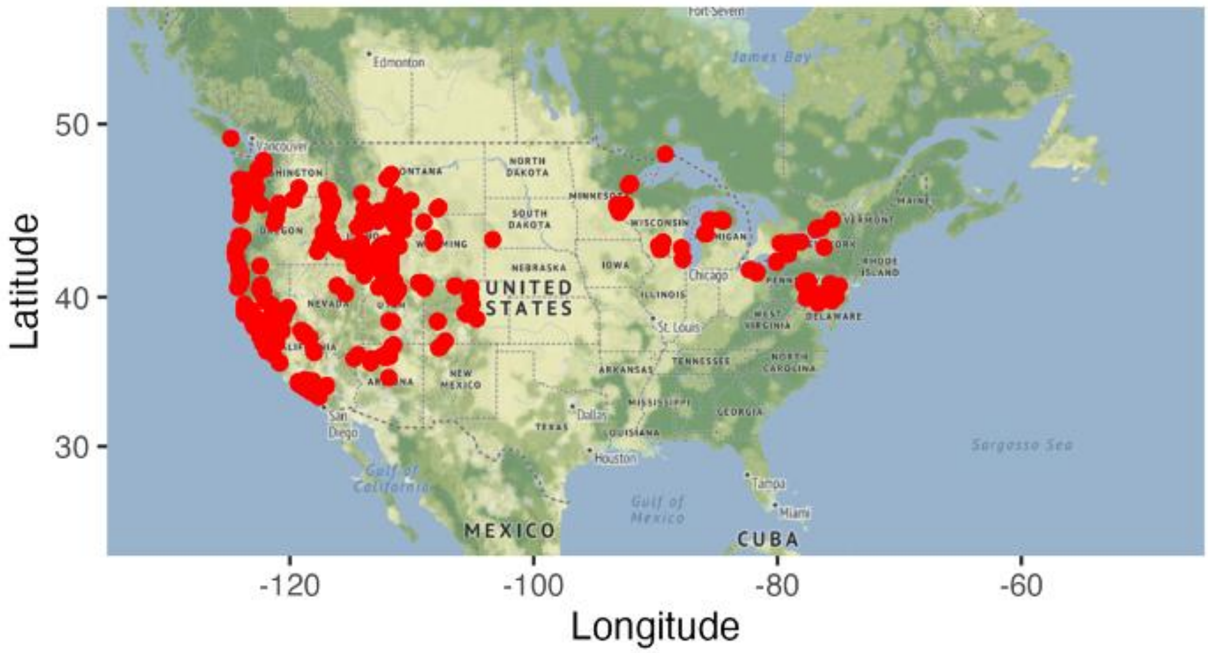

Figure 1: All records of NZMS in the USGS database (accessed 6 Oct 2023).

As of now, NZMS have successfully established in Lake Tahoe and the following is a timeline of significant events related to the incursion and responses occurring after the initial detection of the invader.

Sept 6, 2023

• Under Tahoe Resource Conservation District's (RCD) contract to conduct aquatic invasive plant treatments in the Tahoe Keys Offshore infestation, divers from Marine Taxonomic Services Ltd. (MTS) were conducting a site assessment survey[1] in an area east of the known plant infestation area to assess any potential spread of plants eastward from the previously mapped locations.
• Divers discovered an unknown snail species and collected 8 specimens east of the Tahoe Keys approximately 2,000' offshore, Northeast of the mouth of the Upper Truckee River.
• RCD was immediately notified that evening, with subsequent notification to Tahoe Regional Planning Agency.

Sept 7 – 8, 2023

[1] *Surveys in the general area for plants have occurred over the last several years. A lakewide transect in the core area was completed 5 years ago but the methods in this and all other previous surveys did not include a target to look for NZMS. It appears nearly impossible to date this invasion or estimate its spread beyond this initial sighting with current data.*

• Photographs of snails were provided to two biologists/taxonomists; but a positive identification was not able to be determined from the photos. Photos indicate snails are in high to low densities, growing on algae, plants and sediments.

• Additional specimens were collected per the direction of California Department of Fish and Wildlife (CDFW), and sent to Doug Post at CDFW Aquatic Bioassessment Lab.
• Tahoe RCD, TRPA, and MTS developed a plan for MTS to conduct a concentrated survey around the area of discovery.

Sept 11 – 12, 2023
• Doug Post from CDFW provided a positive ID of NZMS.
• Specimens were sent to Pisces Molecular for DNA verification.

Sept. 12-13
• MTS divers conduct targeted rapid assessment line survey to obtain a rapid delineation of infestation.

Sept 13 - 15
• In coordination with MTS, Tahoe RCD, TRPA, and CDFW, a grid survey plan in the known NZMS general area was developed.

Sept 15
• Positive DNA results from the company Pisces Molecular were received for New Zealand mudsnail for all 6 specimens.

Sept 15 – October 11
• Lakewide transects were modified to dive closer to the lake bottom (deeper) and at a slower rate to increase NZMS visual detection probability. No other visual detections by MTS divers outside of the known infested area along the south shore shelf.

Sept. 20 – Sept. 27
• Divers conducted a large-scale grid survey, including deepwater transects. Snails found down to 150' deep on one of the three deep transects. The divers found areas with high densities and some areas with just a few snails. A fairly well defined edge was seen in the invasion to the west of the Tahoe Keys, but no such edge was detected to the east. A map of snail distribution and estimated densities along the south shore is presented in Figure 2.

• Sept 21 - The Tahoe Science Advisory council was engaged to discuss the impacts of snails to the Lake Tahoe ecosystem and make recommendations related to the technical understanding of the invasion. A request was made to form a rapid response Technical Science Advisory Committee to address this invasion.

• Sept 26-29 - University of Nevada, Reno Global Water Center and Tahoe Science Council scientist, Sudeep Chandra, worked with managers to create a committee charge and formed a committee of 5 scientific experts and 1 contributing scientist.

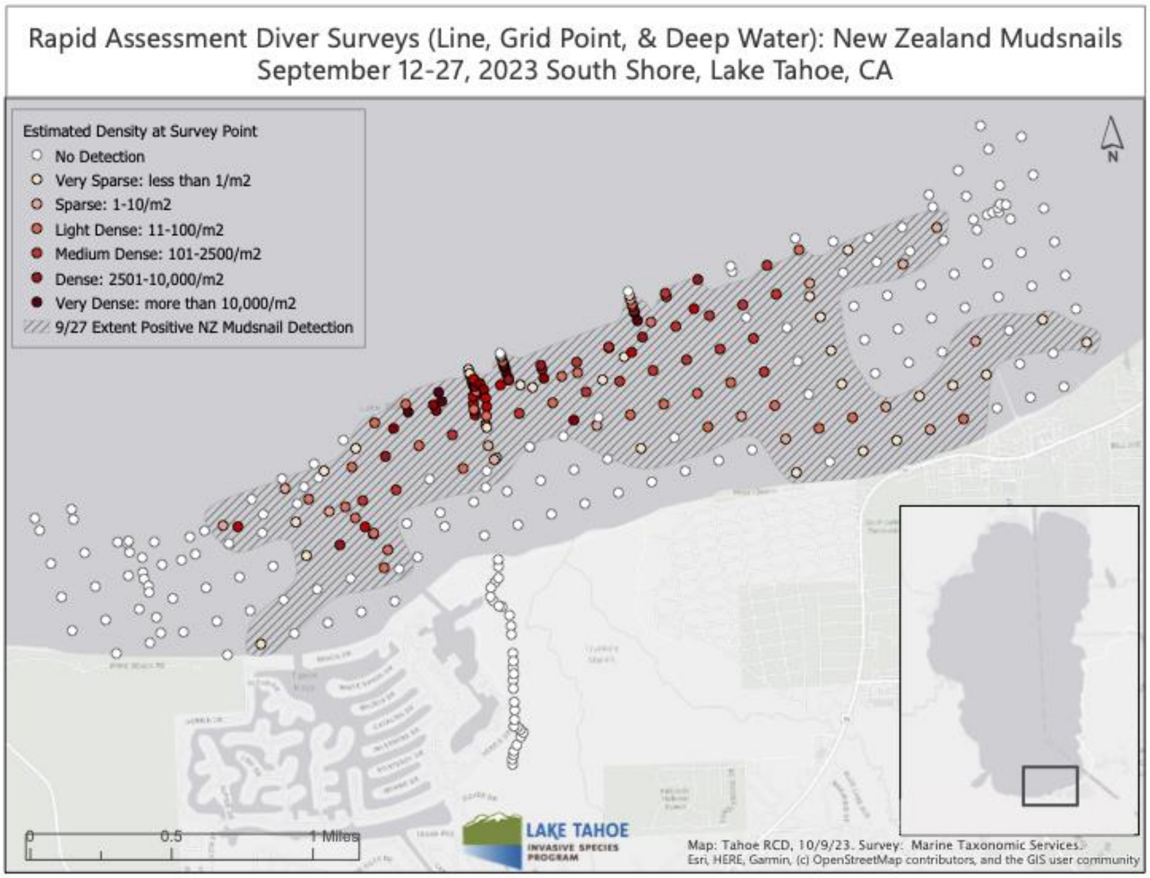

Figure 2. Map of known infested snail locations and their estimated densities through dive surveys conducted by MTS. Map courtesy of Sara Mathews (RCD).

• Oct 6-7 - New Zealand mudsnail invasion Technical Science Advisory Committee convenes and responds to the charge, questions, and develops a memo for submission to the management community.

• Oct 12 - Technical Science Advisory Committee submits this Memorandum addressing questions raised by the managers in the charge to the committee.

Provide additional details to answer how to approach assessment of the extent and severity of the infestation?

An intensive focus on the currently infested site.
As presented to the committee, the confirmed established sites for NZMS are along the South shores of Lake Tahoe (Figure 2). The initial cursory estimations indicate a range of densities with both large and small sized individuals. It is critical to collect information from this site in the coming 2-4 years, starting as soon as possible (fall 2023) since NZMS are able to reproduce year round. Monitoring should focus on quantifying the size/age-structure of the population, the current densities, the relative expanse of the population, and their potential impacts to ecosystem processes (i.e. fisheries, overall food web structure, invertebrate density and diversity (including microfauna), organic matter concentrations, processing of carbon, nutrient excretion, algae composition and bacterial composition). Understanding the life history and expansion of the species in Tahoe and the species' relative impacts (before and after in the areas they are colonizing) is a critically important opportunity that will be lost once the species is firmly established. We also note a very strong need to initialize monitoring contracts as soon as possible, so that institutional and other delays won't allow this window of opportunity to close. Semi-natural field experiments within the invaded area may be used to understand the impacts of NZMS on soft sediments and hard substrates like rocks. The south shore is also home to deep water sensitive native plant and invertebrate taxa so it is critical to understand baseline conditions (diversity to ecosystem) prior to further spread.

As discussed below, different tools used at different scales (lake to watershed to regional), will be needed to quantify the location and spread of NZMS. However some of the tools will need to be calibrated to Lake Tahoe's specific ecosystem. For example, previous eDNA studies within Lake Tahoe by the committee members (Jerde and Chandra) suggest low concentrations of detectable eDNA in the lake water depending on the physical location of water sampling and the specific taxa that are searched for. In addition, eDNA collections from sediment-water interfaces that are homogenized in a lab, may yield more information than simple water collections from the lake. These methods need to be tested. As a result, the existing infestation should be seized as an immediate opportunity to develop Lake Tahoe specific methods for the entire basin and regional areas. These may involve (but are not limited to) issues related to collecting eDNA samples from low productivity (oligotrophic) waters and specifically tailored bottom grab/ dredge sampling to refine our ability to detect the species. Methodological ways to enhance the probability of detection will greatly assist our understanding of this invasion and help in risk assessment of other water bodies.

We have divided the monitoring and surveillance of NZMS into two spatial types, lake and watershed to regional scale. Multiple methods need to be employed to detect taxa. The relative strengths and costs of each method are presented in Table 1.

Recommendations to survey at the lake scale.

- As stated above, we need on the ground real-time spatial surveys in the Eastern areas adjacent to the current infestation. These surveys need to be completed using multiple methods (discussed below), quickly (i.e. fall 2023) to see how far the snails are moving along the margins.
- In all future surveys, we need the surveyors to collect covariate/environmental data along with organism samples (both physical and visual). This data will prove to be critical in all future management and control efforts.
    - The covariate/environmental data should include the following parameters (where possible) in the sediment-water interface.
        - conductivity,
        - depth,
        - benthic habitat characterization,
        - ultraviolet light penetration,
        - chlorophyll A,
        - calcium,
        - DO,
        - pH,
        - turbidity,
- As an overall strategy, our suggestion is to have a complimentary or tiered sampling and monitoring approach. This would involve starting with large-scale rapid detection methods that are cheaper and faster. Then if/when a detection is found, the survey would go back and confirm with more refined, intensive and potentially expensive methods.
- We also suggest leveraging efforts that already exist for monitoring in the lake and basin. This would involve adding NZMS to their search images/objectives (e.g., plant assessment, rake surveys, collected by US Forest Service etc.).
- It is important NOT to delay these collections into next year, the sooner the better in terms of assessment.

The following is a list of potential survey techniques (note: this is NOT an exhaustive list)

- Visual surveys
    - SCUBA/snorkel
        - Produces high quality data
        - Very expensive and time consuming
        - Provides a very clear answer to the question: Are they there presently?
        - The data gained is extremely spatially explicit, especially with respect to the size of the entire lake. These will show specific areas where the snails

are present and where the divers had eyes on them. The surveys' abilities to detect snails depend on hyper local conditions (ie. clarity wave action ect.).

        - These observations provide real-time opportunities to collect environmental data as well as natural history information about the NZMS itself (i.e. size distributions of shells, or DNA/tissue samples of the organisms).
        - These efforts are not scalable because there is too little area covered by the divers' visual field.
        - These methods are not destructive of the aquatic invasive species (AIS) (leave the NZMS in place and unharmed).
    - Cameras
        - Often used in locations or times (weather/seasons) when diving is not possible.
        - Can be an effective and useful tool for looking back through time, as they produce a video record of the survey.
        - These methods can cover a lot of ground relatively quickly and cheaply.
        - These are best for detection of high density infestations, as low densities are likely to be missed on occasion by the camera and impacted by local conditions (i.e. turbidity etc.)
        - The quality of the survey can be negatively affected by surface water conditions (i.e. chop or in marinas near wake zones etc.).
        - These methods may not be as effective at finding infestations in heavily vegetated areas, particularly if the NZMS are found in the deeper architecture of the plants or on the benthos.
        - This method is also not destructive of the AIS.
    - ROVs (remote operated vehicles)
        - These have similar issues as the general camera surveys as discussed above.
        - There may be issues with motor thrust from the ROV disturbing sediment/benthos and obscuring near-benthic visibility.
- Benthic grab collection sampling
        - These methods generate clear positive or negative signals.
        - They produce very fine spatial and temporal resolution on density.
        - Aging shells is possible with these collection methods.
        - Destructive sampling of non aquatic invasive species but also destructive of potentially sensitive/T&E species (i.e. sensitive native endemic macroinvertebrate species).
        - Unfortunately these produce very limited spatial extent information per sample (i.e. hyper local).

    - Types: (there are known and unknown biases and issues with all of these and the specific choices should be based on scientific knowledge and prior experience)
        - Ponar (large and petite)
        - Eckman (large and small)
        - Shipek
        - Sediment: Hand cores/push cores
        - Kick nets
        - Suction sampling
        - Artificial substrate
    - Community/public shore walks
        - These kinds of detections will indicate the presence of extremely large infestations.
        - These may be very useful as an educational tool for the general public.
- Molecular
    - eDNA
        - In order to have fairly complete coverage of the lake we recommend that samples are collected in multiple locations within the water column including: benthic, sediment, and potentially vertical tows through the water column.
        - This method produces presence/absence data only and uses a tiny amount of the water/material collected. This allows the rest of the sample to be preserved for later, more refined or detailed analysis (i.e. looking for other species etc.).
        - This method should be the most cost effective over time.
        - The method is completely non-destructive and leaves the non aquatic invasive species in place.
        - This method can be targeted to a specific organism (NZMS) or can be used to get a larger ‘community’ analysis of other taxa shedding DNA in the area.
        - This method is not indicative of species being present locally and could instead indicate the species is present on a more broad spatial scale. Spatial detection resolution is therefore limited.
        - This method also provides broad temporal resolution of positives, as the DNA could exist for an unknown length of time.
        - eDNA is an indirect method (i.e. inferential) and therefore can produce both false positives and false negatives. Detections should always be followed up with more site specific survey methods in order to confirm the presence.

- Quantitative PCR can be used to estimate the relative concentration of DNA in the sample, which may be used to indicate the strength of the signal (i.e. relative infestation size).
- Unfortunately this methodology doesn't have some state agencies' buy-in on use of the tool for positive detection. What this means is that some agencies may need to have an non aquatic invasive species/organism either in-hand or sighted by a trained individual in order to make management decisions.
- We feel this method may be most useful as a screening tool.
- The eDNA analysis itself could be done at many different universities or for-profit institutions which are specializing in this kind of work (potential places to do the work: Washington State, Jonah ventures in Boulder CO, UC Davis, UN Reno, NatureMeterics).
- eDNA is primarily an early detection tool and should not be used for repeated monitoring of known high density sites.

Table 1. Summary of potential survey tools and their constraints/criteria

Tool	Cost	Time to results	Scale-able	Non destructive	Density resolution	Spatial resolution	False-neg prob	Other
SCUBA	$$$$$	Fastest	No	Yes	Coarse	Med	Med	
Cameras	$$	Fast	Maybe	Yes	Poor	High	High	
Benthic grab samples	$$$	Slowest	No	No	Fine	Low	Med	
eDNA	$$	Fast	Yes	Yes	Coarse	Unknown	Low-med	Need to fine-tune methods, may require corroboration
Citizen shore walks	$	Fast	Yes	Yes	Poor	Med	High	

Surveys and monitoring at the regional scale.

Implementing a regional AIS surveillance program could answer the following questions: 1. Are there established NZMS elsewhere in the region? 2. Which lakes in the region are not currently populated by NZMS? 3. Are there unknown AIS established elsewhere but not currently in Lake Tahoe. Additionally, depending on the methods used, the surveys could provide a current biotic inventory of established and native species which is useful for assessing the impacts of future AIS incursions and measuring the impacts of disturbance, urbanization, climate change, and pollution. The benefits of a regional biotic survey (beta diversity) plan are useful beyond the early detection of invasive species (Buckland et al. 2012, Socolar et al. 2016). The committee emphasizes and acknowledges the need for regular biotic baselines throughout Lake Tahoe and the region to make better recommendations for the NZMS incursion and future invasions. Biotic baselines are critical for tracking the invasion's progress, identifying priority areas for protection and control, and measuring impacts on the Lake.

Nearby populations of aquatic invasive species are often the source of a new invasion due to increased regional propagule pressure (Lockwood et al. 2005). With the incipient invasion of Lake Tahoe, the Lake now becomes a likely source of new invader propagules and invasions for nearby lakes. We recommend building a regional surveillance plan (Tucker et al. 2020) for Angora Lakes, Bear River Reservoir, Boca Reservoir, Caples Lake, Cascade Lake, Donner Lake, Eagle Lake, Echo Lake, Fallen Leaf Lake, Granite Lake, Independence Lake, Lake Spaulding, Lake Valley Reservoir, Marlette Lake, Prosser Creek Reservoir, Serene Lakes, Spooner Lake, Stampede Reservoir, Star Lake, and Washoe Lake. Some of these lakes are at greater risk than others due to access, proximity, and recreational traffic that is likely to increase the opportunities of NZMS transport, survival, and establishment (Muirhead and MacIsaac 2005, Geist et al. 2022). In addition the tributaries of these same water bodies should be included in surveillance efforts.

Table 2: Nearby lakes that may be considered for a regional AIS surveillance program

Lake	Area acre (approx)	Straight Line Distance to Lake Tahoe (km)	Road access	Recent biotic surveys
Angora Lakes	30	8.25	yes	unknown
Bear River Reservoir	727	43.5	yes	unknown
Boca Reservoir	980	19	yes	unknown
Caples Lake	620	26.25	yes	unknown
Cascade Lake	214	0.75	yes	unknown
Donner Lake	960	19	yes	unknown
Eagle Lake	18	2	no	unknown
Echo Lake	323	12	yes	unknown
Fallen Leaf Lake	1403	2.25	yes	unknown
Granite Lake	7	1.25	no	unknown

Independence Lake	700	31	yes	unknown
Lake Spaulding	700	46	yes	unknown
Lake Valley Reservoir	300	40.5	yes	unknown
Marlette Lake	380	1.75	no	unknown
Prosser Creek Reservoir	750	17.5	yes	unknown
Serene Lakes	77	25.5	yes	unknown
Spooner Lake	100	3	yes	unknown
Stampede Reservoir	3450	26	yes	unknown
Star lake	25	10.25	no	unknown
Washoe Lake	5800	10.75	yes	unknown

Risk assessment and biotic inventory surveys form the basis of a broad-scale invasive species surveillance program (Davidson et al. 2021, Koch et al. 2020), which now includes NZMS. The committee recommends developing a database of biotic surveys that are currently occurring throughout the basin to identify knowledge gaps in the biotic inventory and efforts to prevent the further spread of NZMS and other AIS. This database should include survey date, geographic location(s), methods, effort, and a biological inventory of relative counts or presence-absence detection of species-level identification of organisms as well as where the physical samples are currently archived. This effort could take a similar form to the iNaturalist platform, where instead of individuals marking on a map what and where organisms were located, we would have a map with spatially explicit data indicating the information mentioned above. We note the initiative by the Tahoe Science Advisory Council to create a Tahoe Observatory Network which could be home to a repository of information related to this information. Ideally, a surveillance program would seize upon the strengths of multiple surveillance approaches across multiple agencies, ranging from, but not limited to creel surveys, diver inspections, molecular samples, gut surveys, and benthic grab samples.

Different survey methods may be more efficient for regional NZMS surveillance efforts than within-lake diver transects. For example, eDNA metabarcoding approaches are known to be sensitive, require less expertise for sample collection, and can be collected across broad geographic areas quickly (Jerde 2021). The added advantage of eDNA would be the ability to screen the same samples for other known invasive species at risk of invading the basin, confirming established AIS, and surveying the current distribution of many native taxa to assess AIS impacts. However, inspecting plant fragments and/or fish gut contents for NZMS may also be a low-cost survey method suitable for many lakes or water bodies. These quick surveys using plant fragments and fish guts may be prioritized for a rapid survey within the year.

Unfortunately NZMS can, and do, move upstream (Geist et al. 2022). Consequently, all connected streams, meadows, and wetlands into Lake Tahoe have an incursion risk and should be monitored. Due to the complexity and fragility of these environments, it may be prudent to use single species or eDNA-based approaches for monitoring NZMS in tributaries.

The committee recognizes that a broad surveillance program can suffer from a ‘weakest link’ problem (Peters & Lodge 2009). This is to say, a location or invasion pathway that goes unmonitored and unmanaged can become the beachhead for new invasions through increased propagule pressure within the basin. This is why any Lake Tahoe surveillance program's strength depends on having a comprehensive basin and regional AIS surveillance program. This can not be stressed enough.

Additional consideration for developing a regional surveillance.

- Establish a committee to collate the existing monitoring/surveillance programs and determine the future programs and projects related to monitoring the lake, inflows, meadows, and ecosystems outside of the basin and in the region. Determine their schedule for monitoring including a priority for monitoring immediately. Many monitoring programs may be wrapping up their field collection as Fall 2023/ Winter approaches. What do they measure exactly? Will it help with determining risk? Can they collect DNA samples? There is an urgency here, so it is important not to delay this assessment into 2024. We strongly suggest there is a need to do initial surveys this fall/early as possible to get background/baseline data.
- One goal might be to have a regional database (iNaturalist type thing mentioned above) with specific locations that everyone is sampling in the basin and what kinds of samples they have and where the physical/biological samples are located. It is important not to lose site of sample storage of existing specimens. Using local museums (e.g., University of Nevada Natural History museum could be a partnership opportunity).
- Utilize eDNA as an initial screening tool across the basin.
    - Could be useful throughout the year as the NZMS reproduces continuously, although winter sampling of eDNA can be problematic and should be evaluated.
- Site prioritization may occur by identifying sensitive habitats or ecosystems. This will be an important area of initial investment. For example the Marlette ecosystem and Meiss Meadows are critical ecosystems which support Lahontan cutthroat trout. Parts of the lower and upper Truckee river support native mussels, and only 4.5 acres are left in Lake Tahoe which support endemic/ sensitive invertebrate taxa that have declined up to 99% since measurements in the 1960s. These must be priority locations for monitoring and surveillance.
- Survey efforts across the basin may be either random or specific to where humans are having the most impact/access (i.e. boat launches, fishing access etc.).

- Conduct an AIS risk assessment to identify potential invasive species that should be in the search image of visual surveyors and ensure the DNA sequences of these species are detectable by molecular techniques. Do not limit this to the 10 most risky but rather make this comprehensive to ensure the highest probability for early detection. Similar to survey methods in the lake, these surveys should follow up NZMS detections with visual survey methods, kicknets, benthic sample dredges and other methods.

Finally, in addition to targeting NZMS, it is important to collect baseline data on biodiversity (fishes, invertebrates, algae and bacterial composition), determine ecosystem processes (food web structure, nutrient state) starting immediately, before the spread of the snails around the lake basin and gather available data from the nearshore monitoring programs and make this information publicly available to facilitate comparisons in the future. It will be very important to have best practices in place related to data transparency and the locations of collections.

Best data science practices need to be supported. Data on survey efforts, locations, and findings has been challenging to acquire for this NZMS scoping. Yet it can motivate decisions on what surveys are more sensitive to early detection, which systems have had more or less surveillance efforts to date, and the identification of systems at high risk but with the most uncertainty as to possible NZMS presence. We recommend a regional data-sharing effort to document environmental sampling to help inform the current NZMS invasion and preparations for future invasions. Many existing data platforms are available for sharing survey data. Examples include iNaturalist, Dryad, DataOne, and the Global Biodiversity Information Facility (gbif.org). Data should conform to the FAIR guiding principles for scientific data management and stewardship for making data Findable, Accessible, Interoperable, and Reusable (Robinson et al. 2023).

What options are available to eradicate, contain, control, or manage the infestation?

There are two levels or 'scales' of containment when addressing the establishment of an invasive species and/or reducing the expansion specifically of NZMS:

(1) Containment of known, localized population within Lake Tahoe to reduce spread within the lake.
(2) Containment to eliminate (or at least greatly reduce) the movement of NZMS outside Lake Tahoe to surrounding watersheds, non-infested lakes, streams, rivers, ponds, or other freshwater habitats.

Actions to minimize movement are driven by the capacity of NZMS to move, either by their own action, and/or by external vectors and natural events. The mobility and dispersal capacities for the snails are summarized here:

- They have the ability to climb up aquatic plants and then 'release' their hold and float/cling on the underwater surface tension of the water.

- They are easily dispersed across sediments and other surfaces by wave and current action.
- They are known to move upstream in search of food sources.
- NZMS can 'hitchhike' on plant fragments, algae/moss mats floating or otherwise dispersing in the water column.
- They can pass through some fish & waterfowl guts alive.
- They are able to burrow into, and live within mud/sediment/benthos to avoid stresses or disturbances.
- They are able to close up (seal the operculum to their shells) and 'fall' off of plants or other surfaces if disturbed. In this state (closed shell) they are able to live out of the water for several weeks (Cheng and LeClair 2011).
- Neonates (immature snails) disperse by crawling on hard surfaces, and floating through the water column and are therefore easily transported by mass water movement.

Containment within Lake Tahoe:

The committee recognizes that the our ability to constrain NZMS into and out-of the current infestation area (e.g. Southern shores of Lake Tahoe[2]) is extremely difficult due mass water movement, fish/waterfowl movement and watercraft movement in and around the lake. Nonetheless, we want to emphasize that human activities will likely increase the spread of the snails and we should try to slow this spread because this is a positive action that can be taken by managers. Thus, to minimize the movement and to reduce the NZMS spread from the current infested area in Lake Tahoe, the following actions are recommended (ordered in the level of actions that could be pursued to minimize the spread):

- Minimize human sources of disturbance wherever possible as NZMS prefer disturbed areas. It is therefore important to minimize and avoid disturbance within the infested areas, which includes limiting plant removal activities, broad-scale dredging, and any surveys that disturb the benthos.
- Restrict boaters and all recreation movement within the infested areas.
- Limit or restrict anchoring in infested areas.
- Decontamination and inspection of commercial equipment (e.g., pier and buoys installers) moving near or within the infested areas. If possible this would be most effective if it was made part of their contract.

Containment to prevent movement out of Lake Tahoe:

Lake Tahoe should be considered a primary ecosystem in the region containing snails and potential for infecting other water bodies due to its high-use recreational activity. The following actions are recommended to minimize movement of NZMS out of the lake.

- Motorized vessels: Use exit boat decontamination/inspections that have a focus on NZMS. This has an added benefit of also limiting the spread of invasive plants, clams, and other species that are in the lake.

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[2] At the time of this memorandum, we assume the only location in the lake containing snails is along the Southern shore of Lake Tahoe.

- Require decontamination and inspection of commercial equipment coming and leaving Lake Tahoe.
- Non Motorized vessels/watercraft and fishing gear are likely very important in spreading this species. Any program should:
    - Conduct outreach/education coupled to any decontamination protocols. These would be likely target the following areas:
        - Angler shops, bait shops, big retailers (Cabela's etc.), dive shops
        - Fire fighters who's equipment is used in Lake Tahoe and surrounding waters.
        - Commercial/private 'guides' - fishing equipment, rafts, kayaks, etc.
        - Consider a sticker program similar to the motorized craft program that confirms that boats/watercraft are 'Tahoe only' or inspected and washed prior to introduction & exit of the lake.
    - Install wash stations with full staffing in areas where non motorized personal watercraft equipment is used (e.g. beaches, public access points etc.) with a goal to see and use this equipment. Suggested station types include:
        - Boot/gear decontamination type stations at shore fishing and stream fishing access points.
        - CD3 system like the ones already in place.
    - Require the use of check stations for all watercraft users (e.g. rafters, floating tubes, fisherman, contractors, divers, float planes, etc). We note that this would need adequate enforcement.
        - Enhance oversight on current practices. This may involve hiring external consultants (not part of the AIS program) to objectively determine if marinas, contractors, vendors, etc. are in compliance with inspections and equipment cleaning.

<u>To minimize movement of NZMS within the region</u> (if population is found outside of Tahoe Lake)

- Outreach/Education regarding necessary decontamination protocols for watercraft of all types.
    - Target angler shops, bait shops, big retailers, dive shops
    - Guides- fly fishing, kayaks, etc.
- Wash station
    - Boot/gear decontamination type stations
    - CD3 system
- Required check stations for water users… floating tubes, fly fisherman
- Many of the same tools as above

Control and Eradication Efforts within Lake Tahoe

Currently, there are no successful methods to control or eradicate NZMS from natural systems. This is particularly true when the population of snails has spread across the spatial scale currently seen in Lake Tahoe (approximately 8 million square meters of lake habitat). In order to provide guidance on any potential methods of control, we need further information on the distributions of snails around the lake, in streams, wetlands, meadows or other locations. It is also important to note that if, by some chance, we were able to eradicate the snails from the area of South Lake Tahoe, but the snails exist in other regional or watershed locations or in other areas of the lake, the snails can, and eventually will, reestablish in the South lake area. Thus control efforts are not likely to be possible at the scale and time frame we see currently in the lake. Any efforts that attempt control or eradication within the lake will incur significant costs and a very low chance of success.

Below are some control options that could potentially be effective in small, extremely limited or enclosed areas of infestation (i.e. hatcheries, small first or second order streams, tiny farm ponds etc.). As a committee we are not in agreement as to whether financial resources should be directed toward attempting these types of control efforts for this species in this lake. The majority of members believe that any funds would be better spent towards quantifying the impacts of this invasion on the Tahoe ecosystem and more importantly towards prevention of the spread of NZMS to other locations within the basin and other areas.

<u>Physical Removal</u>:

Due to the mobility and high reproductive rates, coupled with their distribution at both relatively shallow and deep areas, complete removal or killing NZMS populations is extremely difficult and logistically complicated. The most immediately effective method would be physical removal using diver-guided suction devices that minimize substrate disturbance while ‘lifting’ the snails and depositing them in fine-meshed screened containers. However, snails also prefer disturbed habitat so this action, although effective in the short term (i.e. months) would be likely to increase their numbers on longer time scales (i.e. years). Given the varying densities at South Lake Tahoe, this method would need to be rigorously tested for efficacy and efficiency. In addition, monitoring protocols and BMP’s would need to be developed before removal started. Small infestations (e.g. new loci of spread) would be most suited to physical removal of this sort. Using the Asian clam control project in the late 2000s as an example, efforts such as this will likely cost in the millions to tens of millions of dollars to perfect and calibrate.

<u>Burying/Covering</u>:

Bottom barriers have been used in attempts to control Asian clams, with very limited success. However, NZMS are gastropods not bivalves, and may be more (or less) susceptible to low dissolved oxygen. Bottom barriers have the advantage of working in isolated areas and thus potentially preventing movement of the covered snails. This method would be difficult to implement at the lake scale, and given the depth some snails have been found (150 m), such efforts would be costly.

<u>Chemical Treatments</u>:

There are few potential chemicals (e.g. molluscicides) with EPA labels for use, and most require extended contact time for lethality, which would be challenging to achieve in localized areas of open water. Table 3 below lists these possible chemical treatments, including methods to increase pH to levels lethal to the NZMS. These chemical treatments would be limited to small size due to cost, permitting, optics, and impact to other species.

Table 3. Summary of Chemical Treatment Options for small localized areas with NZMS

Chemical Treatments	**Concentrations based on Research**	**Reference**
Copper Products	~30 ppb for 1 month	Oliver et al. 2021 Stockton-Fiti 2023
Bayluscide	1 mg/L nicolosamide concentration over 8 h resulted in a 98% mortality, half life is in days (2.6 days in sediment)	McMillin and Trumbo 2009
Bases (Sodium or Calcium Hydroxide)	Achieve pH 12 for >39h (NaOH) and >65h (CaOH)	Barenberg and Moffitt 2018
Acids	Further research needed, high alkalinity neutralizes	Stockton 2011
Salinity increase	Potassium chloride potential, but research needed to combine with another chemical	Stockton 2011, Moffitt and Stockton 2017

In addition, the current prohibition against using aquatic pesticides in Lake Tahoe would require a special exemption from the Lahontan Regional Water Quality Control Board. The process of getting approval could take months to years.

A combination of bottom barriers and ‘injected’ or inserted chemicals may provide local exposure concentrations and durations sufficient to kill NZMS, but at this point this is entirely theoretical and would likely only be feasible for small areas (e.g. <10 sq meters). An approach like this was found to be effective for eradication of invasive marine alga *Caulerpa taxifolia* (Anderson 2005).

<u>Heat/ Cold</u>

Freezing for several hours is required to kill NZMS. Although ice does form in Lake Tahoe along some shallow areas (e.g. Tahoe Keys lagoons), most shorelines do not freeze, and even shallow near shore areas in Lake Tahoe proper, typically do not freeze in the winter.

High water temperatures (>40 ºC) can kill NZMS; however, creating those temperatures at depths of >30 m is difficult to conceptualize. Shallow water populations might be controlled with hot water or steam, but this method is likely to disturb the benthos and ultimately spread snails.

Copper Barriers and Weirs

Depending on the location of the infestation (a closed, contained area), copper barriers may be put in place to limit the spread of the NZMS to upstream areas (Hoyer and Myrick 2012) with considerable effort to minimize reintroduction into this protected area. Installation of weirs containing copper plating can limit upstream migration of NZMS in flowing water habitat and therefore slow the snail’s spread into sensitive areas (Moffitt and Stockton 2017).

<u>What is the likely impact of the current infestation and how could you assess the impacts (if any) from snails to the ecosystems in the Lake Tahoe basin?</u>

NOTE: This is not an exhaustive overview of the impacts of invasive mudsnail invasions on aquatic ecosystems. The literature consists largely of experimental studies, natural observations, and theoretical understanding of impacts to freshwaters. The impacts of snails on flowing (lotic) waters (rivers, streams) dominantes the literature. There is less published peer reviewed literature on the snail's effects on stationary (lentic) water.

New Zealand mudsnails have been reported to achieve densities of 40 to over 800,000 individuals per square meter. There are also many instances of dramatic 'boom and bust' cycles with NZMS. In these, very high densities occur soon after an invasion but the high numbers crash into much lower densities in the years to decades following the invasion, depending on the ecosystem. This 'boom and bust' pattern is fairly common when invasive species establish within an ecosystem (Lockwood et al. 2013). The broad range of potential densities is concerning for this panel because the overall density of snails will influence the ecological persistence, movement, and impact to the Lake Tahoe ecosystem.

Due to their eating habits, mudsnails can reduce biofilms of bacteria and algae which grow on benthic substrates, reduce the community composition of certain types of algae (e.g., diatoms) while leading to an increase in unwanted filamentous algae. Filamentous algal blooms (e.g., green algae *Zygnema*) are of particular concern in Lake Tahoe and the other so-called pristine, 'clear water' bodies in the world. The snails can alter nutrient cycling (e.g., nitrogen) and nitrogen fixation which may benefit some algal taxa like cyanobacteria which fix nitrogen. Lake Tahoe's nearshore algal biofilms have been shown to be limited by nitrogen down to 30 meters in the lake. As a consumer of algae/detritus, NZMS will likely impact the processing of carbon and organic matter, native invertebrate density and composition, and the flow of energy into aquatic food webs. Native snails have been shown to be highly vulnerable to invading New Zealand mudsnails. In addition, the NZMS can influence the behavioral characteristics of other invertebrates (e.g., Baetidae mayflies) by reducing their feeding rates, and altering the colonization of substrates.

Lake Tahoe houses a number of endemic macroinvertebrate species of concern (e.g. ramshorn snail, Tahoe stonefly and two species of blind amphipods etc.) which are sensitive to environmental perturbations due to their current low densities. These sensitive endemic macroinvertebrate species likely play a small but important role in the ecosystem. It has been shown that fish predators can consume invasive snails, but the well protected snails often pass through the digestive systems unharmed thereby facilitating their movement to new locations. In other words fish and other predators can act as dispersal vectors for the snails within a system. NZMS survival rates after consumption by fish ranges widely across studies and fish taxa but is significant. As a result, mudsnails are considered to be a nutritionally poor food for fish consumers and therefore their impacts on fish populations are mixed; with some demonstrated negative effects on fish health and zero impacts in other studies. The ecology of Lake Tahoe's current fish communities has not been been the subject of detailed study for the past 20+ years, yet what we have observed is a 10 fold decline in native nearshore fishes between 1960 and the early 2010s.

The potential for large-scale ecological impacts of NZMS in Lake Tahoe and the associated tributaries and wetlands appear to be large. As a result, it is likely that we will need to alter management strategies to protect the lake's nearshore and offshore water quality and clarity (e.g, Total Maximum Daily Load) and the overall health of freshwater ecosystems in the basin (lakes, streams, meadows). Given this assessment, we feel that the questions listed below will need to be addressed sooner rather than later.

We believe that the prioritized list of questions (below) will assist in the development of a risk assessment for the NZMS. With the current published data, at this time, we are not able to determine the exact risk posed for Lake Tahoe. Yet based on the literature that we do have (see above), we feel we have a good idea of what the impacts may be if the snails expand and increase in numbers throughout the lake and within the basin. In addition to evaluating the risk of the impact, we want to consider questions around gathering baseline information (prior to an expansive invasion around the lake), so that future impacts (years to decades) can be evaluated for this and other AIS. **We emphasize the need for collecting baseline conditions from Lake Tahoe, its tributaries and sensitive ecosystems (e.g. meadows) prior to the expansion of the snails across the basin.**

1. What is the potential and perceived impact of the snails on human recreational use (e.g. recreation on beaches, swimming, fishing) and to the water supply of Lake Tahoe. Answering these questions presents an opportunity to work with and educate stakeholders in the basin including the Tahoe lakefront homeowners association, water purveyors and fishing guides. NOTE: NZMS are known to clog filters and can alter the nutrient cycling of organic matter, so working with water purveyors and homeowners who draw water from the lake will be important.
2. What are the priority and/or sensitive locations within the basin where more intense focused baseline studies are needed? A joint management and science team should be convened quickly to determine which ecosystems (e.g., stream, meadow, within lake deep water plant beds etc.) need to have baseline ecological assessments (not just biodiversity) prior to invasion. Some ecosystems identified by this panel include the deep-water plant beds, Cascade Lake and Meiss Meadows (Cutthroat trout populations), Marlette Lake (which holds a brood stock for native Cutthroat trout), and the Upper

Truckee River (where Margaritifera spp. mussels occur), other meadows which support willow fly catcher or frogs which may use invertebrates for their food supply.

3. How will the invasive mudsnails change the benthic ecology of Lake Tahoe and other smaller water bodies? The bottom of lakes act as critical areas for nutrient and particle processing, which in turn support the lake's fish communities and biodiversity. Questions to address whether snails will a) impact the growth, composition, and chemistry of biofilms (bacterial, pathogens, and algae), b) change nutrient cycling in the nearshore (defined down to 21 meters for Lake Tahoe) on hard (rock) and soft (sand, organic bottom) substrates, c) alter the color and optics of the near-shore substrate due to high densities of NZMS shells and d) affect the composition and density of the invertebrate and fish communities should be prioritized. Efforts should be made to catalog and store DNA samples for genetic preservation of endangered or declining species.
4. What are the current baseline conditions of the lake food webs and what are the functional characteristics (nutrient, carbon processing, particulate removal) for the lake (nearshore, offshore)? How are these conditions different in the more sensitive areas rich with endemic (only found in) biodiversity (e.g., deep water plant beds)? What is the diet and density of fishes across seasons in different locations throughout the lake. There is a 10 fold decline in native fishes since the 1960s so baseline characterizations for present day are needed to further understand changes to the lake's biology and their feedbacks through the food web.
5. What is the distribution and baseline conditions for other sensitive taxa (e.g. amphibians etc.) outside of the main lake across the region's meadows and streams? This work could support the efforts of the Tahoe Environmental Observatory Network led by the US Forest Service. Work in these areas could be completed in coordination with the USFS Lake Tahoe Basin Management unit which currently conducts surveys and has historical baseline data in Lake Tahoe.

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Supplementary Information.

In another (hypothetical) rapid response situation, would you change rapid assessment survey methodology from what was carried out for NZMS?

This requires a more detailed discussion. We recommend the following: surveillance of Lake Tahoe's biology (native and non native) needs to occur annually, targeting existing species BUT also thinking about the next likely invaders to the lake. Surveillance is VERY IMPORTANT and needs to be prioritized. Multiple methods will likely need to be developed and would require additional conservations that were not possible due to time constraints of this panel. It is critical at this point to consider an evaluation of multiple survey methods at the low density sites to evaluate costs, feasibility, limitations, and detection sensitivity.

How should the Lakewide Monitoring Plan be adapted to include NZMS? Are there other high risk species that we should be including in monitoring efforts?

We did not have time to discuss this but there are local scientific experts along with agency experts that could be consulted. This should be a priority and using existing local expertise is important to consider.

Answers to specific questions presented by the managers to the Technical Science Advisory Committee.

How do snails move around?

- They have the ability to climb up plants and "release" to float on surface of the water
- They are easily dispersed from sediments and other surfaces by wave and current action
- They will crawl upstream in search of food sources
- Can hitchhike on plant fragments, algae/moss mats
- They can pass through live through fish & waterfowl guts
- Disturbance of sediments will move them
- Burrow into, and live within mud to avoid stresses or disturbances
- Will close up (seal their shells) and fall to ground off of plant material or surfaces
- Neonates (immature snails) disperse by crawling on surfaces, and through water column with and are easily moved by water movement

Can they be suspended in the water column and hydrostatically attach to boats?

They can be transported in the water depending on the flow and energy of the waves. They will attach to motorized and non motorized boats.

What is the likelihood of them being pumped into live wells and ballast tanks?

Likely.

Should we extend a no-wake zone in the currently infested areas of the South Shore?

In the long run the snails will be able to transport around the lake whether through human facilitated movement, fishes/birds, or via physical action. We agree that extending a No Wake Zone in south lake along the shelf could help reduce the movement of snails and elevate them into the water column. In addition, this would be good practice for minimizing other invasive species that might establish in the South shore like plants and allow time for management of these species, if detected through regular monitoring.

Close off area of infestation w buoys/signs (no boating, no filling ballasts, no anchoring, no fishing?)

We recommend limiting or restricting anchoring in infested locations.

“Spill where you fill” re: ballast
Why wouldn’t you do this anyway? Could help minimize the spread of other invaders that may establish in the lake. We recommend doing this for NZMS and all invasive species.

Discuss feasibility and efficacy of control methods currently used at Lake Tahoe and how they might be used/adapted for NZMS (diver-assisted suction, barriers, UV light). Other methods and how they might be used at Lake Tahoe (copper barriers, freezing, etc.)

There are NO feasible control methods at the current scale of infestation. Details are discussed in the report.