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Economic Analysis of Selected Filter Beds Used for Water Treatment

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Abstract: The aim of the present study was to assess the possibility of use economic analysis to compare selected filter beds used in water treatment plant. There were considered selected masses which are commonly used for removal iron and manganese from the groundwater. Water purification with these minerals is one of the most important processes in water technology. Underground water taken by wells is polluted with increased concentration of iron and manganese. That is why many of individual, urban and also industrial water treatment plants do their best to remove them from the water. Thousands of tons of different filter masses set for iron and manganese purification from the water are bought on the Polish market every year. Tests carried out within experiments are presented in this paper, which include analysis of filter beds such as: Filtersorb FMH, Filter AG, Pyrolox and Defeman. Selected masses differ with origin, density, mesh size, diameter and price. For the complete economic analysis of the selected filters there considered the following factors affected the operating costs: cost of filter beds, environmental fees for water intake, costs of equipment to aerate the water, cost of chemical reagents for the regeneration of beds, cost of a dosing pump, costs of reagents for filter regeneration. The analysis showed that the cost of exploitation of the filter depends mainly on the purchase and filtration rate. In addition, significant parts in the costs of exploitation of the filter is environmental fee for water intake, but lower than buying filtration bed. The cheapest in the exploitation turned out to be Defeman and Filter-AG, the most expensive - Filter-FMH.

Keywords: filter beds, economic analysis, water treatment, operating costs, filter bed

JEL codes: Q51, Q52

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1. Introduction

The filtration process is provided for removal contaminants from cleaning fluids with a diameter bigger than 0.1 μm. Filtration is the basic process and most widely used throughout the world in the water treatment technology. The filtration may be used at different stages of water treatment.

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The selection of particular equipment and filter materials depends among other things on the amount of purified water and contaminants within it (Skoczko et al, 2016: 88; Kowal, 2009: 242). The process of filtration involves water flow through the filter - porous material, which makes possible the separation of larger particles in the water than size of the filter material pore. Sometimes, by the action of the adhesion forces much smaller particles are stopped in the filtration columns. The particles may be retained on the surface of the filter bed and inside the bed in intergranular pores (Kowal, 2009: 244; Magrel, 2000: 125). During filtration, water flows in a certain direction, with a suitable speed through the porous filter bed. Water overcomes irregular way between the particles filling the filter. Removal of particles with small diameter from the water with the filter material is result of many mechanisms, such as filtration, sedimentation, flocculation, cohesion, adhesion and diffusion, adsorption, electrostatic interactions. These forces make possible to provide transport suspension close the filtration bed particle, determining the mechanism of attraction (Maćkiewicz, 1987: 35; LeChevallier, 1992: 54).

For the purposes of this paper, it is assumed that all used filter beds purifies treated water to the required parameters using the same weight for each single column weight. The aim of the study was to compare the economic efficiency of four filter beds used for water treatment: Filtersorb FMH, Filter AG, Pyrolox and Defeman. The analyzes were made on the basis of collected bibliographic data and catalogs available on the web pages relating to selected filter media for groundwater treatment available on the Polish market (www.terstan.pl, www.ekoserwis.poznan.pl, www.vilmart.pl, www.wigo.pl). The calculation cost did not include the purchase of electricity and the operation of the pumps. It has been assumed that filtration is one of the many processes carried out in a water treatment plant and does not require separate power supply. The analysis only includes costs that are closely related to the filtration process used, ie: purchase costs, environmental charges, unit costs of water aeration, chemical regeneration chemicals, and the cost of the regenerative reagent pump. On the basis of the aforementioned costs, there were calculated the unit costs of the filtration process (PLN/m^3) on a scale of: one and five years.

2. Characteristics of filter beds

There were carried out tests included analysis of filter beds such as: Filtersorb FMH, Filter AG, Pyrolox and Defeman. They were chosen for analysis among the available in the market materials used for water filtration and removal of iron and manganese compounds. For the economic analysis, the previously mentioned active filter media were chosen because based on the research conducted by many researchers (Cicszwili, 1990: 47; Anielak, Nowak, 2002: 27; Kaleta et al., 2009: 51; Jeż-Walkowiak et al., 2011: 112; Michael, 2012: 91, Granops, 2005: 153), it is clear that ordinary, popular quartz sand can successfully be replaced by chemically active masses, because some of their parameters (eg mechanical strength) are much better than sand (Cicszwili, 1990: 136; Granops, 2005: 155) The use of these masses can allow for the complete removal of iron and manganese compounds in one-stage filtration, sometimes without introducing air into the water. Therefore it was decided to analyze the economic active mass for the total operating costs. Selected masses differ with origin, density, mesh size, diameter and price.

Table 1. Selected properties of Filtersorb-FMH, Filter-AG, Pyrolox, Defeman

Parameters	Filtersorb-FMH	Filter-AG	Pyrolox	Defeman
Colour	Black	Light gray	Black	Black
Cleanliness	> 85%	-	-	-
Moisture content	< 0,5%	-	-	-
Bulk density	1560 g/l	385 – 415 g/l	2000 g/l	1900 g/l
Mesh size	20 x 40 mesh	12 x 30 mesh	8 x 20 mesh	-
The size of the	-	0,67 mm	-	-
Uniformity	-	1.8	-	-
Hardness (scale Mohsa)	-	6	-	-
Diameter	0,7 x 1,25 mm	-	-	-
pH-value	> 6,2 pH	Wide range of	6,5-9,0 pH	7,0 – 8,5 pH
Bed depth	0,8 m (optimal 1,2 – 1,5 m)	0,6 – 0,9 m	0,46 m	-
The maximum water temp.	-	60°C	-	-
Operating flow	-	12,2 m^3/h	12 m^3/h	-
Speed backwash	-	19,5-24,4 m^3/h		-

Parameters	Filtersorb-FMH	Filter-AG	Pyrolox	Defeman
Free space	-	50% of the height	40% of the height	-
The expansion of beds	-	20-40% of the height	15 – 30%	25%
Purchase price	4,0 PLN/ L	4,30 PLN/L	32,50 PLN/L	19 PLN/L

Source: (Author's own elaboration based on catalog cards of manufacturers and Vidović, 2010: 257)

Filtersorb FMH is used to remove compounds of iron, manganese and hydrogen sulphide. It is a catalytic bed, which may actively oxidize compounds already at pH 6.2. By dint of the active outer shell is difficult to remove forms of the compounds which are oxidized. It causes easy removal of sludge, which is filtered on the bed and removed during backwash. Filtersorb FMH consists of dolomite grains, coated with manganese dioxide and manganese dioxide ores in the form of granules (Vidović, 2010: 258, Lumiste 2012: 59). Manganese dioxide present in the bed works as an oxidant without the need for external supply of oxygen, which allows more effective operation. The bed is regenerated with a dilute solution of potassium permanganate at a dose of 2-4 g $KMnO_4$/l. The bed can be washed continuously or periodically. Efficiency of the system is greatly improved with the continuous regeneration of the filter by dosing to the raw water strong oxidants such as chlorine, ozone or aeration of water (Vidović, 2014: 1784; Brebbia, 2012: 325).

Filter AG is a high efficient filter bed which removes suspended particles from the water. It is made up of granular mineral of volcanic origin. The main ingredient of Filter AG is crystalline silica. This material is relatively lightweight, porous, with high capacity for reduction of suspended matter which reduces costs of the rinse. Its kinked edges and irregular surface provides a high surface area and good mixing of the fluid flowing through the filter It leads to the efficient removal of suspended solids even up to the level of 20-40 microns. It also prevents fouling and clogging of the bed in the initial section of the filter, as is the case in conventional sand filters (Akbar-Khanzadeh and Brillhart, 2001: 344).

Pyrolox is a granular filtration material used for the oxidation of hydrogen sulphide, iron and manganese compounds and their separation from the water (Michel, 2012: 95). It is made from natural ore with manganese dioxide. During water treatment, the filter bed accelerates the oxidation's reactions. Hydrogen sulphide, iron and manganese contained in the water are oxidized and captured in a bed. The precipitated particles are then removed during backwash. Before treatment of water in a filter filled with Pyrolox it is recommended to use chlorine or other oxidizing agents. Higher oxygenated water accelerates the catalytic reaction. After the cycle, the filter must be backwashed. Pyrolox does not require the regeneration of chemicals. (Jeż-Walkowiak et al, 2011:,118 ; Munter et al 2005: 1015).

It is the catalytic bed to iron and manganese removal from the water. The filter constitutes catalytic adsorbent. It changes the physical and chemical conditions of water pollutants. Easy soluble forms go to compounds difficult to dissolve. With a strong oxidizing property the bed permits the formation of iron oxides at the surface grains of the adsorbent. Hydroxides of iron are adsorbed in the upper layer of the material. Oxidation of the compounds conduces toward the processes of flocculation, sedimentation and filtration. The secretion of manganese compounds is a complex process that occurs in the deeper layers of the deposit. (Kaleta et al., 2009: 51). Defeman regeneration consists of two actions: the first one binds dissolved oxygen in water and second is properly selected rinsing process. During the normal filtration process, the bed is not consumed and does not require periodic replacement. Water treatment in a bed Defeman requires primary aeration of the raw water and pH adjustment to the limits 7.0-8.5 (Anielak, 2002: 35).

3. Methodology

There are various filter materials for groundwater treatment. The particular masses are characterized by different effectiveness and the impact on the substances contained in the water. Working conditions and purchase price is also their individual feature. It was assumed that all used filters materials for water treatment were required to the appropriate parameters.

Economic analysis included all financial factors influencing the total cost of filtration on selected masses. Factors chosen for analysis are: the purchase, environmental fees, unit cost of purifying water in the filter bed. There were selected filter beds, which took into account: the purchase cost of beds, the cost of environmental fees in the years 2017-2021, the quantity of treated water within 5 year and the unit cost of water treatment.

3.1. The purchase price and the exploitation of filtration

The purchase of beds, equipment and reagents depends on the operating parameters such as the efficiency of the water intake, underground water parameters, performance, etc. Choosing specific devices and their parameters there were guided by the recommendations of manufacturers. The prices are obtained from the manufacturers and distributors of the analyzed materials and are gross prices (Table 2).

Table 2. Purchase cost of filter beds, additional equipment and reagents

Type of beds	Unit price [PLN/L]	Beds volume [dm^3]	Purchase cost of beds [PLN]	Cost of additional devices [PLN]	Cost of reagents
FMH	4,00	400	1600,00	1684,00	30 PLN/kg $KMnO_4$ (36PLN/cycle)
Filter-AG	4,30	375	1720,00	13490,00	-
Pyrolox	32,50	375	12187,50	13490,00	-
Defeman	19,00	400	7600,00	13490,00	-

Source: (Author's own elaboration based on catalog cards of manufacturers)

It was assumed a 24 hour cycle of filtration column. Next the bed was backwashed to maintain optimum treatment efficiency. For the analysis there were adopted the bed volume of 0.375 m^3. The cheapest in the purchase was FMH. Its price was 1600,00 PLN. It is seven times lower than the most expensive beds - Pyrolox. Nevertheless FMH needs special reagents to its regeneration. Its preparation should be calculated stoichiometrically and takes time. The high price of the Pyrolox may be associated with the operations costs. It allows a high degree of removing pollutants. On the other hand the Defeman bed has four times higher price than the Filter-AG (Table 2). Additional devices included air pomp, compressor, static mixer, manometer and others.

3.2. Environmental fees

Water intake, beyond the purchasing cost of the equipment and its exploitation is required to pay fees for using the environment (Ordinance of the Council of Ministers, 2015 item. 1875: 3; and Dz. U. 2017 item. 519: 203). The regulations define that environmental fees must be paid for every type of natural water. They are calculated and shall be paid to the State Treasury every six months, but for the purposes of this analysis, the fee will be calculated for the whole year. The environmental fee depends not only on the amount of water, but also on its final destination. For the purposes of analysis it is assumed intake of ground water intended for human consumption as well as other social and living purposes. Pre-defined parameters and filtration devices are the values which allows operation of selected filter beds. In the case of groundwater used formula:

$$Fee = V \cdot S \cdot w \tag{1}$$

where:

V - the volume of water used per year [m^3]

S - unit rate fees, adopted for the purpose of consumption,

w - differentiating factor depending on how the water intake.

The unit rate of fees (S) for the human consumption of underground water as for the purposes of social and living for 2017 was equal to 0,068 PLN/m^3. Year of output for the start of the analysis is 2017. For the following years, the quantity of treated water resulting from the devices load is assumed, but the value of the environmental fee will fluctuate due to the annual increase in the unit price of the water, which is subject to inflation. The projected increase in environmental fee was determined on the basis of Table 1 of the average inflation calculated from the actual values that occurred in the founding countries (economically developed countries) of the European Union in 2000-2015. The price increase was assumed to be 1.65% (Skoczko et al. 2016: 212).

Table 3. Estimated of environmental fees for the filter beds [PLN]

Year	Rate (S)	Year	Rate (S)
2011	0,060	2023	0,076
2012	0,062	2024	0,077
2013	0,065	2025	0,078
2014	0,067	2026	0,080
2015	0,068	2027	0,081
2016	0,068	2028	0,082
2017	**0,068**	2029	0,084
2018	0,070	2030	0,085
2019	0,071	2031	0,086
2020	0,072	2032	0,088
2021	0,074	2033	0,089
2022	0,075	2034	0,090
		2035	0,091

Source: Author's own elaboration

In table (Table 4) were summarized all necessary factors for calculation the environmental fees. The quantity of filtered water by the bed is directly related to the filtration velocity based on the characteristics of the bed. In calculation, volume of treated water includes the rinsing. The daily volume of filtered water was multiplied by the 365 days in order to obtain the quantity of water treated per year (V). The resulting value was multiplied by the unit rate fees for water consumption (S) and the value of the coefficient differentiating (w). Table 4 shows the obtaining environmental fees for underground water intake since 2017.

Table 4. Environmental fees for the filter beds in the period 2017-2021 [PLN]

Year	Type of filter bed			
	FMH	Filter-AG	Pyrolox	Defeman
2017	5791	3981	3474	5771
2018	6131	4215	3679	6110
2019	6301	4332	3781	6280
2020	6557	4508	3934	6534
2021	6727	4625	4036	6704

Source: Author's own elaboration

The table (Table 5) lists all the factors needed to calculate the environmental fee. The quantity of filtered water by a given bed is directly dependent on the filtration rate determined by the bed characteristics. When calculating the quantity of treated water, the rinsing time of the devices_is taken into account.

Table 5. Partial calculation of the amount of environmental fee for water intake

Filter bed	Filtration speed [m^3/h]	Quantity of filtered water per day [m^3]	Quantity of treated water in a year (V) [m^3]	Unit fee for water intake in 2017 (S) [PLN /m^3]	Differentiation factor (w)	Environmental fee for water intake in 2017 [PLN]
FMH	10,0	233,3	85155	0,068	1,0	5705
Filter-AG	5,5	128,3	46835		1,25	3922
Pyrolox	6,0	140,0	51093		1,0	3423
Defeman	10,0	232,5	84863		1,0	5686

Source: Author's own elaboration

3.3. Additional equipment

Some of the analyzed beds outside the tank filter and its standard features require additional devices. These are: mixing water and air, compressor, dosing pump. Analysis was performed for a one year, five, ten and twenty years use of filter beds to achieve the most accurate results of real exploitation. The costs incurred for the operation of all beds include the purchase cost of beds and the value of environmental fees for water intake. Some of the analyzed beds require incurring additional costs such as:

- purchase mixer water-air and air compressor –Filter-AG, Pyrolox, Defeman;
- purchase of a dosing pump and chemical reagents for regeneration - FMH.

It is assumed that the above-mentioned devices after the 10 years of operation may be replaced with new ones, but and the case of Pyrolox and Defeman it is not compulsory.

4. The unit cost of water filtration

4.1. Annual cost analysis

The table above (Table 6) shows the unit cost of water treatment for analysed beds related to the scale of one year. The lowest unit cost amounted to 0.261 PLN/m^3 for beds FMH. It is connected with the lowest cost of purchase and a relatively high rate of filtration, allowing treatment more water in the same time. Other beds were much more expensive. The highest unit cost of filtration achieved in the most expensive purchase bed Pyrolox (0.571 PLN/m^3).

Table 6. Unit cost of water treatment within one year

Type of filter bed	Purchase cost of beds [PLN]	Cost of environmental fees [PLN]	Cost of buying a mixer water-air and air compressor [PLN]	Cost of buying a dosing pump [PLN]	Annual cost of the purchase of reagents [PLN]	Quantity of treated water per year [m^3]	Unit cost of water treatment [PLN/m^3]
FMH	1600	5791	-	1684	13140	85155	0,261
Filter-AG	1720	3981	13490	-	-	46835	0,410
Pyrolox	12187	3474	13490	-	-	51093	0,571
Defeman	7600	5771	13490	-	-	84863	0,317

Source: Author's own elaboration

4.2. Five-year cost analysis

In the five-year period of operation, the lowest unit cost of water treatment were obtained using the Defeman bed (0,124 PLN/m^3). The highest unit cost of water treatment received Filter-FMH bed (0.236 PLN/m^3), which requires regeneration using chemicals. The cost required for the purchase of reagents for regeneration of the bed over 5 years accounts for nearly two-thirds of the total costs incurred for their use. Among other beds, the biggest cost factor is the cost incurred on environmental fees. The lowest has Pyrolox bed (18904 PLN), then Filter-AG. Significantly higher investment requires Defeman (31399 PLN). The higher cost is due to the higher environmental fees, which is associated with a greater amount of treated water in these beds.

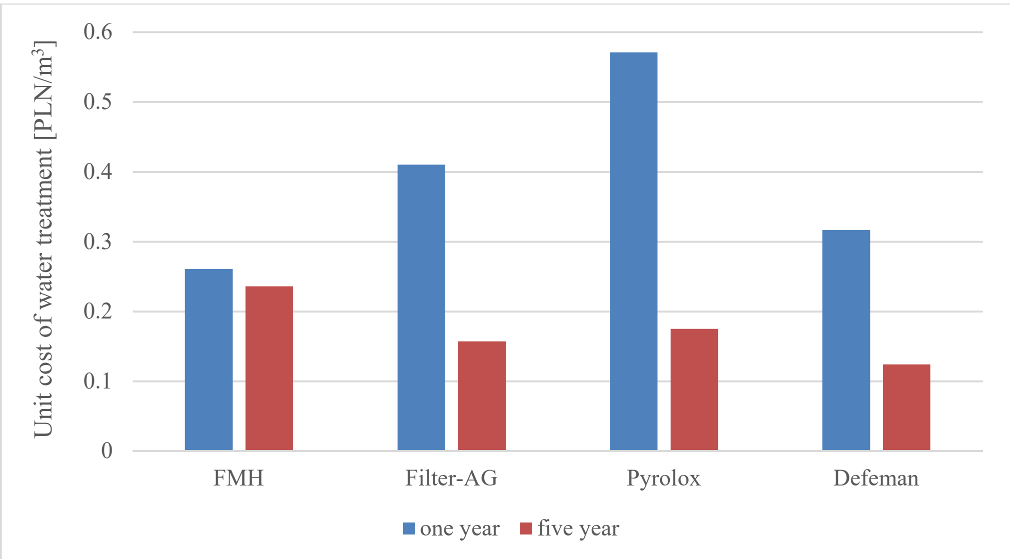
Table 7. Unit cost of water treatment filter beds within 5 years

Type of filter bed	Purchase cost of beds [PLN]	Cost of environmental fees [PLN]	Cost of buying a mixer Water-air and air compressor [PLN]	Cost of buying a dosing pump [PLN]	Annual cost of the purchase of reagents within 5 years [PLN]	Amount of treated water within 5 years [m^3]	Unit cost of water treatment [PLN/m^3]
FMH	1600	31507	-	1684	65700	425772,50	0,236
Filter-AG	1720	21661	13490	-	-	234174,88	0,157
Pyrolox	12187	18904	13490	-	-	255463,50	0,175
Defeman	7600	31399	13490	-	-	424312,50	0,124

Source: Author's own elaboration

4.2. Summary of calculations done

Figure 1. Summary of the unit cost of water treatment by selected filter beds



Source: Author's own elaboration

The Figure 1 provides a summary of the unit cost of water treatment for all filter beds in all years of analysis. The highest costs were obtained for the annual operation. This is due to the division of a large amount of primary costs, such as the purchase of beds and additional devices. Therefore, in the next analyzed period (5 years) was significant drop in the cost of operation for all beds.

5. Conclusion

1. Differences between selected filtration materials were in terms of cost purchase and the filtration velocity.
2. A considerable share in the costs of exploitation of the filter is the environmental fee for water intake, greater than the purchase of the bed.
3. The cheapest in the exploitation is Defeman bed, where five-year operating costs amounted to 0,124 PLN/m^3.
4. The second lowest result of the cost was obtained by use of Filter-AG. The large size of the bed particles causes less pressure loss than other filtration materials. The high filtration rate affects a lower equipment cost and let save space. In addition, the low weight means lower flow required during backwash and better aeration, which increases the removal efficiency of embedded impurities.
5. The most expensive in the exploitation is Filter-FMH bed, where five-year operating costs amounted to 0,236 PLN/m^3. A high price might be related to the high cost of chemicals used to its regeneration. The unit cost of water treatment was higher twice than in other tested filtration materials.
6. The most economical filter was Defeman, but it needs to be replaced every 5 years, which may create additional costs associated with the transport of the material and the subsequent backfilling.

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Analiza ekonomiczna wybranych złóż filtracyjnych używanych do uzdatniania wody

Streszczenie

Celem pracy była ocena możliwości wykorzystania analizy ekonomicznej w celu porównania wybranych złóż filtracyjnych stosowanych w oczyszczalni wody. Do analizy wytypowano wybrane masy filtracyjne, które są powszechnie stosowane do usuwania żelaza i manganu z wód podziemnych. Oczyszczanie wody w wyniku filtracji jest jednym z najważniejszych procesów w technologii wody. Woda podziemna pobierana ze studni głębinowych jest zanieczyszczona zawartością żelaza i manganu. Dlatego wiele indywidualnych, miejskich i przemysłowych stacji uzdatniania wody stara się skutecznie usunąć żelazo i mangan z wody. Każdego roku na rynku polskim kupuje się tysiące ton różnych mas filtracyjnych do oczyszczania wody. Przeprowadzone testy w ramach eksperymentu obejmują analizę złóż filtracyjnych, takich jak: Filtersorb FMH, Filter AG, Pyrolox i Defeman. Wybrane masy filtracyjne różniły się od siebie: pochodzeniem, gęstością, wielkością ziaren, średnicą i ceną. Do pełnej analizy ekonomicznej wybranych mas filtracyjnych wybrano następujące czynniki, które miały wpływ na koszty eksploatacji: koszt złoża filtracyjnego, opłaty za ochronę środowiska przy ujmowaniu wody, koszty napowietrzania wody, koszt odczynników chemicznych do regeneracji złóż, koszt pompy dozującej, koszty odczynników do regeneracji filtra. Analiza wykazała, że koszt eksploatacji filtra zależy głównie od szybkości filtracji oraz ceny złoża. Ponadto znaczne części kosztów eksploatacji filtra to opłata środowiskowa za ujęcie wody, ale niższe niż kupno złoża filtracyjnego. Najtańszym w eksploatacji złożem okazało się Defeman i Filter-AG, najdroższym - Filter-FMH.

Słowa kluczowe*:* złoża filtracyjne, analiza ekonomiczna, koszty eksploatacji, oczyszczanie wody

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