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Storm water harvesting and reuse in Australia: enhanced sand filtration for the treatment of storm water

Craig McTaggart, Leanne Farago, Veeriah Jegatheesan, Li Shu*

School of Engineering, Deakin University, Waurn Ponds Campus, Geelong, VIC 3216, Australia, email: l.shu@deakin.edu.au

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ABSTRACT

This study details the removal of common storm water pollutants along with heavy metals by enhanced sand filtration. Three filtration flow rates were trialled: 5, 10 and 20 m/h. The performance of each filter was rated on the ability to remove turbidity, suspended solids, dissolved solids, phosphorus, nitrogen, lead, copper and Zinc. Conventional sand filter was used as a performance benchmark, and compared with four sand filters that are enhanced with a nylon carpet fibre, polypropylene carpet fibre, Syrian carpet fibre-enhanced and alum sludge-enhanced sand filter. Carpet fibre-enhanced sand filtration was highly effective at filtering simulated storm water and in most cases performing well above the conventional sand filters. The carpet fibre-enhanced sand filters had no drop in flow rates over the 4 h filtration period with following removal rates: up to 90% total suspended solids, 70% zinc, 60% turbidity, 25% phosphorus, 15% nitrogen and 10% total dissolved solids. However, results showed that alum sludge-enhanced sand filter performed the highest, with removal rates up to 100% for total suspended solids, 80% zinc, 90% turbidity, up to 80% phosphorus, up to 40% nitrogen and 3% total dissolved solids. But the flow rates dropped approximately two-thirds of the original flow rates within the first hour.

Keywords: Alum; Carpet; Fibre; Filtration; Sand; Storm water

1. Introduction

Currently in Australia, there is very little storm water harvesting or reuse in practice. This has generally been due to an abundance of rainfall and water storages [1]; however, of late, a nationwide drought [2] has forced governments, water authorities and the general public to be more aware to their water usage, and if there will be a guaranteed source of water if the drought continues. As a consequence, the Natural Resource Management Ministerial Council, the Environment Protection and Heritage Council and the National Health and Medical Research Council in Australia, have produced "Australian guidelines for water recycling: managing health and environmental risks (phase 2), Storm water harvesting and reuse" which provides excellent guide for all the Australian project schemes on storm water reuse [3]. Summary tables, providing quantitative measures of physical, chemical and microbial constituents of untreated storm water from urban catchments as well as

*Corresponding author.

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untreated sewered urban catchments have been provided in that guideline. Further, comprehensive details on the steps to be followed in various storm water reuse schemes (such as open space irrigation, fire control, municipal, residential and industrial uses) have been provided.

Desalination plants have been constructed, as water reserves will not be sufficient to keep up with the current water demands. In order to reuse water that already exists, there has been a growing interest in storm water harvesting and reuse [2], which involves using water that has fallen on roads, footpaths, parklands and buildings. Currently in Australia, this water is generally carried by storm water pipes, and discharged into local waterways or oceans [4].

This study is to investigate the effectiveness of filtration in treating storm water for the purpose of reuse. Enhanced sand filtration is a type of filtration that is commonly used for general water filtration [5]. A basic sand filter is enhanced with a layer(s) of filter media on top of the sand layer to aid the sand and perform better. Throughout the study, a comparison is made between a basic sand filter, alum sludge-enhanced sand filter and a carpet fibre-enhanced sand filter, and ranked on how they perform at removing common storm water constituents.

2. Materials and methods

Table 1 shows the typical composition of storm water along with the chemicals used in this study to prepare the synthetic storm water. Fig. 1 shows the filtration system that was used in this study.

Synthetic storm water was filtered through a sand filter and five enhanced sand filters, each enhanced with one of the three types of carpet fibres or one of the two types of alum sludge. Filters were run at specific filtration velocities (5, 10 and 20 m/h) that could be considered as high rate filtration for 4 h. Effluent samples were taken at every 15 min during the first hour and every 30 min for the rest of the filter run to analyse the water quality parameters. Backwashing of the filter occurred after each run was completed. When tests included other layers on top of the sand, such as alum sludge of carpet, these layers were removed before the sand bed was backwashed. The flow rate was varied so that the sand bed was fluidized, which involved a high backwash flow rate. Generally, the backwashing took 15–20 min for each column with about 50 L of water. The backwash water was released to the laboratory drain but in reality needs to be collected and dewatered.

There were large gravel base (~2 cm) stones at the very bottom of the filter column, then an approximately 10 cm layer of smaller (<1 cm) stones on top, followed by the sand. The sand particle sizes ranged between 600 μm and 1.18 mm in diameter. The three different types of carpet fibres used throughout the testing were nylon, polypropylene and Syrian. The carpet was sourced from GT recycling depot in Geelong, Victoria. GT recycling receives approximately 1 ton of brand new carpet to recycle every day. The carpet comes from carpet manufacturers throughout the region from offcuts and unwanted carpet. The carpet comes attached to the carpet backing and is quite rigid initially. The carpet was removed from its backing, so that it resembled a lot of small fibrous pieces and was soft to squeeze into a ball. The same weight of carpet was used in each column and was compacted to the same height, so that the density was uniform throughout the testing process.

The alum sludge that was used in this study was sourced from Barwon Water Moorabool Water Treatment Plant, located near Meredith, Victoria. The alum sludge was dried in an oven, and then sieved to determine the particle size distribution. The results are shown in Table 2.

There were two variations of the alum sludge used throughout the testing, the first using all of the full size distribution and a second using just the 1.18 mm to 425 μm particles. There was an issue with the larger

Table 1
Composition of synthetic storm water

Pollutant	Range (mg/L)	Quantity (mg/L)	Chemical used	Formula
Total suspended solids (TSS)	85–130	100		
Lead (Pb)	0.05–0.23	0.05	Lead nitrate	$Pb(NO_3)_2$
Copper (Cu)	0.022–0.094	0.045	Copper sulphate	$CuSO_4.5H_2O$
Zinc (Zn)	0.18–0.39	0.23	Zinc sulphate	$ZnSO_4.7H_2O$
Nitrogen (N)	1.9–2.7	2.2	Ammonium acetate	CH_3COONH_4
Phosphorus (P)	0.27–0.37	0.31	Potassium dihydrogen phosphate	KH_2PO_4

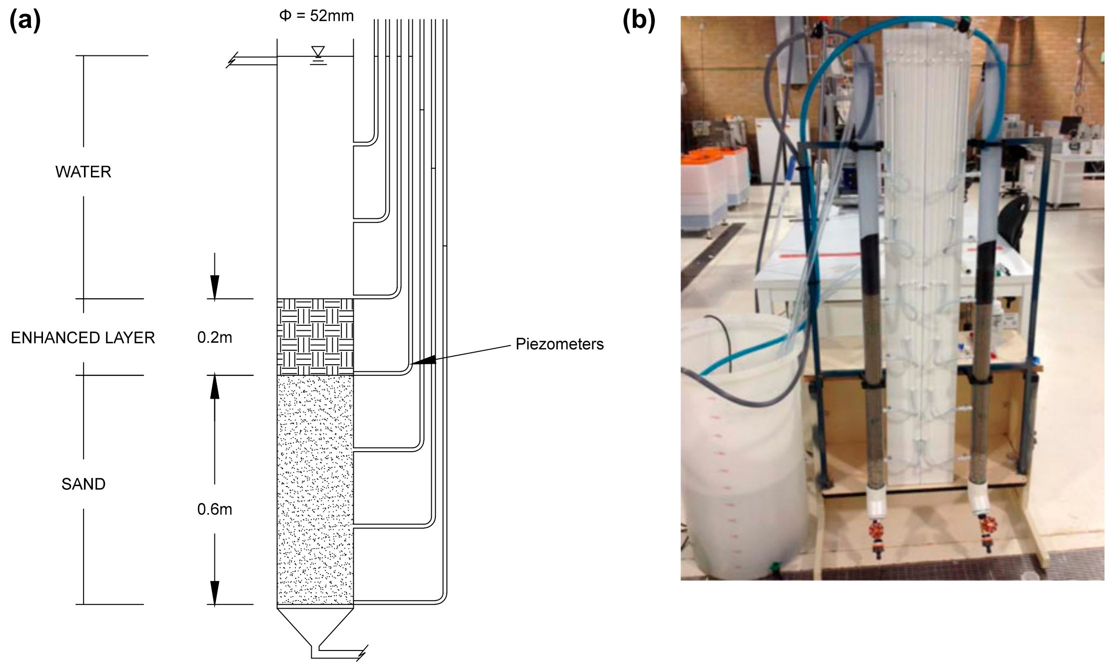

Fig. 1. Filtration system (a) schematic diagram (b) laboratory set-up.

Table 2
Particle size distribution for alum sludge

Size	Percentage
>2.36 mm	0.3
2.36–1.18 mm	6.4
1.18 mm–600 μm	32.8
600–425 μm	21.6
425–300 μm	21.0
300–150 μm	15.5
150–75 μm	1.9
<75 μm	0.5

particles breaking down into smaller particles with movement and the pressure of the water, which resulted in smaller particles and clogging of the filters.

Storm water quality parameters, such as total suspended solids and total dissolved solids were measured by filtering the synthetic storm water sample through a 0.45 μm filter. Turbidity was measured by a HACH 2100P turbidimeter. The pH and conductivity were measured by WTW320 pH meter and WTW LF330 conductivity meter, respectively. The nutrients, phosphorus and nitrogen were measured using the colorimetric method. The heavy metals zinc, copper and lead were measured using an atomic absorption spectrophotometer.

3. Results and discussions

3.1. Turbidity

Breakthrough in the sand filter at 10 and 20 m/h occurred after 1 h of filtration. However, at 5 m/h the breakthrough occurred after 2 h of filtration. The initial maximum turbidity removal efficiencies for the 5, 10 and 20 m/h filtration velocities are 26, 8 and 27%, respectively, and finishing on (after 4 h) −13, −45 and −43, respectively. The removal efficiency of sand filter is quite low compared to enhanced sand filters, however, this is used as a benchmark to show the performance upgrades of the enhanced sand filters.

Fig. 2 shows the turbidity removal for the 4-h testing duration for all three carpet-enhanced fibre filters at a filtration velocity of 5 m/h. The initial maximum turbidity removal rates in the Syrian, polypropylene and nylon carpet fibre-enhanced filters are 57, 42 and 45%, respectively, and finishing on (after 4 h) 31, 21 and 20%, respectively. These values are all much higher than the sand filters, and did not foul during the 4-h test duration. All three carpet fibre-enhanced filters follow a similar trend line, with the filter containing the Syrian carpet fibre performing slightly better than the polypropylene and nylon carpet fibres. Based on these results, filtration runs with higher velocities (10 and 20 m/h) were also made in the filter with Syrian carpet fibre; the initial maximum turbidity removal for 10 and 20 m/h is 51 and 36%,

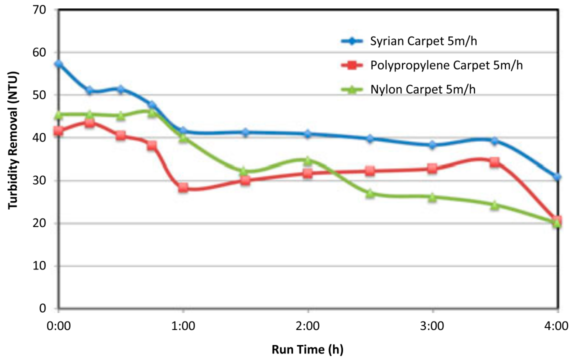

Fig. 2. Turbidity removal for the 4-h testing duration for all three carpet-enhanced fibre filters at a filtration velocity of 5 m/h.

respectively, and finishing on (after 4 h) 22 and −1%, respectively.

Two different types of alum sludge were tested, one with smaller particles, and one that was sieved and only the bigger particles used. Each was tested at 5 and 10 m/h. Fig. 3 shows that the turbidity removal in the filter with smaller alum particles with filtration velocities of 5 and 10 m/h started on 92 and 82% and finished on 89 and 79%, respectively. Whilst the filter with larger particles at 5 and 10 m/h started on 75 and 58% and finished on 73 and 71%, respectively. The turbidity removal was very high when alum sludge was used to enhance the filter performance. Alum sludge has a very small particle size and traps more of the suspended solids. However, this caused very high head loss throughout the testing period. The filtration in the column with larger alum particles was stopped after 1 h, due to the flow rate being unacceptably low.

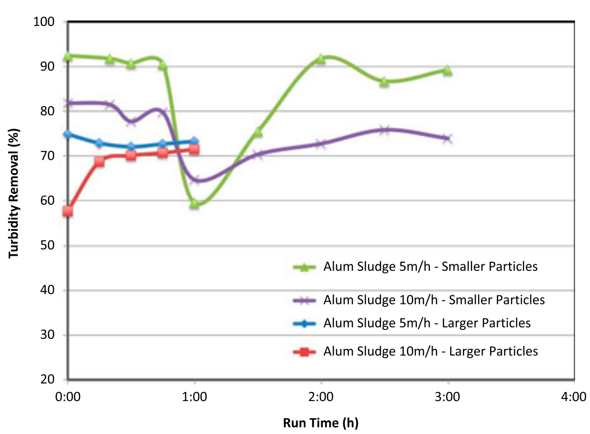

Fig. 3. Turbidity removal in filter with alum particles with filtration velocities of 5 and 10 m/h.

3.2. Total suspended solids

The initial maximum total suspended solids removal in the sand filter at 5, 10 and 20 m/h is 65, 94 and −17%, respectively, and finishing on (after 4 h) 23, 82 and −12%, respectively. These can be used as benchmarks as to how the enhanced sand filters perform. Filters with all three types of carpet performed very similarly in removing total suspended solids. All three carpets removed approximately 80–90% suspended solids for the entire test duration. In the filter with Syrian carpet fibre added, the initial maximum total suspended solids removal rates at 5, 10 and 20 m/h were 89, 92 and 51%, respectively, and finishing on (after 4 h) 89, 95 and 94%, respectively. For the filters with alum sludge, particles are added; the 5 and 10 m/h tests for the filter with smaller alum particles started on 100 and 100% and finished on 94 and 93%, respectively. Whilst for the filter with larger alum particles, the removal of suspended solids at 5 and 10 m/h started on 82 and 32%, respectively. The suspended solid removal was very high when the alum sludge was used. The alum sludge has particles with very small size, which traps more of the suspended solids. However, this caused the flow rates to be very low and reduced it dramatically throughout the testing period.

3.3. Nutrients

3.3.1. Phosphorus

The sand filter that ran at 20 m/h did not remove any phosphorus at any point during the testing duration. This shows that the 20 m/h flow rate is too fast for there to be any phosphorus removal. The 10 m/h flow rate removed between 5 and 7% of the total phosphorus during the testing period. The 5 m/h flow rate removed 29% of the total phosphorus initially, and finished on −10% after the 4-h testing duration.

The filter with nylon carpet fibre performed exceptionally better than the polypropylene and Syrian carpets, as well as the basic sand filter (Fig. 4). At 5 m/h, the filter with nylon carpet started by removing 25% phosphorus, and dropped to 10% by the end of the testing period. Whist the filters with polypropylene and Syrian carpets started by removing 14 and 9% phosphorus, it dropped to −16 and −12%. The initial removal of phosphorus by all three carpets is due to adsorption; however in the longer run, filters with polypropylene and Syrian carpets released phosphorus to the effluent possibly due to desorption of phosphorus from the carpets. This needs further investigation.

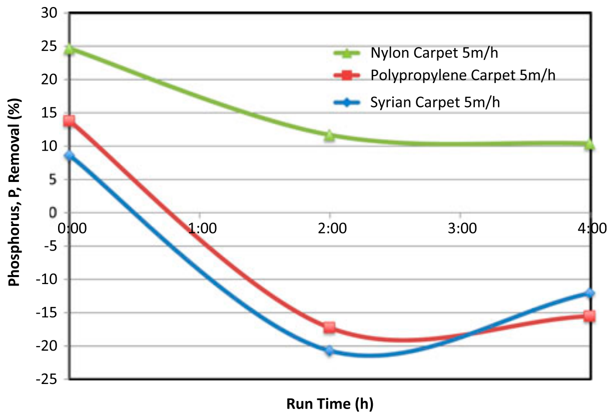

Fig. 4. Removal of phosphorus by fibre-enhanced sand filters at 5 m/h filtration velocity.

The phosphorus removal through the filter with alum sludge was very high, which is in accordance with the literature data [6]. In the case of filter with larger alum sludge particles, 65–80% removal of phosphorus was obtained (Fig. 5). Whilst the filter with smaller alum sludge particles, a 10–50% removal was obtained.

3.3.2. Nitrogen

The sand filter ran at 5 and 10 m/h removed 19 and 12% of nitrogen at the beginning and finishing at 1 and 0%, respectively. However at 20 m/h, the removal of nitrogen started at 3% and increased to 10% over the test duration. In all cases, nitrogen removal is positive and nitrogen is not added to the effluent at any point. Filters with all types of carpet performed equally poor in removing nitrogen at 5 m/h filtration velocity; all filters added nitrogen to the effluent from the beginning. However, the filter with Syrian carpet fibre removed nitrogen for the entire duration at 10 and 20 m/h filtration velocities. At 10 m/h, nitrogen removal started at 10% and finished at 3%, whilst at 20 m/h nitrogen removal started at 15% and finished at 1%. Nitrogen removal in the filter with smaller alum sludge particles started high, at 40 and 20% for the 5 and 10 m/h filtration velocities, respectively, and within the first hour, dropped to approximately 0% nitrogen removal. The filter with larger alum sludge particles started by adding nitrogen into the effluent and continued to do till the end of the tests. Therefore, the filter enhanced with alum sludge particles was unsuccessful at removing nitrogen from the water, and was not as good as the filters enhanced with carpet fibres or the basic sand filter.

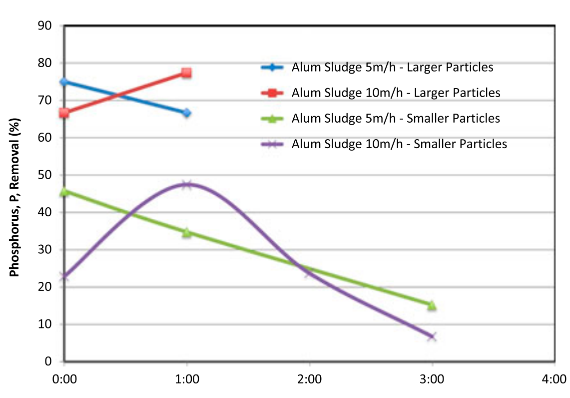

Fig. 5. Removal of phosphorus by alum sludge-enhanced sand filters at 5 and 10 m/h filtration velocities.

3.4. Heavy metal

3.4.1. Zinc

The sand filter at 5 m/h performed better initially, removing 30% of zinc; however, by the end of the 4-h duration, performed the worst, with −32% of removal. The sand filter at 10 and 20 m/h performed similarly, with approximately 20% initially and −12% removal of zinc at the end of the test. One thing to note is that the sand filter broke through zinc approximately 1.5 h into the test at 5 m/h, and at 10 and 20 m/h approximately after 3 h of filtration.

At 5 m/h filtration velocity, the filter with nylon carpet fibre removed 34% zinc initially and then finishing on 23% removal. The nylon carpet does not break through zinc at any period thought the test duration. The filters with Syrian and Polypropylene carpets were similar, starting at approximately 35% and finishing on 10–15% removal of zinc. These two filters added zinc to the effluent for a small period at 2 h into the test, before improving again and removing zinc. The nylon carpet-enhanced sand filter was the best for zinc removal at 5 m/h, followed by the polypropylene and Syrian carpet-enhanced filters. All three carpet-enhanced sand filters were better at Zinc removal than the basic sand filter. Further, the Syrian carpet-enhanced sand filter removed 70% zinc initially, dropping to 20% by the end of the test at 10 m/h filtration velocity. The removal started on 54% and finished on 36% at 20 m/h filtration velocity.

The filter with larger alum sludge particles had a removal rate of approximately 80% for the first hour at both 5 and 10 m/h filtration velocities. Whilst, the filter with smaller alum sludge particles had approximately 50–60% removal rate for the 3-h test duration.

Table 3
Maximum initial removal efficiencies of the basic sand filter and five enhanced sand filters in treating synthetic storm water

	Initial concentration	Basic sand filter			Syrian carpet-enhanced sand filter			Nylon carpet	Polypropylene carpet	Alum—small particles		Alum—large particles	
		5 m/h (%)	10 m/h (%)	20 m/h (%)	5 m/h (%)	10 m/h (%)	20 m/h (%)	5 m/h (%)	5 m/h (%)	5 m/h (%)	10 m/h (%)	5 m/h (%)	10 m/h (%)
Total suspended solids	100 mg/L	84	94	0	89	95	94	88	87	100	100	82	32
Turbidity	54.4 NTU	27	8	27	57	51	36	45	42	92	82	75	58
Total dissolved solids	180 mg/L	0	0	9	11	5	2	−6	10	−5	−5	3	0
Phosphorus	0.31 mg/L	29	7	−9	23	9	−11	25	14	46	47	75	67
Nitrogen	2.2 mg/L	19	12	14	1	10	15	−6	0	0	0	−18	−20
Zinc	0.23 mg/L	30	18	20	33	70	54	35	33	56	60	77	81
Copper	0.045 mg/L	–	–	–	–	–	–	–	–	–	–	–	–
Lead	0.05 mg/L	–	–	–	–	–	–	–	–	–	–	–	–

However, those filters were considered unfeasible due to a very large drop in flow rates.

Lead and copper concentrations in the filter effluent could not be measured in all experiments due to low concentrations. This indicates that either a higher lead and copper concentration, or an alternative measuring device should be used to determine the removal efficiency. Further tests are warranted to provide firm conclusion on the removal of those heavy metals. Table 3 summarizes the performance of all filters in removing all the synthetic storm water quality parameters.

Enhanced sand filter system can be used to treat storm water and its long-term operation will depend on how clogging of filtration can be managed during those long runs of filtration. Vertical or horizontal configurations of sand filters with appropriately placed carpet fibres will be able to remove many pollutants that are present in storm water. Horizontal filters can be constructed at the outlet of a storm water detention pond. Backwashing of the filters will be required periodically which needs to be carried out carefully if the carpet fibres in the filters are to be used for longer periods of time.

3.5. Hydraulic performance of the filter

When the experiments were conducted at 5, 10 and 20 m/h with the filter column that consisted of sand only, the initial head loss values were 29, 46 and 107 cm, respectively. Those values did not vary significantly until the end of those filter runs. Furthermore, introducing three different types of carpets to the sand filter did not change the initial head loss. In fact, the head loss decreased slightly (between 26 and 27 cm at the filtration velocity of 5 m/h). However, when the alum sludge was present in the filter, the head losses were 130 and 170 cm at filtration velocities of 5 and 10 m/h, respectively. Therefore, enhancing the sand filter with carpet fibres will be a good option to treat storm water.

4. Conclusions

This study details the removal of heavy metals along with common storm water pollutants using enhanced sand filtration. Three filtration flow rates were trialled: 5, 10 and 20 m/h. The performance of each filter was rated on the ability to remove turbidity, suspended solids, dissolved solids, phosphorus, nitrogen, lead, copper and Zinc. A basic sand filter was used as a performance benchmark, and compared to a nylon carpet fibre-enhanced sand filter, polypropylene carpet fibre-enhanced sand filter, Syrian carpet fibre-enhanced sand filter and alum sludge-enhanced sand filter. Sand filter and carpet-enhanced sand filter showed small head loss (26–29 cm at 5 m/h) during the filtration compared to that observed with alum sludge-enhanced sand filter (130 cm at 5 m/h).

Results showed that an alum sludge-enhanced sand filer performed the highest, with up to 100% total suspended solids removal, 80% zinc removal, 90% turbidity removal, up to 80% phosphorus removal and up to 40% nitrogen removal. However, flow rates dropped approximately two-thirds the original flow rates within the first hour, this was deemed to be unacceptable, and alum sludge cannot be recommended for storm water filtration, unless a way can be found to maintain constant flow rates.

Carpet fibre-enhanced sand filtration was highly effective at filtering storm water, in most cases performing well above the basic sand filters. The carpet fibre-enhanced sand filters had no drop in flow rates over the 4 h filtration period, up to 90% total suspended solids removal, 70% zinc removal, 60% turbidity removal, 25% phosphorus removal, 15% nitrogen removal and 10% total dissolved solids removal. An aim of the project was to test the removal efficiency of heavy metals, but when the heavy metals were to be measured using the AAS, results were too low, and lead and copper could not be measured. However, zinc results could still be measured, and there was zinc removal using enhanced sand filtration.

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