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Applicability of pebble matrix filtration for the pre-treatment of surface waters containing high turbidity and NOM

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ABSTRACT

Purification of drinking water is routinely achieved by use of conventional coagulants and disinfection procedures. However, there are instances such as flood events when the level of turbidity reaches extreme levels while natural organic matter (NOM) may be an issue throughout the year. Consequently, there is a need to develop technologies which can effectively treat water of high turbidity during flood events and NOM content year round. It was our hypothesis that pebble matrix filtration potentially offered a relatively cheap, simple and reliable means to clarify such challenging water samples. Therefore, a laboratory scale pebble matrix filter (PMF) column was used to evaluate the turbidity and NOM pre-treatment performance in relation to 2013 Brisbane River flood water. Since the high turbidity was only a seasonal and short-term problem, the general applicability of PMFs for NOM removal was also investigated. A 1.0-m-deep bed of pebbles (the matrix) partly infilled with either sand or crushed glass was tested, upon which was situated a layer of granular activated carbon. Turbidity was measured as a surrogate for suspended solids, whereas total organic carbon (TOC) and UV absorbance at 254 nm were measured as surrogate parameters for NOM. Experiments using natural flood water showed that without the addition of any chemical coagulants, PMF columns achieved at least 50% turbidity reduction when the source water contained moderate hardness levels. For harder water samples, above 85% turbidity reduction was obtained. The ability to remove 50% turbidity without chemical coagulants may represent significant cost savings to water treatment plants and added environmental benefits accrue due to less sludge formation. A TOC reduction of 35–47% and UV-254 nm reduction of 24–38% were also observed. In addition to turbidity removal during flood periods, the ability to remove NOM using the PMF throughout the year may have the benefit of reducing disinfection by-products formation potential and coagulant demand at water treatment plants. Final head losses were remarkably low, reaching only 11 cm at a filtration velocity of 0.70 m/h.

Keywords: Hardness; NOM; Pebble matrix filtration; Pre-treatment; Turbidity

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1. Introduction

Surface water is commonly used as a source of drinking water around the world. However, during heavy rains, the fragile topsoil in watersheds may become severely eroded due to factors such as inappropriate land management, thus causing high turbidity in river water samples [1]. During severe conditions, the treatment capacity of a conventional coagulation–flocculation–sedimentation process can be exceeded, causing overloading on subsequent filtration units. The resultant shorter filter runs may lead to increased energy bills [2] as frequent filter cleaning is required by either backwashing or scraping the top filter layer, depending whether they are rapid or slow sand filters (SSF). Furthermore, the higher turbidity will result in demand for extra treatment chemicals with associated additional costs [3,4], and as an outcome generate more sludge. When treatment plants are unable to produce water of the required drinking water quality standards, it is not uncommon to considerably reduce the plant's throughput or even force a complete shutdown. In January 2013, production at South East Queensland's largest water treatment plant (supplying the majority of the region's drinking water) was shut down for a period when high levels of sediment and silt in the Brisbane River exceeded turbidity levels of 4,000 NTU [5]. Although Seqwater's integrated catchment management approach provided a sustainable long-term solution for turbidity control in surface water streams to avoid the total shutdown of plants during such extreme events, other measures may need to be considered [6]. For example, the availability of pre-treatment methods ahead of the main treatment stage ability of water treatment plants to process high turbidity water may be required.

A pebble matrix filter (PMF) process is a pre-treatment strategy originally developed to protect SSF from high turbidity during heavy rainfall periods [7–9]. Bench scale experiments with simulated flood water using kaolin clay ("E" grade) in London tap water [10], and using kaolin clay ("E" grade) in Cambridge tap water [11], both showed above 95% turbidity reduction when inlet turbidity was 500 NTU. Full-scale PMF trials in Sri Lanka using filter beds which had dimensions of 4.8 m × 4.8 m × 3 m high, treated natural flood water from the Menik River and showed an initial turbidity reduction of 58–69%. After five months of operation, reduction in turbidity levels decreased to 45%, with two reasons considered responsible for this drop in efficiency. One possibility was that the cleaning cycle was not efficient due to use of backwash water taken from a sedimentation tank which had a turbidity of 160 NTU. This latter situation may have resulted in accumulation of mud balls in the filter media. The other reason for the recorded loss of process efficiency was surmised to be the large cracks which developed at the base of the filter which promoted preferential flow paths within the filter bed [10]. Field trials of PMFs in Papua New Guinea also showed above 90% turbidity removal efficiency when the raw water of the creek was spiked with sediment from the same creek [12], thus confirming the usefulness of this approach to treating high turbidity waters. The effectiveness of the filter related to physical parameters, such as size and shape of the granular media, depth of filter media, filtration velocity, clean-bed porosity and surface properties of the media and the suspension to be filtered [13,14].

It is established that surface water containing dissolved natural organic matter (NOM) causes many problems in drinking water and water treatment processes. Precursor such as NOM not only contributes to disinfection by-product (DBP)—such as trihalomethanes (THM)—formation during the chlorination process, but also increases chlorine demand [15–17]. In addition, the presence of NOM affects organoleptic properties of water (colour, taste and odour), acts as a substrate for biological re-growth in distribution systems and influences heavily on coagulant demand, which in turn increases the sludge volume produced [18,19]. Since the high flood turbidity was only a seasonal and short-term problem, the applicability of PMFs for NOM removal as well as turbidity removal was investigated in this study so that the filter can be used throughout the year, and not just during flood periods.

As described above, PMF beds appear to be adept at reducing the turbidity of various water types. PMFs are relatively simple in both construction and operation, thus it is of interest to determine their applicability to act as a pre-treatment system for highly turbid flood water. In addition, there is a need to understand in more depth the effectiveness of PMFs for NOM removal. Currently, there is also limited understanding of the impact of other water parameters such as hardness which may impact filter performance. Therefore, this study examined the feasibility of using PMF as a pre-treatment method for treating highly turbid flood water collected from the Brisbane River during the 2013 floods. Since the high turbidity was only a seasonal problem, the ability of the filter to remove NOM without compromising the filtration ability was also investigated to test the capability of the filter in providing additional pre-treatment benefits during non-flood periods.

2. Materials and methods

2.1. Pebble matrix filter

As shown in Fig. 1, the PMF was set up as a two-layer filter, wherein a turbid suspension was introduced first through a layer of pebbles (L1) and then through a matrix of pebbles and sand mixture (L2). The upper layer of the filter with pebbles alone was expected to exert some pre-filtering effect, but the major improvement in suspended solids (SS) concentration was anticipated to be dominated by the pebble–sand mixture that provided the secondary, finer filtration stage.

Typically, the PMF system would be loaded with pebbles of roughly 50–60 mm diameter and sand (d_{10} = 0.3–0.6 mm) as the filter media. Pebbles of this latter size range allowed the sand media to properly settle down into pore spaces within the pebbles after a backwash step. There are two principal methods of obtaining pebbles and sand, namely dredging from rivers or from beaches. However, due to the scarcity of these resources in some countries, the cost of pebbles is often 4–5 times higher than that of sand. In such situations, it has been shown that handmade clay pebbles (balls) can be used as an alternative to natural pebbles [11].

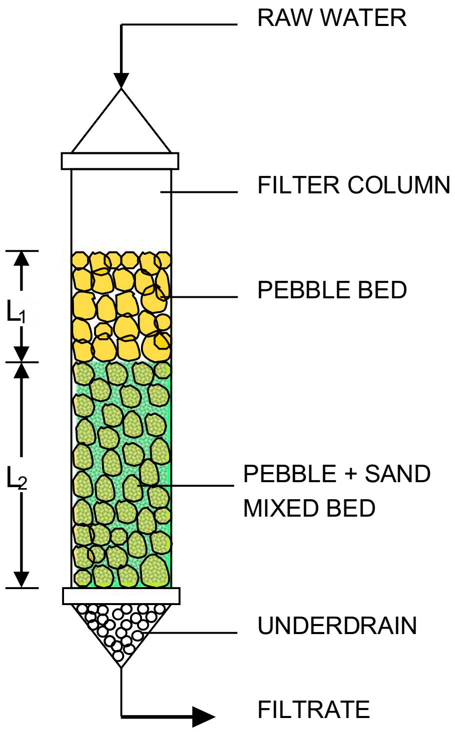


Fig. 1. Schematic of dual-media PMF.

The experimental PMF unit comprised of a 1.3 m long and 244 mm internal diameter Perspex column with two cones made of fibreglass connected at the top and bottom, as shown in Fig. 1. The inlet stream entered the top cone and the bottom cone was connected to a filtrate pipe, backwash water supply and a drain pipe, all equipped with control valves. Turbid water was stored in a 220-l drum on the floor and pumped to an overhead tank located just above the filter column using a continuous rate pump, while recirculating part of the flow back into the storage tank to keep the suspension in motion to reduce the rate of settling in the tank. The overhead tank provided sufficient head, thus permitting flow through the filter bed under gravity. The filtrate quality was measured using a Hach continuous flow turbidimeter and data transferred to a computer using a data logger. Labview program was used to collect online readings from the turbidity meter. The turbidimeter was calibrated using a diluted 4,000 NTU standard. Finally, a 200 mg/L kaolin suspension was diluted to known concentrations and calibrated against the NTU readings of the turbidimeter to obtain the SS (mg/l) and NTU relationship. Head loss through the bed could be recorded manually at regular intervals through manometer tapping points located throughout the column length, which were connected to a manifold with transparent plastic tubing and fastened on to a vertical board. The experimental set-up as shown in Fig. 2 was assembled at the Banyo pilot plant precinct belonging to Queensland University of Technology, Australia.

2.2. Turbid water for laboratory experiments

In order to test the PMF under worst-case conditions, an attempt was made to collect water during the January 2013 event from the Brisbane River; however, this was not possible due to operational resources being focused on managing the event. The rain event that caused the high turbidity during January 2013 severely impacted the bank stabilisation in the Lockyer Creek and the Mid-Brisbane River which were the primary sources of the high levels of turbidity. It was decided to prepare turbid river water by mixing river silt collected during flood events to match the particle size distribution (PSD) and turbidity of the flood water. As one of the primary sources of turbidity during the January event was silt from Lockyer Creek, sediment was collected from the banks of the Lockyer Creek near Lowood on 31 January 2013

Fig. 2. Column set-up at the Banyo pilot plant.

to see if the quality of the water in the Brisbane River at the high turbidity levels could be simulated by mixing these sediments in tap water and later also in river water. PSD gives a good indication of the distribution of different particle sizes of SS in a water sample, which gives rise to turbidity.

Another smaller flood event occurred around 27 February 2013. During this latter event, 2,000 l of flood water was collected from the Lockyer Creek at a location within the Lockyer Valley region a few kilometres upstream of Lowood.

Three sets of experiments were conducted using different turbid water sources in the PMF experimental assemblage. The schematic of the three sets of experiments is shown in Table 1 and a description of filter media and types of different turbidity sources used are explained below.

Typical raw water quality data in the Lockyer Creek during normal and flood events with typical quality of the tap water is given in Table 2 below. On the 27 February 2013, the temperature of the Lockyer Creek was recorded as 20.2˚C, while in February 2013, in Brisbane the warmest on temperature on average was 24.6˚C and the coolest on average was 23.8˚C. As the pilot plant was located in a large warehouse the temperature of the water was assumed to be in a similar range.

2.2.1. *Suspensions created by mixing dry silt mixed in tap water*

Collected silt samples were oven-dried at 60˚C for 24 h and then stored in plastic containers in a cold room at 4˚C for later use. Fig. 3 shows the PSD of both these samples and the graphs indicate that D_{50} of both natural flood water samples were <10 μm and nearly 90% of the particles in samples from river water were finer than 40 μm. In order to prepare a simulated flood sample, it was decided to mix the oven-dried silt in local tap water until the turbidity of the simulated water reached approximately 500 NTU. Afterwards, PSD analysis was carried out on the resulting suspension of the dry sieved silt. As can be seen in Fig. 3, by mixing dry sieved silt in tap water, the simulated flood water did not produce a good representation of the actual flood water, with a D_{50} of about 40 μm.

2.2.2. *Silt wet-sieved through 75-μm sieve and mixed in Banyo tap water*

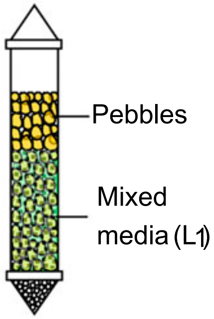
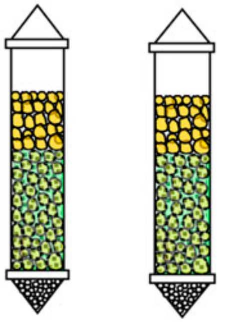
Since the majority of the solids in these river water samples were very fine ($D_{50} < 10$ μm), in an effort to create a water sample more representative of natural flood water for the experiments, it was decided to conduct wet sieving of the silt and use this in synthesising the turbid water. Silt was first soaked in tap water for one hour and then sieved through a 75-μm sieve. Then, a suspension was prepared having a turbidity value close to 500 NTU using the wet-sieved silt in tap water. As can be seen in Fig. 3, the PSD analysis carried out on this sample was a very close representation of the floodwater collected from the Lockyer Creek. Consequently, all filter runs in Set 2 were conducted with feedwater synthesised using the wet sieving process.

Set 3: Flood water collected on the 27 February 2013 from the Lockyer Creek had turbidity of 504 NTU, reducing to 354 NTU at the filter inlet due to some settling in the overhead tank. During the third set of experiments, where necessary, this flood water was diluted with tap water to conduct low turbidity experiments and wet-sieved silt (from Set 2) was added to simulate high-turbidity flood water.

2.3. *Sources of NOM*

In order to add a NOM concentration to the inlet supply, a source of feed water containing high NOM from a local water treatment plant was added to the storage tank. As an indirect measure, the measurement of total organic carbon (TOC) and UV absorption at 254 nm were conducted to quantify the NOM in water. This latter methodology was based upon previously published studies which investigated the characteristics of NOM in water and wastewater samples [22–24].

Table 1
Schematic of the three sets of experiments and filter media specification

			
Column ID = 244 mm Height = 1,300 mm Experiments	(A) Set 1	(A) (B) Set 2	(B) (C) Set 3
Suspension	Kaolin clay mixed in tap water	Sediment from Lockyer Creek mixed in tap water	Flood water from Lockyer Creek
Average inlet turbidity range (NTU)	154–155	50–346	25–1,811
Filtration rate (m/h)	0.65–0.70	0.65–0.70	0.65–0.70
Run numbers	1–2	3–10	11–16
Mixed media (L1)	(A): sand + pebbles	(A): sand + pebbles (B): glass + pebbles	(B): glass + pebbles (C): sand + GAC + pebbles
Mixed media (L1) Depth (cm)	75	75–100	75–100
Fine media specification			
Sand (7M)	River sand: 0.45–1.0 mm; $d_{10} = 0.49$ mm; $d_{60} = 0.90$ mm		
Glass (VF#25)	100% recycled plate glass: 0.4–1.1 mm; $d_{10} = 0.58$ mm; $d_{60} = 0.80$ mm		
GAC (GA1000N)	Coal-steam activated: 0.40–1.68 mm; $d_{10} = 0.65$ mm; $d_{60} = 1.3$ mm		

Notes: Set 1: initial tests were conducted using a suspension of kaolin clay (“E” grade) in tap water to confirm fundamental performance of the PMF.
Set 2: simulated flood water by mixing sediments from the Lockyer Creek at Lowood, in tap water.

Table 2
Typical water quality in the Lockyer Creek during normal/flood events and the quality of tap water

Date/time or period	pH	Turbidity (NTU)	True colour (HU)	Conductivity (μs/cm)	Alkalinity mg/l as $CaCO_3$	Total hardness mg/l as $CaCO_3$
Lockyer Creek [20]						
29 January 2013 @ 0900	7.35	3,370	229	143	44	80
29 January 2013 @ 1630	7.34	2,060	171	174		
30 January 2013 @ 1210	7.71	344	57	301	75	
04 February 2013 @ 1000	7.71	75.2	39	324	78	
Tap water [21]						
July 2012–June 2013	7.74	0.25			77	124

Table 3
Kaolin in tap water (filtration rate = 0.6–0.70 m/h)

	Mixed bed depth (cm)					
Filter run no.	Sand 7M	Glass VF#25	GAC 12 × 40	Pebble only depth (cm)	Total bed height (cm)	Inlet average turbidity and range:(in brackets) (NTU)
1	75	–	–	25	100	154:(144–162)
2	75	–	–	25	100	155:(148–164)

Table 4
Silt wet-sieved through 75-μm mesh and mixed in tap water (filtration rate = 0.65–0.70 m/h)

	Mixed bed depth (cm)					
Filter run no.	Sand 7M	Glass VF#25	GAC 12 × 40	Pebble only depth (cm)	Total bed height (cm)	Inlet average turbidity and range:(in brackets) (NTU)
3	75	–	–	25	100	168:(137–180)
4	100	–	–	20	120	133:(119–162)
5	100	–	–	20	120	71
6	100	–	–	20	120	290:(271–308)
7	100	–	–	20	120	50
8	–	75	–	25	100	346:(316–382)
9	–	75	–	25	100	201:(183–216)
10	–	100	–	20	120	202:(185–212)

2.4. Filter runs

The three sets of experiments conducted using three different sources of water resulted in 16 filter runs with different inlet turbidity loadings ranging from 25 to 1,800 NTU in the inlet water. The first 11 runs were operated as continuous short filter runs (<5 h), while the remaining five runs were operated intermittently up to 26 h. The prefixes a, b, c, d in run numbers indicate intermittent mode of operation; for example, in Run 12a the filter was shut down at the end of the day and restarted the next day as Run 12b without backwashing. The first two runs used kaolin

Table 5
Lockyer Creek flood water; natural (+), spiked with silt (*) or diluted with tap water (#) (a–d indicates continuation of the same filter run next day) (filtration rate = 0.65–0.70 m/h)

Filter run no.	Mixed bed depth (cm) Sand 7M	 Glass VF#25	 GAC 12 × 40	Pebble only depth (cm)	Total bed height (cm)	Inlet average turbidity and range: (in brackets) (NTU)
11	–	100	–	20	120	354:(332–375) +
12a	75	–	20	20	115	1,367:(1,275–1,458) *
12b	75	–	20	20	115	1,164:(673–1,564) *
12c	75	–	20	20	115	1,232:(982–1,482) *
12d	75	–	20	20	115	1,811:(1,792–1,830) *
13a	75	–	20	20	115	523:(338–642) *
13b	75	–	20	20	115	579:(408–771) *
13c	75	–	20	20	115	581:(469–869) *
14a	75	–	20	20	115	516:(320–734) *
14b	75	–	20	20	115	504:(418–608) *
15a	75	–	20	20	115	143:(89–163) #
15b	75	–	20	20	115	172:(158–185) #
15c	75	–	20	20	115	209:(168–242) #
16a	75	–	20	20	115	77:(73–81) #
16b	75	–	20	20	115	25:(24–26) #
16c	75	–	20	20	115	26.5:(26–27) #

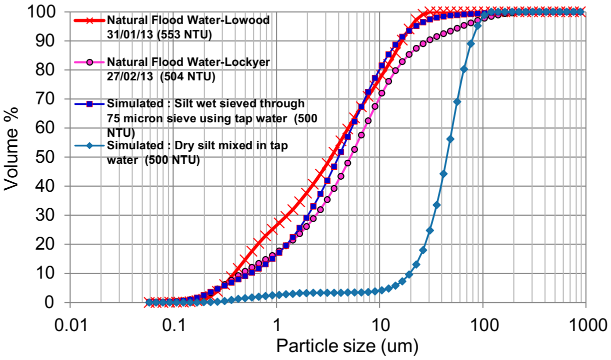


Fig. 3. PSD of natural and simulated flood water.

suspensions; runs 3–10 were conducted using simulated flood water by mixing sediment from the Lockyer Creek in tap water and the final runs 11–16c used natural flood water from the Lockyer Creek to which wet-sieved silt was added to various degrees.

Natural pebbles of approximately 50 mm in size bought from local garden suppliers (Centenary Landscaping Supplies) were used for the filter media for the bed matrix. For the fine media to fill in the pebble matrix, river sand, crushed glass and granular activated carbon (GAC) were investigated, either as a single medium or dual media to obtain best turbidity reduction through the system. River sand (grade 7M) was supplied by River Sands Pty Ltd Australia, crushed glass (Viron VF#25) by PoolWerx Australia and GAC (Acticarb grade GA1000N-12 × 40) by Activated Carbon Technologies Pty Ltd, Australia.

A summary of the experimental program is presented in Tables 3–5. All filter runs were conducted within the filtration rate of 0.65–0.70 m/h, a range that has proven effective for pebble matrix filtration, although filters operated at 1.56 m/h in the laboratory also produced filtrate of below 25 mg/l when the inlet clay suspension had a concentration of 500 mg/L [8].

3. Results and discussion

As mentioned earlier, a PMF is a pre-treatment system specifically designed to remove high sediment load and is not normally responsible for producing the finished quality of water. Therefore, the main parameters studied were filtrate turbidity and head loss development at regular intervals.

3.1. Turbidity reduction in filtration experiments

Once the turbid water entered the top of the column inlet, water flowed down first through a layer of pebbles 20–25 cm deep and then the pebble/fine media mixed bed. The mixed bed was about 75–100 cm deep, the filter material being either sand, crushed glass or sand/GAC dual media within the pebble matrix, which provided the finer media for filtration. All three sets of experiments had final head losses below 11 cm. A summary of results is presented in Tables 6–9 and a discussion of results for each set of experiments is given below.

The initial two experiments (Set 1) were carried out with turbid water simulated using kaolin mixed with tap water, which produced a turbidity level of 154 NTU at the column inlet. The filter had a pebble/sand mixed depth of 75 and 25 cm of pebbles alone on top, giving a total bed depth of 100 cm. These two initial kaolin experiments resulted in a turbidity reduction of 67 and 73%, respectively, which was significantly lower than previous laboratory results [8,10,11] of above 95% turbidity reduction with similar filter media and bed depths (Table 6). A possible reason could be due to different hardness levels in the raw water as discussed under Section 3.3.

In Set 2, 500 g of silt from Lockyer Creek was wet-sieved through a 75-μm filter and mixed with 200 l of tap water, giving an initial tank turbidity of 220 NTU. The average inlet turbidity level was maintained at 168 NTU during the next experiment and average filtrate turbidity was 87 NTU with 48% reduction in turbidity with similar filter media and bed depths (Fig. 5, run number 3). Since the performance of beds with suspensions made up of silt was relatively poor compared to the performance with kaolin suspensions of simular feed turbidity, it was decided to increase bed height when testing natural silt suspensions in order to determine if this approach was beneficial.

Therefore, the pebble/sand mixed bed height was increased to 100 cm and the pebble bed height was maintained at 20 cm above that (total height 120 cm). The next four filter runs were conducted with this new bed arrangement and an average inlet turbidity range of 50–290 NTU (Runs 4–7). These four runs with increased bed heights produced improved turbidity reductions between 58 and 76% in the filtrate. As noted earlier, in previous laboratory experiments the PMF typically has produced turbidity removal efficiencies above 95%, with similar feed water turbidity levels used in the present research. Therefore, in an effort to further improve removal efficiency the fine media was changed from sand to crushed glass (Viron). This latter choice for the fine filtration media was based upon previous studies wherein crushed glass (AFM) was found to be slightly better or at least equally as good as sand media [11]. Consequently, the next three experiments were conducted using pebble/glass as the mixed bed with 20–25-cm-deep pebbles alone bed above the mixed bed (Table 7 Runs 8–10). Inlet turbidity varied between 202 and 346 NTU and the filtrate turbidity was 71–138 NTU, giving a turbidity reduction of 54–65%. These three filter runs (Runs 8–10) showed that there was no major benefit of using glass (Viron) media, in terms of turbidity removal, at least for the type of turbid water used in those experiments. However, compared to a pebble/sand mixed bed (Run 3), a pebble/crushed glass mixed bed (Run 9) produced a head loss about 25% lower. This was also noted in previous experiments when operated under similar conditions with AFM glass media producing 30% less head loss compared to sand [11].

In the first run of Set 3 (Table 8, Run 11), flood-affected river water was filtered through the pebble/crushed glass media similar to Runs 8–10. Although the average turbidity level at the inlet remained the same as in the previous filter experiments, the turbidity removal efficiency dropped to 33%. One explanation may have been that the poor turbidity removal could be due to fine- and low-density particles in Lockyer Creek water. However, the PSD data of various source waters shown in Fig. 3 did not support this latter hypothesis. Instead, the most likely reason for poor turbidity removal appeared to not be related to size, but to hardness of the water as discussed in Section 3.4.

Since it was evident that pebble/crushed glass beds did not improve turbidity removal, for the remaining filter runs in Set 3 it was decided to replace the pebble/crushed glass bed with a pebble/sand system and place an additional pebble/GAC layer above the pebble/sand bed as shown in Fig. 4. The final five filter runs (Runs 12a–16c) had a 20-cm-deep pebble alone bed and a 20-cm pebble/GAC mixed bed

Table 6
Turbidity reduction, run times and final head losses for Set 1

	Turbidity (NTU)				
Filter run no.	Inlet average	Outlet average	% Reduction	Total run time (h:min)	Final head loss (cm)
1	154	51	67	2.00	6.3
2	155	42	73	2.15	7.1

Table 7
Turbidity reduction, run times and final head losses for Set 2

	Turbidity (NTU)				
Filter run no.	Inlet average	Outlet average	% Reduction	Total run time (h:min)	Final head loss (cm)
3	168	87	48	2.05	5.7
4	133	56	58	4.15	6.4
5	71	20	72	2.00	5.8
6	290	123	58	2.00	6.0
7	50	12	76	1.00	6.1
8	346	138	60	3.30	4.0
9	201	71	65	2.00	4.3
10	202	93	54	1.30	4.8

Table 8
Turbidity reduction, run times and final head losses for Set 3 (a–d indicates continuation of the same filter run next day)

	Turbidity (NTU)				
Filter run no.	Inlet average	Outlet average	% Reduction	Total run time (h:min)	Final head loss (cm)
11	354	238	33	2.00	5.5
12a	1,367	612	55	3.20	6.5
12b	1,164	419	64	4.50	7.6
12c	1,232	524	57	8.50	8.1
12d	1,811	510	72	13.20	8.2
13a	523	243	53	4.30	8.1
13b	579	257	56	11.30	10.5
13c	581	239	59	14.45	10.8
14a	516	229	56	6.00	8.0
14b	504	195	61	12.20	8.3
15a	143	68	52	5.00	7.3
15b	172	90	48	19.00	8.3
15c	209	89	57	26.00	9.4
16a	77	33	57	4.00	6.9
16b	25	10	60	13.00	7.8
16c	26	12	54	16.30	9.1

overlying a 75-cm-deep pebble/sand mixed bed making the bed configuration into a triple-media PMF as shown in Fig. 4.

Here, it was assumed that the pebble/GAC bed would not only provide some turbidity reduction together with the pebble/sand bed during flood periods, but also facilitate some NOM removal throughout the year. The last five filter runs (Runs 12a–16c) can be broadly categorised into four inlet turbidity ranges as 1,164–1,811 NTU, 504–581 NTU, 143–209 NTU and 25–77 NTU. These four categories produced turbidity removal efficiencies of 55–72, 53–61, 48–57, and 57–60%, respectively. In the tested inlet raw water with turbidity range of 25–1,811 NTU, the removal efficiency varied in the range of 48–72% which was significantly lower values compared to London and Cambridge experiments producing above 95% removal efficiencies as discussed earlier.

3.2. *NOM removal in the pebble/GAC mixed bed*

For the filter runs 12c–14a, NOM was spiked by adding feed water from a local water treatment plant so that the inlet to the filter contained TOC in the range of 4.99–14.50 mg/l and UV-254 nm in the range of 0.209–0.597. The measurement of TOC and UV-254 nm were used as surrogate parameters for NOM during some filter runs which contained GAC media.

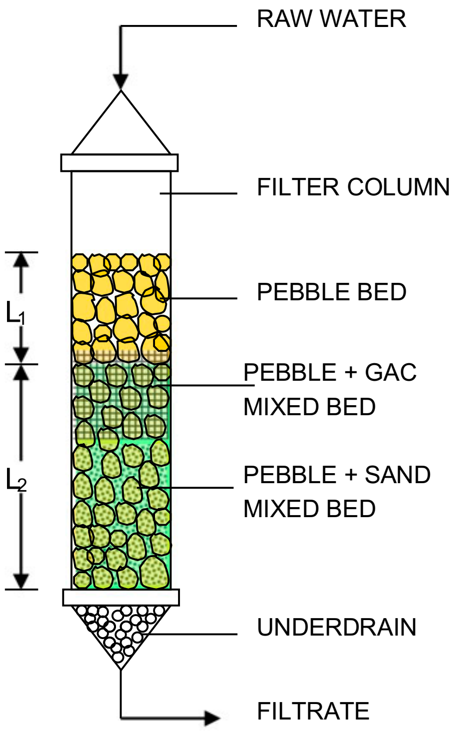


Fig. 4. Schematic of triple-media PMF.

As can be seen in Table 9, a consistent TOC reduction of 35–47% and UV-254 nm reduction of 24–38% were observed in the filtrate. The NOM removal was attributed entirely to the 20-cm-deep pebble/GAC mixed bed. A much higher reduction could be expected if the bed depth was increased to 40 cm and biological activity has fully developed.

It was assumed that the high turbidity peaks would occur only several times in a year and the pre-filter for turbidity removal would only need to operate during these events to protect the main plant. It was understood that the use of GAC purely as an adsorption media to remove NOM would not be cost effective as a pre-treatment.

In relation to adsorption of organic matter, GAC is also a good material for the development of attached bacteria because of its large surface area, so the main benefit to NOM removal would be biological removal through growth on the GAC media over longer periods [25]. Whereas, in our experiment NOM was monitored for six weeks only and thus biological growth may not have been fully developed. Although in these short-term experiments we gained some operational experience using pebble/sand/GAC triple media in the PMF, in order to see the real benefits of GAC for biological NOM removal, long-term experiments are required allowing further biological growth to occur.

3.3. Suspended solids (SS-mg/l) and NTU relationship

SS in a water sample are normally the main species which give rise to turbidity [26]. Elevated levels of SS increase the filter loading rate, eventually leading to filter clogging or breakthrough, causing the plant to shut down. The measurement of SS is time-consuming, technique sensitive and requires large volume of suspension, especially when the SS concentration is low [26–28]. A simple and fast surrogate measurement to lengthy gravimetric analysis of SS would be turbidity, which is based on the optical property that causes light to be scattered and absorbed due to the suspended particles in water, rather than transmitted in straight lines through the sample. However, turbidity is also dependent on other factors such as the size, shape, colour and reflectivity of the particles, hence correlation between turbidity and SS is unique in each location or water source. Therefore, the SS and turbidity relationship was characterised for the tested water sources (silt also came from the same source) and depicted in Fig. 5.

Table 9
TOC and UV 254 nm reduction for Set 3 (a–d indicates continuation of the same filter run next day)

	TOC (mg/l)			UV 254 nm		
Filter run no.	Inlet average	Outlet Average	% Reduction	Inlet average	Outlet average	% Reduction
12c	14.50	8.02	45	0.573	0.351	38
12d	12.54	6.84	45	0.597	0.424	29
13a	5.87	3.07	47	0.209	0.158	24
13b	7.59	4.17	45	0.311	0.235	24
13c	13.74	8.96	35	0.521	0.398	24
14a	4.99	2.66	47	0.228	0.172	25

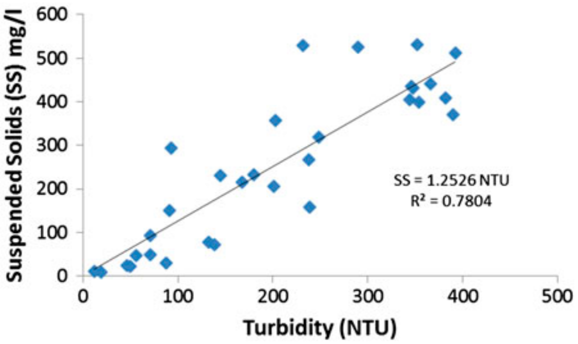


Fig. 5. Variation of SS with turbidity.

The data in Fig. 5 show a good, positive correlation between SS (mg/l) concentration and turbidity (NTU), with a correlation coefficient of R^2 of 0.7804. Hence, measuring turbidity has been demonstrated to be a reasonable surrogate to estimate SS concentration, up to turbidity levels of 400 NTU. Daphne et al. [26] do not recommend turbidity as a surrogate for SS measurement due to the fact that turbidity which is a light scattering property of SS not only depends on the quantity of solids, but also on other factors such as surface texture, size, shape [29,30], colour [31] and reflectivity of the particles [32]. The results of this study are in accord with the latter view as a significant scatter in the turbidity data was observed (Fig. 5).

3.4. *Effect of water hardness on turbidity removal in PMF*

It was important to find an explanation for the relatively poor turbidity removal in these experiments compared to previous results for PMF systems [8,10,11]. Turbidity removal in the PMF may be attributed to possible flocculation of kaolin particles in the upper layer of the pebble bed similar to Banks' clarifier. The success of the Banks' clarifier in which residual sewage humus solids aggregate in the pores of a gravel bed has been attributed to orthokinetic flocculation [33]. It is postulated that the presence of excessive levels of Ca^{2+} and Mg^{2+} ions in water can impact the flocculating process [34,35]. Tests revealed that the flood-affected water collected from Lockyer Creek on 27 February 2013 had a water hardness of 75.1 mg/L as $CaCO_3$, while tap water had a hardness of 124 mg/L as $CaCO_3$ [21]. These hardness values were low compared to those in previous experiments [8,11]. For example, the tap water hardness to which kaolin was added in London was around 271 mg/L as $CaCO_3$ [36] and in Cambridge 322 mg $CaCO_3$/L [37]. The effect of source water hardness on the turbidity removal efficiency can be seen in Table 10. It was discovered that as the water hardness increased the degree of turbidity removal was significantly enhanced. In order to further confirm this observation, in a separate experiment the Lockyer Creek water hardness was increased from 75 mg/l as $CaCO_3$ to 311 mg/l as $CaCO_3$ by adding $CaCl_2$ to the water storage tank. In accord with our deduction regarding the promoting effect of water hardness, the turbidity reduction was substantially increased. This latter conclusion was in harmony with the suggestion of [34] that water hardness could affect coagulation activity, and in accord with findings that clarification was promoted in water sources containing bivalent cations such as Mg^{2+}, Ca^{2+} or Ba^{2+} [35].

Therefore, it appears that without the addition of any chemical coagulants at least 50% turbidity reduction can be expected when the source water contains moderate hardness and much greater turbidity reduction can be achieved with hard waters. For example, on the 10 April 2013, both upstream and downstream of Lowood in the Lockyer Creek the water hardness was 285 mg/l as $CaCO_3$ [38]. However, due to the large amounts of rain water involved during flood events, it is likely that the water will be of lower hardness and as such only a 50% or lower turbidity reduction should be assumed.

Table 10
Effect of source water hardness on turbidity removal in PMF

Source water	Hardness mg/l as $CaCO_3$	Turbidity removal in PMF (%)
Cambridge, UK	322	>95
London, UK	271	>95
Banyo, Australia	124	48–76
Lockyer Creek, Australia	75	33
Lockyer Creek, Australia	311 (adjusted)	87

4. Conclusions

This study indicated that there was no major benefit of using glass media over river sand (7 M) in terms of turbidity removal, at least for the type of turbid water used in the experiments. However, compared to a pebble/sand mixed bed, a pebble/crushed glass mixed bed produced a head loss of about 25% lower when operated under similar conditions.

The triple-media pebble matrix filtration with GAC, river sand (7 M) and pebbles proved to be a satisfactory combination in removing both NOM and turbidity during normal and flood periods. Turbidity reduction appeared to be affected by the hardness of the raw water and the removal efficiency increased with increasing raw water hardness, suggesting coagulation/flocculation taking place within the PMF. The experiments showed that without the addition of any chemical coagulants at least 50% turbidity reduction can be expected when the source water contains moderate hardness and above 85% turbidity reduction with hard waters. However, during floods the hardness of the flood water may reduce due to rain water and turbidity reduction may drop to around 30%. The ability to remove at least 50% turbidity without chemical coagulants may result in significant cost savings to water treatment plants along with the added environmental benefit of producing less sludge in the process due to reduced chemical coagulant usage. The reason being that the filter catches 30–50% of SS without adding coagulants which is a substantial part of the sludge content.

The TOC reduction of 35–47% and UV-254 nm reduction of 24–38% observed in the filtrate indicating some NOM removal was attributed entirely due to the adsorption properties of 20-cm-deep pebble/GAC mixed bed. A much higher reduction could be expected if the bed depth is increased to 40 cm and biological activity has developed over a longer period. The ability to remove NOM in the filter throughout the year may have the benefit of reducing DBP formation potential and coagulant demand at water treatment plants. Further research is required to optimise the system by determining the impact of and how much biological activity could be tolerated without impacting head loss.

Considering the typical filtration rates of 0.7–1.5 m/h applied in roughing filters, PMF may not be an attractive option to very large water treatment plants due to large surface area required. However, the pre-filter could act as detention storage during flood periods. For smaller decentralised systems where land area is not a concern, all of the above benefits would apply.

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