Chapter 4

The industrial effects of zebra mussels in England

4.1 Introduction.

The zebra mussel is one of the most notorious industrial bio-fouling pests in the world. Millions of dollars are spent annually on the mitigation of zebra mussel infestations in North America alone (O'Neill, 1997). In North America, power generating facilities are predominantly affected, followed by water treatment facilities (O'Neill, 1997), while in Europe, reports are more sparse but mainly come from the water treatment sector (e.g. Clarke, 1952; Greenshields and Ridley, 1957; Morton, 1969.d). In Chapter 2, it was noted that over the last 10 years there have been an increasing numbers of reports of bio-fouling by zebra mussels in English Water Treatment Works (WTWs). This chapter documents the range of zebra mussel-related problems in English WTWs, and investigates whether modern water treatment techniques may limit the extent of infestations.

4.1.1 Overview of a typical English WTW layout.

In order to discuss the effects of zebra mussels in England, it is necessary to describe the layout of English WTW. In England there are an estimated 775 treatment facilities that use freshwater drawn from surface waters (www.dwi.gov). All facilities have differing layout plans and treatment regimes, making it necessary to describe a "generalised" facility.

Firstly, water is drawn from rivers through submerged intake pipelines which are often covered with a course crib screen designed to exclude large debris. The raw river water is then pumped or gravity-fed along pipelines to systems of concrete or natural storage reservoirs. From these reservoirs, the raw water is pumped into the facility itself along further pipelines. On-site, the water is treated with a variable mix of filtration and disinfection technologies to remove suspended matter and kill pathogenic organisms. Common treatments include: rapid gravity sand filtration; coagulation; chlorination and ozonation.

Rapid gravity filters (RGFs) consist of beds of sand with grain sizes of between 0.4 and 1.5mm. Water passes through the beds by gravity, creating a head loss, and trapping suspended particles with diameters greater than 2µm (Twort *et al.* 1994). Chlorination has been used in disinfection since the beginning of the 1900s (Van Benschoten *et al.*, 1993), but many companies are currently reducing their usage of chlorine as it reacts with organic matter to form carcinogenic trihalomethanes, or THMs (Maugh, 1983). Ozonation is commonly used in water treatment to kill micro-organisms (Twort *et al.*, 1994); ozone dissipates very rapidly in raw water, leaving no residual. Coagulation uses chemicals such as ferric sulphate, aluminium sulphate or polydiallyldimethyl-ammonium chloride (polyDADMAC) to bind small particles together into a flocc. The flocc can then be removed from the water by horizontal cross flow tanks, clarifiers or filters (Twort *et al.,* 1994).

The main facility mentioned in this study is Coppermills WTW in North London (TQ354882), the layout of which is summarised in Figure 4.1. Coppermills draws water from numerous sites along the River Lee and Thames, supplying a 35 gigalitre reservoir system across the North of London (Andy Smith, Thames Water, pers. comm.). The reservoirs are interlinked and feed into Coppermills WTW through a number of long pipelines, the bulk of water being delivered by a 4.8km long, 2.54m diameter spine tunnel. Upon arrival at the WTW, the raw water is passed through one of 24 RGFs, before being ozonated at 1.2-2.5mg.l^{-1} ozone. The water is then re-filtered with slow sand filters and finally disinfected using chlorine.

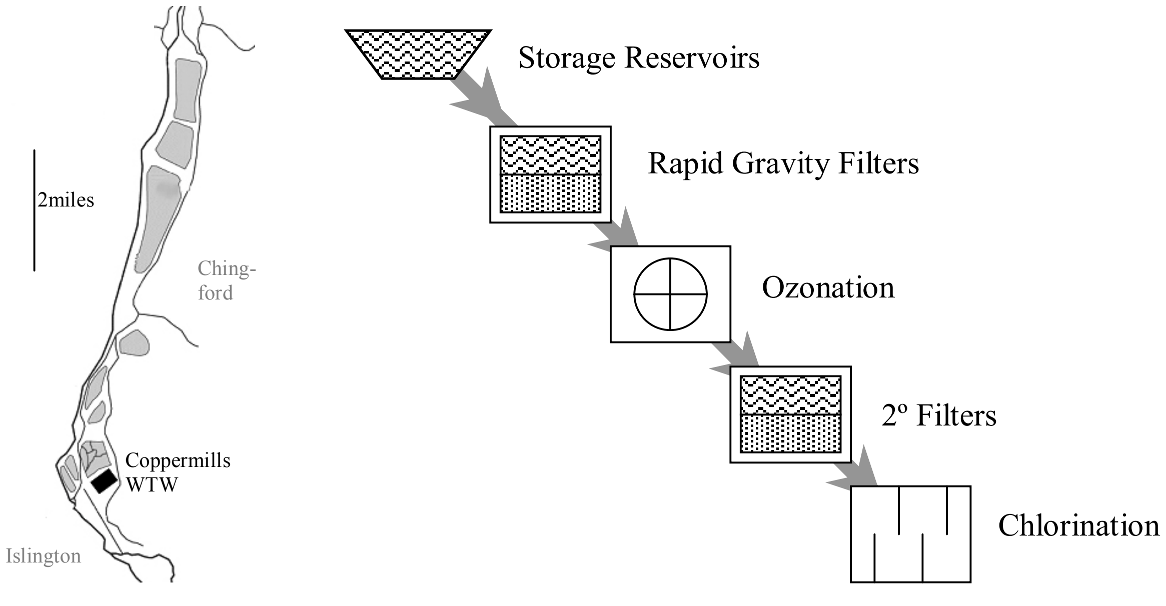


Figure 4.1 ***Right:*** The reservoir supply network for Coppermills WTW.
Left: Process layout at Coppermills WTW, Walthamstow, North London.

4.1.2 Industrial problems associated with zebra mussel bio-fouling.

Initial problems arise in freshwater-drawing industries if adult mussels grow on, or get sucked onto, the meshes of crib screens at pipe intakes. This can clog the screen, reducing the amount of water that can be drawn into the pipeline (McMahon, 1994). Such problems can be relatively easily remedied by the implementation of screen cleaning programmes.

The worst industrial problems occur when adult mussels or settlement-stage veliger larvae are drawn through the crib meshes and into the pipeline itself. If the flow in the pipeline is sufficiently below $1.5 m.s^{-1}$, zebra mussel larvae or adults can attach to the internal surface of the pipeline by means of their byssal threads (Claudi and Mackie, 1994). Long and narrow pipelines are particularly heavily impacted by zebra mussel infestation (Claudi and Mackie, 1994).

Initially, *D. polymorpha* infestations can increase the roughness of the internal pipe surface, increasing the friction and turbulence of flow within the pipeline (Van Cott *et al.*, 1993). Zebra mussels also reduce the internal diameter of the pipeline, reducing the amount of water that the pipe can carry (LePage, 1993). In July, 1989 zebra mussel infestations in a pipeline at Monroe waterworks, Michigan, reduced water availability by 20% (LePage, 1993); as a result of the infestations, there were several water outages between autumn 1989 and spring 1990. Most early English reports regarding zebra mussel bio-fouling also focus on pipeline infestations. Stilgoe (1930) documents a water main belonging to the Metropolitan Water Board that was reduced from *ca.*90cm to *ca.*30cm in diameter by zebra mussel encrustations. Clarke (1952) notes that zebra mussels reduced a pipe in Great Yarmouth from *ca.*60cm to *ca.*30cm in diameter. Later, Greenshields and Ridley (1957) note that zebra mussels reduced the diameter of two pipelines leading to Kempton Park and Walton WTW, London by *ca.*10cm. Even in the late 1960's, some water authorities were still periodically scraping portions of the pipes and channels to clear them of zebra mussels (Morton, 1969.d)

As infestations worsen, clusters of shells and live mussels can break from the surface of the pipeline and flush into the facility. The hard shells and tissue can then clog screens, sampling ports, machinery and small pipelines (Lepage, 1993; Kovalak, 1993). After several years of infestation, or if the pipeline is shut-down for a period, older individuals will start to die off, leading to increased bacterial levels and potential odour and taste problems if the water is supplied to domestic users (Claudi and Mackie, 1994). This occurred in a Berlin WTW in 1895, when following a mains shut-down, mussels in the pipelines started to die, leading to putrid tastes in the water (De Vries, 1895).

Zebra mussels can further affect domestic water supplies through their effects on the ecology of reservoirs and pipelines. An individual zebra mussel can filter as much as 10 litres of water a day (Chapter 5). As a result, high densities of mussels can cause major shifts in the phytoplankton communities of reservoir water. Under some conditions there is an increased risk of phytoplankton blooms of toxic Cyanobacteria (Holland, 1993, Vanderploeg *et al.*, 2001). Cyanobacteria can produce hepatotoxic microcystins which are not removed fully by filtration, coagulation, ozonation, or chlorination treatment processes (Hoeger *et al.*, 2002) and may pose a serious health risk for human populations (Harada *et al.*, 1996, Jochimsen *et al.*, 1998).

4.1.3 Costs associated with zebra mussel infestation and control.

Given a zebra mussel infestation, water treatment facilities may suffer a huge variety of problems, depending upon the layout and throughput of the systems concerned (Claudi and Mackie, 1994). In general, problems include:

1. a reduced flow and throughput of pipelines, reduced water output or reduced cooling efficiency of treatment processes;
2. a disruption of water monitoring equipment, disturbing the control of water quality and flow;
3. a disruption of water treatment processes such as filtration and chemical treatment, leading to a reduction in water quality.

Many facilities work close to their optimum operating parameters (Alf Ives, Thames Water pers. comm.); any reductions in efficiency are extremely costly for water production. Considering the problems associated with zebra mussel fouling, it is unsurprising that many facilities must resort to the implementation of zebra mussel monitoring and control regimes, often at substantial cost. Chemical treatment is by far the most widely used technique for controlling zebra mussel infestations in European and North American facilities (Claudi and Mackie, 1994) and is considered in Chapters 6, 7 and 8. Other facilities resort to the manual and mechanical removal of zebra mussels from infested structures.

It is estimated that the damage and increased operating expenses associated with zebra mussels in North American conduits run to tens of millions of dollars (O'Neill

1996, 1997). Surveys of approximately 766 facilities in Canada and America indicated zebra mussel related expenses totalling more than $69 million across 339 facilities between 1989 and 1995 (O'Neill,1997). Nuclear power plants spent an average of $786,670 each, hydroelectric facilities averaged $90,000 each, fossil fuel electric generating facilities averaged $145,620 each and drinking water treatment facilities averaged $214,360 each. Ongoing annual costs associated with zebra mussel infestation have been estimated at $5 million to $8 million per year (Wianco, 2002). In 2000, it was reported that the initial cost of zebra mussel control measures for Ontario Hydro Power Generation was around $20 million, with an additional $1 million in annual operating costs (Legislative Assembly of Ontario, 2000).

The recent invasions of Ireland in 1997 (McCarthy, 1997) and Spain in 2001 (Araujo and Alvarez, 2001) are still in their initial stages, and so few industrial costs have been documented. However, in Ireland, zebra mussels have started to affect private and public water abstraction stations on Lough Erne. This has necessitated modifications at the Killyhevlin water treatment works, costing the plant over £100,000 (http://www.ehsni.gov.uk/news/news/newszebmuss.shtml). In Spain, zebra mussels now contaminate at least three reservoirs used to generate electricity along Spain's largest river, the Ebro, and so problems will inevitably develop soon.

4.1.4 Water treatment processes that may reduce industrial zebra mussel infestations.

The extent of the problems experienced by a facility is dependant upon how far zebra mussels can penetrate through the industrial system (Claudi and Mackie, 1994). The depth of penetration may be minimised if water is chemically or physically treated upon entering the facility, as is often the case in WTWs. Many water-treatment processes used to kill micro-organisms also control adult and larval zebra mussels. However, no investigations have been conducted into the effectiveness of these techniques within industrial facilities, only in laboratory-scale experiments.

Rapid Gravity Filters (RGFs) should remove planktonic zebra mussel larvae, which have a diameter of at least 70-100μm (Waltz, 1973; Sprung, 1989). A continuous treatment at $0.5 mg.l^{-1}$ TRC Chlorine over 90 days has been successful in preventing new larval settlement and in killing adult mussels (Claudi, 1992). With ozonation, a 100% veliger mortality is achieved with 5 hours of ozone contact time at $0.5 mgl^{-1}$, while a 100% adult mortality is achieved within 7-12 days at concentrations of 0.5 $mg.l^{-1}$ (Lewis *et al.*, 1993). Studies by Mackie and Kilgour (1995) show that the concentrations of aluminium sulphate used for coagulation in most water treatment works ($10mg.l^{-1}$ to $30mg.l^{-1}$) are not sufficient to kill adults or larval zebra mussels by direct toxicity. However, polyDADMAC can control veligers with continuous dosing at around $5mg.l^{-1}$ (Blanck, *et al.*, 1996).

4.1.5 Aims of this study

In this study, recent reports of increases in zebra mussel bio-fouling in water-treatment works in England are explored. The number and distribution of zebra mussel infested facilities is investigated, and structures of particular vulnerability to infestation are identified within the most heavily affected facilities. The effectiveness of pre-existing water-treatment processes in preventing the passage of larval and adult zebra mussels through WTWs is also studied.

4.2. Methods.

4.2.1. Telephone surveys of waterworks and power stations.

As documented in Chapter 2, a telephone survey was conducted of the 23 water companies and 16 major power companies in England, Scotland and Wales. Senior process scientists were interviewed and information was requested on any documented cases of zebra mussel bio-fouling. This included times and localities of each sighting, and any documented increases in the problems observed.

4.2.2. Meetings and site visits to English Water treatment works.

Meetings were arranged with representatives from the most heavily affected water companies: Thames Water, Veolia Water, Yorkshire Water, Anglian Water, Severn-Trent Water and Bristol Water. The effects of the zebra mussel infestations were discussed in depth, including the costs of infestation, and any mitigation strategies in place.

Ten of the most heavily and/or newly affected WTWs were then visited. Site managers were interviewed regarding documented instances of zebra mussel bio-fouling in their treatment processes. Detailed site surveys were conducted to ascertain the precise localities of the zebra mussel infestations and consequent problems.

4.2.3 Quantification of zebra mussel related problems at Coppermills WTW.

Coppermills WTW in Walthamstow, North London was one of the most heavily bio-fouled water treatment works and was used as a case study to quantify the effects of zebra mussel infestation. Two studies were conducted to investigate the effects of a shell influx on the integrity of primary filtration beds.

Firstly, the effects of shell influxes on the depth of a Rapid Gravity Filtration Bed (RGF) were measured by process engineers at Coppermills during 2001 and 2002. The depths of the filtration media in RGF 12 was measured at approximately 6-monthly intervals, starting just after the filtration media was replaced in August 2000. Measurements were taken from three locations along the side of the bed's inlet channel using an ultra-precision laser plane levelling system (spectra physics laser plane 220).

Secondly, the starting head-loss of another affected bed, RGF 4, was studied across 2004. Head loss is a measure of the loss in water pressure due to obstruction by the filter sand grains; *starting* head loss is an indication of the effectiveness of the filter immediately after it has been back-washed to remove algae. On-site head-loss gauges were used to monitor the starting head-loss in RGF 4, and RGF 3 (an unaffected bed) at daily intervals across 2004. The starting head losses of RGFs 3 and 4 were compared across July and August (during an influx), and across October and November (after mussel removal) using paired t-tests, with head losses matched for sampling times.

4.2.4 The effects of rapid gravity filtration on zebra mussel larvae at Coppermills WTW.

To assess how filtration and ozonation at 1.2-2.5mg.l^{-1} affect larval survival and penetration through a facility, three replicate veliger samples were collected from four sites at Coppermills WTW on the 7th July 2004:

1. the Warwick East holding reservoir;
2. above the primary filtration beds (i.e. before passing through the filter medium);
3. below the primary sand filters (i.e. after passing through the filter medium);
4. above the secondary filter beds (i.e. after passing through the ozonation).

Samples were collected using a 53µm plankton net which was drawn through approximately 1m^3 of water at a depth of 1m. Samples were passed through a 1mm strainer to remove large predatory crustaceans (such as copepods and cladocerans) which could have eaten the veliger larvae prior to examination. The samples were held in conical settling tubes containing dechlorinated tap water until inspection.

Samples were inspected within one day of collection using the cross polarization microscopy technique described in Chapter 3. This maximised the chances of observing live veligers. The total number of veligers in each sample was counted and the length of a sub-sample of up to 250 individuals was measured. A further sub-sample of 50 veligers were assessed to see if they were dead or alive. Live veligers could be identified under normal light microscopy by the presence of a beating ciliated velum; under the microscope the velum of a living larva created a flickering halo around the valves.

Larval densities, proportions of living larvae, and larval size distributions were statistically compared at the sites using Kruskall-Wallis and Mann-Whitney tests (with “site” as the independent variable). Differences in the sizes of living and dead mussels at each site were investigated using Mann-Whitney tests (with alive/dead as the independent variable, and larval diameter as the dependent variable).

4.2.5. The effect of ozonation and coagulation on veliger larvae at Saltersford WTW.

Saltersford WTW in Lincolnshire (SK925333) uses pre-ozonation at 1mg.l^{-1}, followed by dosing with ferric sulphate at between 3.5 and 5mg.l^{-1}. To investigate the effects of these treatments, three replicate veliger samples were collected by D. Aldridge (Cambridge University) from the storage reservoir and the ferric dosing tanks (immediately following pre-ozonation) at Saltersford on the 6th July 2004. The samples were collected, inspected and statistically analysed using the same techniques detailed in Section 4.2.4.

4.2.6. The effects of ozonation on adult zebra mussels at Walton-on-Thames water treatment works.

Walton-on-Thames WTW in South London (TQ086663) uses ozonation at 1-1.5 mg.l^{-1} in its initial treatment stage. Surveys of the facility on the 9th October 2000 revealed that adult zebra mussels were living in parts of the facility following this treatment. To investigate how ozonation affected these populations, on the 31st

January 2001, the populations from three different parts of the facility were sub-sampled. Zebra mussels were collected from:

1. the storage reservoirs (before ozonation);
2. above the primary filters (after ozonation, before filtration);
3. in the drain taking water used to clean the filtration beds back to the storage reservoir.

In each area, a flat, metal-bladed paint stripper was used to collect three random 10cm^2 samples from the submerged facility walls. The number of mussels in each sample was counted and the length of each mussel was measured using Vernier callipers. The densities and size distributions of mussels at were compared between sites using Kruskall-Wallis tests, with density and larval diameter as dependant variables respectively, and site as the independent variable.

4.3 Results.

4.3.1 Telephone surveys of WTWs and power stations.

No cases of industrial bio-fouling have been documented in Scotland and Wales. However, the instances of zebra mussel bio-fouling in English industry are far more widespread than previously documented. Eight out of 23 English water companies have reported zebra mussel problems. Out of a total of 1,205 water treatment works in England, 30 (2.5%) had been affected by zebra mussel bio-fouling by November, 2003. In addition, one cement works contacted us regarding problems in its cooling pipelines resulting from zebra mussel infestation (Andy Smith, Lafarge Cement, pers. comm.). The affected facilities are distributed throughout England (Figure 4.2), but all abstract water from lowland rivers. Of the total of 31 industrial facilities, 18 have documented increasing problems with zebra mussels since 1998, even though they had previously been aware of their presence. A further five facilities only discovered zebra mussels in their facility between 2000 and 2003. Out of 61 English power-generating facilities, none have documented any problems with zebra mussels.

4.3.2. The effects of zebra mussels in English water treatment works.

In every waterworks affected by zebra mussels, problems originate from an infestation of the pipelines leading from rivers or impounding reservoirs. The effects downstream of these pipelines depend upon the particular layout of each works. Living and dead mussels are often displaced from the surface of the pipelines, particularly at times of large flow fluctuation. These are washed into the works where they clog pipes and processing machinery. Mussels tend to accumulate at the first obstruction to water-flow, such as filtration beds, ozone tanks and microstrainers. The potential affects of zebra mussels within a generalised WTW are summarised in Figure 4.3 and explained with examples in the following sections.

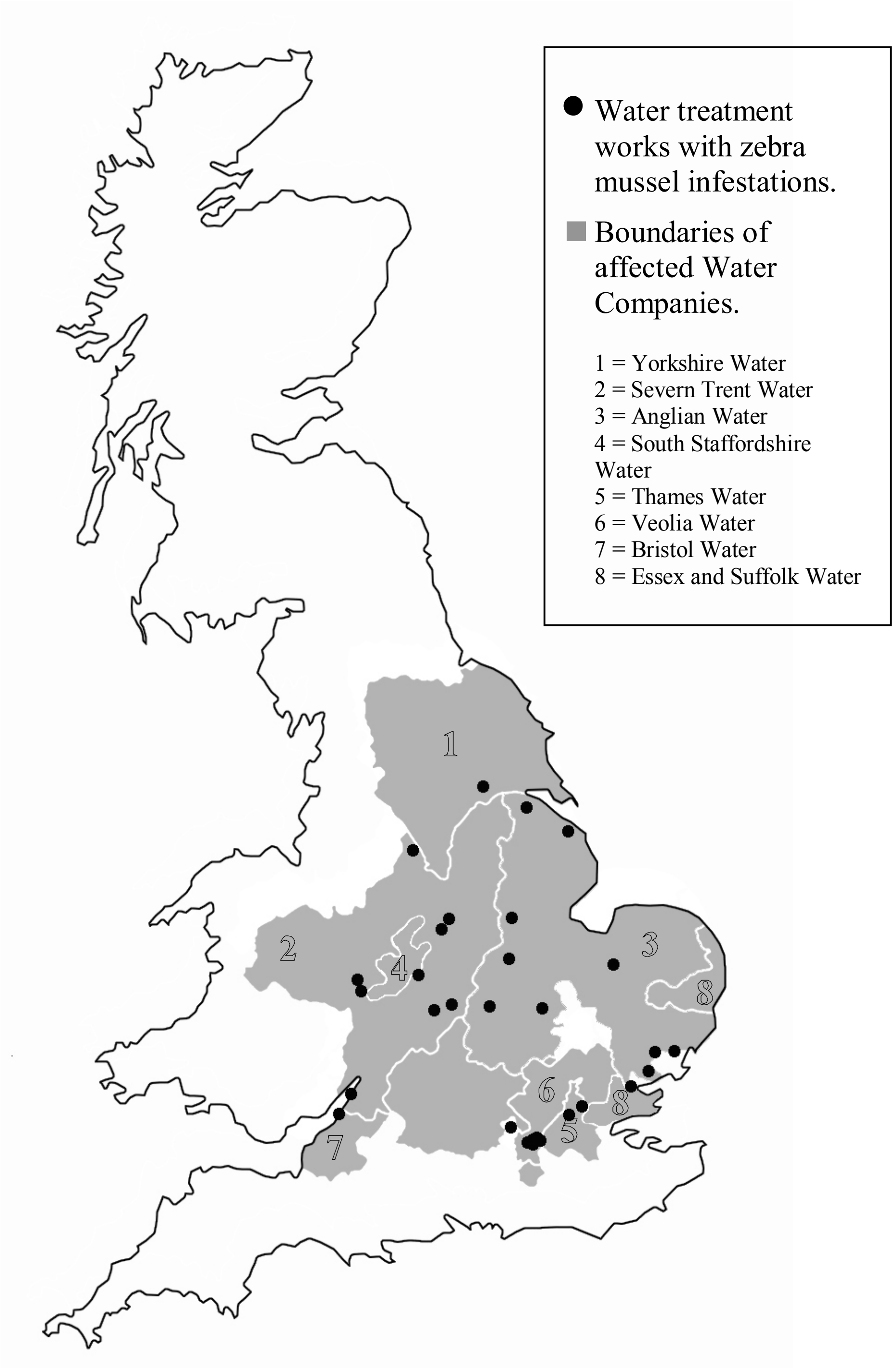
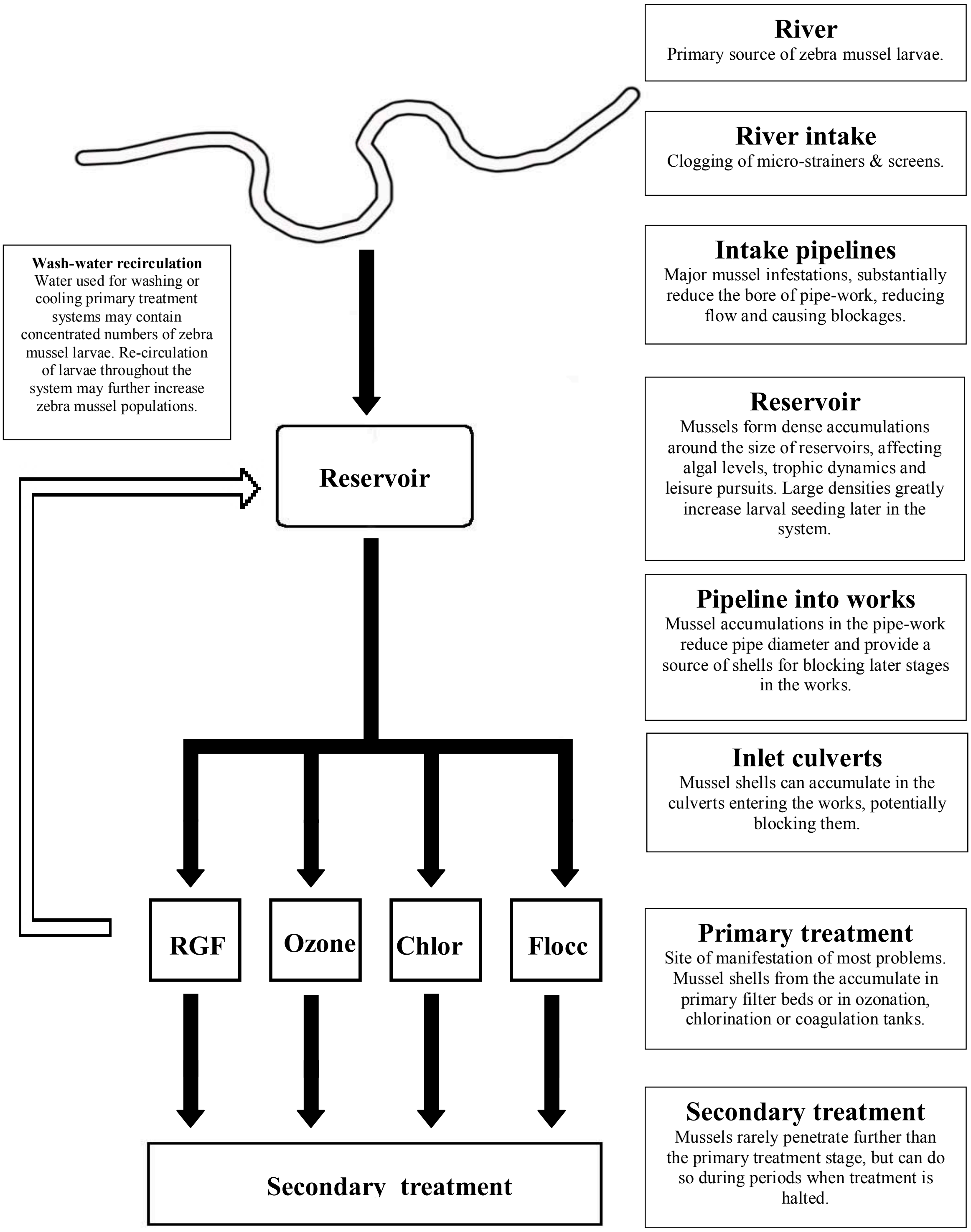


Figure 4.2. Distribution of water treatment facilities affected by zebra mussels within England.



River
Primary source of zebra mussel larvae.

River intake
Clogging of micro-strainers & screens.

Intake pipelines
Major mussel infestations, substantially reduce the bore of pipe-work, reducing flow and causing blockages.

Wash-water recirculation
Water used for washing or cooling primary treatment systems may contain concentrated numbers of zebra mussel larvae. Re-circulation of larvae throughout the system may further increase zebra mussel populations.

Reservoir
Mussels form dense accumulations around the size of reservoirs, affecting algal levels, trophic dynamics and leisure pursuits. Large densities greatly increase larval seeding later in the system.

Pipeline into works
Mussel accumulations in the pipe-work reduce pipe diameter and provide a source of shells for blocking later stages in the works.

Inlet culverts
Mussel shells can accumulate in the culverts entering the works, potentially blocking them.

Primary treatment
Site of manifestation of most problems. Mussel shells from the accumulate in primary filter beds or in ozonation, chlorination or coagulation tanks.

Secondary treatment
Mussels rarely penetrate further than the primary treatment stage, but can do so during periods when treatment is halted.

Figure 4.3 The distribution of problems associated with zebra mussels within a generalised water treatment facility (based on experiences reported by 30 English WTWs).

4.3.2.a Infestation of pipelines leading from rivers to storage reservoirs

In every affected waterworks in England, the main freshwater intake pipeline has an infestation of zebra mussels. No English water company has yet made quantitative measurements of intake pipe infestation, due to the complications of draining these pipelines and the associated reductions in water supply to the facility. However, facilities in the Essex, Veolia, and Severn-Trent regions have performed boroscopic examination of some pipelines and revealed mussel encrustations over 20cm in depth.

Zebra mussel infestations can increase turbulence and the head needed to drive water through a pipe. In 1997, zebra mussels were the main cause of a substantial head-loss in a pipe bringing water from a small lake to a cement works in Derbyshire (Blue Circle Cement, SK167823). No head-loss in any English waterworks has yet been documented.

Further problems have appeared when mussels have become dislodged from pipeline walls, accumulating in regions where flow is substantially reduced (such as in bends or where the pipe diameter increases). In Summer 1999, Anglian's Saltersford WTW in Lincolnshire experienced a massive blockage of mussels in the supply line to their works (Toni Holtby, Anglian Water, pers. comm.). An elbow in the 25km long, 450mm diameter pipe entering the works provided a natural capture area for mussel shells. Around 5 tonnes of mussels were removed using a suction pump to prevent the storage reservoir being drained of water. Mussel influxes continue to occur at Saltersford WTW; the works has implemented an annual cleaning regime, removing several tonnes of mussels each year. The costs of cleaning are estimated to be in the region of £30,000 a year.

Shell blockage also occurred in the inlet culverts at Thames' Coppermills WTW, North London in August 1997 (Alf Ives, Thames Water, pers. comm.). Inlet culverts became filled with a 75cm depth of zebra mussel shells, necessitating an extensive removal project. A month was spent systematically digging and sucking mussels out of each culvert, costing an estimated £300,000. The culverts are now full with zebra mussels again, but cannot be removed because it would be too costly to take the facility out of action for a prolonged period.

During 2003, divers removed over 3 tonnes of mussels from pipelines linking reservoirs and rivers in Thames region (Paul Fellow, Specialist Diving Services, pers.

comm). On one occasion, a 120cm diameter main on the River Lee at Ware became totally blocked by zebra mussels, necessitating removal by divers.

4.3.2.b Blockage of micro-filters and screens.

Many water treatment works have micro-strainers at the inflow to their works in which mussels can accumulate, clogging machinery. At Anglian's Wing WTW in Rutland (SK898026), between 1997 and 2004, zebra mussels became dislodged from an 8km long intake pipe and were captured in a large microstrainer facility, necessitating frequent removal (Toni Holtby, Anglian Water, pers. comm.). Between 2000 and 2003 over 60 tonnes of mussels were removed *per annum*. Mussel influxes followed a brief period of pipeline chlorination in November (leaving a residual of 0.1 to 0.2 $mg.l^{-1}$). Before 1998, the pipeline was chlorinated every second year, but the increasing numbers of mussels being removed necessitated a more frequent purge.

Another example of filter screen blocking occurred in 1997 at Anglian's Alton WTW in Suffolk (TM154349). Large numbers of mussels were discovered growing on the screens of a draw-off tower supplying the works (Nicola Morris, Anglian Water, pers. comm.). To prevent further occlusion, the screens had to be cleaned by using a team of divers .

4.3.2.c Infestation of storage reservoirs.

No WTW has documented any problems associated with reservoir infestation, but when surveys have been conducted, they have often revealed substantial accumulations of mussels around the bottom of storage reservoirs.

Zebra mussel populations in reservoirs can reach densities over two orders of magnitude greater than in the rivers supplying them. As reported in Chapter 2, manual surveys of the River Thames in 2002 revealed mussel densities of up to 41 ± 8 SE $mussels/m^2$ compared to 11,600 ± 300 SE $individuals.m^{-2}$ in the reservoirs it supplies directly.

4.3.2.d Clogging of primary filter inlets and beds.

Thames Water's Coppermills treatment facility in North London receives a continuing influx of loose mussels (both living and dead) into the RGF inlets and beds from the inlet culvert (Section 4.3.3). There were at least seven distinct shell influxes between 2000 and 2003 (Roy Grubb, Water Manager, Thames Water, pers. comm.). A typical example occurred in October 2001 when two of the RGFs had to be drained and external companies contracted to clean them at an approximate cost of £10,000 per bed. Figures 4.4, 4.5 and 4.6 show the extent of an influx. The first manifestation of problems involved an increase in the depth of the RGF 12 from 656 ± 3mm in August 2000 to 720mm in September 2001 (Figure 4.7).

Figure 4.4 A Primary filter bed inlet at Coppermills WTW, North London before an influx of mussels.

Figure 4.5 The same filter bed inlet as in Figure 4.4, after an influx of mussels.

Figure 4.6 Mussel shells in a primary filtration bed at Coppermills WTW (October 2001).

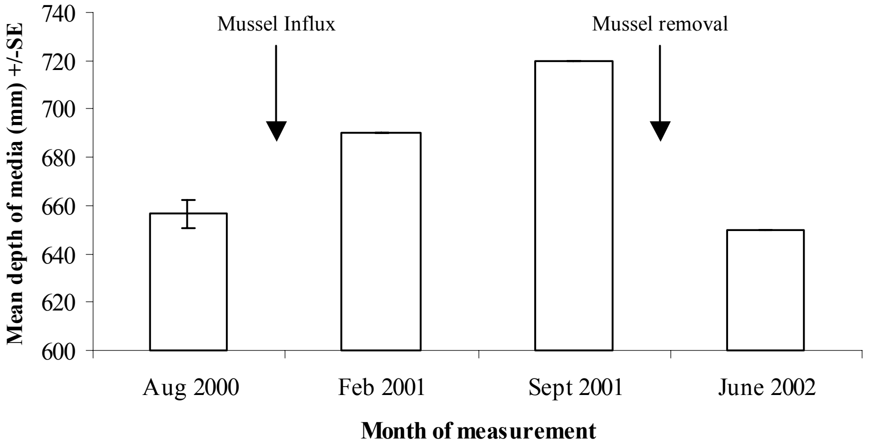


Figure 4.7 Depths of sand in Rapid Gravity Filter 12 at Coppermills WTW before, during and after an influx of zebra mussels. Data supplied by Alf Ives (Thames Water).

RGF 4 had a mean starting head loss of 51.5 ± 0.43cm SE across March and April which dropped to a mean of 24.3 ± 2.6cm SE during July and August after the zebra mussel influx (Figure 4.8). In contrast, the head loss in the unaffected RGF 3 rose from a mean starting head-loss of 53.7 ± 0.4cm in March and April to a mean of 111cm ± 1.1cm SE in July and August. The starting head-loss of RGFs 3 and 4 differed significantly across July and August (Paired t test, t = 29.59, d.f.=109 p<0.001). The shells were removed in early September, and by October and November RGFs 3 and 4 did not significantly differ in mean starting head loss (Paired t-test, t = 1.47, d.f.=112, p = 0.147).

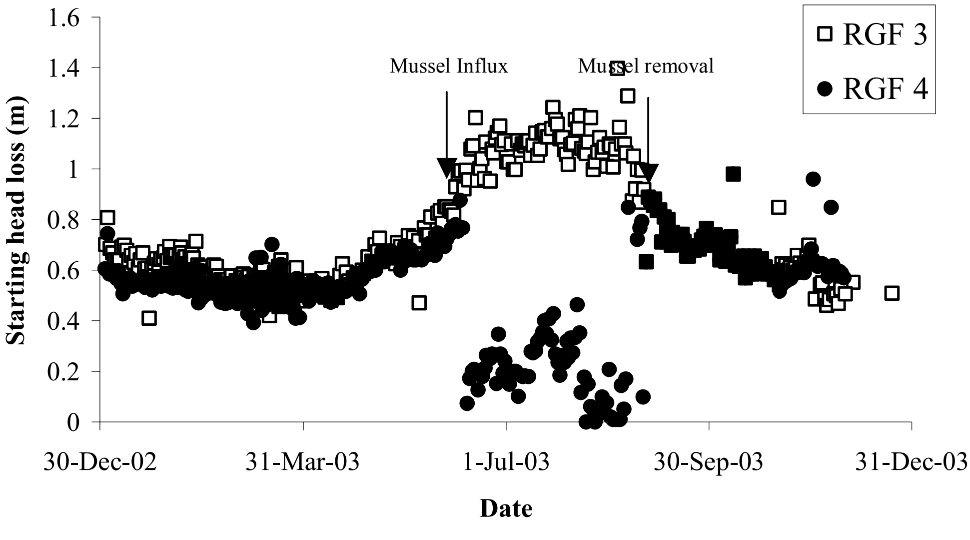


Figure 4.8 Starting head-loss in RGF 4 before, during and after an influx of zebra mussel shells. (Compared to an unaffected bed, RGF 3).

Over 30 tonnes of mussels and sand had to be removed to restore the integrity of filter bed 4. The shells also prevented the sand's cleaning and reclamation (Roy Grubb, Water Manager, Thames Water, pers. comm.).

Evidence from river and reservoir surveys indicates that the mussels are entering Coppermills from within a 4.8km long, 2.54m diameter spine tunnel which was constructed *ca.*1990. Anecdotal evidence indicates that influxes of zebra mussels into the primary inlet often follow large changes in flow rate through the spine tunnel (Alf Ives, Thames Water, pers. comm.). Populations in the tunnel appear to be increasing: the number of influxes of zebra mussels into the works has risen from one in 2001, to two in 2002 and to four in 2003.

4.3.2.e Blockage of ozone tanks.

Seven WTWs across the country have reported problems with dead zebra mussel shells accumulating in ozone treatment facilities. In Anglian Water's Alton WTW in Suffolk, over 50 tonnes of mussels were taken out of three ozone tanks in 2002 (Nicola Morris, Anglian Water, pers. comm.). The influx followed a large increase in flow in the supplying pipeline.

Similar problems were also noted at Veolia's Walton-on Thames WTW in South London. Large numbers of dead zebra mussels were found in the facility's ozonation chambers for the first time in 2001 (Lindsay Neal, Veolia Water, pers. comm.). The mussels were promptly removed by means of a drainage pipeline (Figure 4.9). Zebra mussels were being washed into the ozone chambers from large populations in the pipelines leading from the settlement reservoirs, as revealed by boroscopic imaging of these pipelines. The facility has implemented a £250,000 pre-chlorination strategy to clear these pipelines of zebra mussels.

Problems associated with ozone tank blockages have involved a reduction in the contact time of water, and the destruction of ozone diffusers due to the sheer weight of shells. The cleaning of ozone tanks is very problematic due to the hazardous nature of the disinfectant. Cleaners must wear full protective equipment, including breathing apparatus (Figure 4.10).

Figure 4.9 Mussels in the drainage chamber of an ozone tank at Walton-on-Thames WTW.

Figure 4.10 Protective equipment used to clean mussels from ozone tanks at Alton WTW, Suffolk.

4.3.2.f Blockage of narrow-bore sampling ports and pumps.

Mussel shells often block small sampling pipelines that branch from the main pipelines. Yorkshire Water's Loftsome Bridge WTW in East Yorkshire (SE702295) encountered mussels in their turbidity measuring equipment for the first time in Summer 2003 (Jenny Banks, Yorkshire Water, pers. comm.). Coppermills WTW in North London experiences similar problems; in future, the ports are to be shortened and screened, allowing removal of the mussels (Michael Chipps, Thames Water, pers. comm.). In Severn Trent Water's Church Wilne WTW in Derbyshire (SK447315), mussels constantly accumulate in the machinery of pumps drawing from the raw water main, necessitating frequent pump replacement at a cost of around £100,000 per year (Helen Pickett, Severn Trent Water, pers. comm.).

4.3.2.g Problems down-stream of primary treatment.

Mussels have rarely been documented after chlorination, ozonation or filtration treatment stages. The few situations where mussels have caused problems in later stages of treatment have usually followed facility repairs, allowing mussels to bypass primary stages of treatment. In 1997, zebra mussels were found in the heat exchange pipes of a new ozone facility at Thames Water's Coppermills WTW in North London (Paul Steel, Thames Water, pers. comm.). The new ozonation system was only six months old and was supplied with water from the primary sand filters. A problem was first noticed when the ozone generator started to overheat and trip out due to a decreased efficiency. The ozone plant was shut down for two weeks while the exchangers were removed and examined. Dead zebra mussels were found blocking the fine pipes of the heat exchangers. The problem has not been repeated since, indicating that mussels cannot usually penetrate this far into the facility.

4.3.3 The effect of rapid gravity filtration on larvae at Coppermills WTW.

At Coppermills waterworks larval densities increased from 105.9 ± 29.5 SE veligers.m^{-3} in the Warwick reservoir, to 227.1 ± 46.4 veligers m^{-3} above the rapid gravity filters. Veliger abundance dropped to 25.9 ± 12 SE veligers m^{-3} below the RGFs and then to 17.0 ± 6.2 SE veligers.m^{-3} in the secondary filter beds. The densities of veligers differed significantly between the 4 sample points (Kruskall-Wallis, H= 8.2, d.f.=3, p = 0.042; Figure 4.11).

The proportion of live zebra mussel larvae was significantly higher in the two sites above the primary filters than those below (Mann Whitney U, U=45, n=12, p=0.0074; Figure 4.12). Survivorship dropped from 70.0 ± 7.2% SE immediately above the RGFs to 4.9 ± 2.5% SE below them.

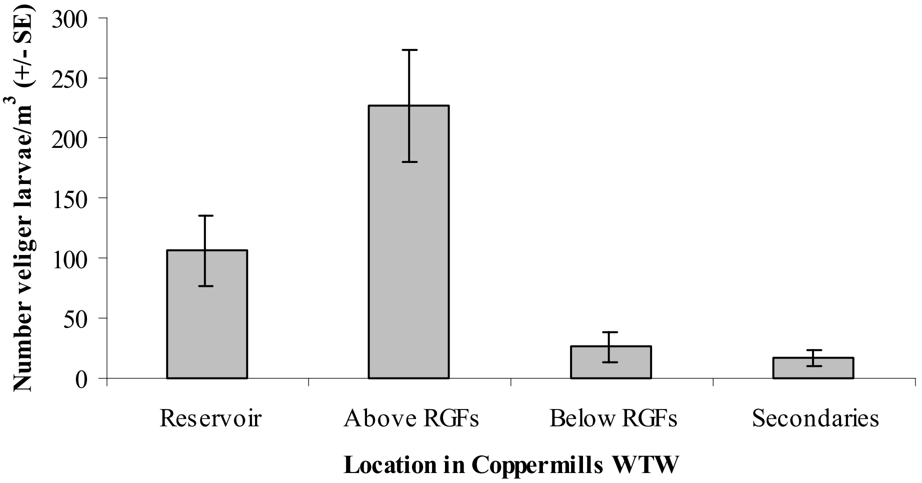


Figure 4.11 Numbers of zebra mussel larvae m^{-3} at different treatment stages in Coppermills WTW, North London in early July 2004.

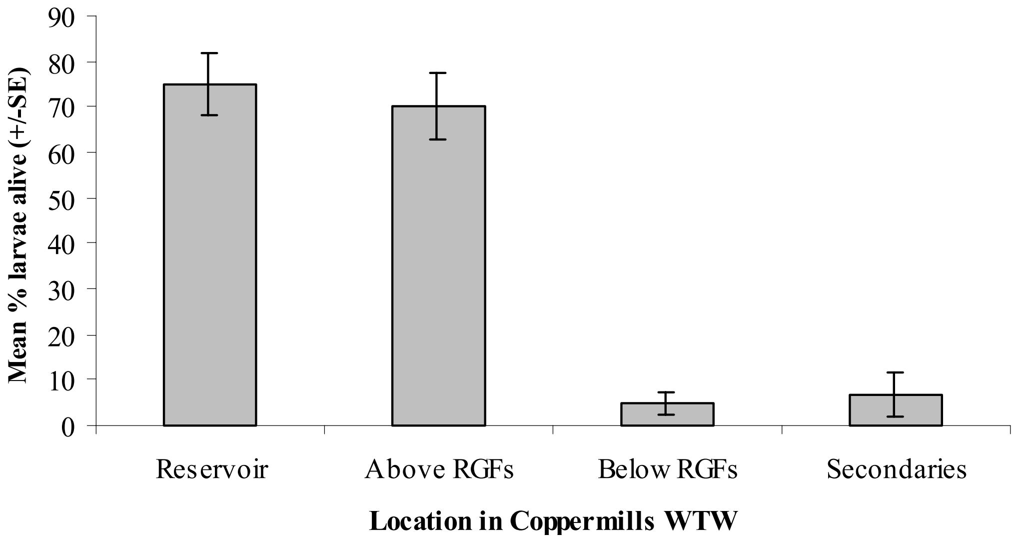


Figure 4.12 Percentages of zebra mussel larvae alive at different treatment stages in Coppermills WTW, North London in early July 2004.

The size distributions of larvae at Coppermills also differed significantly between the four sample points (Kruskall Wallis, *H*=258.61, d.f.=3, $p<0.001$; Figure 4.13). The larvae in the reservoir (median shell length 180µm) were larger than those above and below the RGFs (median shell length 100µm) and those in the secondaries (median shell length 120µm).

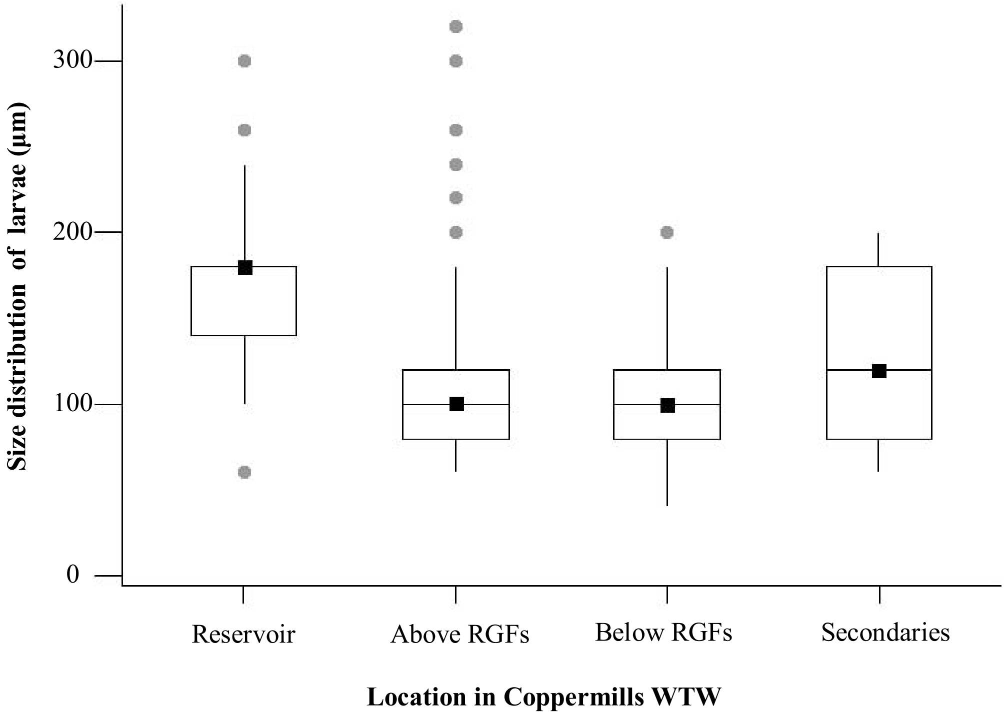


Figure 4.13 Size ranges of larvae at different treatment stages in Coppermills WTW. ■ = Median, Box = Inter-quartile range, ● = Outlier, Line = range of values.

There was no significant difference between the sizes of the living and dead larvae in the reservoirs (Mann-Whitney, *U*=3796, n=100, *p*=0.7321; Figure 4.14), or the secondaries (Mann-Whitney *U*=1204, n=50, *p*=0.3343). However, above the RGFs dead larvae were significantly larger than live larvae (Mann Whitney *U*= 7328, n=150 *p*=0.0096). Under the RGFs, dead larvae were significantly smaller than live larvae (Mann-Whitney *U* =183.5, n=56, *p*=0.0228). No on-going zebra mussel problems had been documented beyond the treatment points.

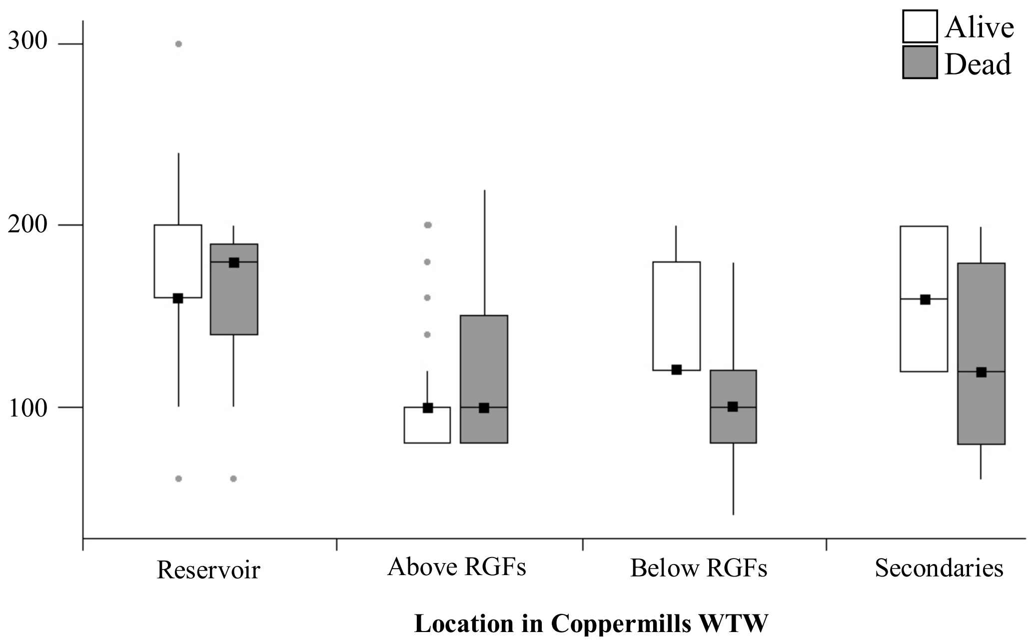
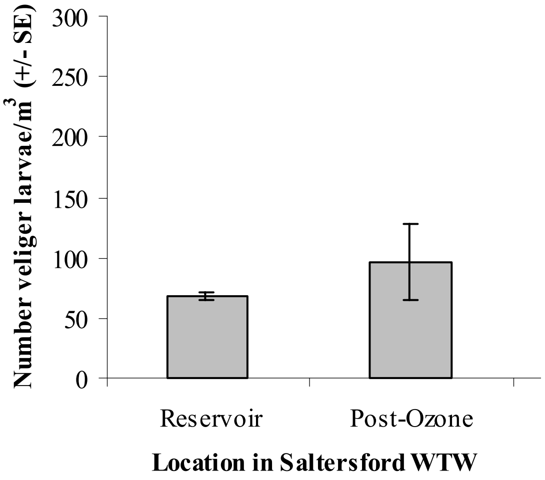


Figure 4.14 Size ranges of living and dead larvae at different treatment stages in Coppermills waterworks, North London. ■ = Median, Boxes = Inter-quartile range, ● = Outlier, Line = Range of values.

4.3.4 The effect of pre-ozonation and coagulation on zebra mussel larvae at Saltersford WTW.

At Saltersford WTW, there was no significant difference in the numbers of larvae in the reservoir and below the ozonation and ferric dosing (Mann-Whitney U, *U*=17431, n=6, *p*>0.05; Figure 4.15). However, there were more larvae alive in the reservoir than after ozonation and flocculation (t-test on arcsine transformed data, *t*= 7.15, d.f.= 3, *p*=0.006; Figure 4.16). Survivorship dropped from 75 ± 5% SE before ozonation and ferric dosing to 28 ± 6% SE afterwards.



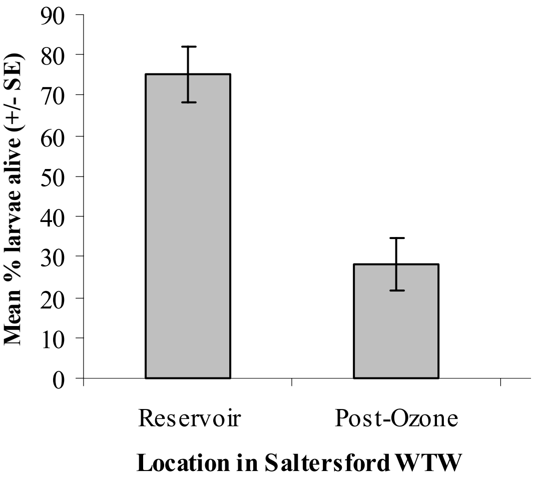


Figure 4.15 Numbers of veliger larvae m^{-3} at two sites in Saltersford WTW.

Figure 4.16 Percentages of veliger larvae alive at two sites in Saltersford WTW.

There were no significant differences in the sizes of larvae before and after the treatments at Saltersford (Mann Whitney U=22788.5, n=262, p=0.0573; Figure 4.17). There was a significant difference between the sizes of living and dead larvae in the reservoir (Mann Whitney, U=3407.5, n=100, p=0.0022, Figure 4.18). However, there was no difference in the sizes of living and dead larvae below the ozone/ferric dosing (Mann Whitney U=2902, n=150, p=0.4037, Figure 4.18). No zebra mussel problems have been documented below the dosing points.

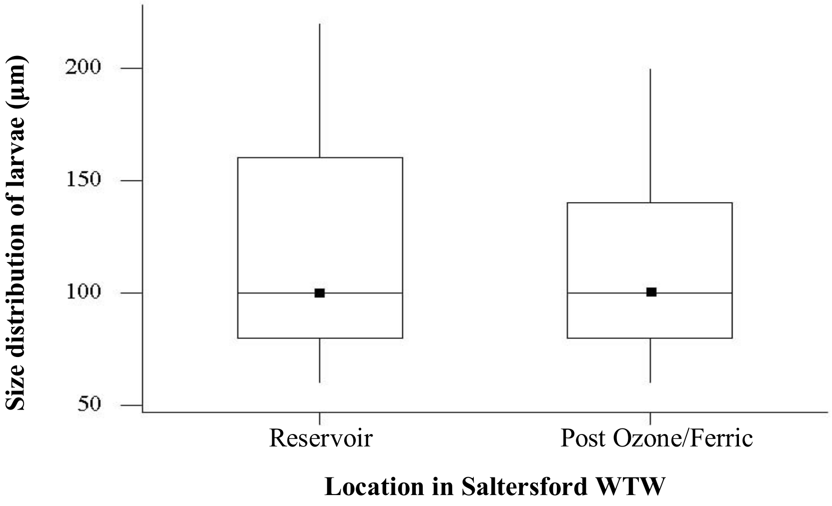


Figure 4.17 Size ranges of larvae at different treatment stages in Saltersford WTW.
■ = Median, Boxes = Inter-quartile range, ● = Outlier, Line = Range of values

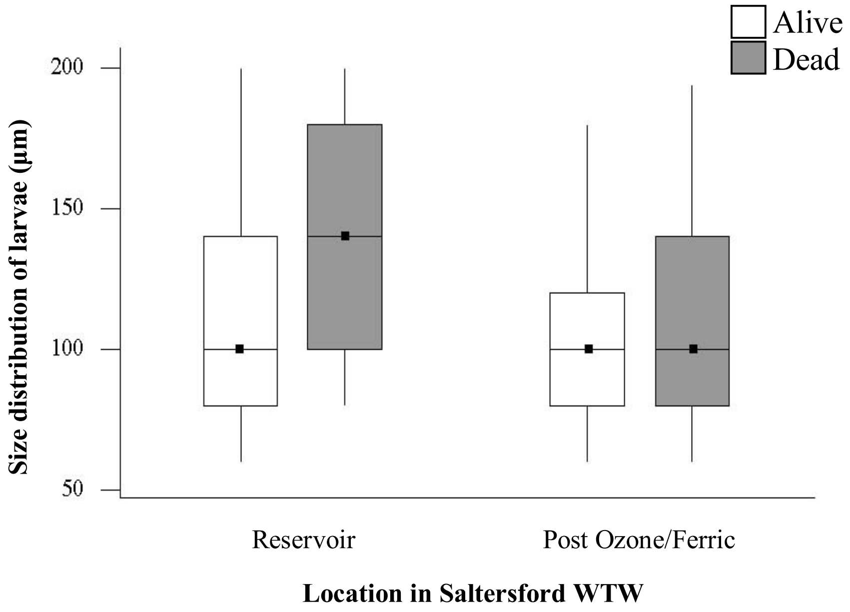


Figure 4.18 Size ranges of living and dead larvae at different treatment stages in Saltersford WTW. ■ = Median, Boxes = Inter-quartile range, ● = Outlier, Line = Range of values

4.3.5 The effects of ozonation on adult zebra mussels at Walton-on-Thames WTW.

The densities of mussels in each of the sampling locations at Walton-on-Thames facility did not significantly differ from each other (Kruskall-Wallis, H = 5.40, d.f.=2, = 0.067; Figure 4.19). However, the size distributions of zebra mussels throughout the works did significantly differ ((Kruskall-Wallis, H = 377.4, d.f.= 2, p <0.001); Figure 4.20), the mussels in the primary filter (immediately after ozonation) being significantly smaller than those elsewhere.

Figure 4.19 Densities of zebra mussels infesting different treatment stages at Walton-on-Thames WTW.

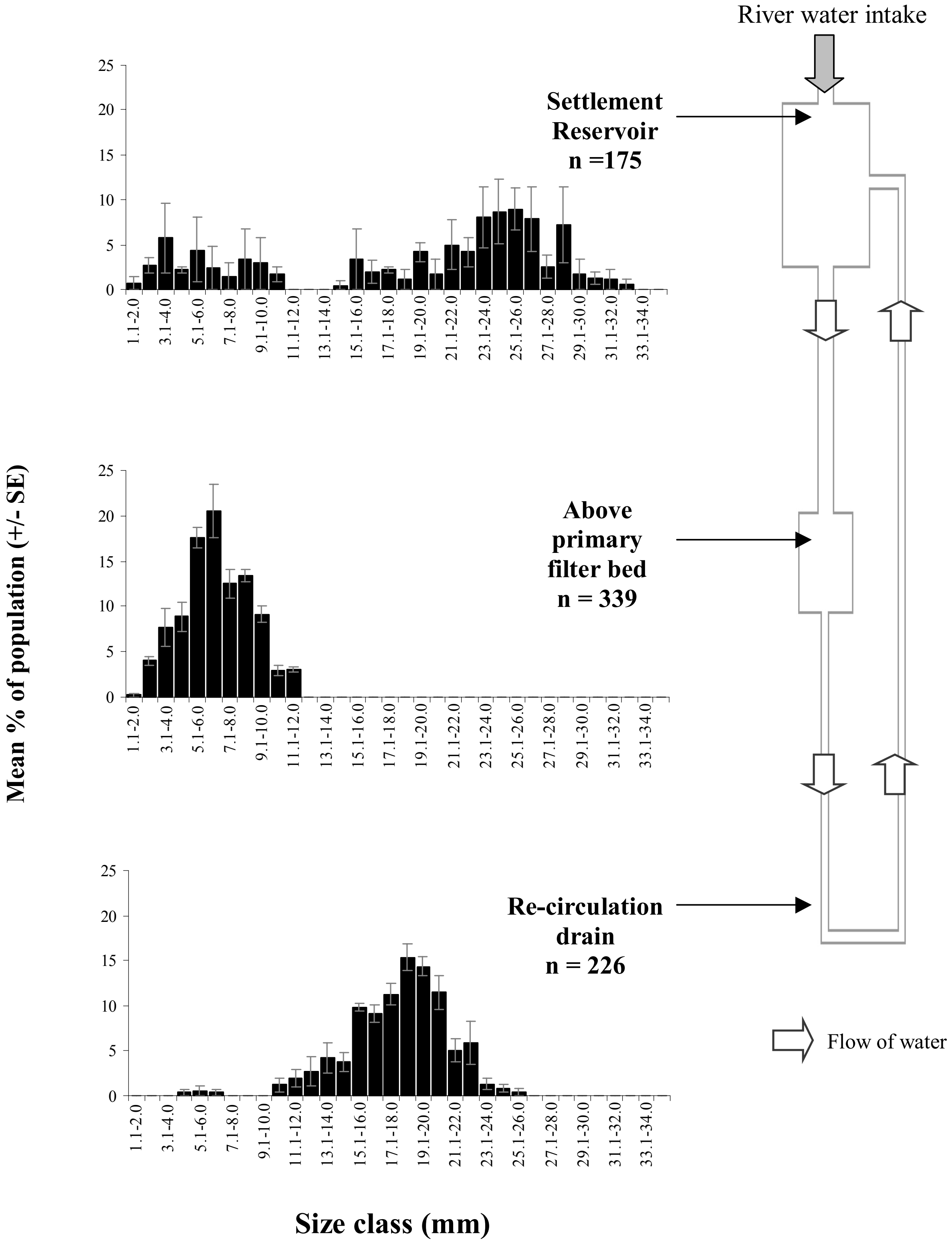


Figure 4.20 Size ranges of adult zebra mussels infesting different treatment stages of of Walton-on-Thames WTW on the 31st January 2001. ***Right:*** Schematic of sampling point locations.

4.4 Discussion

There has clearly been a massive increase in zebra mussel bio-fouling problems in English water treatment facilities since 1998. English water companies are spending an estimated total of at least £1 million *per annum* on the mitigation of zebra mussel infestations. Only 30 WTWs have been affected so far, but many more facilities could be affected in the future; there are 1,175 remaining WTWs in England. However, 33% of the water supplied in Britain comes from groundwater sources (www.dwi.gov.uk) which will not be susceptible to zebra mussel infestation, reducing this figure to an estimated 775 susceptible WTWs. Although data is unavailable regarding the precise locations of the abstraction points for these facilities, many are likely to abstract from rivers and reservoirs suitable for zebra mussel survival and reproduction (Chapter 2). There were no cases of bio-fouling in Scotland and Wales; this could be expected given the absence of reports of *D. polymorpha* from these countries.

Eight English water companies and Water Services Northern Ireland were so concerned with current and future bio-fouling by *D. polymorpha* that in 2004 they commissioned the Water Research Centre (WRC), in collaboration with Cambridge University, to produce a report specifically aimed at preventing problems with zebra mussels (Hall *et al.,* 2004). In May 2004, a "zebra mussel working group" was formed containing ecologists, chemical engineers and representatives of eight Water Companies. The group meets twice annually to discuss on-going problems with zebra mussel bio-fouling in England and to commission new studies on control strategies.

Of 61 power-generating installations in England, none have documented any problems with zebra mussels. This is not surprising; of these power stations, 43 (70.5% of the total) draw their cooling water from estuarine or coastal sources and will not be exposed to *D. polymorpha.* The remaining 18 power stations are generally located immediately adjacent to their freshwater sources, alleviating the need for long pipelines which would be prone to zebra mussel infestation.

4.4.1 Types of problems encountered with zebra mussels in England.

The problems detailed in section 4.3.2 share many common characteristics:

1. zebra mussels are abundant in pipelines and reservoirs supplying the facility;
2. shells get displaced from the walls of these conduits, often at times of erratic flow, and flush into the WTW;
3. problems occur when shells accumulate at the first barriers to laminar flow such as screens, inlets, filtration beds, ozone tanks, small pipelines, pumps and cooling systems. The main bio-fouling costs to date are associated with removing these shells;
4. problems are rarely encountered downstream of these initial barriers unless they are bypassed during repair.

Zebra mussels have severely compromised water treatment in a number of WTWs by causing disruptions in water flow, decreasing the efficiency of filtration, reducing the effectiveness of ozonation or by disrupting water monitoring equipment. These effects cannot be allowed to persist and must be mitigated in order to preserve the quality of public water supplies according to DWI regulations (Water Supply regulations, 2000). Water companies may continue to mitigate problems by physically removing the shells, but this is often costly and requires parts of the facility to be temporarily shut down. However, projections by water companies in England show a decreasing margin between supply and demand over the next 25 years (www.environment-agency.gov.uk/commondata) and as a result shut-downs may become increasingly difficult in the future.

4.4.2 Reasons for the recent increase in zebra mussel bio-fouling.

There are two possible reasons for the recent spate of zebra mussel bio-fouling problems. Firstly, in some parts of the country, such as in Yorkshire and in the Anglian regions, zebra mussels are spreading and colonising new areas. Possible reasons for the spread are reviewed Chapter 2 and by Aldridge *et al.*, (2004).

Secondly, many on-site problems are likely to have increased due to the recent elimination of pre-chlorination at many waterworks intakes. Pre-chlorination was first implemented at the beginning of the Second World War to prevent pathogenic infection (Greenshields and Ridley, 1957). Typically, a continuous dose of around 0.5-1.0 p.p.m chlorine was applied to all piped water. After the War, chlorination was reduced due to public health fears, prompting a spate of zebra mussel problems in the 1950s (Clarke, 1952; Greenshields and Ridley, 1957). Despite this, many water companies continued to chlorinate at levels high enough to keep mussels under control (Morton, 1969.d). The situation changed when the new 1989 Water Act (Water Supply Regulations, 1989) placed strong limitations on permissible levels of chlorination. A growing body of evidence indicated that the by-products of disinfection could be hazardous to public health. Of particular importance were Trihalomethanes (THMs), carcinogenic compounds produced by the reaction of chlorine with organic matter. The 1989 Water Act placed a strict limitation of $100\mu g.l^{-1}$ THMs on all supplied water (averaged over three months).

After the implementation of the 1989 regulations, many water companies looked to change their operations to reduce THM formation. Some reduced the amount of chlorine applied or shifted the point of chlorine application to later in the treatment process (reducing the amount of exposed organic material in the water). Others radically changed their treatment processes, implementing newer ozonation, flocculation, filtration or membrane technologies in their facilities. Without sufficient pre-chlorination, pipelines were left unprotected from zebra mussel infestation. Between 1990 and today, it appears that generations of zebra mussels have been allowed to grow inside these pipelines, leading to some of the effects that are currently being manifested. In addition, many new pipelines have been constructed since 1989 without pre-chlorination in place, leaving them vulnerable to zebra mussel infestation. The spine tunnel in Thames Water's Coppermills WTW is one such pipeline, the absence of pre-chlorination undoubtedly exacerbating the problems that are currently being observed.

It must be noted that pre-chlorination will become increasingly difficult in future years. As of 2004, THM limits will no longer be taken as an average over three months, but as a spot check (Water Supply Regulations, 2000). This may mean that even short periods of chlorine dosing result in excessive THM levels.

4.4.3 The effect of rapid gravity filtration on larvae at Coppermills WTW.

At Coppermills waterworks, larval densities were greatest directly above the rapid gravity filters. This is likely to be the result of spawning by the substantial numbers of mussels that infest the every stage of the facility prior to these filters, including the rapid gravity filter inlets and walls. The rapid gravity filters at Coppermills waterworks were particularly effective at removing and killing larvae. The filters removed 88% of larvae, killing 93% of the remainder. The larvae in the reservoir were larger than anywhere else in the treatment process, which would indicate a selective removal of large larvae by the filter beds. Above the RGFs dead larvae were significantly larger than living larvae, which is likely to be the result of a natural bottleneck in survivorship with the developmental transition from the larval D-stage to umbonal stage (Schneider, 2003). Below the filters, the reverse was true: it appears that small larvae suffer greater mortality. This is because the earliest life stages of bivalve larvae are the most sensitive (Bayne, 1976). As larvae develop their tolerance for environmental conditions and toxins increases. In this case, smaller larvae have thinner shells (Sprung, 1993) which are more likely to get broken open during the filtration process.

Although filtration appears to remove the majority of zebra mussel larvae, a small number of larvae were able to penetrate and survive rapid gravity filtration. This would indicate that bio-fouling could potentially occur downstream of the filtration process. However, filtration also greatly reduces water concentrations of the zebra mussels food source, phytoplankton. As a result, zebra mussels would be unlikely to thrive down-steam of the filters.

4.4.4 The effect of pre-ozonation and coagulation on larvae at Saltersford WTW.

Unlike the rapid gravity filters at Coppermills, ozonation and ferric dosing at Saltersford did not reduce the total number of larvae in the water. However, the treatments were effective at killing larvae, giving a 63% mortality. This was not as effective as filtration, a greater proportion of larvae surviving the ozonation and flocculation processes. In a similar result to the Coppermills surveys, in the reservoir dead larvae were larger than living ones, indicating a natural mortality. However, this difference disappeared below the ferric dosing and ozonation; the treatments seem to kill larger quantities of smaller larvae. Again, this is probably due to the lower tolerance of younger larvae to environmental conditions and toxins.

4.4.5 The effects of ozonation on adult zebra mussels at Walton-on-Thames WTW.

At Walton, it is important to note that zebra mussel larvae actually survived 1.5mg.l^{-1} ozonation and grew in later stages of the facility. However, they have not been documented anywhere past the primary filters in *supplied* water, only in re-circulating drains carrying water used to clean the primary filters back to the reservoir. The densities of mussels throughout the facility do not significantly differ, indicating that ozonation is not affecting adult mortality. However, the mussels in the primary bed are significantly smaller than anywhere else in the rest of the facility. There are three possible reasons for this:

1. that ozonation or other filter bed conditions are limiting mussel growth. This effect has not been observed to this extent in any previous literature;
2. that zebra mussels have only recently developed the ability to attach and survive in the filter bed. Again, this level of adaptation has not been documented in any previous literature;
3. that at some point in time before the surveys the filter bed was drained, all the mussels died, and there has only recently been a re-infestation.

The latter explanation is perhaps the more likely, although there is no record of the bed having been taken out of action. Whatever the situation, the survival of zebra mussels in the re-circulating drain is perhaps the greatest worry for Walton-on-Thames WTW. Larvae spawned in the storage reservoirs and pipelines are surviving ozonation and being re-circulated back into the storage reservoir. This has the potential to increase infestations dramatically and could explain why the Walton works has encountered unusually large problems when its intake pipeline is only a few hundred metres long.

4.4.6 Summary of the effectiveness of current water treatment techniques for controlling zebra mussels.

In each of the three WTWs studied, the first treatment stages do seem to prevent bio-fouling of later points in the supplied water system; no documented cases of bio-fouling have been seen at later stages in any of the facilities. However, this still leaves many of the upstream pipelines susceptible to infestation and the effects observed in Section 4.3.2. For comprehensive control of zebra mussel infestation, facilities would need to move these treatments back to the water intakes themselves.

In many cases this would not be feasible as it would require the construction of new facilities in inaccessible areas.

4.4.7 Future effects of zebra mussels on English Industry.

It is clear that zebra mussels create substantial problems to fresh-water drawing industries. Without comprehensive control strategies, problems will continue, potentially getting worse as the number of zebra mussels in each facility grows and new facilities become affected.

Zebra mussels should be an important consideration in the construction of new underground pipelines and reservoirs if future problems are to be avoided. Many proposed water supply schemes in Britain could be particularly affected. Of particular concern are proposed national water grids that will result in rivers in Britain being connected by huge underground pipelines (Leake, 2002). Also at risk is a new national water company called Watergrid. Watergrid will supply industries and developers with water taken directly out of England's inland waterways (Davies, 2003) which are likely to become increasingly infested with zebra mussels in the future (Chapter 2).

4.4.8 Conclusions.

1. The zebra mussel, *Dreissena polymorpha*, is currently a major bio-fouling pest of water treatment facilities in England.

2. Thirty Water Treatment Works from eight water companies in England have experienced problems with zebra mussels. Problems have included blockage of pipelines, reductions in pipeline water flow and clogging of inlets, screens, filter beds, ozone tanks, pumps, sampling ports and heat exchangers.

3. Problems have increased since 1998 because of a spread of zebra mussels around England and changes in water treatment during the 1990s which have left intake pipelines unprotected from infestation.

4. Water treatment techniques used for the purification of water largely control downstream zebra mussel bio-fouling. However, upstream pipelines and reservoirs are still susceptible to zebra mussel infestation.

5. Without comprehensive new control strategies, problems caused by zebra mussels will worsen in future years as the number of mussels in each facility grows. The spread of zebra mussels around England and the construction of new abstractions may see an increasing number of facilities being affected. Water companies should also consider the impacts of zebra mussels when designing new treatment facilities.