Magazine of Civil Engineering. 2024. 17(8). Article No. 13201

Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

Research article

UDC 628.3

DOI: 10.34910/MCE.132.1

Hydraulic operating features of filtering cassettes as part of treatment facilities on highways

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Keywords: surface runoff, shungite, filter cassette, hydraulic mode, filtration

Abstract. Surface runoff water (SRW) from highways is highly polluted and has negative impact on adjacent areas and water bodies. The article describes constructed wetlands (CW), including detention ponds and facilities for sorption post-treatment, one of the simplest methods to treat the SRW from highways. It is established that filter cassettes (FCs) based on gabion constructions (GC) and loaded with shungite rock (SR) are used as sorption post-treatment facility. One of the reasons for the unsatisfactory operation of such facilities on the St. Petersburg Ring Road (the SPb RR) has been analyzed. It is shown that the SR recommended for loading into the FC has a fractional composition of 2÷4 cm and thus mostly providing a turbulent filtration mode of SRW passing through the facility. The impossibility of using SR with the optimal towards sorption treatment fractional composition of (0.1÷0.3) cm within the existing GC is shown. It is also shown that the use of permeable for SRW containers — the filter cartridges (such as FOPS® filters) is shown to be one of the simplest and most effective ways of using SR of optimal fractional composition and working with a large amount of sorption materials. The approach to the organization of complex multistage treatment of surface runoff is shown.

Citation: Kozinetc, G.L., Chechevichkin, V.N., Tryaskin, M.A., Chechevichkin, A.V., Yakunin, L.A. Hydraulic operating features of filtering cassettes as part of treatment facilities on highways. Magazine of Civil Engineering. 2024. 17(8). Article no. 13201. DOI: 10.34910/MCE.132.1

1. *Introduction*

Surface runoff water (SRW) from highways, currently classified as highly polluted [1, 2], has a negative impact on natural landscapes in the area of highway right-of-way [3–5], on water bodies and watercourses adjacent to them.

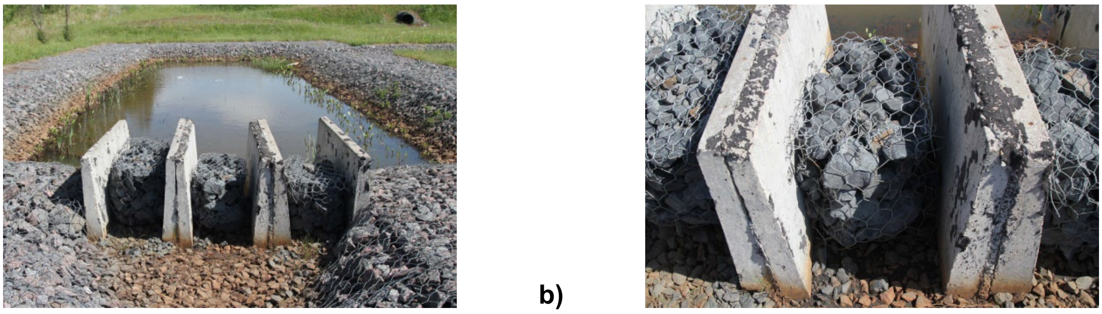
The SRW entering water bodies without proper treatment contain significant amounts of toxic pollutants that exert an extremely negative influence on their biocenosis [6, 7]. This leads to degradation of water bodies, ranging from eutrophication to complete disappearance of all life in them.

In order to reduce the negative impact of SRW treatment facilities of various designs are used on highways. The most common of these are constructed wetlands (CWs), the tank-type treatment facilities and the sorption-filtration facilities based on filter cartridges [8–11].

There are about 220 CWs (Fig. 1, 2) on the St. Petersburg Ring Road (RR), which have long ceased to comply with the regulatory document[1], or with the aesthetic ideas of modern man, or with common sense

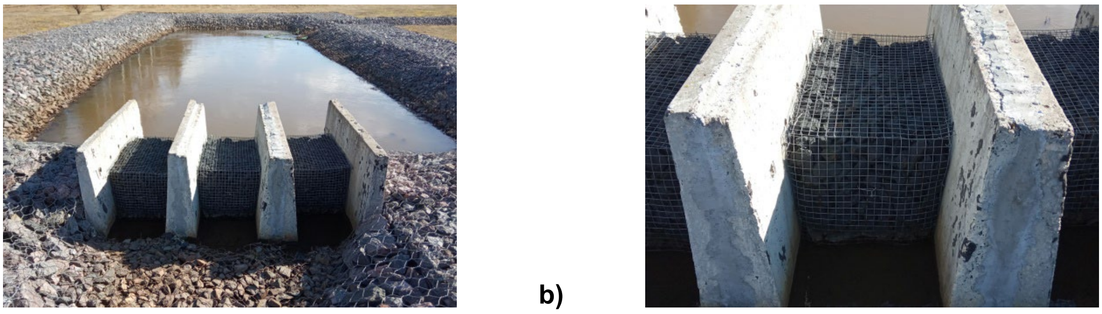
[1] Federal Road Agency (Rosavtodor). Metodicheskie rekomendatsii po soderzhaniiu ochistnykh sooruzhenii na avtomobil'nykh dorogakh [Methodological recommendations for the maintenance of treatment facilities on highways]. ODM 218.8.005–2014. 2017. 83 p. URL: https://rosavtodor.gov.ru/storage/app/media/uploaded-files/210odm-2188005-2014.pdf?ysclid=m67l2a01ap610205907 (Accessed: 22.12.2024)

in the field of environmental safety. The detention ponds of the CWs have turned into unattended settling tanks filled with toxic sludge consisting of a mixture of insoluble forms of heavy metals, asphalt pavement microparticles and soot, as well as petroleum products, fragments of dead plants and debris. In their current state, such ponds are not only a pitiful sight, but also a real environmental threat. Today, no one would hardly be surprised by the absence of macrophytes in the CWs, rusty and torn mesh of GC at the air-water interface, territory littered with household waste etc., which are the consequence of improper maintenance (at least according to ODM 218.8.005-2014). These shortcomings of actually CWs on the RR were discussed earlier [2, 12]. Scientific publications dealing with the CWs problems are quite widely represented in domestic [13–17] and foreign periodicals [18–26].



a) b)

Figure 1. Exterior of the CW (a) and the SRW post-reatment facility based on filter cassettes with shungite-III (b) located on the SPb RR (2018).



a) b)

Figure 2. Exterior of the CW (a) and the SRW post-reatment facility based on filter cassettes with shungite-III (b) located on the SPb RR (2024).

The use of shungite rock (SR) for sorption post-treatment of the SRW within the CWs became widespread at the turn of the 21st century and exclusively in Russia, during the construction of major highways (RR, Federal Highway M10 “Russia”, Federal Highway M11 “Neva” etc.), while discarding the real hydrodynamic conditions of its use in sorption processes.

The study of SR properties, which began in the 19th century [27] and continued in the 20th century, is still relevant today [28–36]. The use of SR (mainly structural type III) for the purification of various water environments is currently carried out in laboratory conditions [37–44] without assessing its real capabilities in the processes of treatment of large volumes of polluted water (as is the case with SRW). The internal structure of shungite-III is unique. It has the appearance of the combination of mutually opposite components (hydrophobic globules of non-graphitized carbon and hydrophilic globules of silicate and aluminosilicate nature). This circumstance ultimately determines the bifunctional properties of shungite-III in aqueous environment. The presence of metal oxide forms in its composition additionally determines its catalytic properties. However, these properties are manifested at low concentration loads and at low velocities of liquid phase movement through the shungite-III layer due to its small porosity and, accordingly, small specific surface area (less than (10÷15) m2/g for shungite-III, while for activated carbons it is 500–1000 m2/g). This is the reason that shungite-III quickly becomes saturated and loses its geoprotective properties upon contact with heavily polluted SRW, subsequently acting as an inert filter material (at best).

The main purposes of the study are to assess the actual operating conditions of the filter cassettes (FC) with SR and the possibilities of their improvement. The research tasks are defined as follows:

- investigation of SR particle size distribution, used in actual FC;

- calculation of the characteristics of the hydraulic operating modes of the FC with SR loading.

2. Methods

One of the CWs on the RR (111th km of the inner ring, intersection with the Karasta River) was selected as a research object, the appearance of which is shown in Fig. 1 and 2. On its territory, the samples of SR from FC (shungite-III) were taken and the necessary measurements were carried out.

The amount of SRW from a given catchment area (W_{srw}, m³) was calculated for one average rainfall (lasting up to 3 h) for the North-West in accordance with recommendations [45]:

$$W_{srw} = H_{\max} \times F \times 10^{-3}, \tag{1}$$

where $H_{\max}$ is maximum precipitation layer for one average rainfall [45], mm; F is catchment area, m².

The size of the SR particles in the form of equivalent grain diameter (d_g, cm) was calculated from the projection areas of these particles on the photographs using the raster graphics editor Adobe Photoshop [46]. Filtration coefficients K_f for the SR particles up to 0.5 cm in size were taken from reference data [47], and for particles larger than 0.5 cm were calculated using the Izbash formula [47]:

$$K_f = \left(20 - \frac{14}{d_g}\right) \times P \times \sqrt{d_g}, \tag{2}$$

where K_f is filtration coefficient, cm/s; P is porosity of the layer and equals 0.4; d_g is equivalent diameter of the SR particle, cm.

The SRW flow rate for continuous treatment Q_{tr} (m³/h) through one FC filled with the SR was determined through the specific flow rate q (cm²/s) according to formula (3)

$$Q_{tr} = q \times B, \tag{3}$$

where B is width of the FC, cm.

For the SR particles of 0.05 to 0.5 cm in size, q values were calculated assuming laminar flow using formula (4):

$$q_{lam} = K_f \times \left(\frac{h_1^2 - h_2^2}{2L}\right), \tag{4}$$

where L is length of the FC, cm.

For the SR particles 1–10 cm in size, q values were calculated using the formula based on the dependence proposed by Puzyrevsky for turbulent filtration [47]:

$$q_{turb} = K_f \times \sqrt{\frac{h_1^3 - h_2^3}{3L}}, \tag{5}$$

Depression curves were calculated for a rectangular array (the FC) according to formula (4) for laminar and formula (5) for turbulent filtration at given values of K_f, q, h_1, h_2 and L [47].

3. Results and Discussion

For comparison, Fig. 3 shows:

- shungite-III (piece size 8–12 cm), which was used for loading the FCs on the RR in 2018 (Fig. 1);
- shungite-III (piece size 4–6 cm), which was used for reloading the FCs on the RR in 2024 (Fig. 2);
- fraction of the SR with particles 0.4–0.5 cm in size, which is the maximum (as will be shown below) for the sorption process to be carried out in the laminar filtration mode [48, 49].

Compliance with the conditions of laminar flow of SRW through a layer of SR is mandatory, since the dynamics of sorption in the SR layer is determined exclusively by external diffusion kinetics (only the outer surface of the SR grains is involved in the process).

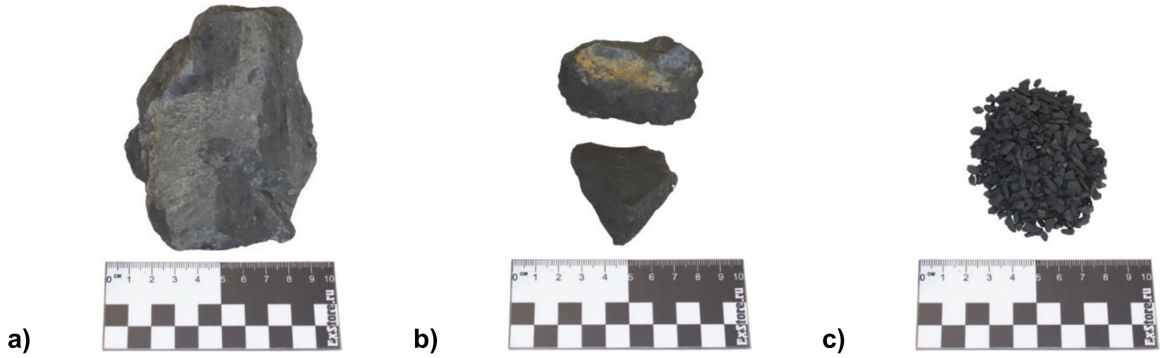


Figure 3. Schungite-III used in the FCs on the SPb RR in 2018 (a) and in 2024 (b), as well as the SR for sorption filters, operating in the optimal sorption-hydraulic mode (c).

Laminar filtration through granular media, defined by Darcy's law [47], has limitations on the ratio of the linear velocity of the liquid phase υ (cm/s, m/h) and the grain diameter of the layer d_g (cm):

$$\upsilon \times d_g < 0.01 \div 0.07. \quad (6)$$

For different given d_g of the SR, the values of υ were calculated, on the basis of which the dependence shown in Fig. 4 (based on the maximum value of the range (6)) was plotted. The area of existence of the laminar flow mode through the SR layer, shown in Fig. 4, determines the limits of optimal values of υ for different d_g of the SR.

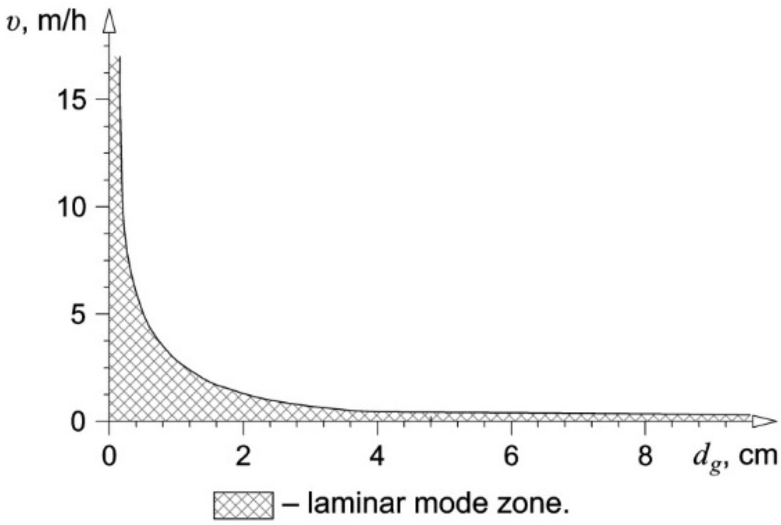


Figure 4. Zone of laminar filtration mode for SR of a different particle size distribution.

It follows from Fig. 4 that for granular layers with the SR particles of 8 to 12 cm in size (used at some other CWs of the SPb RR) the range of water velocities in the laminar mode will be from 0.035 to 0.25 m/h, for the SR fraction (2÷4) cm used according to the recommendations ODM 218.8.005–2014 will be from 0.09 to 1.25 m/h, and for the SR fraction (0.4÷0.5) cm – from 1.0 to 10 m/h, respectively.

What is the hydraulic mode of the SRW flow through the real FCs within the CWs on the RR?

The diagram of the FC filled with SR, the operation and construction of which was described earlier [50], is shown in Fig. 5. The FCs (Fig. 1b and 2b) are assembled on the basis of reinforced concrete trays (type II, intertrack[2]) and GC filled with SR in accordance with ODM 218.8.005–2014. The length of the tray

[2] Ministerstvo transportnogo stroitel'stva (Glavtransproekt), Moskovskii gosudarstvennyi proektno-izyskatel'skii institut (Mosgiprotrans). Al'bom vodootvodnykh ustroistv na stantsiiakh [Album of drainage devices at stations]. M., 1975. 90 s. URL: https://gostrf.com/normativ/1/4293830/4293830933.htm (Accessed: 22.12.2024)

is 1.5 m, the length of the FC in it is 1.0 m, the inlet cross-sections are 0.5 m × 0.5 m. Some of the characteristics of the SPb RR treatment facility are presented in Table 1.

Table 1. Some characteristics of the CW at the SPb RR.

Parameter	Unit	Value
Catchment area	ha	2.12
Surface area of detention pond	m^2	160
SRW flow rate for continuous treatment	m^3/h	14.8
Rainfall layer height in the pond	cm	22.3
Number of FCs installed	pcs.	3

For the 3 FCs available at the object under study (total inlet cross-section – 0.75 m^2) the filtration rate υ has been calculated and is 19.7 m/h.

The actual filtration rate υ' taking into account the fraction of the cross-sectional area of impermeable particles of the SR loading will be 2 times higher [47].

For a single FC of 0.5 m x 0.5 m x 1.0 m the maximum flow rate of the SRW, still providing laminar mode, will be: Q_{tr} = 0.06 m^3/h (for d_g from 8 to 12 cm); Q_{tr} = 0.31 m^3/h (for d_g from 2 to 4 cm); Q_{tr} = 2.5 m^3/h (for d_g from 0.4 to 0.5 cm).

Accordingly, to ensure laminar filtration mode of the entire volume of SRW from one rainfall, it is necessary to have in the composition of treatment facilities the number n (pcs.) of FCs: n = 247 (for d_g from 8 to 12 cm); n = 48 (for d_g from 2 to 4 cm); n = 6 (for d_g from 0.4 to 0.5 cm).

Currently, only 3 FCs are installed at the facility instead of the required 48 (according to ODM 218.8.005–2014), i.e. 16 times less than the calculated number.

In such conditions the mode of the SRW passing through the FCs of the considered CW will have a pronounced turbulent character, and it is impossible to speak about any sorption treatment.

It should be noted that the velocity mode in the FC is determined not only by the particle size of granular material $\left(d_g\right)$, but also by the difference of SRW levels at the inlet and outlet of the FC $\Delta h = h_1 - h_2$ (Fig. 5).

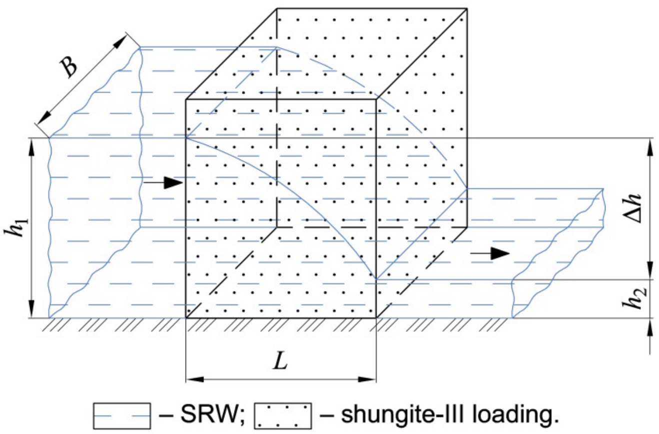


Figure 5. Schematic diagram of the FC on the SPb RR.

Table 2 shows the calculated values of filtration coefficients K_f (cm/s) for a single FC, as well as characteristics such as: SRW flow rate for continuous treatment Q_{tr} (m^3/h), linear velocity $\overline{\upsilon}$ (m/h) and values of Reynolds number (Re), which were calculated for the SR particles of 0.05 to 1.0 cm in size by formulae (3, 4), and for the SR particles of 1.0 to 10.0 cm in size by formula (2, 3, 5). The data in Table 2 were also calculated for two values of Δh (Fig. 5), equal to 10 cm and 1 cm, because of the estimation of the average water surface elevation in the object pond for an average 3-hour rainfall in St. Petersburg (Δh = 10 cm) and the minimum experimentally determined value of water surface elevation (Δh = 1 cm).

As can be seen from Table 2, the average values of linear velocity of the SRW flow through the FC for Δh = 10 cm are in the zone corresponding to the laminar mode only for SR particles of 0.5 cm and less in size. The average values of linear filtration velocity $\overline{\upsilon}$ (m/h) given in Table 2 were determined as arithmetic averages between the values of linear filtration velocities in the inlet section ($h_1 \times B$, Fig. 5) and in the outlet section $\left(h_1 \times B\right)$.

Even for the minimum value of Δh = 1 cm, a laminar filtration mode can be ensured only for the SR particles of 1 cm or less in size. Loadings of the SR with particles larger than 1 cm in any case provide a guaranteed turbulent filtration mode. A similar conclusion can be drawn from the evaluation of the Reynolds number values given in Table 2. These values only for the SR particles smaller than 0.4 cm (at Δh = 10 cm) and 1.0 cm (at Δh = 1 cm) are less than the critical level Re = 5÷9 [51], which determines the limit of applicability of Darcy's law.

Thus, FC with SR at any inflows of SRW into the CW detention ponds operate in a purely turbulent mode and cannot provide any significant sorption treatment.

Table 2. Values of characteristics of hydraulic operation modes of the FC with SR loading.

d_g, cm	K_f, cm/s	Δh = 10 cm			Δh = 1 cm		
		Q_{tr}, m³/h	$\overline{\upsilon}$, m/h	Re	Q_{tr}, m³/h	$\overline{\upsilon}$, m/h	Re
0.05	0.06	0.011	0.17	0.025	0.0007	0.052	0.007
0.10	0.25	0.045	0.68	0.20	0.0032	0.061	0.017
0.20	0.85	0.153	2.30	1.2	0.0108	0.206	0.114
0.40	2.2	0.396	5.94	6.8	0.0277	0.529	0.60
0.50	2.8	0.504	7.52	10.5	0.0353	0.674	0.95
1*	3.5	0.63	9.45	26	0.0443	0.846	2.40
1**	2.4	1.71	25.7	71	0.378	7.22	20
2	7.3	5.15	77.3	440	1.13	21.4	118
4	13.2	9.36	140.3	1560	2.05	39.2	432
5	16.5	11.7	176	2444	2.56	48.8	678
8	20.6	14.6	219	4880	3.19	60.8	1350
10	23.5	16.7	250	6990	3.64	69.40	1930

* The calculation is carried out under the condition of compliance with Darcy's law.

** The calculation is carried out under the condition of non-compliance with Darcy's law.

Fig. 6 shows the depression curves calculated by formula (4) for a FC with a 0.3 cm grain size of SR and by formula (5) for a FC with a 3 cm grain size of SR. The areas under the curves (determined by the method described in [46]), corresponding in the actual process to the volume of the FC filled with water, are close to each other (the difference is not more than 4 %), which indicates that the degree of filling of the interparticle volume of the layer (about 70 %) is practically the same for laminar and turbulent modes. Thus, due to the continuity of the flow, the linear velocity varies significantly from the inlet section of the module to its outlet section, and a part of the loading volume (not filled with water) does not participate in the filtration and mass transfer process at all.

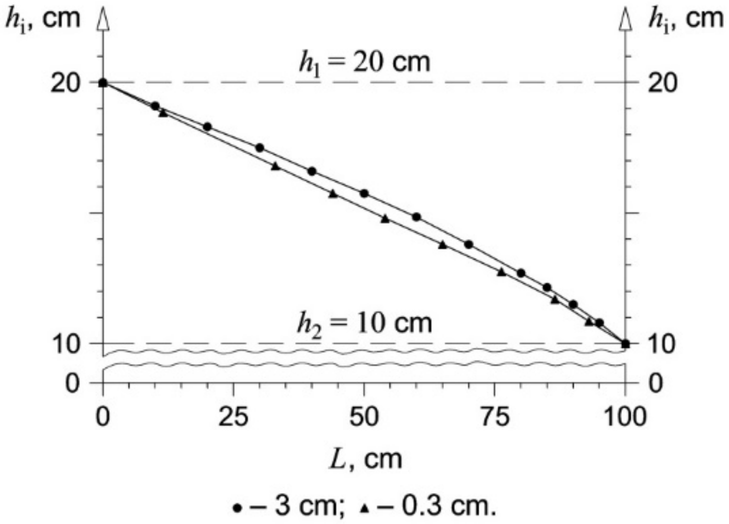


Figure 6. Depression curves calculated for a standard FC with a SR load of a different particle size distribution.

How can the situation with the actual treatment of the SRW on the SPb RR be improved? There are two ways.

The first way is to significantly increase the number of parallel FCs (as it was said earlier – by 16 times when they are filled with the SR of particles 2–4 cm in size) in order to reduce the linear filtration velocity to acceptable for laminar filtration values. However, in this case, the effective formation of the sorption front will require a FC 6–7 m in length (instead of 1 m in fact). In addition, the SR of particles 2–4 cm in size are practically not retained by any of the standard meshes (from 50÷70 mm to 100÷120 mm) of gabion structures currently used, and another structural solution is required to accommodate it.

The second way is to use fractions of the SR no more than 0.5 cm in size (and better from 0.1 to 0.3 cm). It is advisable to use ready-made products – FC, that allow easy manipulation with quantities of the SR of several tons, for the convenience of manipulation with significant amounts of the SR with a particle size from 0.1 to 0.3 cm (required for sorption treatment of SRW).

The FOPS® filters are considered to be the most developed filters of this type in practical terms [9–13].

The basic diagram of a possible facility for complex treatment of the SRW from the RR section under consideration is presented in Fig. 7.

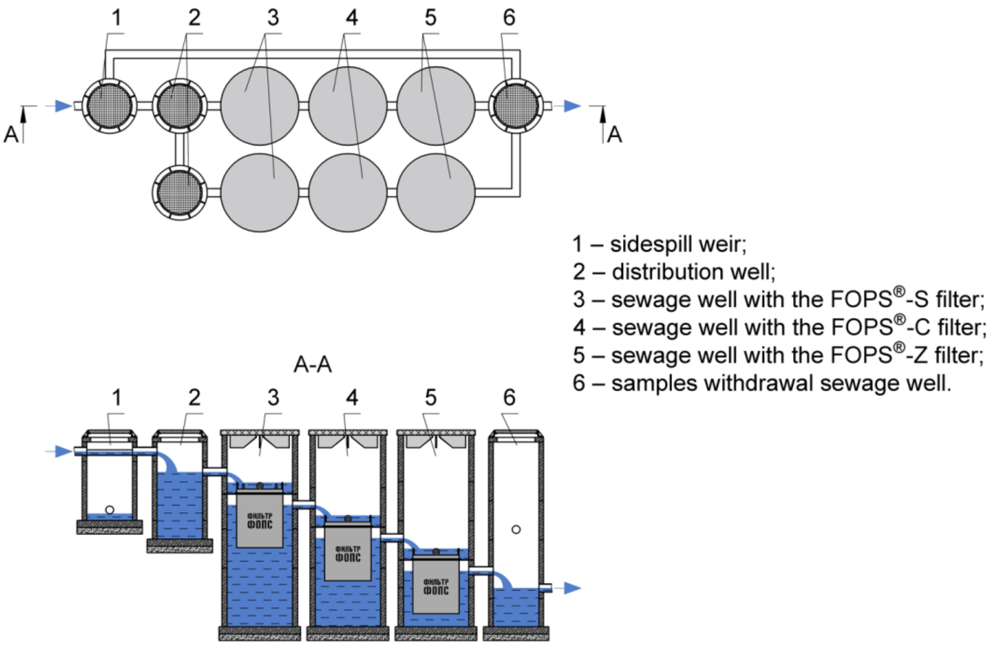


Figure 7. Schematic diagram of the facility for complex treatment of the SRW from the RR section under consideration based on the FOPS® filters.

The complexity of the treatment lies in the use of three cascade facility, in which the following are sequentially located: the filter-separator (FOPS®-S), the carbon filter (FOPS®-C) and the zeolite filter (FOPS®-Z). The required capacity of the facility is achieved by using of two parallel branches (3 filters in each) with a capacity of up to 8.0 m^3/h each. The bed height in the filters is 1.8 m, which provides acceptable dynamics of the sorption process with a material grain size from 0.1–0.3 cm in size.

In this scheme FOPS®-C filter with activated carbon load can be replaced with a FOPS® filter with shungite-III loading (fraction 0.1–0.3 cm).

4. Conclusion

1. The use of SR in accordance with current regulatory documents in the form of crushed stone with particle size 2–4 cm and more for sorption post-treatment of SRW contradicts the generally accepted practice of sorption processes in liquid media, where materials with grain size of no more than 0.5 cm are used.
2. The use of SR (fraction 2–4 cm) in FCs under real conditions provides a turbulent mode of SRW flow passage.
3. The placement of SR with particles 0.1–0.3 cm in size (optimal from the point of view of the sorption processes) is impossible with the FCs based on GC used in the existing SRW treatment facilities on the RR.
4. The implementation of the optimum conditions of SRW treatment process is possible when using SR with particles 0.1–0.3 cm in size, placed in water-permeable containers of industrial manufacture (filter cartridges), such as the FOPS® filters, convenient for treatment facilities operation.
5. The use of SR placed in filter cartridges (such as FOPS® filters) allows them to be used for complex treatment of surface runoff water as a part of multi-cascade treatment facilities.

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Received 23.10.2024. Approved after reviewing 10.12.2024. Accepted 12.12.2024.