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Possibilities of using planted soil filters for wastewater treatment under unfavourable spatial conditions – concepts of new eco-technologies

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ABSTRACT

The scientific and engineering literature lacks information on the possibility of using constructed wetlands (planted soil filters) within land properties with unfavourable dimensions, shapes and steep slopes. The lack of sufficient solutions enabling efficient wastewater management at such locations is not conducive to environmental protection or comfortable living conditions. The aim of the article is to review traditional planted soil filters and assess the possibility of their adaptation to difficult terrain conditions, e.g. steep erosion slopes. The need to maintain a sufficiently large active area of the bed system while simultaneously reducing the land area occupied by these beds was the basic criterion for the analyses. The article proposes new eco-technologies. These include planted shelf and step soil filters. The proposed solutions are based on gravitational flow of wastewater and self-purification processes (physical, biological and chemical processes). They can operate as horizontal subsurface flow systems and hybrid systems (horizontal and vertical subsurface flow). Filter structures also provide the stabilisation and safeguarding of the ground against erosion. A retaining wall with a footing (shelf filter) and gabion baskets and mattresses (step filter) are the basic elements of technical soil protection. The analysed solutions are examples of sustainable use of space.

Keywords: wastewater treatment, shelf filter, step filter, planted soil bed, space utilization

INTRODUCTION

Constructed wastelands (CW), based on planted soil beds (PSB), are used most frequently to treat wastewater from individual households or groups of households not connected to the sewage system. The treatment of wastewater takes place close to the point of its generation, which is characteristic of decentralised wastewater management systems. These systems particularly cover rural and less economically developed areas (Wu et al., 2014; Stefanakis, 2016; Gorgoglione and Torretta, 2018). Wastewater treatment at CWs is based on physical, chemical and biological processes, including the sorption of pollutants, reduction and oxidation reactions, the neutralisation of pollutants involving microorganisms, and the uptake of pollutants by higher plants. These phenomena underpin the self-purification processes that commonly occur in terrestrial and aquatic ecosystems (Kadlec, Wallace, 2009; Valipour and Ahn, 2016; Zubala, 2022; David et al., 2023).

An example wetland wastewater treatment plant (WWTP) comprises a sedimentation tank and a downstream planted soil filter (planted soil bed), which is the main object of analysis in this study (Fig. 1). The receiving bodies for treated wastewater can be the soil and ground waters (discharge via the absorbing well, subsurface leaching system, etc.) as well as surface waters, i.e. reservoirs and watercourses.

All components of modern WWTPs operate based on the principle of interconnected vessels, most commonly in a serial configuration. The

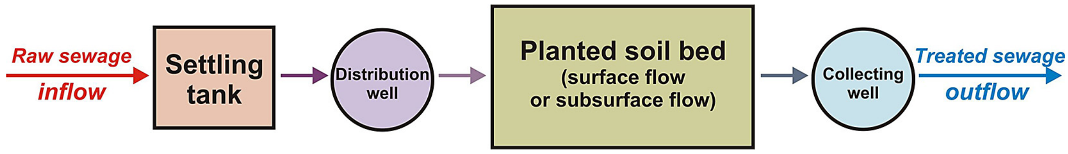

Figure 1. Layout of a wetland wastewater treatment plant with a planted soil bed

flow of wastewater between the individual treatment plant units is gravitational, which is possible thanks to the use of appropriate longitudinal gradients and height differences. This translates into significant energy savings in the operational phase, as compared to municipal treatment plants. Depending on the hydraulic conditions of the process, including the wastewater flow direction, a distinction is made between CWs with beds (filters) with horizontal subsurface flow (HSF), with beds with vertical subsurface flow (VSF), and beds with surface flow (SF). Combined systems with higher treatment efficiencies (hybrid treatment plants, e.g., VSF+HSF) are becoming increasingly popular (Dotro et al., 2017; Gorgoglione and Torretta, 2018; Vymazal, 2022). An example of a standard HSF wetland wastewater treatment plant is provided in Figure 2.

The purpose of a sedimentation tank is to pretreat wastewater using the processes of sedimentation, flotation, fermentation and microbial hygienisation (UN-HABITAT, 2008; Dotro et al., 2017; Hassan et al., 2021). A sedimentation tank can be a sealed rectangular tank or a round well made of plastic or concrete. At the PSB, wastewater treatment is primarily carried out using the processes of sedimentation (retention of suspended solids within the spaces between filling particles), adsorption (retention of pollutants on the filling particle surfaces), filtration, mineralisation of organic substances involving aerobic and anaerobic bacteria, elimination of nitrogen and phosphorus compounds in chemical reactions, due to the bacterial activity, and as a result of appropriately selected vascular plants (e.g. basket willow, common reed, rushes, bulrush, great manna grass, cyperus) (Wu et al., 2014; Timotewos et al., 2017; Benbouzid et al., 2024).

The removal of pollutants in planted soil filters (PSFs) primarily involves the action of microbial biofilm that forms as wastewater flows through the ground. It is mainly made up of bacteria that develop on the surface of soil grains and on the surface of plant roots and rhizomes. Plants serve an auxiliary role in the wastewater treatment process. Plant roots and rhizomes maintain the filtering properties of the bed at the appropriate level by loosening its internal structure. Plant transpiration reduces the volume of treated wastewater flowing out of the bed, which is evident during the growing season (Bois et al., 2021; Kataki et al., 2021).

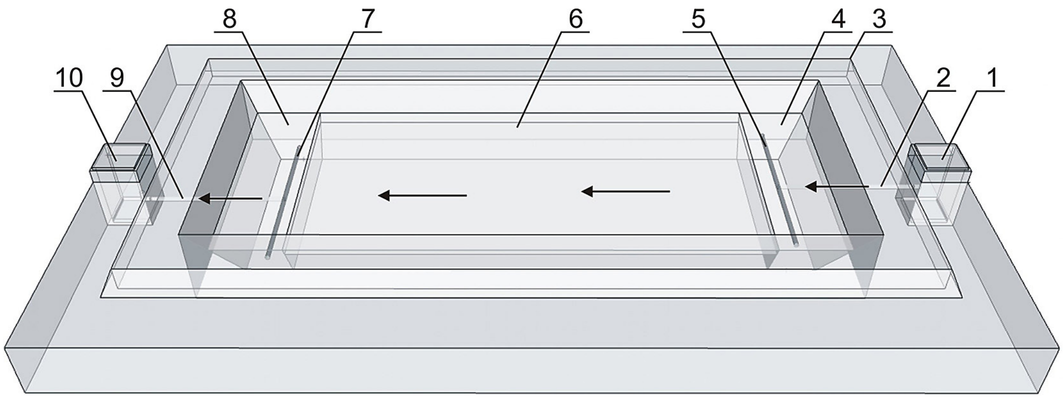

Figure 2. Construction of a standard HSF planted soil filter: 1 – distribution well, 2 – inflow of treated sewage, 3 – embankment protecting the bed, 4 – filling of the marginal part of the bed – backfill of the distribution pipe (e.g. crushed stone or gravel), 5 – perforated transverse pipe distributing treated sewage, 6 – filling of the central part of the bed (e.g. sand covered with humus), 7 – perforated transverse pipe collecting purified sewage, 8 – filling of the marginal part of the bed – backfilling of the collecting pipe (e.g. crushed stone or gravel), 9 – outflow of purified sewage, 10 – collection well (regulation)

Traditional PSBs with horizontal subsurface flow are earthen structures located in (natural or artificial) depressions on relatively flat ground. The beds are often shaped like elongated rectangles, with the wastewater flow being treated running parallel to their longer sides (Fig. 2). The depth of PSB is determined by the vegetation species used (rooting depth) and ranges from 0.5 to 1.2 m. The slope of the bed bottom towards the wastewater discharge is slight, typically 1-2% (Wu et al., 2015; Stefanakis, 2016; Dotro et al., 2017). In the transverse direction, the bottom of the bed is levelled. The beds are surrounded by dykes of native soil, which protect them against rainwater inflow from the adjacent areas (Fig. 2). The bottom and slopes are sealed with a thick film, which prevents wastewater from seeping into the substrate. The bed is usually filled with coarse sand covered with a top humic layer. Less frequently, the bed is filled with crushed stone or gravel. The filling must be highly permeable to reduce the risk of clogging up (Vymazal, 2005; Wu et al., 2015; Wang et al., 2024). The bed surface is levelled in all directions. As for the PSF with horizontal subsurface flow, the inflow and outflow drainages (perforated pipes) are installed transversely in a strip of coarse gravel or crushed stone (Fig. 2).

Unfortunately, constructing a traditional PSF involves occupying a considerable area of land, which can be problematic under certain spatial conditions. To achieve satisfactory treatment efficiency, approximately 5–10 m^2 of the PSF area is usually allocated per user of the wetland treatment plant (Vymazal, 2005, 2010; Dotro et al., 2017).

Although the scientific literature addressing constructed wetlands is extensive, and many review articles and manuals on the subject have been published in recent years (Wu et al., 2015; Stefanakis, 2016; Shukla et al., 2022; Muduli et al., 2023), there is a lack of data on the feasibility of using the presented treatment systems within land properties with unfavourable dimensions and shapes, as well as steep slopes.

The use of traditional PSFs is only possible on land parcels with sufficiently large areas and favourable shapes located on relatively flat land and stable ground. This is due to the required significant surface area of such a bed, its elongated shape, and the recommended low longitudinal slope. For this reason, the use of traditional PSFs for wastewater treatment is excluded in areas with highly varied relief, especially within plots located on steep slopes, banks and escarpments. A limiting factor is the risk of intense erosion at the site, which increases with the increase in the slope (Seeger, 2024). These problems can be addressed by using appropriately constructed PSFs based on sets of small sub-beds occupying a smaller total area than a single traditional planted soil bed (miniaturisation of the existing systems).

The study aimed to develop and present a concept of planted soil beds (filters) for wastewater treatment under unfavourable terrain conditions, the designs of which can also serve as elements of technical soil protection against erosion. Particular attention was paid to the design and construction principles of these treatment systems. Based on literature data and own experience, the use of a planted shelf soil filter and a planted step soil filter was proposed, which are the subject of patent application P.448780 (Zubala and Patro, 2024a) and the subject of utility model application W.132200 (Zubala and Patro, 2024b) by the authors of this work. The essence of these solutions is to make use of the self-purification processes that occur in traditionally constructed wetlands and to achieve a sufficiently large active area of the bed (filter) system while reducing the area of land occupied by these beds, measured according to the horizontal rectangular projection of a single module. The proposed structures are also expected to safeguard and stabilise steep slopes. The figures were created using graphics programs CorelDRAW and SketchUp.

PLANTED SHELF SOIL FILTER

Shelf filter construction

The basic components of a planted shelf soil filter (PShSF) for wastewater treatment are boxes filled with suitable substrates arranged vertically (a set of beds in the form of shelves). An important component of the structure is a reinforced chamber (e.g. made from reinforced concrete), the design of which, combined with additional safeguards, allows the beds (shelves) to be maintained in a stable position (Fig. 3). The chamber can also act as a retaining wall to protect a steep slope against erosion (Abramson et al., 2001; Ortigao and Sayao, 2004).

In the side wall of the bed-supporting chamber, there are openings to allow the passage of the pipe supplying the wastewater being treated into the upper bed and the pipe discharging purified

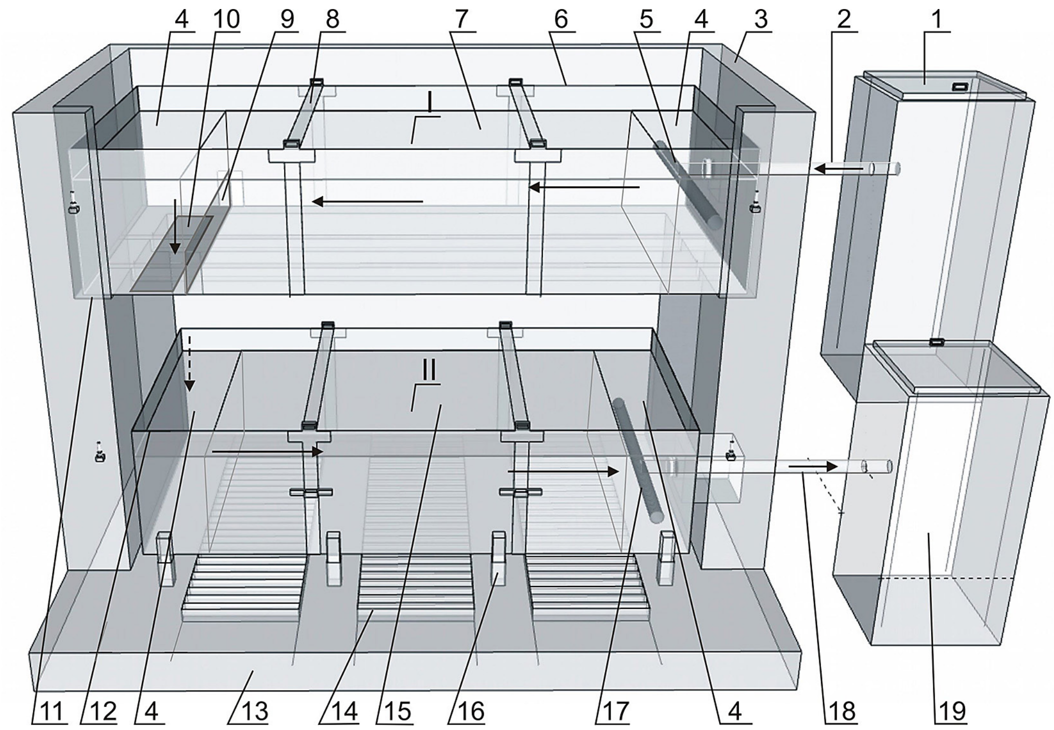

Figure 3. Construction of the PShSF: I – upper planted soil bed, II – lower stone and gravel bed, 1 – distribution well, 2 – inflow of treated sewage, 3 – wall of the shelf filter chamber, 4 – filling of the marginal part of the bed (e.g. crushed stone or coarse gravel), 5 – perforated transverse pipe distributing treated sewage, 6 – upper box, 7 – filling of the central part of the upper bed (e.g. sand covered with humus), 8 – box reinforcement clamp, 9 – transverse overflow partition, 10 – perforation in the bottom of the upper bed (drainage holes), 11 – protrusion in the side wall, 12 – lower box, 13 – base of the shelf filter chamber, 14 – gutter with a set of rollers – support of the lower bed, 15 – filling of the central part of the lower bed (e.g. gravel or medium crushed stone), 16 – retaining wedge, 17 – perforated transverse pipe collecting purified sewage, 18 – outflow of purified sewage, 19 – collecting well

wastewater from the lower bed. The size of the openings should enable good access from the outside of the chamber to the connection pipes installed in the walls of the boxes (bed casings).

In its central part, the upper box is filled with sand covered with a thin layer of humic material. The bed is planted in this part with suitable plant species that support the wastewater treatment process. Good light conditions in the upper bed promote the growth of vegetation. In the upstream part of the bed (from the side of the wastewater-supplying well), there is a transverse perforated pipe that distributes wastewater in the strip of crushed stone or coarse gravel. On the opposite side, at the bottom of the box, there are drainage openings (perforations) of approximately 5 mm in diameter, through which the wastewater being treated flows and then falls onto the surface of the initial section of the lower bed. Above the upper box's perforation is a strip of a well-permeable crushed stone or coarse gravel, and a transverse baffle (gate) should be placed at its boundary to maintain the appropriate level of the wastewater being treated. The wastewater flows over the upper edge of the baffle (Fig. 3). The upper box rests circumferentially on wall projections extending into the chamber interior and, in the central part, on longitudinal (e.g. steel) beams (Fig. 3).

The lower box is filled with a mineral material of medium particle size (e.g. gravel, crushed stone, aggregate, suitably prepared bedrock), which is water-resistant and enables stable subsurface gravitational flow of the wastewater being treated. The lower bed can operate without vegetation or be planted with plant species tolerant of increased shade and gravel substrate. In the downstream part of the lower bed (from the side of the well receiving treated wastewater), in the strip of crushed stone or coarse gravel, there is a transverse perforated pipe that collects wastewater (Fig. 3). The lower box rests on steel rollers placed transversely in channels at the bottom of the bed-supporting chamber. The rollers facilitate the movement (insertion/withdrawal) of the lower box.

Wastewater treatment at both beds takes place in the horizontal subsurface flow system. However, where required, consideration may be given to supplying the wastewater being treated to the surface of the upper bed filling (suitable design modification is required). Under this variant, the bed would operate in the vertical subsurface flow system, which, according to some authors, is more favourable for nitrogen removal processes (aerobic conditions promoting nitrification) (Vymazal, 2010; Zhuang et al., 2019; Vymazal, 2022).

Like traditional wetland treatment plants, wastewater treatment at the PShSF occurs through physical, biological and chemical processes. Sedimentary pollutants are retained within the spaces between the bed-filling particles. Lighter pollutants are adsorbed on the well-developed internal surface formed by the filling particles. An important role is played by bacteria and other decomposers that mineralise organic matter. Nitrogen and phosphorus are removed from the wastewater with the involvement of bacteria and higher plants. Phosphorus can also be precipitated in its reactions with chemical compounds naturally occurring in the mineral filling (e.g. iron in river sand). An important part of the wastewater treatment process in the shelf filter is the additional aeration of the liquid, as it falls gravitationally from the upper bed onto the lower bed. Oxygen is one of the most important factors determining efficient water self-purification, including nitrification processes (Sun et al., 2019; Lin et al., 2020; Shukla et al., 2022).

The bed-supporting chamber should be shielded from the outside by a technical door to protect the beds from cooling, which is particularly important in cold seasons and areas in the cold climate zone. The door also prevents the emission of odours during warm seasons and in areas in the warm climate zone.

Shelf filter construction principles

The walls of the PShSF chamber should be constructed vertically, whereas the bottom, which at the same time is the foundation slab, must be levelled. Where the filter chamber is located on a steep slope, a suitable excavation (indentation) must be made in advance, with the dimensions adapted to the dimensions of the chamber, also taking into account the access area. The walls and the bottom should be made of durable materials, e.g. reinforced concrete, which is resistant to varying external factors. Since the foundation slab of the bed-supporting chamber should provide adequate stability for the structure, its thickness should be matched to the expected load. The foundation slab can be extended towards the slope, thus creating a stabilising footing. For greater safety, a frost-proof substructure (e.g., crushed aggregate) should be provided under the foundation slab. In order to protect against penetrating water and frost damage, the material of the load-bearing layer must be permeable to water. This will reduce the risk of cracking associated with the deformation of frozen ground. Since the reinforced concrete structure can block water flow, effective drainage should be included in the design (Fig. 4) (Abramson et al., 2001; Ortigao and Sayao, 2004).

The base of the chamber (foundation slab) should extend outwards beyond the footprint of the chamber, which will facilitate access to the beds during inspection of the treatment plant operation, maintenance or repairs (Fig. 5). Where terrain conditions are particularly difficult, vertical stabilising posts should be cast into the ground below the chamber.

The internal dimensions of the bed-supporting chamber must be larger than the dimensions of the boxes: an expansion joint of at least a few centimetres must be provided on each side to facilitate the seating and lifting of the boxes. Once the boxes have been placed inside the supporting chamber, wedges should be placed in the expansion joints to prevent uncontrolled movement of the beds. The bend of the side walls on both sides is also a safeguard for the upper box (Fig. 3 and 5). The upper box rests circumferentially on wall protrusions extending into the chamber interior and, in the central part, on longitudinal (e.g., stainless steel) beams. The lower box rests on steel rollers in transverse channels at the bottom of the bed-supporting chamber. Similarly to the foundation slab, the roller sets should also be extended beyond the footprint of the chamber to facilitate controlled outward movement of the lower box. The lower box can be locked in the working position by inserting stop wedges in the holes located at the bottom of the chamber base (wedges tangential to the outer wall of the lower box) (Fig. 3 and 5).

The transverse perforated pipe supplying the wastewater being treated to the upper bed should be located within a strip of crushed stone at approximately 1/3 of the depth measured from the

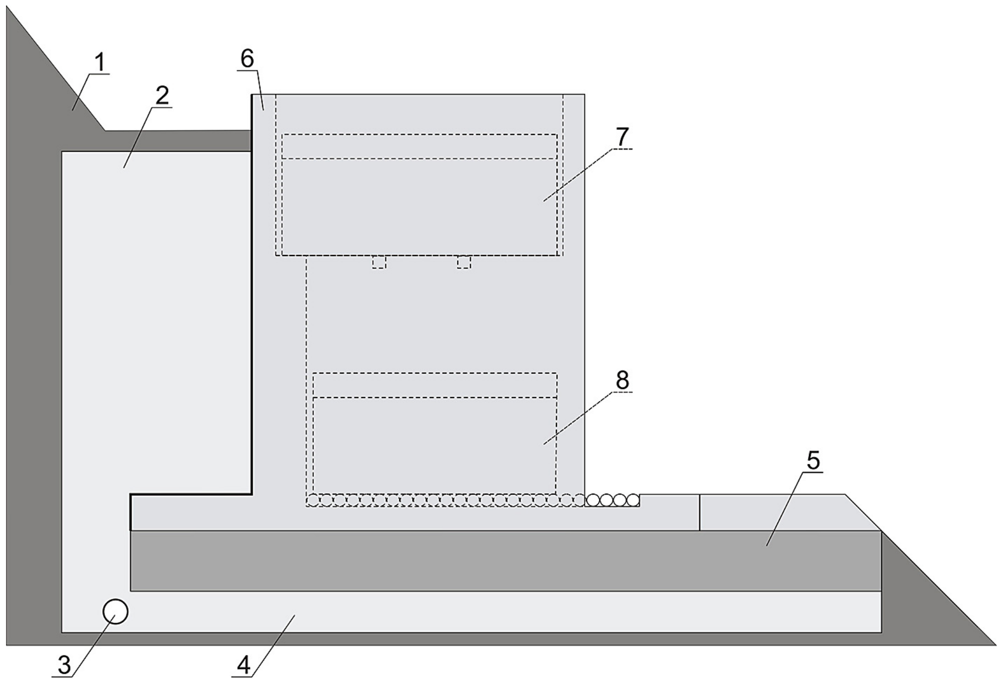

Figure 4. PShSF with elements of anti-erosion protection (side view): 1 – ground, 2 – filling (e.g. crushed stone), 3 – drainage, 4 – frost-proof layer (e.g. crushed stone), 5 – foundation, 6 – shelf filter chamber, 7 – upper box, 8 – lower box

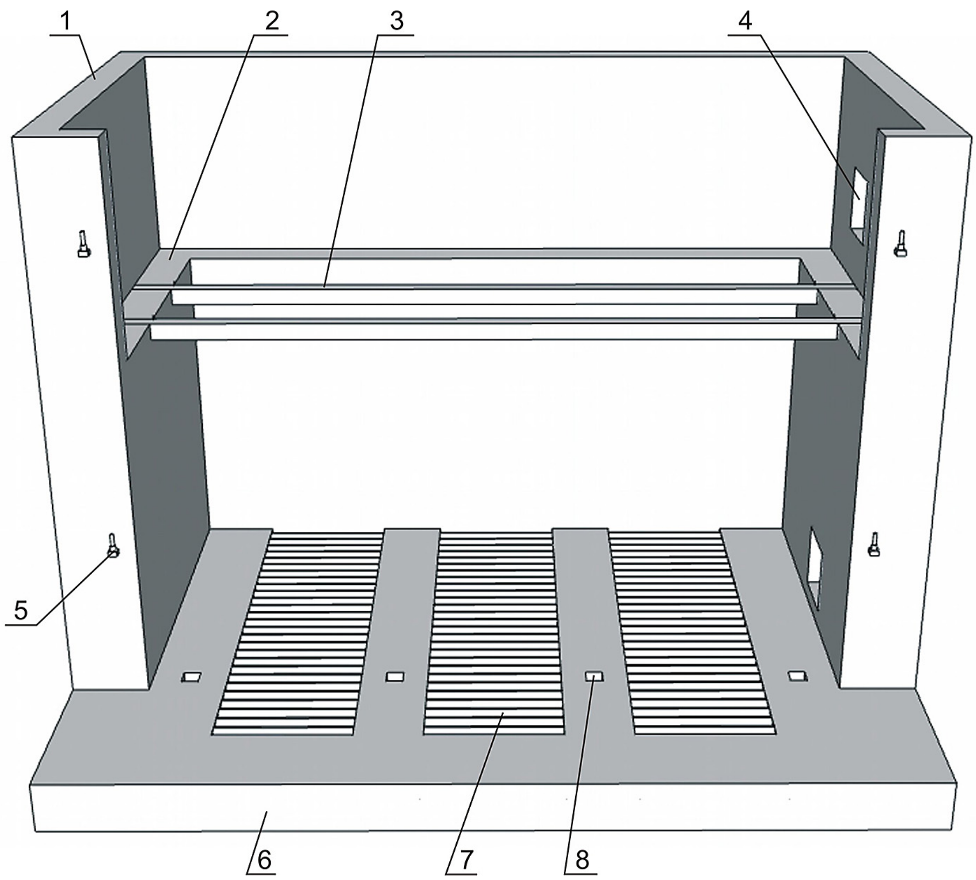

Figure 5. PShSF chamber: 1 – vertical wall, 2 – protrusion in the side wall (internal step) – upper bed support, 3 – longitudinal beam – upper bed support, 4 – hole (pipe passage), 5 – hinge for mounting technical doors, 6 – horizontal base (bottom/foundation plate), 7 – gutter with a set of rollers – support of the lower bed, 8 – hole for the retaining wedge

surface of the filling. On the other hand, the transverse perforated pipe discharging purified wastewater from the lower bed should be located at approximately 1/3 of the height measured from the bottom of the box (Fig. 3).

As the treated wastewater moves gravitationally between the upper and lower bed, the setting of these elements in relation to each other must be well aligned. The perforated part of the bottom of the upper box must be positioned precisely above the surface of the lower box filling (the wastewater being treated must not fall outside the lower box).

In the bottom of the upper box, in the vicinity of the perforated section, a stationary transverse gate should be placed to maintain the level of the wastewater being treated at the height of approximately 1/3 of the bed filling, measuring from the bottom (Fig. 3). It is necessary to ensure that the openwork section of the upper box bottom is highly permeable. Where necessary, the perforation can be periodically flushed from underneath using water under pressure (e.g. treated wastewater).

The bed boxes must be leak-proof and made of a robust material resistant to changing external factors (e.g., rusting). The recommended material is a 0.5 cm-thick stainless steel sheet. Handles should be permanently attached to the boxes to allow ropes to be attached for handling and moving them. Both boxes should be reinforced with transverse (e.g. steel) clamps to prevent bending and deformation of the walls when moving them (Fig. 3).

Sealed connection pipes should be installed where pipes pass through the box walls. Adequate vertical separation must be provided between the boxes to facilitate access to the lower bed. The suggested distance between the upper box's bottom edge and the lower box's top edge is 100 cm. The planting density at the bed should be selected according to the plant species' requirements (Fig. 6).

Drying out of the shelf beds during periods with high atmospheric temperatures can be prevented by feeding rainwater previously collected from sealed surfaces. Such treatments will also help sustain plant vegetation in the absence of wastewater inflow (e.g., in the area of holiday and recreational buildings used periodically).

Hinges should be installed in the front walls of the chamber for a technical door that provides thermal and anti-odour insulation. Inside, the door leaves should be fitted with insulating and gas pollutant-trapping material. Ventilation openings should be made in the door leaves at the height of the gap between the beds (Fig. 6).

The well supplying the wastewater being treated and the well receiving purified wastewater should be of sufficiently large diameter (e.g., 100 cm) to allow better access to the pipes connecting the wells with the beds. This will also provide a larger retention capacity, which is used when it is required to periodically close the outflow from the well supplying wastewater to the upper bed. The pipes should be housed inside the box structures, protecting them against mechanical damage and low air temperatures. The supplying well and

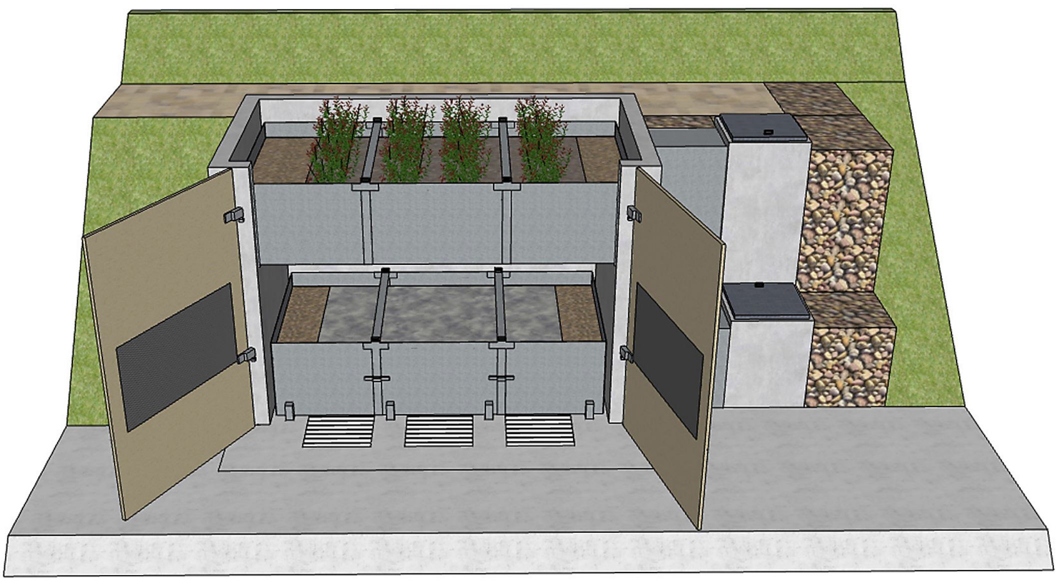

Figure 6. An example of PShSF location with plantings in the upper bed

discharging well should be located tangentially to each other (greater stability) (Fig. 6).

The two wells can be permanently connected by a pipe with closure or periodically by using a bypass so that it will be possible to bypass the shelf beds when maintenance or repairs are required. In such a situation, wastewater would flow from the supplying well directly to the discharging well and then, for example, to a subsurface leaching system, which would take over treating the wastewater in the soil. The discharging well can also be constructed as an absorbing well with a permeable bottom.

PLANTED STEP SOIL FILTER

Step filter construction

The basic components of a planted step soil filter (PStSF) for wastewater treatment are prefabricated reinforced concrete boxes filled with suitable substrates. The boxes are arranged in a stepped pattern inside a structure (form) made from gabion baskets positioned on a reinforced ground. A gabion structure allows the beds (steps) to be maintained in a stable position while providing anti-erosion protection for a steep slope, bank, or escarpment (Fig. 7).

Gabions are baskets filled with suitable substrates (stones, gravel, crushed stone, pebbles, paving stones, slag, etc.). They are made of interconnected welded steel wire elements and offer very high strength, durability and flexibility. Due to their high resistance to mechanical impact and adverse weather conditions, gabions represent a good solution as retaining walls to reinforce steep slopes and escarpments while preventing water erosion, landslides and rockslides. In addition, they are significantly less expensive than concrete structures due to faster and less labour-intensive construction work. Gabions remain flexible under external loads and can be adapted to designs on unstable foundations, which distinguishes them from rigid structures (Munro, 2018, Beckert, 2021; Alsubih et al., 2023).

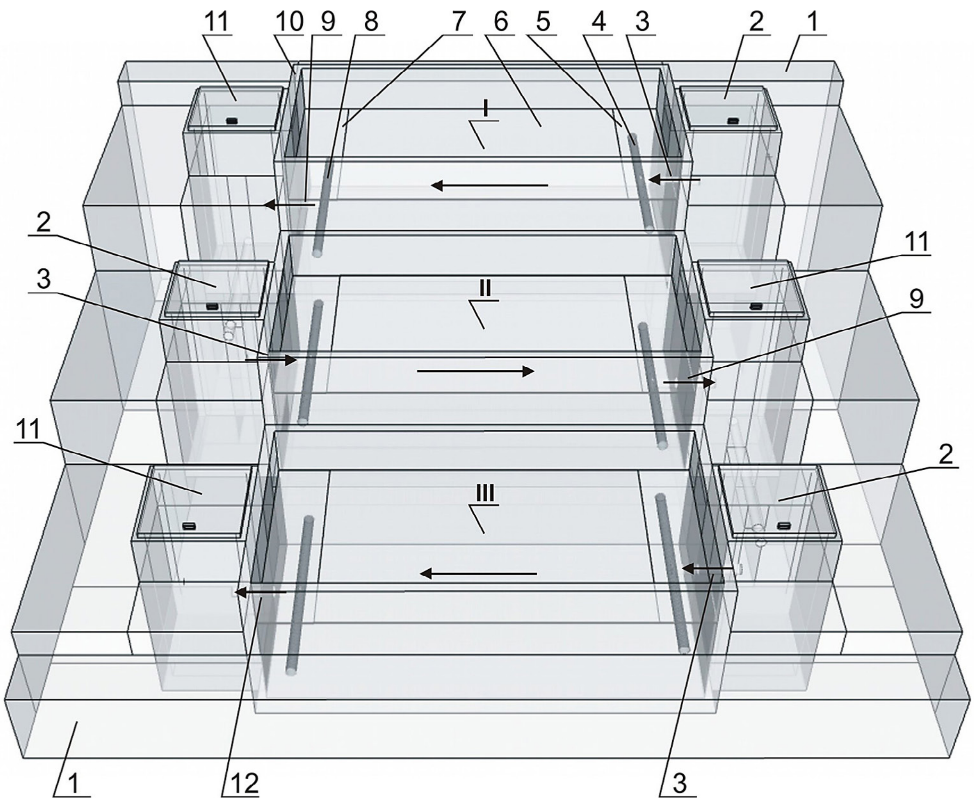

Figure 7. Construction of PStSF in the protective gabion system: I – upper bed, II – middle bed, III – lower bed, 1 – supporting structure (gabion casing), 2 – distribution well, 3 – inflow of treated sewage, 4 – transverse pipe distributing treated sewage, 5 – backfill of the sewage distribution pipe (crushed stone or gravel), 6 – filling of the central part of the bed (e.g. sand covered with humus), 7 – backfill of the sewage collection pipe (crushed stone or gravel), 8 – transverse pipe receiving sewage, 9 – treated sewage outflow, 10 - reinforced concrete bed box, 11 – collection well, 12 – purified sewage outflow

In the side walls of reinforced concrete boxes (step filter sub-beds), there are openings to allow the passage of the pipes supplying and discharging the wastewater being treated, and for the lower bed (the final bed), the passage of the pipe discharging purified wastewater to the final receiver. Inspection wells are fitted tangentially to the side walls of the boxes, through which the wastewater being treated is supplied and discharged (Fig. 7).

In the central part, the boxes are filled with a mineral material, e.g., sand, covered with a layer of humic material. In the bed, a stable subsurface gravitational flow of the wastewater being treated takes place. The bed is planted in this part with suitable plant species that support the wastewater treatment processes. In the initial sections of the sub-beds (from the side of wastewater-supplying wells), there are transverse perforated pipes that distribute wastewater in the strip of crushed stone or coarse gravel. On the opposite sides of the sub-beds (from the side of the wells receiving the wastewater being treated), transverse perforated pipes are collecting the wastewater. These are located within a strip of crushed stone or coarse gravel (Fig. 7).

If required, modifications can be made to the structures presented so that the wastewater being treated will be fed to the filling surface of the individual beds. Under this variant, the beds would operate in a vertical subsurface flow system. An alternating bed system with vertical and horizontal flows can also be applied.

Wastewater treatment at PStSFs is carried out by physical, biological and chemical processes that also occur in traditionally constructed wetlands. These are presented in the previous sections of this article.

Step filter construction principles

The gabion structure (form), which serves as the base (mattresses) and the retaining walls (baskets) for the particular PStSF modules and is a component of anti-erosion protection for the slope, escarpment or bank, should be constructed in such a manner so that the walls of all recesses are vertical, and the bottoms are levelled (Fig. 7–9). Before locating the gabion structure on a slope or escarpment, suitable excavations (indentations) must be made in them, with dimensions to match the dimensions of the basket set.

Due to the steep slopes and loads, gabions must be made of the highest quality construction materials, ensuring adequate strength and resistance to mechanical impacts and adverse weather conditions. For the construction of gabion baskets, it is recommended to use wire mesh coated with an anti-corrosive zinc-aluminium or zinc coating before welding. Adjacent baskets should be connected

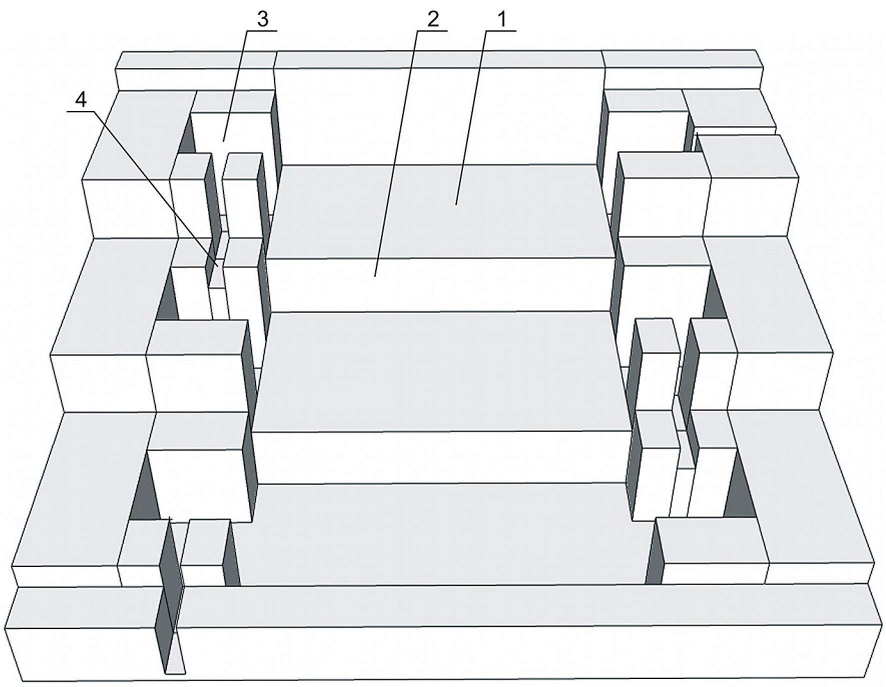

Figure 8. PStSF gabion design: 1 – bed box recess, 2 – horizontal base of the bed box, 3 – inspection well recess, 4 – gutter – passage of the pipe connecting the inspection wells

by brackets and filled with stones, gravel, crushed stones or pebbles. No absorbent material should be used. Since the gabion structure is heavy, gabion baskets should be placed on a hardened ground. The base can be a strip footing, a gabion mattress or a layer of compacted crushed stone with a depth of at least 30 cm. The reinforcement will prevent gabion baskets from deforming in the case of soil settlement (Fig. 9) (Kozłowski, 2011; Munro, 2018; Beckert, 2021).

The step filter boxes should be made of durable and leak-proof material, e.g. reinforced concrete, which is resistant to varying external (weather conditions) and internal factors (wastewater volume and quality). The external dimension of the bed boxes and inspection wells should be slightly smaller than the internal dimensions of the supporting gabion chambers in which they are embedded (expansion joint of a few centimetres). The outer surfaces of the longer walls of adjacent boxes should meet and overlap each other to about half their height (Fig. 7, 9 and 10), which will provide greater stability (reinforcement) of the step filter structure and better thermal conditions in the sub-beds (mutual insulation).

Transverse perforated pipes supplying wastewater to the boxes should be located within a strip of coarse crushed stone at approximately 1/3 of the depth measured from the surface of the filling. On the other hand, transverse perforated pipes discharging wastewater from the beds should be located at approximately 1/3 of the height measured from the bottom of the boxes (Fig. 7). Sealed connection pipes should be installed where pipes pass through the box walls.

The planting density at the sub-beds should be selected according to the plant species' requirements (Fig. 10).

The wells supplying and receiving the treated wastewater should be of sufficiently large diameter (e.g. 100 cm) to allow better access to the pipes connecting the wells with the bed boxes and the pipes connecting adjacent wells. The pipes connecting adjacent wells should be housed inside the box structures in gabion channels (Fig. 8 and 10), protecting them against mechanical damage and low air temperatures. The wells should be located tangentially to the side walls of the boxes (sub-beds) (Fig. 7 and 10). This will ensure better use of the available land, greater stability of the step filter structure, and better thermal conditions in the sub-beds and wells. If necessary, vertical stabilising posts should be concreted into the ground below the lower bed.

The purified wastewater can be discharged to the receiver using, e.g. the subsurface leaching system located in the gabions or via a pipe directly to the water receiver. The gabions themselves have good permeability, which, in turn, reduces the need for expensive drainage facilities in such structures. The final receiving well can also be constructed as an absorbing well with a permeable bottom.

CONCLUSIONS

A way to counteract the exclusion of a property with an unfavourable location from the possibility of using treatment systems based on planted soil filters is to modify them accordingly or to propose completely new solutions. In order to

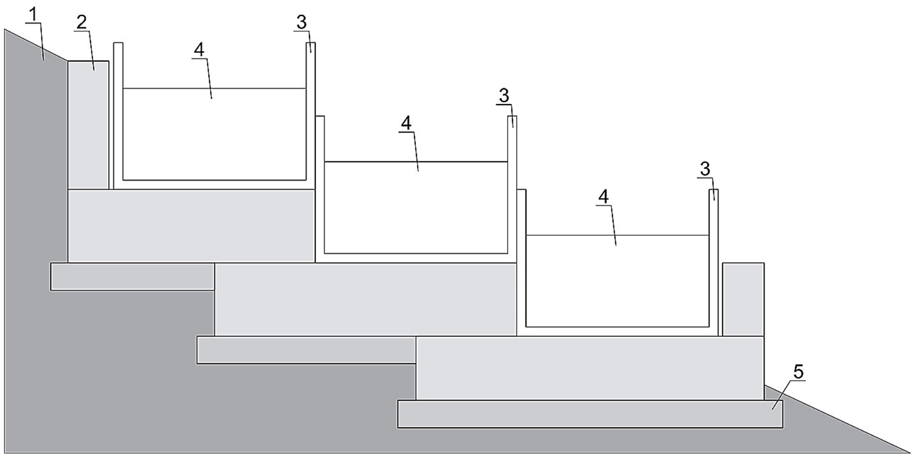

Figure 9. PStSF with elements of anti-erosion protection (side view): 1 – ground, 2 – supporting structure (gabion casing), 3 – bed box, 4 – planted soil bed, 5 – base (e.g. strip footing)

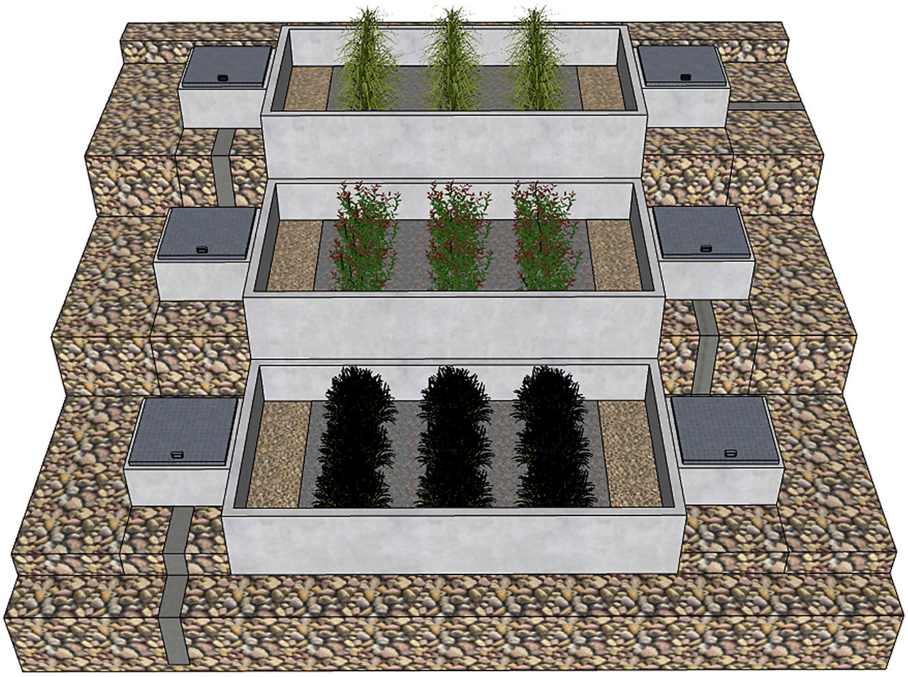

Figure 10. An example location of PStSF in the gabion system, including plantings

meet the growing needs, new types of filters have been proposed. Due to their shape and construction, they are called shelf and step filters. These systems can serve two functions at the same time, as they enable the management of wastewater (thus reducing the risk of environmental pollution) and technically protect the ground at their location (reducing the risk of soil erosion).

The shelf filter allows a sufficiently large surface area of the beds to be obtained, with a smaller area of land occupied by these beds, measured according to the horizontal rectangular projection (the total area is the sum of the areas of sub-beds stacked on top of each other). The step filter also allows the required active surface area to be obtained, but in this system, many small, tangential sub-beds (steps) are adapted and distributed according to the slope.

Wastewater treatment at both filters is carried out in the horizontal subsurface flow system. If necessary, the wastewater can be spread on the surface of the upper bed filling (initial stage). Under this variant, the bed would operate in a vertical subsurface flow system, which should increase the efficiency of nitrogen removal (more favourable oxygen conditions).

For the shelf filter, the slope-stabilising component is the reinforced concrete chamber wall (retaining wall with footing), in which the sub-bed boxes and the base (foundation slab) are embedded. However, the ground-protecting component in the step bed system is a structure (form) made of gabion baskets with recesses for sub-bed boxes.

In operational terms, both solutions should be considered cost-effective, as they use wastewater self-purification processes with gravitational flow (e.g., no energy consumption). Moreover, these systems enable the sustainable use of space, which is becoming scarce in many parts of the world.

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