Invasion of the non-indigenous nuisance mussel, *Limnoperna fortunei*, into water supply facilities in Japan

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**ABSTRACT**

The aquatic nuisance mussel, *Limnoperna fortunei*, arrived in Japan before 1987 possibly with the Asian clam imported as food from mainland China. Now the mussel’s distribution has spread to two river systems in central Japan.

Water authorities reported several cases of damage caused by *L. fortunei*. Most cases of damage were caused by dead mussels clogging small diameter pipes for raw water sampling and monitoring and for cooling water. Clogging of cooling water pipes stopped raw water pumping to a water purification plant and caused the shutdown of a turbine dynamo-electric generator in a hydraulic power plant. The attachment of *L. fortunei* caused the malfunction of a water level gauge. There was a heavy accumulation of dead *L. fortunei* in slurry treatment facilities and rotten mussels developed an offensive odour.

Although the screens and pipes of the raw water intake and transmission were inhabited by *L. fortunei*, problems relating to their decreased hydraulic capacity were not reported. This may have been due to the low reproduction rate and short lifespan of *L. fortunei*. There was one reproduction period each year, during May to September and their lifespan was two years at most. The growth rate could be about 15 mm yr⁻¹ in shell length. Although chlorine in either free or combined form is effective for the control of *L. fortunei* larvae, so far water supply authorities have not considered prechlorination in the intake, mainly because prechlorination deactivates the biological nitrification along the pipelines.

**Key words** | freshwater mussel, impact, inhabitation, invasion route, *Limnoperna fortunei*, water supply facilities

**INTRODUCTION**

The freshwater mussel *Limnoperna fortunei* (Dunker, 1856) is a small, byssate bivalve (Figure 1) that is indigenous in China. Countries inhabited so far are China, Korea, Taiwan, Thailand, Argentina and Japan (Morton 1973; Nakai 1995). *L. fortunei* belongs to the same family as the edible mussel, moule (*Mytilus galloprovincialis*). Like the zebra mussels (*Dreissena polymorpha*), *L. fortunei* adheres to hard surfaces with byssal threads and the byssal adhesion leads to biofouling of natural and man-made structures. This epibenthos infestation of water intake structures and pipes has caused biofouling and related problems in China and Korea (Morton 1975; Choi et al. 1982; Tan et al. 1987; Cai 1991). In Japan, *L. fortunei* was first found in Lake Biwa in 1992 (Matsuda & Uenishi 1992); later, Kimura reported that the mussel found in the Ibi River in 1990 was *L. fortunei* and that the first infestation should have occurred before 1989 based on the shell size of the mussel (Kimura 1994). Presently, its distribution has spread to rivers and a lake in central Japan and 7 out of 47 prefectures are infested. This paper describes how *L. fortunei* arrived in Japan, its density in rivers, lakes, water facilities, and the types of damage it is causing.
Biofouled pipe surface with *Limnoperna fortunei*.
HABITAT DISTRIBUTION AND DENSITY IN SURFACE WATERS

Two water systems were confirmed to be infested: the Lake Biwa-Yodo River system and the Kiso-Nagara-Ibi River system. Figure 2 shows habitat distribution and habitat density in the Lake Biwa-Yodo River system and the Kiso-Nagara-Ibi River system. *L. fortunei* inhabited more than 100 km along the rivers from the estuary. No *L. fortunei* was found in brackish water in the estuary, but a subspecies (*L. fortunei kikuchi* Habe) was found, probably because of the low salinity tolerance and osmoregulation of *L. fortunei*. The highest abundance recorded was more than 10,000 individuals m$^{-2}$. In the Lake Biwa-Yodo River system, the most infested area was the impounded water at the Amagase Dam, and the habitat distribution had not spread further north of Lake Biwa. Figures 3 and 4 show weekly variations in the concentration of *L. fortunei* larvae at the Amagase Dam in the Yodo River (Oida et al. 1998) and in the Nagara River, respectively. The reproduction period was from May to September, during which the water temperature was above 20°C. At the Amagase Dam, the larvae concentration also varied widely with the discharge from the dam, which suggested that the larvae had run out with the dam discharge. The highest reproduction rate occurred in the impounded dam water and the inflow water diluted the concentration of larvae. The greatest abundance of adult *L. fortunei* was observed in the dam reservoir, as shown in Figure 2.
The lifespan of *L. fortunei* was estimated from the seasonal changes in shell length frequency. Figures 5 and 6 show data from Lake Biwa and the Yodo River, respectively. In Figure 5, a new peak with shell length less than 10 mm appeared in September 1995 (the distribution became bimodal), and this cohort was believed to be the mussels produced in that year. Tracing this cohort with time, we deduced that the shell length grew by 15 mm yr⁻¹. Assuming that reproduction time was July, the average shell length of 1-year-old *L. fortunei* found the following July would be around 15 mm. The data also suggest that most of the adult *L. fortunei* die between the first and the second reproduction period. Iwasaki and Uryu investigated the gonad development of both sexes of *L. fortunei* in the Uji River (a tributary river of the Lake Biwa-Yodo River system) from 1994 to 1995, and reported that the species reproduced from June to September 1995 (Iwasaki & Uryu 1998). They also suggested a lifespan of 2 years based on the shell size distribution.

However, higher reproduction and growth rates have been reported for *L. fortunei* in other countries. Reproduction occurs twice a year in Hong Kong (Morton 1982); *L. fortunei* lives for more than 2 years in Korea (the largest expected value of average lifespan was 4.5 years) (Choi et al. 1982), and lives longer in the central part of China (Cai 1991). The lifespans of zebra mussels are also variable between places: these can be categorized into two groups (Nalepa et al. 1993). The first group, slow growing but...
living longer than 3 years, has been reported for European populations. The second group, fast growing, is typical of populations in the UK as well as North America. Some of the characteristics in the population dynamics of L. fortunei are similar to those of zebra mussels in North America (Nalepa et al. 1993; Claudi & Mackie 1994; D’Itri 1997). Adult zebra mussels grow 1.5–2.0 cm yr\(^{-1}\) and most of them die after 1.5–2 years of age. However, the presence of the three distinct cohorts throughout most of the year was indicated by the analysis of the length-frequency distributions of zebra mussels, which suggested that there are two major recruitment events (birth periods) per year (Nalepa et al. 1993). Peak reproduction occurs in June and July, but larvae that are born in the spring can grow to reproduction size and contribute to an autumn recruitment.

**HABITAT DISTRIBUTION AND DENSITY IN WATER INTAKE AND TRANSMISSION FACILITIES**

Since 1994, L. fortunei’s invasions into water supply systems located at the Lake Biwa-Yodo River system have been confirmed through surveys conducted by the water supply departments of local governments in the infested area. L. fortunei resided in the water intake and transmission facilities and entered the flocculators/sedimentation basins of water purification plants. Grit chambers and raw water conveyance mains were biofouled with L. fortunei. The highest abundance reported was 45,000 individuals m\(^{-2}\) in a transmission pipe for raw water from the Yodo River. A biofouled pipe surface with L. fortunei is shown in Figure 1. Figure 7 shows the seasonal variation in shell size frequency of L. fortunei in a transmission main. A similar pattern of the variation in shell size frequency to those in natural waters (Figures 5 and 6) was observed, and the size distributions of L. fortunei surveyed in the autumn had two peaks at 5 mm and 20 mm shell length. The first and second peaks corresponded to the cohorts of mussels born in that year and the previous year, respectively. From the data of the surveys, it is confirmed that the reproduction and settling period was between spring and summer and that the mussel shell grew by about 15 mm yr\(^{-1}\).
The survey of May 1998 divided attached mussels into live/dead. The lower left of Figure 7 shows the shell size distribution of mussels attached to the surface of the main in May 1998. A cohort of mussels whose shell lengths were less than 10 mm had already been observed, and were believed to be newly settled in that year: the water temperature rose earlier than usual in 1998, and might have accelerated the development of gonads and reproduction. About 50% of the mussels with 15–17 mm shell length, which should have been 1-year-old, were dead. This data is consistent with *L. fortunei*’s lifespan of less than 2 years, as previously stated.

The amount of dead *L. fortunei* conveyed from the rubbish removers of grit chambers at a raw water pumping station reached a peak in summer, as shown in Figure 8. This period of the peak corresponded to, or existed just after the reproduction period, which leads to the assumption that *L. fortunei* started to die after the reproduction phase. Figure 9 compares the shell length distributions of mussels attached in a transmission main and of dead mussels deposited on a flocculator. A bimodal distribution was observed for the live and attached mussels, but the dead mussels had a single peak in shell length distribution. The average length of the dead mussels was 22 mm. These results are in accordance with the estimation that *L. fortunei*’s lifespan is between 1 and 2 years and they could live no longer than 2 years in these facilities.

In Figure 10, the abundance of mussels in transmission mains is plotted against distance from the intake gate. The infestation occurred along the direction of the water flux and the intensity of mussel fouling decreased with the distance (in other words, the duration of flow). No mussel attachment was observed in the main further than 10 km from the intake.

The number of *L. fortunei* attached on the transmission main also varied with the hydraulic condition at the settling point. Figure 11 compares the mussel abundance at a straight section, a branched section, and a pipe bend (the inside of the curve). These sections were selected from the same main and were equivalent in distance, so the effects of distance and influent water quality could be disregarded. The least fouled section was the branched section, possibly due to high turbulence. The pipe bend
was the most fouled, perhaps because of the wakes of slow fluid velocity at the pipe wall surface. A detailed hydraulic analysis would be useful.

**DAMAGE**

The damage caused by *L. fortunei* included: dead specimens of *L. fortunei* clogged small diameter pipes transmitting raw water in: (1) sampling pipelines (typically, 25 mm inner diameter) for water quality monitoring; (2) cooling pipes of conveyance pumps in a water intake-and-pumping station; and (3) cooling pipes of a turbine dynamo-electric generator in a hydraulic power plant. The clogging in the second case caused insufficient cooling water supply in heat exchangers and an unexpected shutdown of the raw water pumps to a water purification...
Dead *L. fortunei* accumulated in the inlets of cooling pipes and clogged them (Figure 12) (Nakanishi & Mukai 1997; Yamada *et al.* 1997). The cooling system had strainers that were quite capable of filtering out particles of the mussel’s size, but larvae passed through the strainers (the D-form veliger is 100 µm in length as shown in Figure 1) and settled on the inside surfaces of the pipe between the strainers and the cooling pipes. Dead *L. fortunei* detached, flowed and accumulated in the inlets of the cooling pipes. The same kind of clogging occurred in a hydraulic power plant, where 200 kg of dead *L. fortunei* accumulated and clogged the cooling pipes of all eight heat extractors of a turbine dynamo-electric generator (see Figure 13). The clean-up and restoration took 10 days of 24-hour work. The decrease in effective hydraulic radius of the cooling pipes by the attachment of *L. fortunei* had already been emphasised (Cai 1991).

Grit chambers and flocculators received a large amount of sediment from dead *L. fortunei*. Strainers in slurry treatment lines were heavily clogged and needed restorative work before being taken back into operation. *L. fortunei* adhered to a water level gauge and caused its malfunction in a water intake and pumping station.

Figure 14 shows the cases of damage caused by *L. fortunei* monthly from 1995 to mid-1997 in the facilities of Osaka Prefectural Water Works Department. In the summer of 1995 and 1996, damage was intensive: the season corresponded to the period when *L. fortunei* died and were run off to the facilities downstream. In fact, most cases of damage were related to the dead and detached *L. fortunei* that clogged the constricted parts of the flow. No damage was reported after February 1997 because
counter measures had been taken to meet the situation. Most of the problems (clogging of small diameter pipes) were avoided by inserting sediment traps in pipelines. Although research revealed that chlorine either in the free or combined form is effective for the control of L. fortunei larvae (Water Resources Development Public Co., personal communication), water supply authorities in Japan have not planned a preoxidation step with chlorine in the intake for the following reasons. One is that the nitrification of ammonia by the biofilms growing on the
The internal surface of pipelines will not be expected with chlorination, although the function of the nitrification in the pipelines was not intended in the design and was only noticed after maintenance. The other disadvantages are disinfection by-product (trihalomethanes (THMs) and other halogenated organic compounds) problems and safety problems with storage of liquid chlorine. However, THM formation by prechlorination for the control of zebra mussel larvae has been successfully reduced by the simultaneous dosage of chlorine dioxide and chlorine (Schalekamp, personal communication).

So far, the mussel attachment has not caused problems by reducing the hydraulic transmission capacities of large structures, such as raw water main pipes and screens, by the increased corrosion potential, or by encrusting hulls of ships; nor has the natural death of mussels affected taste, although these kinds of damage have been reported for the zebra mussel (Nalepa et al. 1993; Claudi & Mackie 1994; Schalekamp, personal communication). This is probably due to the low reproductive rate and the short lifespan of *L. fortunei* in Japan. The population densities of zebra mussels, which have higher reproduction rates and a longer lifespan, are expected to be one or two orders of magnitude higher than those of *L. fortunei*: time-average density is 100,000 individuals m$^{-2}$, density may range up to 1,000,000 individuals m$^{-2}$ (Nalepa et al. 1993; Claudi & Mackie 1994; D’Itri 1997). Zebra mussel larvae concentrations in the order of 100,000 individuals m$^{-3}$ were reported (Nalepa et al. 1993; Schalekamp, personal communication), which is ten times the concentration of *L. fortunei* larvae. Water treatment plants have been shut down and influent flow rates reduced considerably because of zebra mussel infestation and clogging (Nalepa et al. 1993).

**INVASION ROUTE**

One possible route for *L. fortunei*’s arrival in Japan is believed to be through the edible freshwater clam (*Asian clam, Corbicula fluminea*) imported from China. In 1987, *L. fortunei* was found among live clams imported from Lake Taihu of Jiangsu Province, China (Nishimura &
Habe 1987). *C. fluminea* is imported alive as food: Figure 15 shows *L. fortunei* attached to *C. fluminea* imported from mainland China. Imported live clams do not necessarily go to markets shortly after arrival. Some may be preserved or released into rivers to adjust the shipment according to the market price. Some areas infested by *L. fortunei* coincide with the areas where the fishery and aquaculture of the Asian clam has developed and where the import business of the clam is popular. A possible entry route of *L. fortunei* into Argentina was suggested to be the trading ships from Korea and Hong Kong (Darrigran & Pastorino 1995).

**SUMMARY**

The non-indigenous mussel, *L. fortunei*, arrived before 1989 in Japan. This small bivalve adheres to hard surfaces with byssal threads and the byssal adhesion leads to biofouling of natural and man-made structures. Its distribution has presently spread to rivers and a lake in central Japan: the Lake Biwa-Yodo River system and Kiso-Nagara-Ibi River system. Seven out of a total of 47 prefectures are presently affected.

Since 1994, *L. fortunei*’s invasions into water supply systems in the Lake Biwa-Yodo River system have been observed. *L. fortunei* resided in water intake and transmission facilities and reached flocculators/sedimentation basins of water purification plants. Grit chambers and raw water conveyance mains were biofouled with *L. fortunei*. The lifespan of *L. fortunei* in the water intake and transmission facilities was up to 2 years, which was the same as in the infested rivers and the lake. The same patterns of shell length frequency and its seasonal variation were observed for these facilities, the rivers, and the lake. *L. fortunei* reproduced from May to September and reached an average shell length of 15 mm in the next season.

The mussels caused clogging problems in water purification plants and an electric-power generation station. The damage reported included the clogging of small diameter pipes transmitting raw water by dead *L. fortunei*. In particular, the clogging of cooling pipes caused the shutdown of raw water pumping motors and a dynamo-electric generator. No critical increase in the hydraulic resistance in raw water transmission mains or screens by the attachment of *L. fortunei* has been reported so far, perhaps due to the low reproductive rate and short lifespan of *L. fortunei* in Japan.

One possible entry route of *L. fortunei* to Japan was with the edible freshwater clam *C. fluminea* imported from China. Considering that the northernmost habitat reported is North Korea and that *C. fluminea* is also imported to other parts of Japan, *L. fortunei*’s distribution cannot be limited to the present infested area. From the perspective of surface water facilities in these regions, their invasion and byssal adhesion are a cause for concern.

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