Impacts of *Limnoperna fortunei* on Man-Made Structures and Control Strategies: General Overview

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Abstract In China and South America, severe fouling problems caused by *Limnoperna fortunei* have been reported for a number of industrial facilities, including water and wastewater processing plants, power plants (nuclear, hydroelectric, thermal), refineries, steel mills, fish culture facilities, water transfer canals and aqueducts, and watercraft. In Japan, biofouling chiefly affects agricultural irrigation systems, balancing reservoirs and balancing tanks. However, most available reports furnish little detail on the components affected and on the measures taken to cope with the nuisance. Objective estimates of the economic losses involved are extremely rare. Although fouling by the golden mussel has occasionally derived in operation at below-standard regimes and even temporary plant shutoffs, as maintenance personnel acquired experience in curtailing mussel growth in sensitive areas, serious incidents have become less common. Fouling by *L. fortunei* has not caused a single definitive plant shutdown. Control methods assessed (either in laboratory settings or in actual plant operating conditions) include antifouling materials and coatings, chemical treatments, manual/mechanical cleaning, filtration, thermal shock, anoxia and hypoxia, desiccation, ozonation, ultraviolet treatment, electric currents, ultrasound, manipulations of flow speed, biological control, and various miscellaneous methods.

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Introduction

In contrast to its known effects on ecosystems, which often differ from those of the zebra mussel (Boltovskoy and Correa 2015; see Chapter "Ecology and Environmental Impact of *Limnoperna fortunei*: Introduction" in this volume), the impacts of *Limnoperna fortunei* on man-made structures and facilities are almost identical to those described for dreissenid species. Hundreds of papers and several excellent reviews have been published concerning these impacts during the long history of the invasion of Western Europe and North America by the zebra and quagga mussels that began in the nineteenth century (Claudi and Mackie 1994; McMahon et al. 1994; Sprecher and Getsinger 2000; Rajagopal et al. 2000; Nalepa and Schloesser 2014). The comprehensive manual by Mackie and Claudi (2010) provides a detailed review of the problems caused by freshwater fouling mussels around the world, for which reason we will not repeat this information here.

History, Spread, and General Appraisal of Macrofouling Problems Caused by the Golden Mussel

Although in its native range (China) the golden mussel has likely been a nuisance for centuries, information in the older Chinese scientific literature is oddly absent regarding *L. fortunei* and reports on macrofouling-related problems are restricted to marine mussels (e.g., Lou and Liu 1958). The presence of *L. fortunei* had been mentioned (Tchang et al. 1965), but information on its impacts on man-made structures is only found in isolated internal reports (GPS (Pipeline Study Group) 1973). This is partly due to the fact that until the first half of the twentieth century, the geographic range of the golden mussel was restricted to southern China, Thailand, Laos, Cambodia, and Vietnam. In the latter four countries, it was probably introduced through human actions (Morton and Dinesen 2010), and the range of *L. fortunei* started expanding greatly in the 1980s (Fig. 1). According to Xu (2013), *L. fortunei* was originally only found in southern China with the Yangtze River as its northern boundary. In the 1980s, it appeared in the Yellow River basin, and recently it has been found in the waters in and around Beijing (Ye et al. 2011) (see Chapter "Distribution and Spread of *Limnoperna fortunei* in China" in this volume). Thus, the first publications to point out the potentially harmful nature of the golden mussel (Morton 1973, 1975), as well as the first investigation on alternatives to control its fouling of raw water pipelines (Morton et al. 1976) are associated with the colonization of Hong Kong's freshwater supply system through water diversion works from the East River, a tributary of the Pearl River, which forms part of the native range of the mussel. At approximately the same time, fouling by *L. fortunei* was reported in

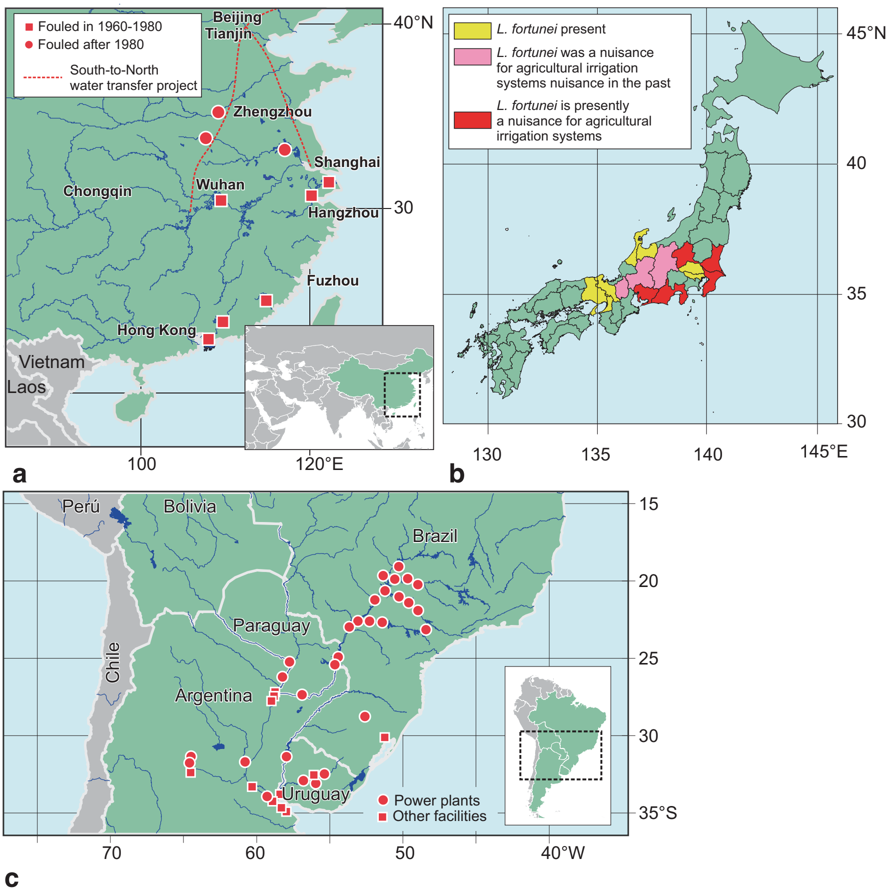

Fig. 1 Location of some industrial facilities in **a** China and **c** South America that have experienced mussel-fouling problems. Power plants include hydroelectric, thermal and nuclear facilities. "Other facilities" include refineries, steel factories, water and food processing plants, etc. **b** Japanese prefectures where *L. fortunei* is present but does not cause major harm (*yellow*), where it was a nuisance in the past (*pink*), and where it presently represents a problem (*red*)

cooling water pipes of one of the largest steel mills in China—the Wuhan Iron and Steel Corporation (GPS (Pipeline Study Group) 1973), and in the 1980s problems became widespread affecting many industrial and water transfer facilities, like those of Handan in Hebei Province (Xiang 1985), Xiamen in Fujian Province, Wuxi and Suzhou in Jiangsu Province. Some, like the water treatment plant in Suzhou, had temporary shutoffs due to pipe clogging by *L. fortunei* (Luo 2006).

In order to facilitate the fast industrialization and modernization process of the last decades, numerous inter-basin water diversion projects have been undertaken in China, thus improving the distribution of water across the country. While beneficial for the country's development, these aqueducts became a major vector for the mussel's geographic spread (Xu et al. 2009a). Vivid examples of these problems are the water diversion works that draw water from the East River, a tributary of the Pearl River (Morton 1975; Xu 2013). One of these pipelines supplies water to Hong Kong and the western part of Shenzhen (Morton 1975), while another, "the East River Water Source Project," transfers water to Huizhou, Dongguan, and the eastern part of Shenzhen (Xu 2013). All the reservoirs, lakes, and water transfer systems connected with these two water diversion works have already been colonized by golden mussels, thus requiring maintenance and cleaning tasks which, according to some estimates, amount to over US$ 1 million per year. Significantly, there are at least 30 such long-distance water diversion works in the Pearl river basin, built at a total estimated cost of US$ 12.4 billion (Guangdong Government 2010), almost all of which are potentially at risk of fouling by the golden mussel. Additional large aqueducts, in particular the huge "South-to-North Water Transfer Project" (Fig. 1), aimed at connecting the water-rich areas of the middle and lower Yangtze River with water-poor Beijing (see Fig. 1 in Chapter "Distribution and spread of *Limnoperna fortunei* in China" in this volume), will further worsen biofouling problems by *L. fortunei*.

In recent years, *L. fortunei*-related fouling became increasingly common in hydroelectric power stations. One of us (M. Xu) has had first hand contact with four of these power plants: Shisanling (in Beijing), Langyashan (in Anhui Province), Tianhuangping (in Zhejiang Province), and Guangxu (in Canton Province). This last one requested assistance for controlling the mussel. Fouling is common on concrete underwater structures, valves, trash racks, gates, etc. Dense mussel beds ca. 10 cm in thickness significantly increase resistance to water flow, enhance corrosion, clog pipes, jam mobile components, and pose serious safety risks for the plant's personnel (Li and Su 2007; Yao and Xu 2013).

This issue has drawn increasing attention since 2000. As of 2013, at least eight major scientific and technological projects associated with freshwater mussel fouling are underway. Several control strategies have been attempted, either on experimental scales, and/or under plant operating conditions, with variable success (Table 1).

Outside of mainland China, reports of problems associated with fouling by *L. fortunei* in industrial and water-treatment facilities started appearing a few years after the mussel's invasion. In Taiwan, Tan et al. (1987) reported heavy clogging of water intake grates at a water treatment facility, but they also mentioned that *L. fortunei* was first described from the island in 1941 (Kuroda 1941, as *Volsella (Limnoperna) lacustris*; although this record was subsequently questioned by Huang (2008). Interestingly, it was not included in the catalogue of Taiwanese terrestrial and freshwater mussels produced by Pilsbry and Hirase in 1905, which suggests the possibility that it was introduced between the turn of the century and 1940. In Korea, where it was introduced in the late 1970s to early 1980s, Kojima (1982) was the first to review its biology, fouling-related problems, and control alternatives. Some years later, it was reported from South America (Pastorino et al. 1993), and from Japan (Kimura 1994; Nakai et al. 1994).

In Japan, *L. fortunei*-related fouling problems are similar to those in other areas invaded. Affected facilities are chiefly water intake structures of drinking water treatment plants, hydroelectric power plants, and agricultural irrigation facilities.

Table 1 Control alternatives used in China for curtailing *L. fortunei* fouling

Control strategy	Type of facility and place	Setting	Assessment of effectiveness	Reference
Filtration	WT pipeline (Huizhou, Guangdong Prov.)	Plant	Filters failed in retaining veligers and became overgrown by mussels after a few months	Zhuang (2006)
Flow speed	Power plant (Handan, Hebei Prov.), WT pipeline (Huizhou, Guangdong Prov.)	Exp.	Only feasible where flow speed can be adjusted to > 2 m/s	Xiang (1985); Ye et al. (2011)
Antifouling coatings	Raw water pipelines (Huizhou and Shenzhen, Guangdong Prov.)	Exp.	Effective over limited time periods. Coatings release antifouling toxic substances, limiting applications in drinking water systems	Luo et al. (2006); Zhuang (2006)
Anoxia	Raw water pipelines (Shenzhen, Guangdong Prov.)	Exp.	Suitable for pipe sections that can be sealed off temporarily. Unfeasible for long-distance aqueducts	Liu et al. (2006)
Desiccation	WT pipeline (Shenzhen, Guangdong Prov.)	Exp.	Requires pipeline shut down for 10–15 days to kill the mussels, which is often unfeasible due to operational constraints	Luo et al. (2006)
Ozonation	WT pipeline (Huizhou, Guangdong prov.)	Exp.	Effective and environmentally friendly in small pipe sections. Continuous ozonization is cost-ineffective for long-distance pipelines	Xu et al. (2009b)
Hydrogen peroxide	WT pipeline (Huizhou, Guangdong Prov.)	Exp.	Concentrations of ~ 1.2–1.8 g/l are effective and economically feasible in restricted sealed off pipe sections. In long pipelines, lethal concentrations are difficult to maintain	Xu et al. (2009b)
Chlorination	WT pipeline (Shenzhen & Huizhou, Guangdong Prov.)	Exp.	Generally effective, but not widely applied in China because it deactivates biological nitrification along pipelines and affects water quality	Liu et al. (2006); Zhuang (2006)

Table 1 (continued)

Control strategy	Type of facility and place	Setting	Assessment of effectiveness	Reference
Manual and mechanical cleaning	Most of the infected man-made facilities in Guangdong Province	Plant	Effective in the short-term, but fouling recovers rapidly, requiring frequent cleaning operations, which are expensive and affect substrata	Ye et al. (2011)
Biological control (cultured fishes)	WT pipeline (Shenzhen, Yao Autonomous County of Ruyuan, Guangdong Prov.)	Exp.& plant	Environmentally friendly and sustainable when applied at the intake end of water transfer systems, but its efficacy is limited	Luo et al. (2006)
Attraction-attachment pools	WT pipeline (Huizhou, Guangdong Prov.)	Exp.	Environmentally friendly and sustainable, effective at the experimental scales tested. Not yet applied in actual operating conditions	Xu (2013)

Exp. experimental, *WT* water transfer

Several water treatment plants have been affected by *L. fortunei* biofouling in the Yodo River system in Japan (Nakanishi and Mukai 1997). Problems included mass attachment of mussels on raw water screening structures, obstruction in strainers and pipes for water quality monitoring, accumulation of dead mussels in settling and flocculation chambers, and blockage of cooling system pipes for intake pumps. Control and mitigation strategies included several approaches. Where possible, mussels obstructing pipes and other components were removed by manual or mechanical cleaning with subsequent disposal of the mussels. Further clogging was deterred by (1) treating the water with chlorine, (2) adding filters and strainers at the intake in order to prevent larvae from entering the system, and (3) duplicating some components in order to allow for the decommissioning and cleaning of one while maintaining the second in operation.

As almost all thermal and nuclear power plants in Japan are located on the coast and use salt water for cooling purposes, biofouling by *L. fortunei* is restricted to hydroelectric power plants. Here, the main problems are mussel growth on intake screens and headrace channels. Manual and mechanical cleaning has traditionally been used to cope with the problem, although disposal of waste materials is still a major cause of concern. Obstruction of bulwark pipes, which protect water-level monitoring instruments, has resulted in gauge malfunctions and failures. These problems were solved by replacing regular bulwark pipes with new ones made of copper alloy. Blockage of electric generator cooling water pipes has occurred in some plants. Mechanical cleaning during routine inspection and maintenance operations has mitigated the problems, but some plants plan on installing alternative control methods such as self-cleaning microstrainers and thermal shock treatments, depending on plant characteristics.

Biofouling by *L. fortunei* has been extensive in agricultural irrigation systems of the Kanto (Katayama et al. 2005) and Tokai (Akehoshi 2011) regions. Mass attachment of *L. fortunei* has occurred on intake screens, irrigation channels, balancing reservoirs, and balancing tanks. Obstruction by *L. fortunei* is also common in strainers and pipeworks (especially small diameter, terminal pipes) of irrigation systems (Ministry of Agriculture Forestry and Fisheries of Japan 2012). Fouling of gauging instruments for water-level monitoring has resulted in their malfunction. Manual and mechanical removal of the mussels is the main control method so far, although alternative strategies, such as desiccation and antifouling coatings, are being considered (Ministry of Agriculture Forestry and Fisheries of Japan 2012).

In South America, the earliest cases of fouling by *L. fortunei* date from around 1994 (Darrigran 1995), ca. 3–4 years after its introduction in Argentina (see Chapter "Colonization and Spread of *Limnoperna fortunei* in South America" in this volume). Subsequently, literature mentioning problems in various industrial facilities grew exponentially, but many of these reports furnish little detail on the components affected and on the measures taken to cope with the nuisance. Many of these publications are based on circumstantial and ancillary data or on previous reports, and are basically restricted to general comments on the perils and harm brought about by the golden mussel. Given the fact that most of the available information on *L. fortunei* comes from biological journals, and that in-depth analyses of its impacts are more technological than biological in nature, this outcome is hardly surprising. Indeed, biological journals shun strictly technological issues, whereas technologically oriented publications normally cover topics of wider interest, rather than in-depth accounts of problems of a single industrial plant. Thus, detailed information on fouling by *L. fortunei* in man-made installations is largely restricted to internal reports of limited distribution, most of which are not accessible to the scientific community.

Furthermore, plant engineers, the chief actors in possession of first hand information, are not encouraged (and often not allowed to), trained for, or interested in publishing descriptions of the problems they encounter or their solutions. Availability of these internal reports is further restricted by the fact that control measures are in some cases potentially harmful to the environment (especially in the case of chemical control methods), in which case disclosure of these operations is avoided. There are a few notable exceptions, where researchers or technical personnel of infested facilities described their experience at regional meetings (Cepero 2003; Bendati et al. 2004; Oviedo Antunes and de Madrinag 2005; Figueiredo de Resende and Martinez 2008; Glaser 2011) or in various other publications (GPS (Pipeline Study Group) 1973; Magara et al. 2001; Portella Kleber et al. 2009; Mata 2011; Netto 2011). However, most literature where fouling-related problems in Argentina (Darrigran et al. 2002; Darrigran et al. 2007b); Brazil (Colares et al. 2002; Simeão et al. 2006; Rolla and Mota 2010; Borges et al. 2013); China (Morton 1975; Liu et al. 2011a; Liu et al. 2011b; Ye et al. 2011; Xu et al. 2012; see Table 1); Japan (Magara et al. 1999; Magara et al. 2001; Goto 2002; Yoshida 2006; Hamada 2008; 2010; Sawada and Nakamura 2010; Akehoshi 2011); Korea (Kojima 1982) and Uruguay (Brugnoli et al. 2012) are addressed (see also publications on control methods listed below) furnish limited information on affected plant components. Objective estimates of economic losses involved are extremely rare.

In South America, the large majority of the plants impacted by mussel fouling are located along the upper Río de la Plata estuary, Paraná, Paraguay, and Uruguay rivers, and their tributaries. There are also infested facilities (including a nuclear power station) in central Argentina (Córdoba province), chiefly along reservoirs connected with the Paraná waterway by the Tercero-Carcarañá rivers (Río de la Plata basin), as well as San Roque Reservoir (31.37°S, 64.47°W), which is fed by a small endorheic basin (see Chapter "Colonization and Spread of *Limnoperna fortunei* in South America" in this volume). Although practically all facilities using river, lake, or reservoir waters colonized by the mussel experience some difficulties, most acute problems affect those that use raw, untreated water, usually for cooling purposes. Water used for potabilization or closed-system cooling circuits (like the Argentine thermal power plant Termoeléctrica General Belgrano, in Campana, Buenos Aires Province) is subject to treatment (addition of chemicals, filtration) immediately after intake, thus eliminating or significantly reducing densities of mussel larvae before they reach other plant components. In this case, clogging and overgrowth problems are normally restricted to the intake piping systems, pumps, trash racks, grates, and screens. Typically, power plants (hydroelectric, thermal, nuclear) use untreated water to eliminate excess heat, and are therefore affected the most by mussel fouling (O'Neill 1997).

While problems have been described throughout the area colonized by the mussel, Brazil has been impacted more severely because of the large number of hydroelectric plants involved. As of 2013, the mussel was present in at least 33 Brazilian hydroelectric power plants along the Paraná River and its tributaries (Borges et al. 2013; Fig. 1c). Netto (2011) estimated that shutoff of a single 40 MW turbine for servicing may cost as much as US$ 17,000 per day in lost power generation alone.

It is noteworthy that not all installations using raw water from mussel-infested areas are equally prone to fouling. The mode in which water is used may largely determine whether a system will get fouled or not. For example, large gated communities in the vicinity of major cities, like Buenos Aires, often process their own water when a nearby source is available. These settlements usually have separate lines for potable water and irrigation water; the latter is only filtered, but not made potable. Thus, irrigation pipes are in principle vulnerable to mussel fouling. However, normally they are not affected because, as opposed to potable water, which is used permanently, irrigation water is used intermittently, often with long gaps during rainy weather. During these stagnant periods, water in the pipes becomes anoxic rapidly, thus killing organisms trapped inside, including *L. fortunei* larvae and settled individuals (Boltovskoy and Correa 2006).

Facilities and Components Affected

The problems caused by *L. fortunei* are practically identical to those reported for *Dreissena* species (but not the efficacy of many of the control methods; see following chapters), which allows extrapolating from the extensive literature for the dreissenids (Mackie and Claudi 2010; Prescott et al. 2014). Any facility drawing raw water from a surficial source colonized by the mussel (rivers, lakes, reservoirs) can be affected. In Asia and South America, some of the installations that reported problems associated with mussel fouling include the following (Fig. 1):

Water and wastewater processing plants. China: Suzhou; Japan: Hanshin Water Supply Authority, Lake Biwa-Yodo River system, Osaka Prefectural Water Works Department; Argentina: AySA La Plata, AySA Palermo, AySA Bernal, Aguas Santafesinas, Aguas Cordobesas; Taiwan: Jyr-Tan pumping station

Nuclear power plants. Argentina: Central Nuclear Embalse, Central Nuclear Atucha I

Hydroelectric plants. China: Shisanling (Beijing), Langyashan (Anhui Province), Tianhuangping (Zhejiang Province), Guangxu (Shenzhen); Japan: Yahagi River; South America: Itaipu (Brazil/Paraguay), Yacyretá (Argentina/Paraguay), Salto Grande (Argentina/Uruguay), Fitz Simon, Cassafousth, Reolín, Piedras Moras, San Roque, La Calera (Argentina), Constitución (Uruguay), over 30 plants on the upper Paraná River and its tributaries (Paranaíba, Aporé, Claro, etc., Brazil)

Thermal power plants. Argentina: Central Puerto

Refineries. Argentina: Shell CAPSA (Dock Sud), ESSO (Campana)

Steel mills. China: Wuhan Iron and Steel Corporation; Argentina: Acindar

Food processing plants. Argentina: Tres Cruces

Fish culture facilities. China: Longtan Reservoir in Guangxi Province; South America: Itaipu Reservoir (clogging of net cages for pacu—*Piaractus mesopotamicus*), Esturiones del Río Negro (clogging of fish farming components for sturgeon—*Acipenser baerii baerii* in Río Negro, Uruguay)
Irrigation canals. Widespread in China and Japan
Water transfer canals, pipelines, drainage systems, and aqueducts. China: Shenzhen Dongjiang, East River to Plover Cove, Xizhijiang River, and many others
Navigation dams. Brazil
Stream level gauging components. Widespread in Japan
Watercraft (commercial and leisure boats, ships). Widespread in Argentina, Brazil, Paraguay, Uruguay
Fish diversion components. Widespread in Japan

The most common raw water components affected by mussel fouling include the following (see McMahon et al. 1994; Prescott et al. 2014):

Heat exchangers and condensers (Fig. 2a, b, j, l);
Pipes (Fig. 2f, i);
Strainers, filters, trash racks, grates, screens (Fig. 2c, d, g, n);
Penstocks;
Holding ponds, storage tanks, pump suction chambers, pump wells;
Water intake tunnels (Fig. 2f);
Sand filtration systems;
Pumps, nozzles, and sprinklers;
Vent lines, and air release valves;
Fire protection equipment;
Grit chambers, flocculators (Fig. 2e);
Submerged monitoring instrumentation, level gauges;
Pump and turbine shafts, seals, and wear rings;
Boat engines (cooling water ducts, filters, pumps) and submerged rudder and propulsion components (Fig. 2h).

The problems most commonly reported are associated with the following:

Clogging (by colonies of living *L. fortunei* and/or by dead, dislodged shell clusters), pressure loss, overheating;
Corrosion, erosion, and abrasion;
Deterioration of metal, concrete and other materials from fouling by organisms associated with mussel beds (bacteria, fungi);
Wear (pump/turbine shaft seals, pumps and turbine wear rings, slurry pump seals);
Jamming of moving components, poor sealing (stop logs, valves, boat underwater rudder and propulsion components);
Sediment accumulation;
Accumulation of dead specimens (e.g., in grit chambers, flocculators);
Nuisance to bathers (in recreational areas from colonization of submerged rocks);
Promotion of *Microcystis* growth, hindering use of the waterbodies for recreation, causing fish mortality, hampering potabilization, etc.;
Pollution, water quality deterioration from decomposition of dead mussels and mussel waste products.

While the economic losses involved are probably significant, with very few exceptions detailed information on the extra costs of dealing with the golden mussel have not been reported. Fouling problems invariably involve an increase in the number of man-hours devoted to cleaning and other maintenance procedures. For

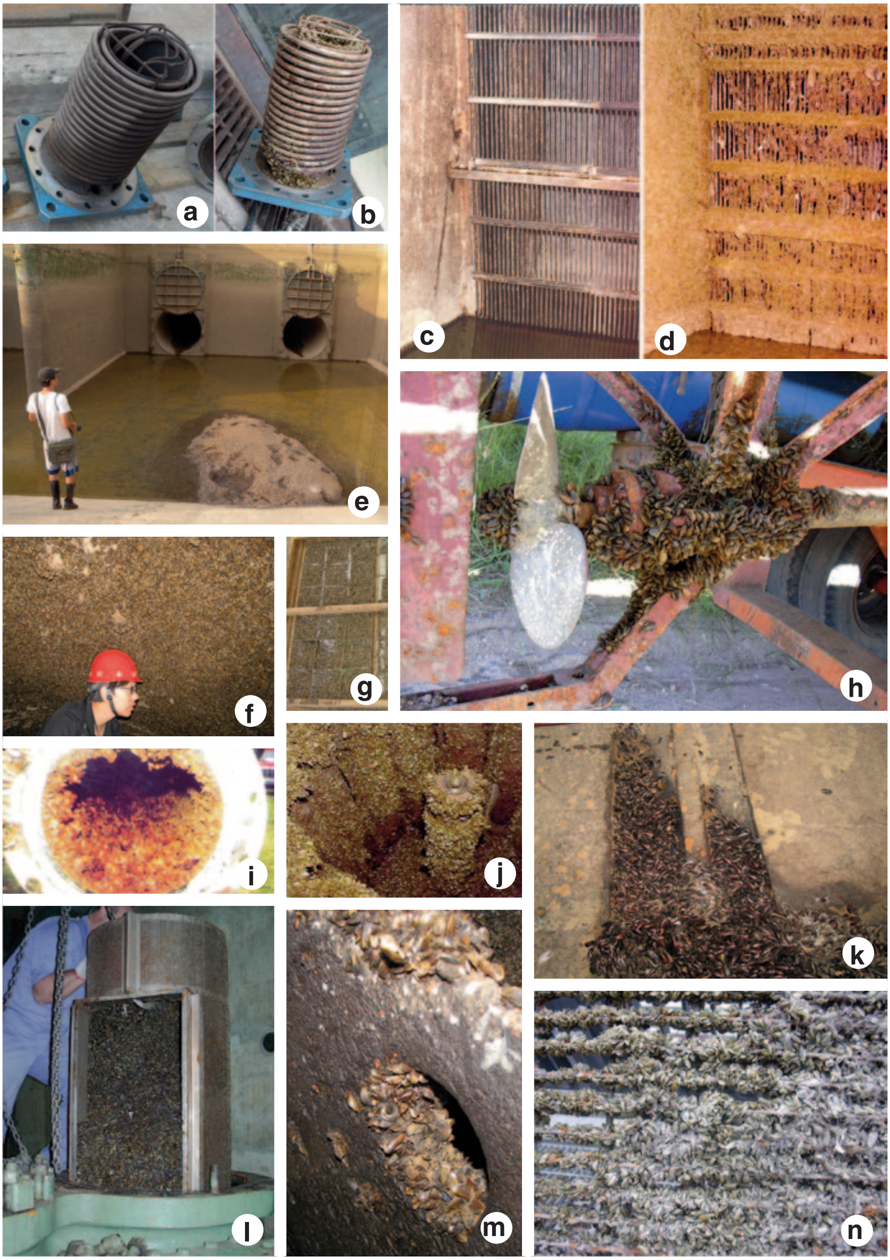

Fig. 2 Various industrial plant components fouled by *L. fortunei*. **a** and **b** Heat exchange elements clean (**a**) and fouled (**b**) (Embalse de Río Tercero nuclear power plant, Argentina). **c** and **d** Steel grate protecting the raw water intake at the Atucha I nuclear power plant (Argentina) clean (**c**) and heavily fouled (**d**). **e** Grit chamber at Yonghu Pump Station in Huizhou, Guangdong Province, China (notice accumulation of dead *L. fortunei* shells on the bottom). **f** Internal wall of water transfer pipe of the East River Water Source Project. **g** Screen at the water intake of Dongjiang

example, at the Salto Grande (Argentina/Uruguay) hydroelectric power plant each turbine is subject to a cleaning and maintenance routine every 7 years. Before the introduction of *L. fortunei* cleaning the penstock walls took 2 days of work. With the establishment of the mussel in the reservoir, the same operation now requires 10 days (Glaser 2011). Additional maintenance procedures not only involve higher costs from increased man-hour expenditures, but they also affect the lifetimes of the components that decrease from additional handling. In some cases, partial blockage of cooling systems involves operation at below-standard regimes, which may significantly affect power production and, consequently, revenues (e.g., the Central Puerto thermal power plant in Buenos Aires, Argentina). Chemical control strategies involve the costs of initial design and installation of the dosage components, and the costs of the chemical products. In many cases, detoxification of the water may be required before returning it to the lake or river, which further increases costs. Environmentally friendlier treatments, like UV, are limited by the turbidity of the water and, when viable, may use large amounts of electric power (Perepelizin and Boltovskoy 2014).

Through consulting work and personal contacts, we know that some plants have had serious fouling-related problems leading to temporary shutoffs (e.g., a water treatment plant in Suzhou, China; the nuclear power plants Atucha I and Embalse in Argentina; the hydroelectric plant Yacyretá in Argentina/Paraguay, a water treatment plant in the Yodo River area, Osaka, Japan, etc.). However, as maintenance personnel became familiar with the problem and acquired experience in curtailing mussel growth in sensitive areas, serious incidents have become less common. To our knowledge, fouling by *L. fortunei* has not caused a single definitive plant shut down. All plants have developed alternatives for curtailing the impacts of fouling and remain operational (see Chapter "Control of *Limnoperna fortunei* Fouling: Antifouling Materials and Coatings" in this volume).

Control Strategies Assayed

As of 2013, there are around 100 publications dedicated specifically to the investigation of various methods aimed at eliminating *L. fortunei* fouling in industrial installations, over half of them centered on chemical treatments and antifouling materials and coatings. Most are based on laboratory studies, and a smaller num-

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Pump Station in Huizhou (Guangdong Province, China). **h** Propeller shaft and supporting structure fouled by *L. fortunei* (leisure boat, Embalse de Río Tercero, Argentina). **i** Raw water pipe (drinking water processing plant in Villa del Dique, Argentina; from Anonymous 2006). **j** Fouling of hydroelectric plant components in Itaipú (Brazil/Paraguay; from http://sosriosdobrasil.blogspot.com.ar/2011/04/praga-do-mexilhao-dourado-deixa-em.html). **k** Fouled gate slots at Xizhijiang Pump Station in Huizhou (Guangdong Province, China). **l** Fouled filters of a transformer cooling unit, Salto Grande hydroelectric plant (Argentina/Uruguay). **m** Clogged hole in butterfly valve at Xizhijiang Pump Station in Huizhou (Guangdong Province, China). **n** Steel grates protecting the raw water intake at the Embalse de Río Tercero nuclear power plant (Argentina) ber present studies in actual operating plants. The following listing summarizes the most relevant works, grouped thematically (see also Table 1):

Antifouling materials and coatings: Stupak et al. (1996); Gemini (1999); Matsui et al. (1999); Ohkawa et al. (1999); Garcia Sola et al. (2000); Matsui et al. (2001); Nagaya et al. (2001); Ohkawa et al. (2001); Caprari and Lecot (2002); Matsui et al. (2002); Caprari (2006); Faria et al. (2006); Luo (2006); Zhuang (2006); Perez Bergmann et al. (2010a); Perez Bergmann et al. (2010b)

Chemical treatments: Morton et al. (1976); Darrigran et al. (2001); Cataldo et al. (2003); Luo et al. (2006); Zhuang (2006); Darrigran et al. (2007a); Xu et al. (2009b); Asolkar et al. (2010); Kim et al. (2011); Netto (2011); Pereyra et al. (2011); Calazans and Fernandes (2012); Calazans et al. (2012); Godoy Fernandes et al. (2012); Liu et al. (2012); Pereira and Soares (2012); Pereyra et al. (2012); Calazans et al. (2013); Netto (2013); Mata et al. (2013); Montresor et al. (2013)

Manual/mechanical cleaning: Glaser (2011); Ye et al. (2011); Ministry of Agriculture Forestry and Fisheries of Japan (2012)

Filtration: Zhuang (2006)

Thermal shock: Montalto and Marchese (2003); Perepelizin (2011); Perepelizin and Boltovskoy (2011a); Perepelizin and Boltovskoy (2011c)

Anoxia and hypoxia: Liu et al. (2006); Perepelizin (2011); Perepelizin and Boltovskoy (2011b); Ye et al. (2011)

Desiccation: Iwasaki (1997); Montalto and Ezcurra de Drago (2003); Darrigran et al. (2004)

Ozonation: Xu et al. (2009b)

Ultraviolet treatment: Santos (2011); Santos et al. (2012a); Perepelizin and Boltovskoy (2014)

Electric currents: Maeda et al. (2003); Katsuyama et al. (2005)

Ultrasound: Santos et al. (2012b)

Manipulations of flow speed: Xiang (1985); Nagaya et al. (2001); Matsui et al. (2002); Oviedo Antunes and de Madrinag (2005); Ye et al. (2011); Xu et al. (2012)

Biological control: Luo et al. (2006); Xu (2013)

Miscellaneous methods: Ratkiewicz (2006); Padula Paz et al. (2012); Rackl et al. (2012); Xu (2013); Xu et al. (2013); Dengo and Carraro (2013)

These methods are treated in detail in the sections that follow.

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