Invertebrates as biomonitors of sand-filter efficiency

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Abstract

Invertebrate presence in potable water has been documented and verified by several investigators. It has been acknowledged that with present water treatment technology, only partial invertebrate removal is possible. In this regard, sand filtration has been recognised as that part of the treatment process that should control invertebrate levels within acceptable limits. Invertebrate densities in the filtrate of differently designed sand filters were compared ("old" vs. "new"). The results obtained show that there is a difference in invertebrate removal efficiency between old and new filters. New filters are able to maintain invertebrate levels within acceptable limits while older filters are unable to do so. From previous pilot-plant studies it has been established that complete fluidisation of the sand bed ensures adequate invertebrate removal irrespective of media characteristics, filtration rates, turbidity differences or head loss. In the present study, a strong relationship between the density of organisms and the backwash rate achieved by the different types of filters investigated was observed. Older filters do not achieve the required minimum backwash rate for fluidisation and are therefore less efficient in invertebrate removal, compared to new filters that achieve more than the minimum required backwash rate for fluidisation. The filtrates of both new and old filters were found to contain similar invertebrate families.

Introduction

Although free-living organisms form an integrated part of nature and chemical processes that keep the ecosystem in balance, these organisms should be absent from potable water (World Health Organisation, 1984). These organisms, which include bacteria, viruses, algae, protozoa and invertebrates may cause adverse health effects, aesthetic problems, objectionable tastes and odours, may act as a food source for fungi and bacteria and can interfere with potable water treatment and distribution (Steynberg et al., 1994). The relationship between viruses, bacteria, protozoa and algae and their effects on potable water production and quality have been studied. Invertebrate-related problems have only recently been addressed (Van Lieverloo et al., 1994; Steynberg et al., 1996 and Clasen, 1996).

The first recorded macro-invertebrate infestation of a water system was by Malloch (1915) who reported that Chironomidae larvae were found in the public waterworks supply of Boone, Iowa (USA). Malloch (1915) also reported a specimen of the genus *Chironomus* from the reservoir supply of Champaign, Illinois. Bahlman (1932) noted that a similar problem existed in Cincinnati, Ohio, while Brown (1933) and Arnold (1936) reported that the Chironomidae occurred in a number of Californian systems. Other American cities reporting similar infestations, included Charlottsville, Virginia and Elizabeth City, N.C. (AWWA, 1929, as cited by Levy et al., 1984); Peoria, Illinois (Flenje, 1945a) and Alexandria, Virginia (Flenje, 1945b); Washington (Brown, 1973); Lake St. Clair, Detroit, Michigan (Hudgins, 1931), Ohio River (Chang et al., 1959) and Indianapolis (Crabill, 1956). Several locations have been reported in England (Floris, 1935 and Kelly, 1955). Ainsworth et al. (1981) reported that approximately 150 different kinds of animals had been found in the British water mains and that few distribution systems were without any animals.

The presence of organisms in potable water may be due to the penetration of unit processes or colonisation of the complete purification system. The types of organisms which enter potable water in this way are those that are aquatic for the whole or for part of their life cycle. Service reservoirs may also be a point of entry for flying insects gaining access through badly protected vents and overflows (Viljoen and Steynberg, 1991). Another possibility is submerged air valves where infested water may gain access under situations of reduced pressure in the pipes. The presence of organisms due to bad maintenance of infrastructure is appropriately termed an occurrence and is reliant on external recruitment (Steynberg et al., 1996). Animals present which are aquatic for the whole of their life cycle, entering the purification plant and colonising the distribution system, are termed infestations (English, 1958).

Levy et al. (1984) and Luczak et al. (1980) have suggested that certain invertebrate types live and reproduce within the distribution system, while other organisms are temporarily suspended in the water column within the pipe network. Studies on the nature of the encrustation and tubercles within the pipeline suggest that there are adequate food sources (direct/indirect) enabling benthic invertebrates to infest sections of the distribution network that provides a favourable habitat (Luczak et al., 1980 and Allen et al., 1980). Investigations by Van Lieverloo et al. (1994) showed that invertebrate numbers in distribution systems are probably determined by the amount of nutrients supporting the growth of biofilms. Biofilms developing on the main walls and deposits accumulating in mains because of sloughing of the biofilm probably serve as a food source to invertebrates in drinking water.

Types of organisms present in the distribution system may vary in density and composition. It has become important in the potable water industry to contain the numbers of organisms within acceptable limits, thereby preventing consumer complaints.

Rand Water is a South African bulk water utility which treats and supplies potable water to 12 m. people and industries over an area of 17 000 km^2 (mean production = 2 800 Mℓ/d). At Rand Water, a sure-kleen in-line filter capable of filtering the total volume of water passing through a pipeline was installed in

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February 1989. During the testing and commissioning of the filter it was necessary to remove the three filter elements on four occasions. Concern was expressed regarding the large number of Chironomidae larvae that were found stuck on the filter elements (Viljoen and Steynberg, 1991). The occurrence of these larvae and complaints received from the Elandsrand Goldmine and Sasolburg City Council initiated the first investigations into the presence of Chironomidae and other invertebrates in Rand Water's distribution system.

This initial study culminated in a Water Research Commission (WRC) report which had the following important findings (Steynberg et al., 1996):

- Invertebrates are only partially removed by conventional water treatment processes and sand filtration has been recognised as that part of the treatment process that should remove most invertebrates. This is substantiated by work done by Evins and Greaves (1979).
- Different types of invertebrates are present in the distribution system and there appears to be a seasonal dominance in terms of the organisms present, with a general decrease in organism numbers during winter when water temperatures are between 6 and 17°C.
- Invertebrates were found to affect the aesthetic quality of potable water, but the health-related effects (as demonstrated by Levy et al., 1986) were found to be inconclusive although opportunistic pathogenic bacteria were observed to be present.
- The sizes to which different invertebrates can grow had an effect on their presence being detected by consumers, therefore, size-dependent guidelines were defined in order to establish acceptable invertebrate densities in potable water.
- Differences in the removal efficiency of invertebrates by different filters on a pilot-plant scale could not be explained in terms of media characteristics, filtration rates, differences in turbidity or by head loss.
- Results confirmed that filter maintenance is more important than small differences in media characteristics.

The present paper is a summary of three years of data, from November 1993 to December 1996, collected during routine invertebrate monitoring at Rand Water which was initiated due to the findings of Steynberg et al. (1996).

Methods

Monitoring at Rand Water is conducted on a routine basis at the filtrate of sand filters and at the mains (water leaving the purification works after disinfection with chlorine) with the aim of:

- monitoring the efficiency of sand filtration;
- ascertaining compliance of the distributed water to guidelines; and
- providing recommendations which can assist in the reduction of invertebrate densities.

Data obtained from the filtrate of individual sand filters at Rand Water's purification plant (Vereeniging) will be discussed in this paper.

At Vereeniging the situation is that rapid gravity sand filters which are old and of a different design and technology (Filter Houses 1 and 2) are operated in conjunction with newer rapid

TABLE 1
DIFFERENCES IN FILTER CHARACTERISTICS OF OLD AND NEW RAPID GRAVITY SAND FILTERS

Filter characteristic	Old filters	New filters
Filter type	Candy & Patterson	Candy
Commissioned date	Filter House 1 : 1923 Filter House 2 : 1952	Filter House 3 : 1982
Open/closed	Open	Closed
Treatment process	Coagulation and flocculation, sedimentation, stabilisation, secondary sedimentation, filtration, disinfection	Coagulation and flocculation, sedimentation, stabilisation, filtration, disinfection
Filter surface area (m^2) Effective sand size (d10) **(specified = 0.75 mm)**	Small (55 m^2) 1.02 mm	Big (149 m^2) 0.63 mm
Uniformity coefficient (d60/d10) **(specified = 1.20 mm)**	1.57 mm	1.32 mm
Backwash process	Manual : 5 min. air scour and 10 min. water	Computerised : 5 min. air scour and 10 min. water
Backwash cycle	48 - 100 h	48 - 72 h
Backwash rate achieved (BA)	10 m/h	32 m/h
Minimum backwash rate required (BR) for fluidisation	33 m/h	25 m/h

gravity filters of a more advanced technology (Filter House 3). Table 1 indicates pertinent differences between old and new filters. In the present study, a comparison between the performance of old filters and new filters in terms of their efficiency in invertebrate removal is made.

Sampling

Sampling of the filtrate of four filters prior to backwashing was undertaken on a weekly basis. A monitoring cycle of the filtrate of all filters in Filter Houses 1, 2 and 3 was completed within a period of two years. Access to the filtrate at Filter Houses 1 and 2 was obtained through a filter basin for individual filters. At Filter House 3 access to the filtrate of individual filters was obtained through a manhole leading into the sump.

A submersible pump was connected by means of a 70 mm layflat hosepipe to a flow meter. A 50 µm mesh bag was attached by means of rubber bands to the flow meter. A volume of 10 m^3 of filtrate passed through the mesh bag in approximately 45 min and trapped the invertebrates present in the filtrate. The mesh bag was removed from the filtration apparatus and placed into labelled plastic bottles containing 100 ml of water sampled. An additional litre of filtrate was sampled and taken to the laboratory for the measurement of the concentration of suspended material by means of turbidity measurements and other water quality variables such as pH and conductivity which are monitored for operational purposes. The results thereof will not be discussed in the present paper.

Sample preparation and preservation

The invertebrates were removed from the mesh bag by flushing with distilled water through a glass funnel containing a 50 µm net at its neck. The contents of this net were washed into a 30 ml glass bottle and preserved with 95 % ethanol. Rose Bengal solution (0.4 %) was added for staining.

Enumeration of organisms

The 30 ml concentrated sample was emptied into a standard (90 mm diameter) petridish which was used as a counting chamber. A stereo-microscope mounted on a movable arm which allows the optics to move rather than the counting chamber, was used to identify and count all the organisms in the counting chamber.

The different types of organisms were identified to family level, but in order to implement the provided guidelines, all other types of organisms, except the Diptera, were combined as “All Organisms”. The Diptera have been allocated stricter guidelines due to the large sizes (2 cm or more) that they can potentially reach in the distribution system. Therefore, they were counted separately from “All Organisms” and recorded as Diptera (see Guidelines Implemented). Organism density was expressed as organisms/m^3 and was calculated by dividing the total counts of invertebrates by the total volume filtered during sampling.

Guidelines implemented

Guidelines are required so that acceptable levels of invertebrate densities in potable water can be defined. A single series of guideline values applied for all invertebrates in potable water was found to be too simplistic (Steynberg et al., 1996). A size-dependent approach was used in setting guidelines, where more stringent guidelines were set for macroscopic invertebrates like the midge larvae (Chironomidae) which are responsible for most of the invertebrate-related water quality complaints received. The guidelines set for these organisms were based on calculations that take into account that 0.7 % of the water supplied by Rand Water is used directly as drinking water and on the assumption that an individual consumes at least 2 l of water a day.

The guidelines implemented used by Rand Water for potable water are (Steynberg et al., 1996):

	Diptera	All organisms
Recommended limit	1 org/m^3	20 org/m^3
Maximum permissible limit	4 org/m^3	100 org/m^3
Crisis limit	7 org/m^3	250 org/m^3

The recommended limit set is considered the nominal water quality criteria which Rand Water will endeavour to meet at all times. Should the maximum be exceeded immediate and detailed investigations are necessary to remedy the situation. When the crisis limit is exceeded, the treatment plant where the poor water quality is produced must be isolated and remedial action taken to rectify the problem.

Results

A comparison of densities for “All Organisms” and the Diptera (Chironomidae larvae) is indicated in Figs. 1 and 2 respectively. Summary statistics are given in Table 2.

A similar trend was observed in both instances (Figs. 1 and 2) where the filtrate of Filter House 3 maintained invertebrate and Diptera levels within the recommended limits, while in the filtrate of filters in Filter Houses 1 and 2 invertebrate counts were

TABLE 2
SUMMARY STATISTICS FOR FILTER HOUSES 1, 2 AND 3 (NOVEMBER 1993 TO DECEMBER 1996). UNITS = ORGANISMS/m^3

Sampling point	Sample size (n)	Mean		Standard deviation		Range			
		All organisms	Diptera	All organisms	Diptera	All organisms		Diptera	
						min.	max.	min.	max.
Filter House 1	149	126	5.8	50	1.4	26	241	3.2	8.9
Filter House 2	70	119	4.9	51	1.0	21	222	3.0	4.2
Filter House 3	92	14	1.3	12	1.0	< 1	41	< 1	3.6

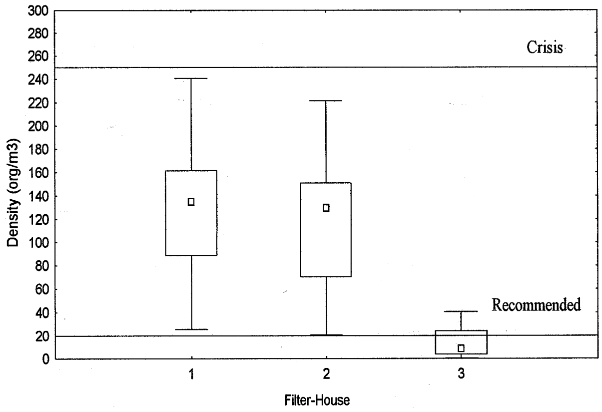

Figure 1
Comparison of densities of all organisms at the different filter houses

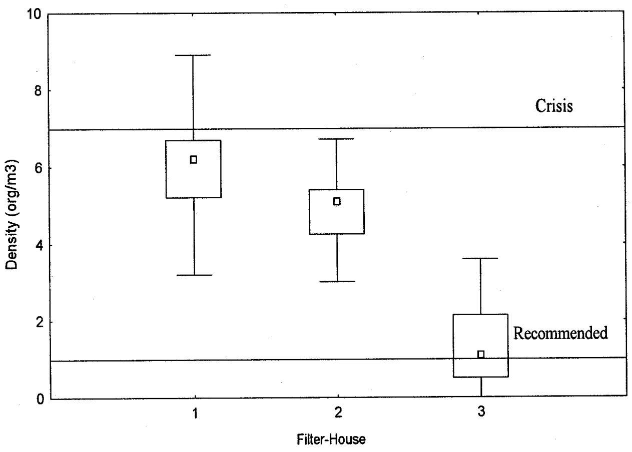

Figure 2
Comparison of Diptera densities at the different filter houses

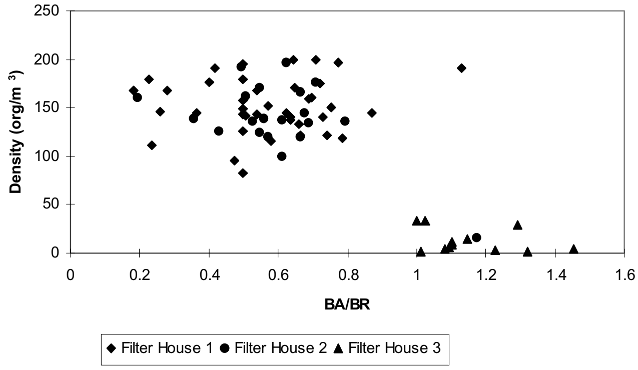

Figure 3
Comparison of invertebrate densities (All organisms) with ratio of backwash achieved and backwash required. (BA - backwash rate achieved, BR - backwash rate required, BA/BR - backwash rate achieved divided by backwash rate required to give ratio)

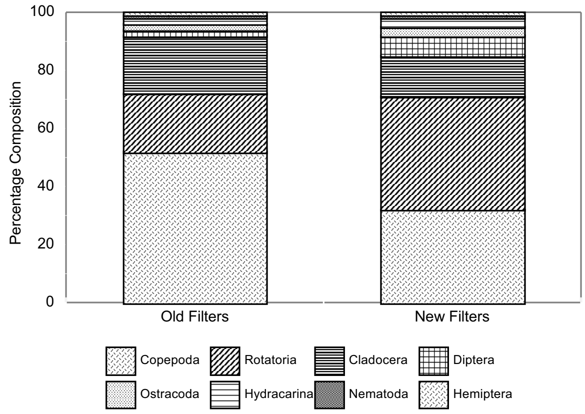

Figure 4
Percentage composition of organisms observed in the filtrate of new and old filters

above the maximum permissible limit for most of the time. Student t-test comparing mean density results obtained for the individual filter houses verified these observations. Comparison of Filter Houses 1 and 2 showed no significant difference (p-value = 0.36) for "All Organisms". Comparison of densities obtained for "All Organisms" at Filter House 3 with those of Filter Houses 1 and 2 showed highly significant differences (p-value = 0.00). A similar trend was verified for the Diptera with Filter House 3 being significantly different from Filter House 1 and 2 (p-value = 0.0001). See Table 2 for the relevant mean values.

Important differences between old (Filter Houses 1 and 2) and new (Filter House 3) filters are noted in Table 1**.** Pilot-plant studies conducted by Steynberg et al. (1996) showed that proper backwashing of the sand filters was more important than small differences in media characteristics. Therefore, the current study focuses on backwash rates of the sand filters in an attempt to explain invertebrate density differences observed in the different filter houses.

Figure 3 shows the relationship between the ratio of the backwash rate achieved (BA) to that required (BR) and the density of invertebrates observed. The BR is a theoretical value calculated using Wen and Yu's (1966) fluidisation velocity equation which takes into account the backwash rate required for a specific sand particle size. Where the backwash rate was achieved (BA/BR > 1) in most instances the density of invertebrates was low and usually within recommended limits. This was the trend for filtrate of filters at Filter House 3 (Fig. 3). In contrast, where the backwash rate was not achieved (BA/BR < 1), the invertebrate densities were higher and usually above the recommended limit. In most instances this was observed for Filter Houses 1 and 2 (Fig. 3). Figure 3 also shows outliers, the presence of which can be explained in terms of discrepancies between the actual (BA) and calculated theoretical values (BR) obtained with regard to sand sizes. At the same time it is known from experience that filters in Filter Houses 1 and 2 have a history of inadequate backwashing due to inadequately designed infrastructure and underdrain systems.

In terms of the types of organisms that have been recorded, Copepoda, Cladocera and Rotatoria appear to be dominant in old (52, 20 and 20% respectively), and new filters (32, 39 and 12% respectively - see Fig. 4). The Diptera which have been the cause of complaints only form a small percentage of the invertebrates recorded (2% in old filters and 7 % in new filters - see Fig. 4).

Discussion

One persistent problem in the potable water industry is the infestation of both filtered and unfiltered water and distribution systems by invertebrates (Levy et al., 1986). These animals are not known to directly affect the health status of treated water; however, they may indirectly contribute to bacterial growth in the distribution network by decaying, supporting bacteria on their external surfaces or by ingestion of bacteria. Nevertheless, the presence of invertebrates lowers the aesthetic quality of potable water supplies. Knowledge of the identity and invertebrates in potable water is essential to determine their possible effects on potable water quality, to identify treatment options and to determine future water quality guidelines (Steynberg et al., 1996).

Although it is highly desirable to remove invertebrates totally from potable water, studies have shown that with present technology, only partial removal is possible (Evins and Greaves,1979; Ainsworth et al.,1981; Van Lieverloo et al., 1994 and Steynberg et al., 1996). As observed in the present study (Filter House 3) although total removal of invertebrates is unlikely to be achieved it is possible to maintain invertebrate numbers within acceptable limits. In the case of filters at Filter House 3 (Fig. 1 and 2) the filtrate on average was found to contain Diptera levels at 1.34 org/m^3 and "All Organisms" occurred at an average density 13.61 org/m^3 (Table 2) which is below the recommended limit implemented.

Van Liverloo et al. (1994) showed that distribution systems in which invertebrates are breeding, harbour between 100 and 1 000 times more organisms than occur in distribution systems in which no invertebrate breeding takes place. Containment of invertebrate densities is essential in order to reduce consumer complaints due to aesthetic problems caused by the presence of invertebrates in potable water and to reduce possible health-related problems. The differences in densities observed between the different filter houses show similar trends at distribution lines that are fed from these sand filters and a relationship between invertebrate density and turbidity has been observed (personal observation). The invertebrate densities observed in the filtrate of old filters differed from new filters as a result of the physical characteristics of the rapid gravity filters (Table 1) and the consequent backwashing efficiency.

Part of the treatment of raw water filtered by the old filters is a secondary sedimentation stage after stabilisation (Table 1) in exposed tanks which could allow for external recruitment of invertebrates. At the same time these secondary sedimentation tanks provide ideal breeding areas for invertebrates. In the case of the new filters there is no secondary sedimentation and the stabilised water is filtered directly without exposure; therefore, recruitment or additional breeding areas for invertebrates is avoided.

In addition, the old filters are open and are therefore more vulnerable to flying insects which can gain access to the head of the filter in order to lay eggs. The newer filters are covered, limiting insect access. This has been confirmed at the Bewl Bridge treatment works (Elynn and Bolas, 1985) where it was found that Chironomidae larvae which enter distribution systems originated from eggs laid on the head of open sand filters. In addition, Ainsworth et al. (1981) describes one Chironomidae species found in the distribution system of South East England that is parthenogenic (females able to reproduce without males). Another unusual feature of this species is that eggs can develop within the larvae and if emergence of the aerial adult is prevented viable eggs are released. Such species can therefore successfully reproduce within a distribution system. It is uncertain whether species with a similar life-cycle exist in South Africa and this aspect will require more research.

In pilot-plant studies conducted by Steynberg et al. (1996), it was found that smaller sand grains (d10 = 1.18 mm) removed invertebrates only marginally better than coarser sand grains (d10 = 0.629 mm - 0.706 mm). However, the percentage removal of invertebrates increased with increased backwash rates (Steynberg et al., 1996). Findings of Steynberg et al. (1996) showed that the same removal efficiency of invertebrates is obtained if the backwash rates applied result in the same degree of fluidisation of the sand bed.

According to Evins and Greaves (1979) in their studies conducted at Castle Carrock, Staines and Fobney, filter media appeared to play a role in the removal of invertebrates; however, the quality of the raw water was also considered to be an important factor. In rapid sand filters, sand of 0.5 mm up to 1 mm in diameter was used, resulting in an effective pore size of 100 µm to 150 µm. The mean number of organisms found in the effluent of rapid gravity filters prior to backwashing was 1.6 times higher than those found directly after backwashing (Evins and Greaves, 1979).

The results obtained from the present full-scale study (Fig. 3) support the pilot-plant results obtained by Steynberg et al. (1996). The old filters have larger effective sand sizes (Table 1) as a result of calcium carbonate encrustration which in turn affects the backwash rate required for complete fluidisation of the sand bed. For effective cleaning of the filter-bed, the fine sand-grains in the bed should be fluidised. The backwash rate for fluidisation, is a function of grain size, where large grain sizes require higher backwash rates (Table 1). The sand grain sizes in older filters is much larger (due to scaling) than that of new filters, therefore, a higher backwash rate is required. The results as indicated by Fig. 3 show that in the case of older filters, where the backwash rate achieved is lower than that theoretically required, the density of invertebrates is higher and frequently exceeds the recommended limits of 20 org/m^3. In contrast to the new filters, where the backwash rate achieved is frequently higher than that theoretically required, invertebrate densities are maintained within recommended limits (Fig. 3). Therefore, it appears that proper backwashing of sand filters and complete fluidisation of the sand bed is most important for the effective removal of invertebrates irrespective of sand particle size

In terms of the types of invertebrates observed in the filtrate of both old and new filters (Fig. 4), the Cladocera, Copepoda and Rotatoria are dominant. Interestingly, the Chironomidae larvae (Diptera) which have been the cause of consumer complaints, form a very small percentage of the overall composition (Fig. 4). This is because they are easily visible due to the big sizes (2 cm) that they can potentially reach in the distribution system and the fact that they are red in colour (common name - "bloodworm"). Although there were no differences in terms of the types of invertebrates that were found in the filtrate of old and new filters, where filters are not properly backwashed (old filters - Fig. 3) it is known from experience that "dead spots" on the sand bed can occur where it is not properly fluidised forming ideal breeding areas for Diptera and other invertebrates. The older filters are therefore more vulnerable because of inadequate backwashing and subsequently harbour more invertebrates than the newer filters where, due to proper fluidisation of the sand bed (Fig. 3), these sand filters are not vulnerable to invertebrate colonisation.

Recommendations and conclusion

The observations from the present study indicate that proper backwashing and complete fluidisation of the sand bed is essential in order to ensure that invertebrate densities are kept within acceptable limits. This is more important than any changes in filter media characteristics although increases in sand size will affect required backwash rates. It is therefore important to ensure that, when designing sand filters, the fine filter media can be fluidised under all circumstances.

In the case of the old filters discussed in the present study, several short-term measures can be implemented in order to restrict invertebrate access. These include, covering the head of filters, enclosing the secondary sedimentation tanks and installation of a garden sprinkler system (Elynn and Bolas, 1985). However, none of these measures will be appropriate if renovation of the filter underdrain system and proper infrastructure for adequate backwashing are not addressed.

Proper filter maintenance is another factor that could be addressed in collaboration with operations personnel. Maintenance would involve sensitising filter operators to the importance of proper backwashing and to the fact that different types of filters will require different maintenance and backwashing schedules.

Despite their diverse roles in nature, the information presented in this paper shows that invertebrates can play an important role in assisting with the monitoring of sand-filter efficiency.

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