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Comparative analysis of constructed wetlands: The design and construction of the ecotechnology research facility in Langenreichenbach, Germany

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ABSTRACT

The Langenreichenbach ecotechnology research facility contains 15 individual pilot-scale treatment systems of eight different designs or operational variants. The designs differ in terms of flow direction, degree of media saturation, media type, loading regime, and aeration mechanism. Seven systems were constructed as planted and unplanted pairs, in order to elucidate the role of common reed (*Phragmites australis*) in these technologies. The facility is unique in the fact that it is located adjacent to the wastewater treatment plant for the nearby village, enabling all of the pilot-scale systems to receive the same wastewater. The construction of the Langenreichenbach research facility is placed within the overarching discipline of ecological engineering. An overview of the treatment wetland design spectrum (ranging from passive to highly intensified designs) is discussed and the specific designs implemented at Langenreichenbach are presented in detail, along with the internal sampling methods for both saturated and unsaturated systems.

1. Introduction

In many parts of the world, wastewater from individual dwellings and small settlements has historically been discharged into the environment with only coarse primary treatment in a septic tank or without any treatment at all, often posing a significant threat to public and environmental health (Gardner et al., 1997; Mara, 2003). In order to limit groundwater contamination and eutrophication of surface waters, regulations for the discharge of treated wastewater have become more stringent in recent years, making nutrient removal an increasingly common requirement for small and decentralized treatment systems. Given the increasing emphasis on reuse of treated effluent (particularly in the drier regions of the world), the fate of pathogens in decentralized treatment systems is also of concern. Owing to the variable wastewater flows and relatively remote locations typical of onsite and decentralized treatment systems, technologies must be robust and capable of operating with minimal maintenance or supervision. For these reasons, there is a growing awareness that technologies designed with natural processes and ecological principles in mind, or ecotechnologies such as treatment wetlands, are especially appropriate for decentralized applications (Sasse, 1998; Wallace and Knight, 2006; Hoffmann et al., 2011). Compared to conventional wastewater technologies, treatment wetlands are low-cost, relatively simple to operate, and can be constructed out of local materials. Recent research has also demonstrated that treatment wetlands are not only capable of meeting secondary treatment standards, but can also achieve high levels of total nitrogen removal through careful design and technology selection (Tanner et al., 2012). These aspects lend to the widespread implementation of treatment wetlands throughout the world.

Subsurface oxygen limitation is one of the main rate limiting factors for traditional horizontal flow treatment wetland designs, especially when nitrification (and subsequent total

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nitrogen removal) is a treatment objective (Brix and Schierup, 1990). As a result, one of the biggest driving forces fuelling the evolution of treatment wetland technology has been the desire to increase subsurface oxygen availability (and thus, treatment performance). Design variants now span from completely passive systems (horizontal flow), to moderately engineered systems (unsaturated vertical flow systems with pulse loading) up to highly engineered or intensified systems (with increased pumping, water level fluctuation, or active aeration) (Fonder and Headley, 2010). Although technically classified as treatment wetlands, these various designs represent a broad spectrum of technologies. This technical diversity can be likened to that of the general term "activated sludge", which encompasses a broad range of aerated suspended-growth technologies. Across the wetland technology gradient from passive to intensified systems, there are trade-offs between the system footprint and energy requirement. A decrease in required area typically comes at a cost of increased electricity consumption, and potentially more complex design and operational requirements.

By virtue of being ecological technologies, treatment wetlands bridge the gap between "hard engineering" and natural science. Because of this, treatment wetland professionals are widely scattered amongst the various disciplines of engineering (agricultural, chemical, environmental, civil and mechanical) and natural sciences (biology, botany, chemistry, ecology, geology and microbiology) within universities, research institutes, non-profit organizations, and consulting engineering firms across the globe. The broad base of expertise among the professionals in this field makes highly synergistic and inter-disciplinary research efforts possible (and desirable). That said, the majority of treatment wetland research today is strongly delineated by geography, just as it has been in the past. Some of the geographical limitations can be attributed to local regulations, which sometimes dictate specific designs that are readily accepted by local authorities; as is the case in Austria (Österreichisches Normungsinstitut, 2005), Denmark (Brix and Arias, 2004), France (Macrophytes et Traitement des Eaux, 2005), Germany (Gesellschaft zur Förderung der Abwassertechnik, 1998), England (CIRIA, 1997; Wessex Water, 2006), and Spain (García and Corzo, 2008), among other countries. In such instances, there is more motivation (and often, more funding) to dig deeper into the mechanisms and science of the "locally designated" design as opposed to expanding research efforts across geographical boundaries (and thus, across different types of treatment wetlands). As a result, the treatment wetland discipline is often characterized by pockets of intense research based on the locally accepted design and/or basic discipline of the professionals (be it engineering or one of the sciences). Collaboration across these boundaries is not unknown, but it is not especially common.

An interesting aspect about the advancement of treatment wetland technology is that new developments often come from practitioners and consultants working in the private sector. These individuals, who may not publish scientific papers very often (or at all), have developed variations of wetland technology through internal research and development efforts and lessons learned the hard way (mainly through trial and error at their own expense). Because economics and treatment efficiency are the main driving factors for any consulting engineer, these technology advances are typically quite pragmatic in nature and quickly implemented upon proof of concept. However, such advancements are often underpinned by experience and professional instinct rather than scientific results.

Most of the treatment wetland design and operational modifications developed in the last decade aim at improving subsurface oxygen availability; some of the more common approaches are briefly reviewed here. The simplest (most passive) modification is that of the shallow horizontal subsurface flow wetlands, highlighted by García et al. (2005). Their findings suggest that by limiting the depth of the HSSF bed, all of the wastewater is forced through the root zone. Their results show improved treatment performance for COD, BOD_5, and NH_4-N in shallow beds (27 cm water depth) compared to deeper ones (50 cm water depth). Recirculation of treated effluent has also been shown to improve removal of ammonium nitrogen and organic matter (García-Pérez et al., 2006; Gross et al., 2008; Konnerup et al., 2011). Other operational adaptations to improve subsurface oxygen availability include water level fluctuations such as batch loading (Stein et al., 2003; Caselles-Osorio and Garcia, 2007; Corzo et al., 2008; Põldvere et al., 2009), "fill-and-drain", "reciprocating", or "tidal flow" operation (Behrends, 1999; McBride and Tanner, 2000; Austin, 2005; Sun et al., 2005; Ronen and Wallace, 2010; Wu et al., 2011). The use of active aeration (e.g., an air pump connected to subsurface network of air distribution pipes) has also been applied to HSSF beds (Wallace, 2001; Higgins, 2003; Ouellet-Plamondon et al., 2006; Maltais-Landry et al., 2009) and saturated VF systems (Murphy and Cooper, 2011; Wallace and Liner, 2011), often showing a more than ten-fold increase of removal rates compared to passive systems. Many of the reports on intensified treatment wetland designs come from private sector engineering practice. Although interest in intensified designs is widely recognized, design guidance has yet to be published (Kadlec and Wallace, 2009).

To date, no study has investigated the recent advances in subsurface flow treatment wetland design in an actual side-by-side comparison. The differences in basic research conditions (be it geographical differences in climate or wastewater characteristics, domestic versus industrial wastewater, real wastewater versus synthetic wastewater, indoor versus outdoor climate conditions, laboratory scale versus full scale, etc.) severely limit the comparisons and general conclusions about fundamental principles that can be drawn between results from different studies. With this in mind, a research facility was established in 2009 at the village of Langenreichenbach (near Leipzig, Germany). Planted and unplanted replicates were constructed in order to elucidate the role of wetland plants (*P. australis*) in conventional and intensified subsurface flow treatment wetland systems.

The facility at Langenreichenbach represents the next generation of ecotechnology research. We use here the term ecotechnology, as the facility at Langenreichenbach contains planted and unplanted replicates of many wetland designs, and a wetland without plants is technically not a wetland at all. Thus the term ecotechnology is used when referring to the broader spectrum of technologies, in order to include both planted and unplanted systems as well as passive and intensified systems.

2. Facility description

The Langenreichenbach ecotechnology research facility contains 15 individual pilot-scale treatment systems of eight different designs or operational variants. The designs differ in terms of flow direction, degree of media saturation, media type, loading regime, and aeration mechanism. The facility is unique in the fact that it is located adjacent to the wastewater treatment plant for the nearby village, enabling all of the pilot-scale systems to receive the same (domestic) wastewater. The surrounding villages can be classified as rural-residential. An areal view of the Langenreichenbach research facility is shown in Fig. 1.

Raw wastewater is taken from a pressure sewer line before it enters the adjacent treatment plant and receives primary treatment in a sedimentation tank with a total working volume of 16.5 m^3, which provides an approximate residence time of 2 days.

Fig. 1. The Langenreichenbach ecotechnology research facility in Germany. The system abbreviations, starting from the bottom left hand corner and going clockwise are: VS2, VS1, VG, VA, HA, H25, H50, and R. All systems with the exception of the last were installed in pairs (one planted with *P.* australis, the other left unplanted).

The sedimentation tank was originally an unsaturated straw filter (part of the original facility, which was constructed in 2000, see Baeder-Bederski et al. (2005), but in the 2009 upgrade of the facility, it was retrofit into a primary sedimentation tank. The effluent from the sedimentation tank passes through a bank of two commercial-size septic tank filters (Zoeller, screen size 0.8 mm) to prevent carry-over of large solids into the pump chamber from which the treatment systems are loaded. The mean water quality data for the wastewater pumped to the treatment systems is shown in Table 1. The septic tank is located in the bottom left hand corner of Fig. 1.

Two submersible pumps deliver the primary treated wastewater to the systems from a pump chamber. All of the inflow to each system is measured by an electromagnetic flow meter and recorded by a central control computer. All flow passes through the main control building (shown in the center of the picture in Fig. 1) where a series of computer-controlled pneumatic valves determines to which bed the wastewater is loaded. Each bed is loaded intermittently (generally every 30–60 min) with a pre-defined volume of wastewater. A feedback loop between the flow meters, a programmable logic control (PLC) system, the central computer and the pneumatic control valves help determine when the inflow to a given bed starts and stops (based on delivered volume) and enables accurate control of the hydraulic loading rate received by each bed. The outflow from each bed returns to the main control building (via gravity) for effluent flow measurement before it is discharged to the nearby wastewater treatment plant for final disposal. Outflow from each system is measured by recording the number of times a calibrated 10-L vessel (Rotring SCS, Bremen, Germany) fills and empties each day. All flow data is recorded using a PLC system connected to the central control computer.

The defining characteristics of each design are provided in Tables 2 and 3. There are two pairs of horizontal flow systems, three pairs of vertical flow beds, two pairs of systems with aeration and one reciprocating system. Following the nomenclature in Table 2, the arrangement of the test cells in Fig. 1 are as follows (starting lower left, going clockwise): VS2p/VS2, VS1p/VS1, VGp, VG, VAp/VA, HAp/HA, H25p/H25, H50p/H50, and R. Due to the continued debate about the role of plants in treatment wetlands, seven of the designs at Langenreichenbach were constructed with and without plants in order to further investigate the role that *P. australis* plays in treatment performance. *Phragmites* was chosen because it is the most commonly used plant in European full-scale treatment wetland applications and therefore represents a useful reference plant. The systems were planted in September 2009 at a density of 5 plants per square meter. The designation "p" in the system name is used to denote the planted system within each pair. The facility went into operation in June 2010, and the treatment systems were monitored starting in August 2010.

Table 1
Mean influent wastewater characteristics for the treatment systems at Langenreichenbach, Germany (August 2010–December 2011).

	$CBOD_5$ (mg/L)	TOC (mg/L)	TSS (mg/L)	Total nitrogen (mg/L)	NH_4-N (mg/L)	NO_3-N (mg/L)	NO_2-N (mg/L)	Redox potential (mV)	Electrical conductivity (μS/cm)	pH	Dissolved oxygen (mg/L)
Average	240	147	140	72	53	0.4	0.0	−148	1584	7.4	0.3
Standard deviation	74	38	59	16	16	0.3	0.1	78	267	0.2	0.3
Count	65	64	66	66	62	62	62	66	66	65	65

Table 2
Design and operational details for the 15 treatment systems.

System abbreviation[a]	System type	Depth of main media (m)	Saturation status	Main media type	Dosing interval (h)	Surface area (m^2)	Hydraulic loading rate[b] (L/m^2 d)
Horizontal flow							
H25, H25p	HF	0.25	Saturated	Medium gravel	0.5	5.64	18 (3)
H50, H50p	HF	0.50	Saturated	Medium gravel	0.5	5.64	36 (4)
Vertical Flow							
VS1, VS1p	VF	0.85	Unsaturated	Coarse sand	1.0	6.20	95 (4)
VS2, VS2p	VF	0.85	Unsaturated	Coarse sand	2.0	6.20	95 (4)
VG, VGp	VF	0.85	Unsaturated	Fine gravel	1.0	6.20	95 (4)
Intensified							
VA, VAp	VF + Aeration	0.85	Saturated	Medium gravel	1.0	6.20	95 (3)
HA, HAp	HF + Aeration	1.00	Saturated	Medium gravel	0.5	5.64	130 (12)
R	Reciprocating	0.85	Alternating	Medium gravel	1.0	13.2	160 (27)

Standard deviations are given in parenthesis.
[a] Systems planted with *P. australis* are denoted with "p" in the system abbreviation, other systems are unplanted.
[b] Average values for August 2010–December 2011.

Table 3
Grain size characteristics of the sand and gravel.

Media type	Nominal size (mm)	d_{10} (mm)	d_{60} (mm)	Uniformity coefficient
Coarse sand	1–3	0.8	1.8	2.3
Fine gravel	4–8	3.5	5.5	1.6
Medium gravel	8–16	5.0	9.6	1.9
Coarse gravel[a]	16–32	10.5	11.2	1.1

[a] A 15-cm layer of coarse gravel was used as the drainage layer in the reciprocating bed and in all VF beds. Coarse gravel was also used as the influent distribution and effluent collection media in all HF beds.

Table 4
Temperature and rainfall data for Langenreichenbach, Germany.

Month	Mean air temperature (°C)	Minimum air temperature (°C)	Maximum air temperature (°C)	Rainfall (mm/month)
July 2010	21.9	9.1	38.9	90.5
August 2010	17.7	9.0	30.1	129.8
September 2010	13.1	3.2	25.5	128.6
October 2010	8.2	−1.4	19.7	11.7
November 2010	5.2	−11.0	18.0	92.6
December 2010	−4.3	−19.3	4.1	29.6
January 2011	1.4	−9.9	12.5	34.9
February 2011	3.0	−6.5	11.0	6.9
March 2011	4.5	−8.7	18.9	11.1
April 2011	11.6	−0.9	26.4	26.6
May 2011	14.7	−2.6	32.5	28.4
June 2011	18.5	6.7	32.8	47.9
July 2011	17.6	6.4	30.8	146.4
August 2011	18.9	6.6	32.7	66.1
September 2011	15.9	4.8	30.3	69.0
October 2011	9.7	−3.7	27.0	25.7
November 2011	3.7	−5.4	15.8	4.0
December 2011	4.7	−3.7	13.6	47.0

Note: Data were logged by the onsite weather station at the research facility.

The village of Langenreichenbach (51.5°N, 12.9°E) is located in eastern Germany, approximately 50 km northeast of Leipzig. The research facility at Langenreichenbach is equipped with an onsite weather station that measures air temperature, humidity, rainfall, air pressure, wind speed and direction, and solar radiation. Measurements are collected every 10 min. Temperature and rainfall data for July 2010–December 2011 are given in Table 4. The total rainfall at the site during 2011 was 514 mm. Mean air temperatures in the wintertime are sub-zero, with a minimum recorded air temperature of −19.3 °C. The research facility operates year-round, with the only exposed pipes being thermally insulated and fit with low-wattage frost-protection lines to prevent the water in the pipes from freezing. This was done to enable cold-weather operation without affecting the operating temperature inside the treatment systems themselves.

2.1. Horizontal flow systems

The first design chosen for Langenreichenbach is historically the most common treatment wetland design, consisting of a saturated, horizontal flow bed with a saturated gravel depth of approximately 50 cm. This design, which is based on guidance from sources such as Cooper et al. (1996), Davison et al. (2005), and Crites et al. (2006) was chosen for its widespread implementation and its ability to be operated passively (e.g., without energy inputs). This type of system is very commonly used in countries such as Australia, Czech Republic, New Zealand, Spain, Poland, the United Kingdom, and the United States. The nomenclature designated for this pair of systems is H50 (Horizontal flow, 50 cm depth). Fig. 2 shows the main design details for the H50 systems. Because the horizontal flow systems at Langenreichenbach operate throughout the winter months, subsurface influent distribution was chosen (as opposed to surface distribution, which is common in many warm-climate HSSF applications). The H50 systems are each 4.7 m long by 1.2 m wide, and are operated at a hydraulic loading rate of approximately 36 mm/d, equating to a nominal hydraulic residence time (*n*HRT) of approximately 5.5 days.

The second set of passive horizontal flow systems are horizontal flow beds with a saturated gravel depth of 25 cm (named H25 and H25p for unplanted and planted replicates, respectively). These systems are also each 4.7 m long by 1.2 m wide; however, they are operated at a hydraulic loading rate of approximately 18 mm/d (half that of the H50 systems), resulting in an *n*HRT of about 5.5 days. Fig. 3 shows the main design details for the H25 systems.

This design was chosen primarily based on the results from García et al. (2005). As mentioned previously, their results showed higher removal rates of organic material and ammonium nitrogen in shallow (27 cm deep) HSSF beds compared deeper (50 cm) ones. The premise of this design is that greater treatment performance may be achieved by forcing all of the wastewater through the rooting zone of the plants, which has been shown to occur mainly in the top 20 cm of a HSSF bed (Headley et al., 2003).

2.2. Vertical flow systems

The research facility at Langenreichenbach also contains several vertical flow (VF) design variants. The first design is based on the most commonly implemented vertical flow systems, based on design guidance from sources such as Austrian, Danish, and U.S. design standards (Crites and Tchobanoglous, 1998; Brix and Arias, 2004; Österreichisches Normungsinstitut, 2005). This type of system is widely implemented in countries such as Austria, Belgium, Denmark, Germany, the Netherlands, the United Kingdom, and the United States. Vertical flow wetlands are also very common in France, although the technology has been adapted to receive raw as opposed to primary-treated domestic wastewater (Molle

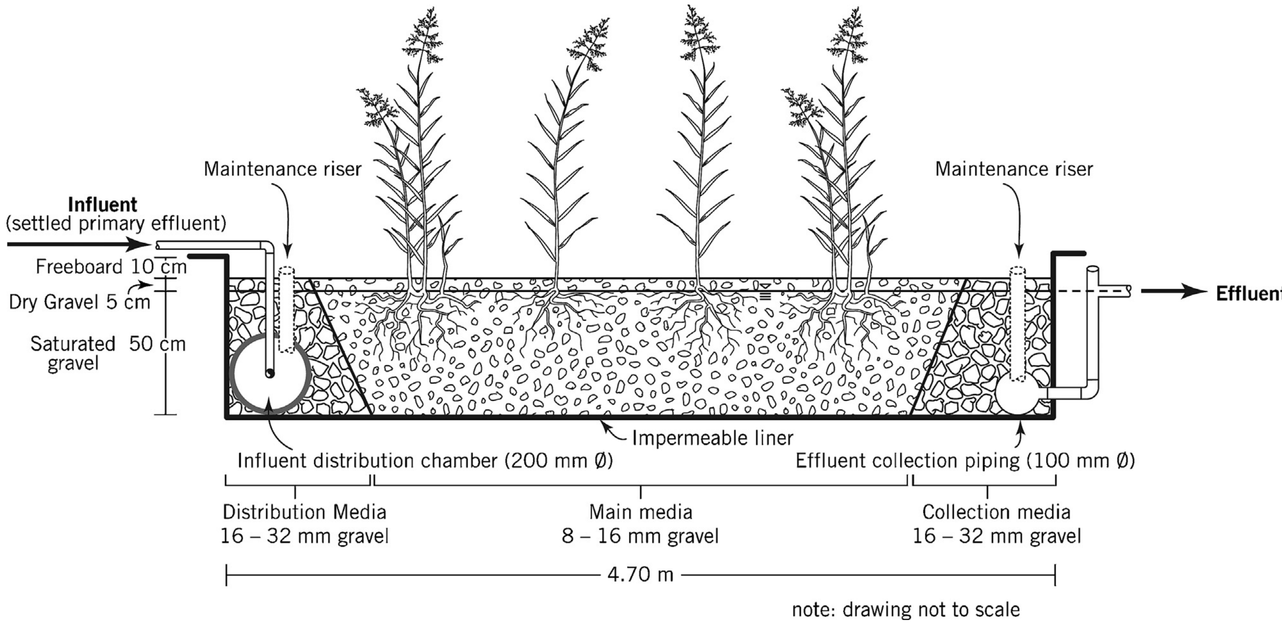

Fig. 2. Profile view of the H50 design (horizontal flow systems with a saturated depth of 50 cm).

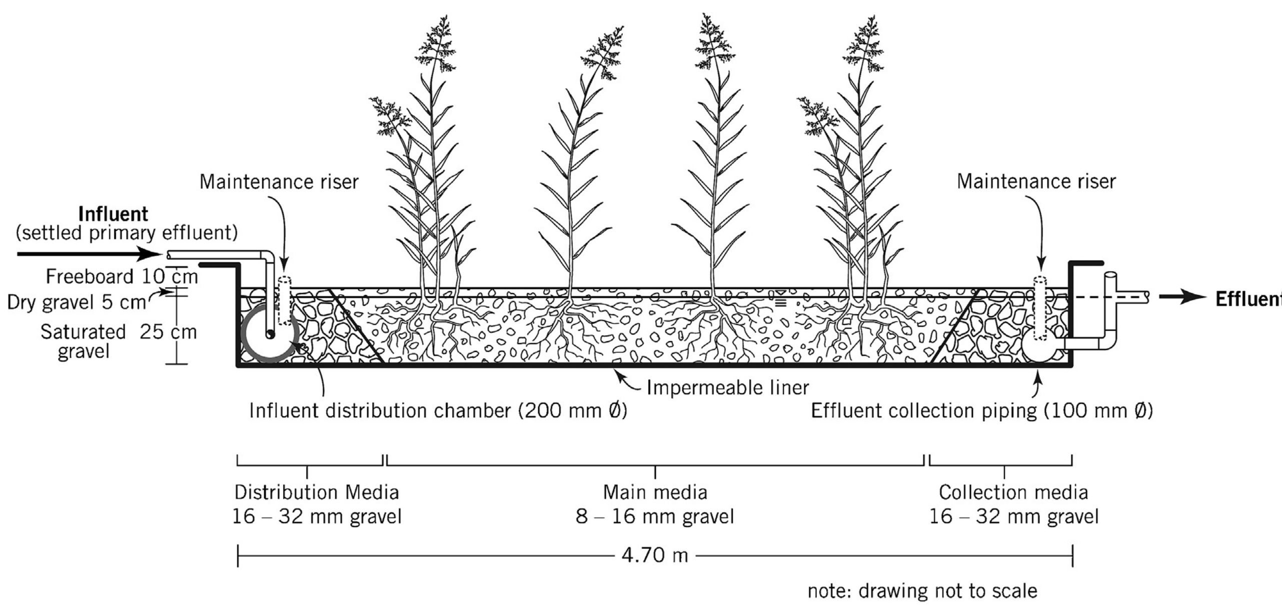

Fig. 3. Profile view of the H25 design (horizontal flow systems with a saturated depth of 25 cm).

et al., 2005). Vertical flow systems are typically unsaturated and intermittently pulse-loaded, and the main media layer is typically sand. Fig. 4 shows the main design details for the four sand-based vertical flow systems (VS1, VS1p, VS2 and VS2p) at the research facility. Coarse sand was used as the main filter media (Table 3). Each bed measures 2.75 m by 2.4 m, and contains an outlet shaft of 0.5 m by 0.8 m (the outlet shaft is located within the "footprint" of the bed; refer to Section 3.2 for further detail). The outlet shaft is subtracted from the total surface area of the bed, for an effective area of 6.2 m^2 per bed. The systems designated VS1 and VS1p are dosed once every hour, whereas VS2 and VS2p are dosed once every two hours. The systems receive a hydraulic loading rate of approximately 95 mm/d. The reasoning behind the choice in dosing regime was in order to investigate the difference between smaller, more frequent doses and larger, less-frequent doses. Crites and Tchobanoglous (1998) suggest that dividing the daily hydraulic load up into smaller, more frequent doses potentially enhances oxygen transfer by avoiding temporary saturation of the media and promoting capillary flow as opposed to gravity drainage. Loading frequency is a potentially important operational design variable that is rarely stipulated in design guidelines. In practice, loading frequency varies from once per day (large doses) to every 20 min (micro doses). Loading frequency is often dependent on the preference of the designer.

Washed, well-graded sand that is typically used in vertical flow wetlands is not available everywhere in the world. This does not preclude the implementation of ecotechnologies in regions without "good" sand but it does require a modification in media choice, which in some instances means settling for a small-diameter gravel or similar material. The impact on treatment performance when

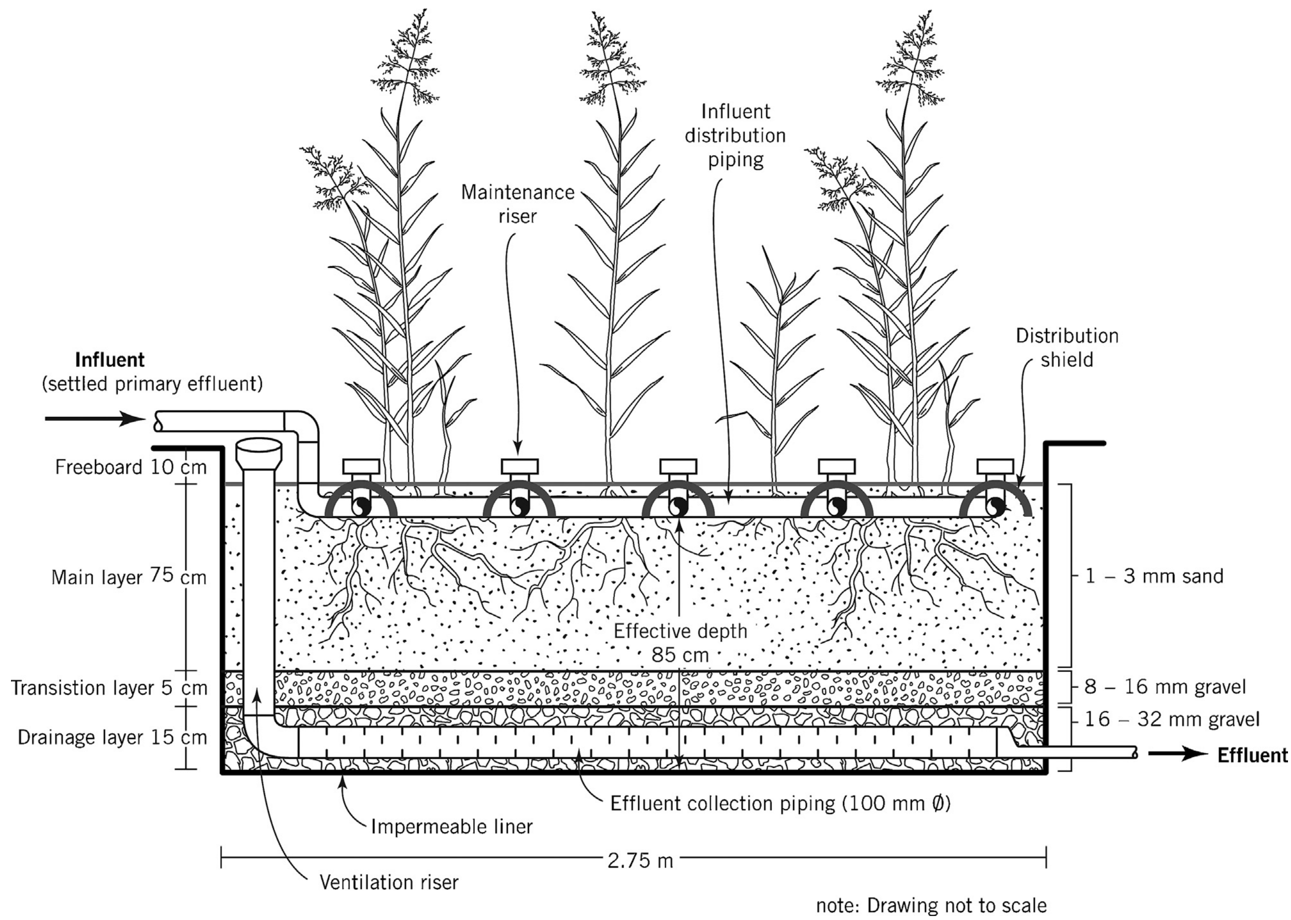

Fig. 4. Profile view of the VS design (sand-based unsaturated vertical flow systems, with and without plants: VS1, VS1p, VS2, VS2p).

using coarse sand as opposed to fine gravel is generally not known. Some of the authors have faced this challenge when constructing decentralized ecotechnologies in Jordan, Oman and islands of the South Pacific, where readily-available sand (used in the construction industry) tends to be unwashed, poorly sorted and generally too fine for use in wastewater treatment systems. The next most suitable material (well-sorted and free of fines) often has a nominal grain size in the order of 4–8 mm. We therefore decided to include at the Langenreichenbach facility a pair of unsaturated, vertical flow wetlands with a main media of 4–8 mm nominal diameter (Table 3). The design is otherwise identical to that of the sand beds (VS) described previously. Fig. 5 shows the main design components for the unsaturated vertical flow wetlands with gravel as the main media (designated VG and VGp). This pair of systems is loaded at the same hydraulic loading rate as the sand beds (95 mm/d), to enable direct comparison against planted and unplanted sand-based systems. The VG beds are loaded once every hour.

Since the research facility at Langenreichenbach operates year-round, it was important to consider the impact cold weather operation would have on the designs. As can be seen in Table 4, it was common for mean daily air temperatures at the site to be sub-zero in the winter months, with daily temperatures dipping down to nearly −20 °C. Figs. 4 and 5 feature some of the design modifications incorporated in order to enable year-round operation. Due to risk of freezing, the wastewater could not be dosed to the surface of the bed during winter, as is common in many warm weather vertical flow wetland applications. The design modification included the addition of distribution shields (half-pipe tunnel) over the influent distribution pipes, and 10 cm layer of the main filter media (sand or gravel) over the top of the bed. The orifices in the distribution pipes face upwards (Fig. 6) projecting the influent onto the underside of the shield, providing for secondary distribution and increasing the surface area over which the wastewater is received. This design modification is an example of something commonly used in engineering practice, but not reported in the literature (as discussed in Section 1). A single downwards-facing drainage hole is included with each distribution manifold so that wastewater would drain out of the pipes between dosing events. The drain-back aspect is extremely important for cold-climate applications, as the water in the pipes may otherwise freeze, damaging the distribution system (Wallace, 2000). Each distribution lateral is equipped with a maintenance riser to facilitate regular flushing of accumulated solids from each distribution line. Fig. 6 also shows the collection system that was installed at the bottom of each vertical flow bed. It consists of three lengths of 100 mm diameter perforated pipe; each length of perforated pipe is connected to a 100 mm ventilation riser. Ventilation risers are commonly used in Danish VF wetlands and are believed to facilitate the drawing of air through the drainage system and into the base of the filter media (IWA, 2000; Brix and Arias, 2005; Tanner et al., 2012).

2.3. Intensified systems

The remaining systems at the Langenreichenbach research facility consist of intensified designs (aeration and reciprocation). There are two (saturated) vertical flow and two horizontal flow beds each equipped with an integrated aeration system (Wallace, 2001),

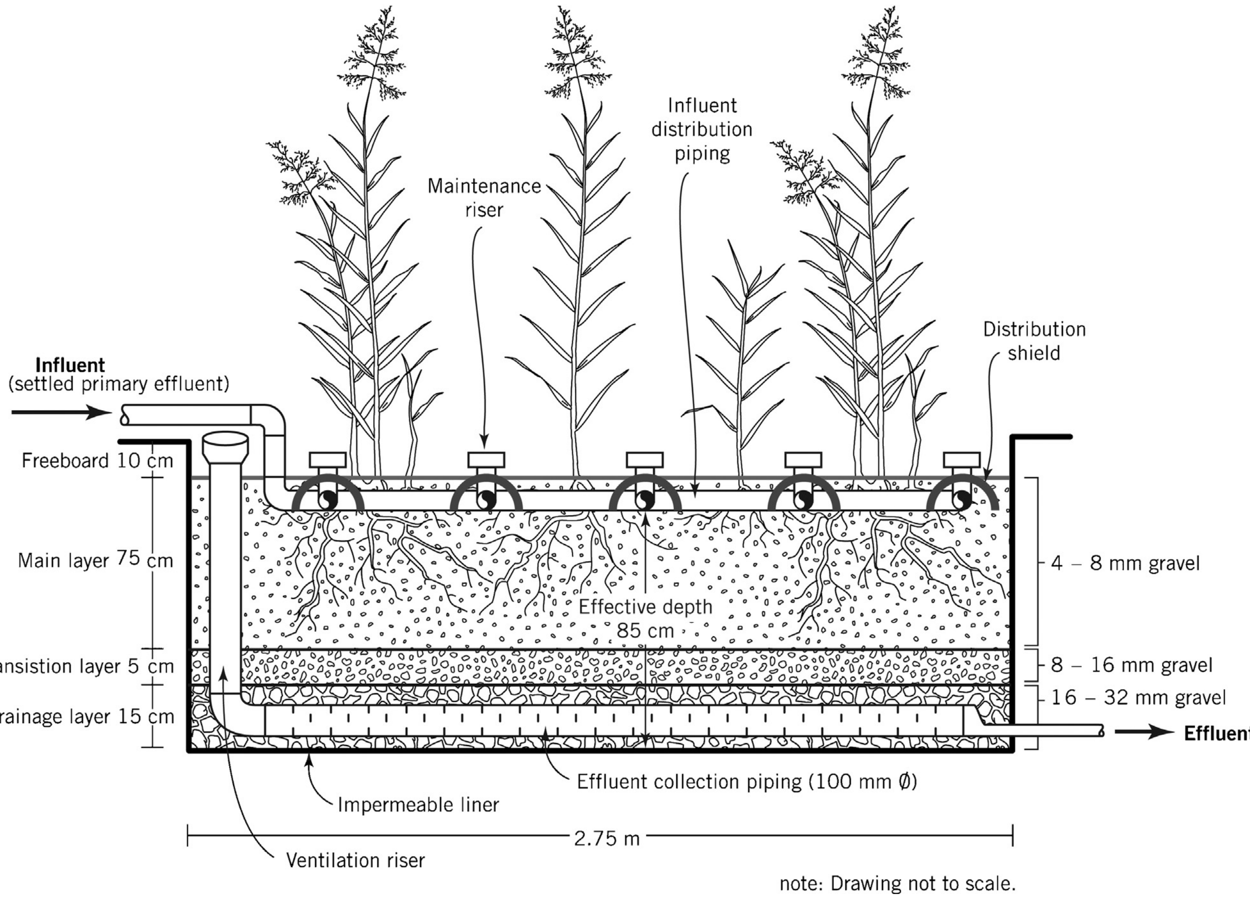

Fig. 5. Profile view of the VG design (gravel-based unsaturated vertical flow systems, with and without plants: VG, VGp).

plus one reciprocating fill-and-drain system (Behrends et al., 1996; Austin and Lohan, 2005).

The basic theory of wastewater aeration is well known and has been in engineering practice for the last 90 years (Crites and Tchobanoglous, 1998). However, aeration of gravel beds (e.g., subsurface flow (SSF) treatment wetlands) is a relatively new development and has only been seriously studied since the late 1990s. There is a fundamental difference in how aeration (the introduction of air bubbles at the bottom of the treatment reactor) functions in tanks and ponds compared to SSF wetlands. In tanks and ponds, the rising air bubbles create a hydrodynamic mixing effect (Imhoff and Fair, 1929), which provides uniform distribution of dissolved oxygen in the water column. As a result, air diffusers commonly used in wastewater treatment are high-volume devices,

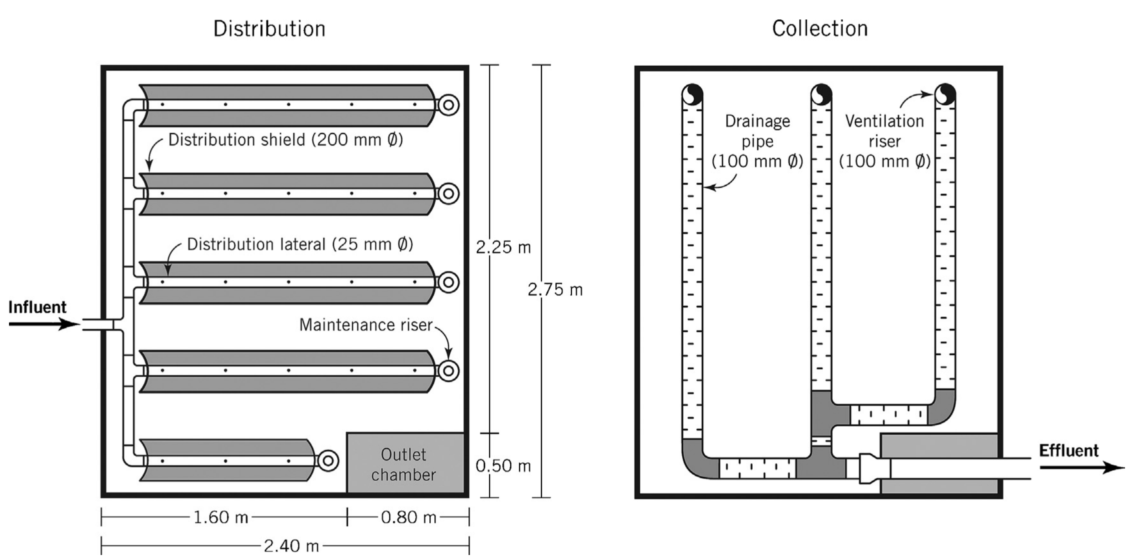

Fig. 6. Plan view of the distribution and collection systems for the vertical flow beds (VS1, VS1p, VS2, VS2p, VG, VGp, VA, VAp).

since dissolved oxygen can be distributed at a considerable distance from the air diffuser due to hydrodynamic mixing.

In the gravel-based environment of aerated subsurface flow wetlands, this hydrodynamic mixing is greatly reduced, and qualitative observations indicate the "zone of influence" from an individual bubble entry point is approximately 30 cm in diameter (0.07 m^2). This implies that effective aeration of SSF wetlands requires a very uniform distribution of small quantities of air across the entire bottom area of the wetland (Wallace, 2001).

Once introduced into the wetland, an air bubble must work its way upward through the gravel matrix that occupies the saturated water column. This introduces two competing effects: (1) "coalescence" of bubbles (fine bubbles aggregating into larger bubbles, which decreases oxygen transfer), and (2) "retardation" of bubble movement (the air bubble must work its way through the interstitial spaces of the gravel matrix; this delay in the bubble transit time increases oxygen transfer). The relative impact of these two mechanisms have not yet been quantified, but empirical studies indicate the combined effect results in an oxygen transfer efficiency of approximately 4.7% per meter of diffuser submergence (Wallace et al., 2007), which represents an intermediate range between coarse bubble diffusers (2.6% per meter) and fine bubble diffusers (6.6% per meter) used in free-water conditions (U.S. EPA, 1989). To date, both horizontal and vertical flow aerated SSF wetlands have been implemented in practice. However, there has been no study comparing the relative merits of the two flow configurations.

The ability to mechanically aerate the wetland greatly exceeds the oxygen transfer rate possible in passive wetland designs, with proportional increases in treatment efficiency. Additional details on oxygen transfer are included in a separate publication (Nivala et al., in this issue).

In the case of the aerated beds at Langenreichenbach (VA, VAp; HA, HAp), drip irrigation tubing (Geoflow, Inc.) with known airflow – pressure drop characteristics was utilized so that the aeration grid could operate in a "balanced" condition; a scenario where every possible distribution orifice is releasing air, and the air blower is operating at (or just slightly above) the static water column pressure in each wetland system. This allows the most energy efficient distribution of air while ensuring uniform coverage of the air distribution network.

2.3.1. *Aerated vertical flow beds*

For the vertical flow aerated systems (VA, VAp), the density of the aeration orifices is 0.078 m^2/orifice. While the continuous aeration system was designed to meet the overall wastewater oxygen demand, the density of the aeration distribution grid (0.078 m^2/orifice) has a slightly larger spacing than the typical zone of influence of each air outlet (0.07 m^2/orifice, as discussed in the previous section), indicating the potential for anoxic or anaerobic zones to exist within the VA and VAp test cells. The details of the VA design are shown in Fig. 7.

The saturated vertical downflow configuration of the VA and VAp test cells offer two process advantages. First of all, the cross-sectional influent organic loading rate over the distribution area (g BOD/m^2 d) is much lower in this reactor configuration than in horizontal flow designs. As clogging of SSF wetlands has been linked to the BOD loading applied to the inlet cross section (Wallace and Knight, 2006), distributing the influent BOD load across the largest possible area (e.g., the entire surface of the VF wetland) minimizes the potential for clogging (Wallace and Liner, 2011). A second process advantage of the saturated vertical flow design with aeration is that the wastewater is applied at the top of the bed and travels downwards to the collection system, while the air bubbles flow in the opposite direction. Thus, the water in the bed should be extremely well mixed. Internal water quality sampling (discussed in Section 3.1) in the VA beds confirms this supposition (unpublished data).

2.3.2. *Aerated horizontal flow beds*

The density of the aeration orifices in the horizontal flow aerated systems (HA, HAp) was approximately 0.07 m^2/orifice, indicating the potential for uniformly aerobic conditions. However, the flow path of the wastewater is horizontal, so the application of the net wastewater oxygen demand is non-uniform, being highest at the inlet region and lowest at the outlet region (Wallace and Knight, 2006). With a uniform aeration grid (like the HA and HAp designs), there is the potential for anaerobic or anoxic zones to exist in the inlet region of the bed because the oxygen demand at the influent of the bed is likely to exceed the oxygen transfer rate of the oxygen provided to the inlet portion of the bed. The presence of localized anaerobic zones amongst a predominantly aerobic system may be beneficial for treatment processes such as nitrogen removal, where the nitrate generated by nitrification in aerobic zones can be subsequently denitrified within the anaerobic zones.

Because the applied wastewater oxygen demand is non-uniform, the aeration grid was separated into two sections (front half and back half) that can be operated independently to investigate various modes of operation. Because the movement of water (horizontal) is different than that of the air (vertical), this process configuration has less mixing than the aerated VF configuration.

Since the oxygen transfer is independent of the surface area of the wetland, greater bed depths are possible with mechanically aerated wetlands. Also, as the oxygen transfer is proportional to the water depth (Wallace et al., 2007), deeper beds actually result in more efficient oxygen transfer in mechanically aerated wetlands. As a result, the aerated beds (HA, HAp) were constructed with a bed depth of 100 cm, which is deeper than the other horizontal flow designs at Langnreichenbach (bed depths of 50 cm and 25 cm). The main facets of the HA design are shown in Fig. 8. The aeration system was run continuously (24 h per day).

2.3.3. *Reciprocating wetland*

The final system at the Langenreichenbach research facility is a two-cell reciprocating design. Sequential filling and draining of wastewater has shown to increase subsurface oxygen availability, and thus removal of oxygen demanding compounds such as COD, BOD, and ammonium nitrogen. As a saturated cell is drained, air is drawn into the bed, which oxygenates the exposed biofilms on the gravel surfaces (Green et al., 1997). Frequent water level fluctuation has been shown to increase treatment performance compared to beds with a static water level (Tanner et al., 1999). As the rate of oxygen transfer is related to the frequency of the water level fluctuation, it is common to design an internal recycling system to rapidly fill and drain multiple cells or compartments. Such operation is often termed tidal flow, reciprocating, or fill-and-drain (Sun et al., 1999; Behrends et al., 2001; Austin, 2006; Ronen and Wallace, 2010; Wu et al., 2011).

The reciprocating system at Langenreichenbach is composed of two cells. Wastewater is dosed once per hour onto the upper surface of the first cell (Bed A, Fig. 9). The distribution system is similar to that described for the vertical flow beds (details for the reciprocating bed are shown in Fig. 9). The internal recycling network is comprised of two pumps and a network of perforated pipes on the bottom of each bed (Fig. 10). A timer controls the beginning of the pumping cycle from one bed, and a float switch set at the maximum water level in the receiving bed controls the end of the cycle. For example, at the start of a cycle, the water level in Bed A is at maximum (standing water depth of 95 cm), and the water level at

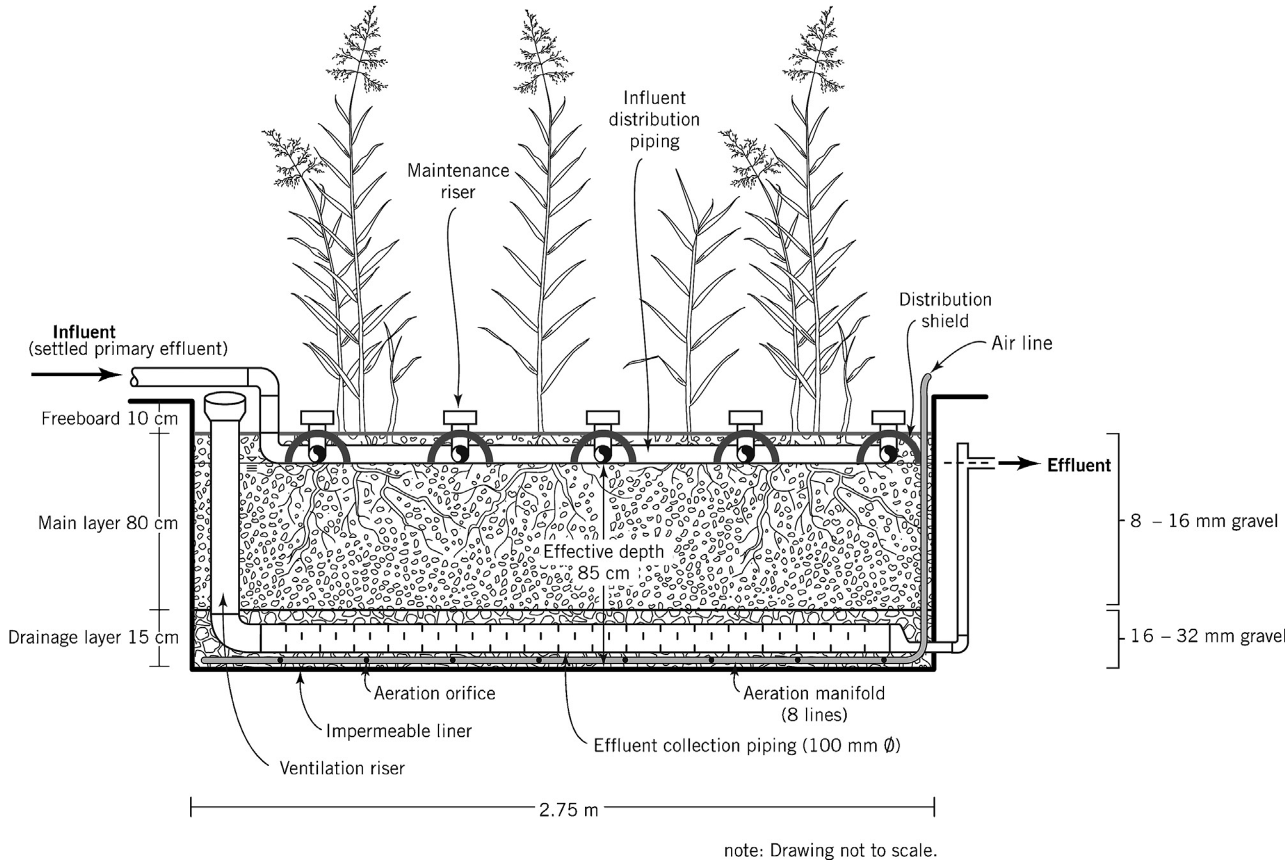

Fig. 7. Profile view of the VA design (gravel-based saturated vertical flow systems with aeration; with and without plants: VA, VAp).

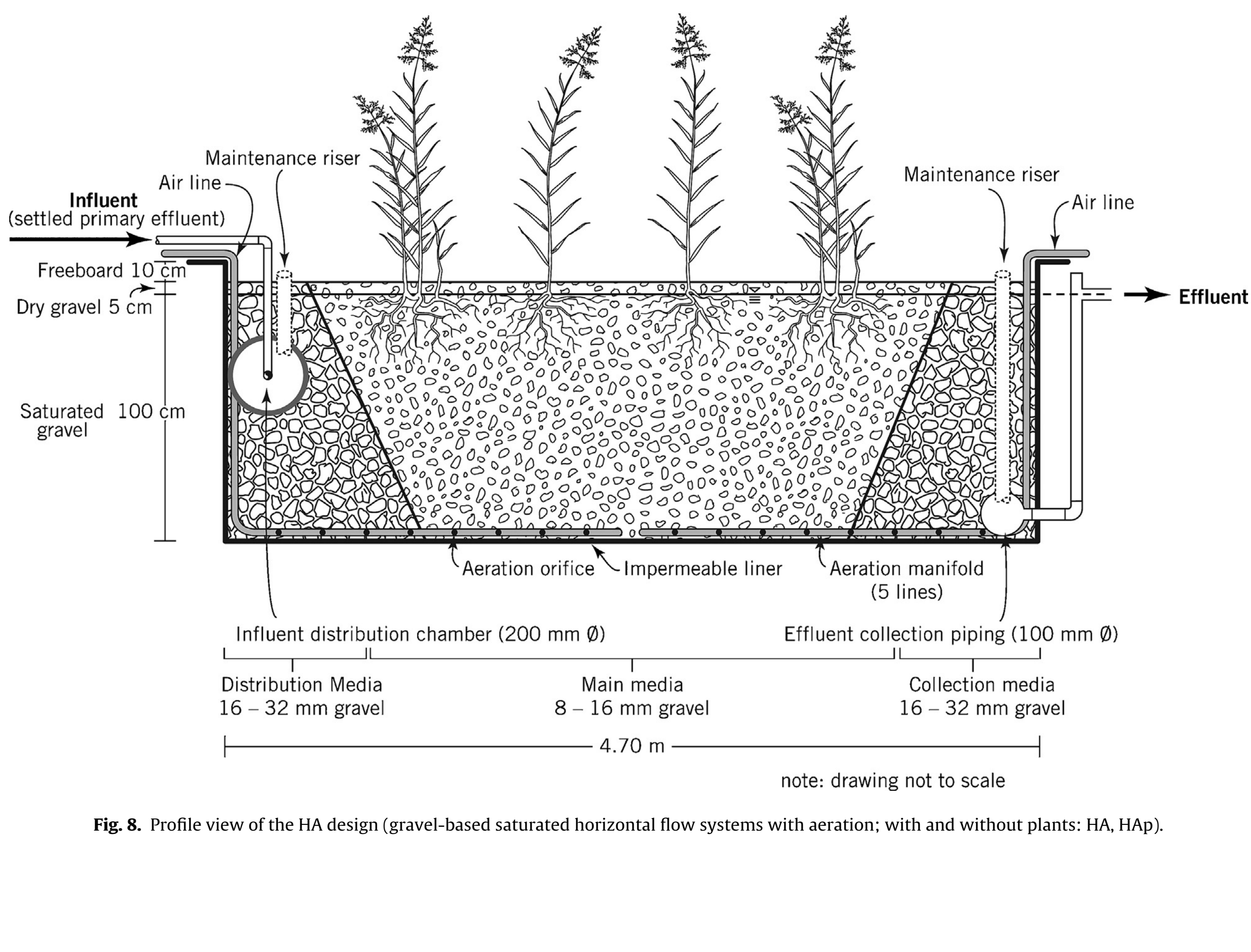

Fig. 8. Profile view of the HA design (gravel-based saturated horizontal flow systems with aeration; with and without plants: HA, HAp).

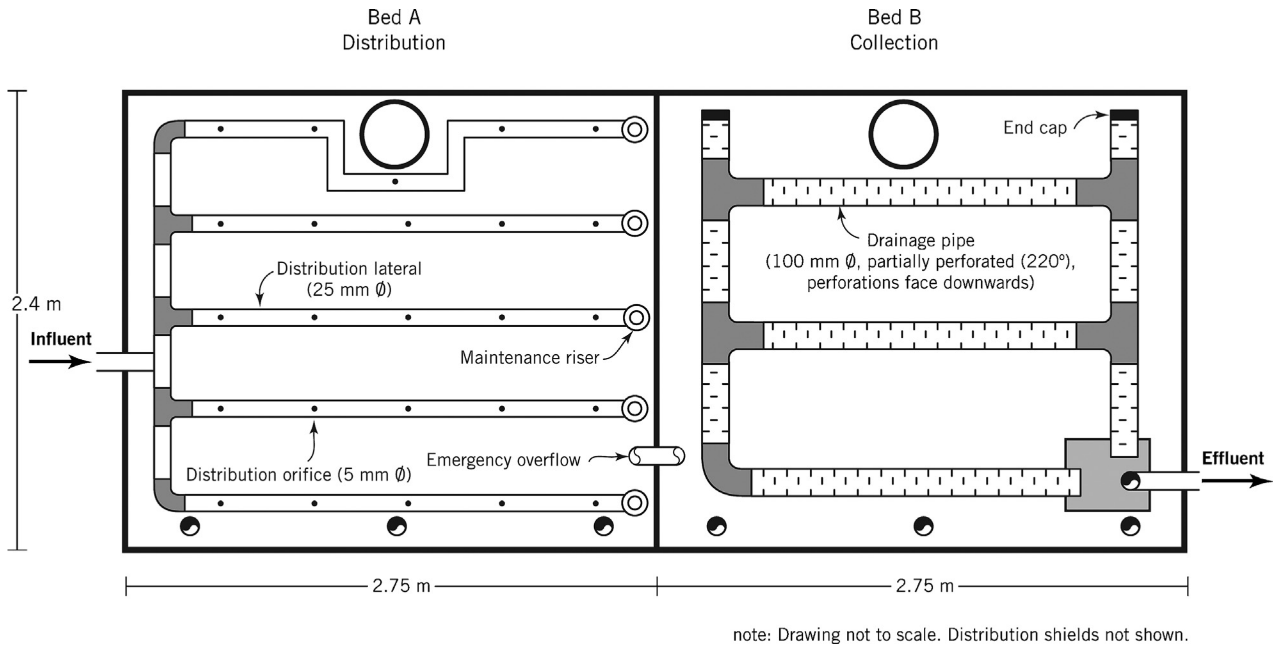

Fig. 9. Plan view of the distribution and collection system for the reciprocating design (R).

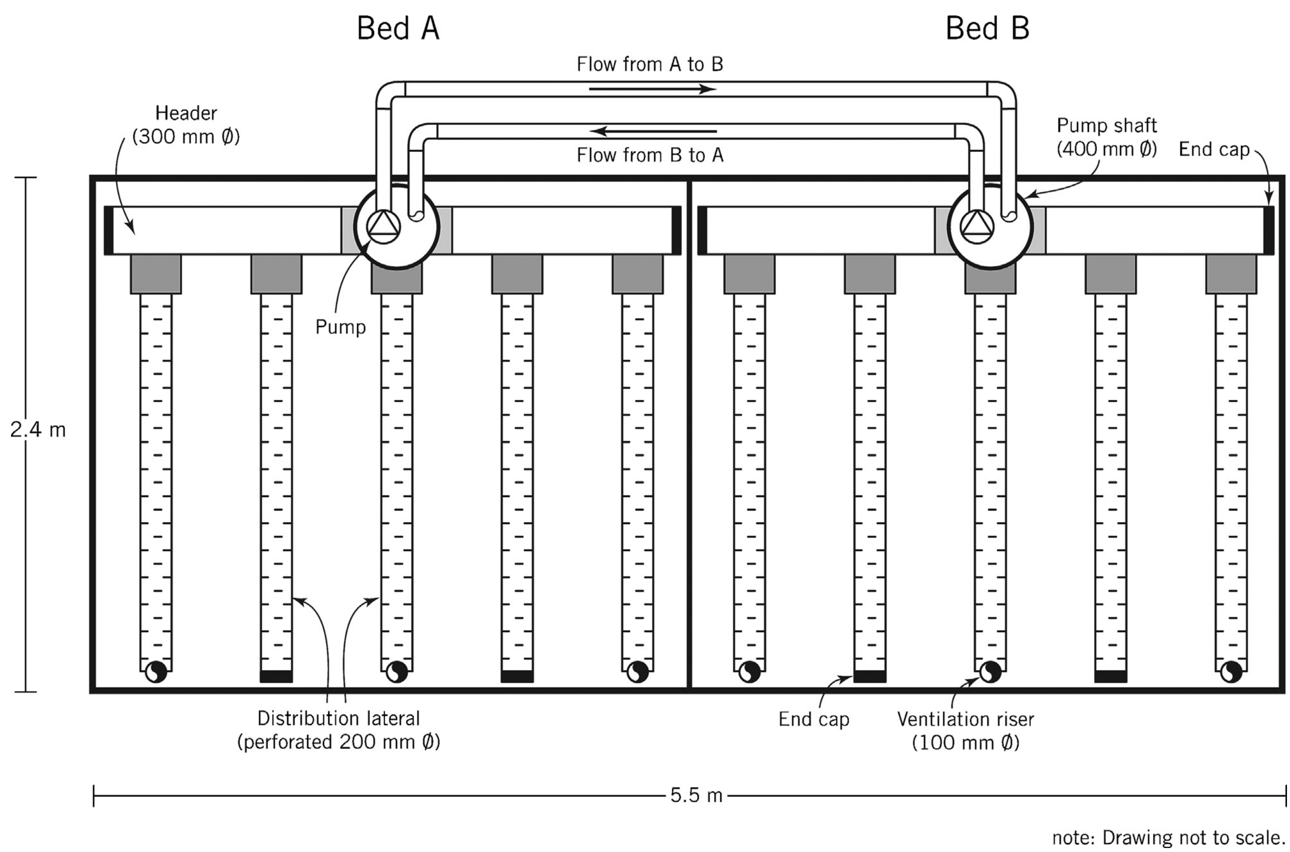

Fig. 10. Plan view of the internal recycling system for the reciprocating design (R).

Bed B is at the minimum (standing water depth of 45 cm). At the end of that cycle, the water level in Bed B is at the maximum level (standing water depth of 95 cm) and at the minimum water level in Bed A (standing water depth of 45 cm). As the water level in Bed B approaches maximum, water fills the network of partially perforated pipes at the top of the bed (collection piping is shown in Fig. 9). These collection pipes subsequently drain to the effluent collection box and outlet pipe. In this way, a water volume equivalent to that which entered Bed A at the start of a cycle is displaced from Bed B through the outlet pipe. This outlet configuration ensures that water remains below the surface of the media, rather than the more common practice of flooding the surface of

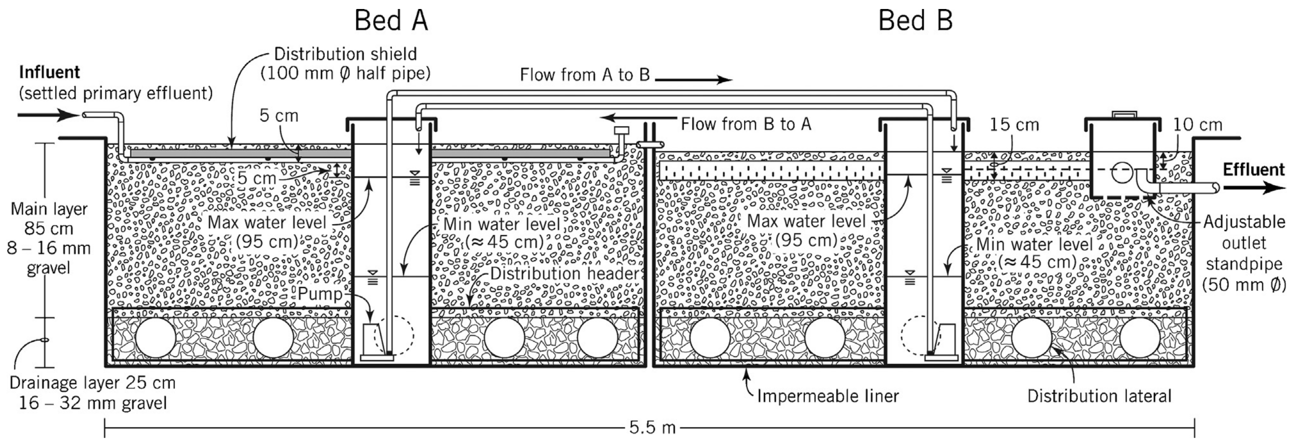

Fig. 11. Profile view of the reciprocating design (R).

the bed, which can be problematic in single-household applications and locations with sub-zero winter temperatures. A profile view of the reciprocating system, including the vertical placement of the piping networks in relation to the maximum and minimum water levels is shown in Fig. 11. The internal pumping of water from one bed to the other occurs every 30 min; as a result, treated effluent is discharged from Bed B once each hour. The system is set up so that it is possible to change the minimum and maximum water levels in each bed, as well as the frequency of the internal reciprocating pumping cycles. Thus, the proportion of saturated versus unsaturated media and the number of reciprocating cycles per day can be adjusted.

3. Internal sampling

The majority of studies on treatment wetlands are limited to reports of inlet and outlet water quality data. This is largely due to the fact that laboratory-scale systems are often too small for internal sampling points to be realistically constructed, and because full-scale systems are rarely constructed with research and internal sampling in mind. The facility at Langenreichenbach is unique because the systems are small enough to be run in a controlled manner but they are large enough to provide results that are comparable to full-scale designs, and are thus able to provide valuable information to both the scientific and engineering design communities.

All of the treatment systems at Langenreichenbach (with the exception of the reciprocating system) were constructed with the option of internal sample collection. Due to the varying depth and saturation status of each design, the internal sampling equipment had to be individually designed and installed during the construction process (well before the systems received any wastewater).

3.1. Saturated systems

The horizontal flow saturated beds (H25, H25p, H50, H50p, HA, and HAp) were constructed with sampling tees to allow internal sample collection. The tees were made of 25 mm diameter PVC pipe, with holes drilled through the horizontal section to allow sample collection at a specific depth (Fig. 12). One sampling tee was installed at the mid-depth of the H25 beds at four locations (12.5%, 25%, 50%, and 75%) along the flow path (Figs. 13 and 14). The sampling tees for the H50 and HA beds were constructed in triplicate and secured together with zip ties to enable sample collection at three depths (corresponding to the upper, middle, and lower third of the bed) at four locations (12.5%, 25%, 50%, and 75%) along the flow path (Figs. 13, 15 and 16). To reduce potential confusion during sampling, triplicate tees were designed with access pipes of different heights above the gravel surface reflecting the relative depth of the sampling tee (Figs. 12, 15 and 16). All access pipes were capped with a close-fitting rubber stopper (not shown) to prevent gravel or animals from entering the pipes.

The same internal sampling tee design was used for the saturated vertical flow beds with aeration (VA, VAp). Sampling tees at three depths (corresponding to the upper, middle, and lower third of the bed) were installed at three locations in each bed (Fig. 17).

A peristaltic pump with flexible tubing is used for sample collection. One end of the tube is inserted to the bottom of a sampling tee. In order to ensure that a representative sample is collected, the stagnant water inside the tee is pumped out and discarded is discarded before collecting the actual sample. Because some systems (specifically H25) have such a low hydraulic loading rate, wasting too much water before sample collection could potentially impact collection of subsequent samples from the same treatment system (on the same day).

The approach developed for sampling at Langenreichenbach was to purge slightly more than the stagnant water volume in the sampling tee before collecting the water sample for analysis. Thus, the sample extracted from the tee is in theory water that has been freshly drawn from the surrounding gravel media, as opposed to stale water that may have been trapped in the tee for some time. The calculated internal volume for the mid-depth tee in the saturated systems ranged between 260 mL and 440 mL; for logistical reasons, approximately 500 mL of “waste volume” was pumped prior to the collection of each water quality sample. The wasted volume was pumped into a graduated plastic beaker, so that the volume of wasted sample water could be easily estimated as the peristaltic pump was running. The wasted sample volume was kept in the waste beakers until sampling for a single bed was complete (generally four internal samples for each horizontal bed, and three internal samples for each VA bed), and then returned to the bed (at the location from which it was extracted) in order to keep the water balance for the system as accurate as possible.

In order to minimize the risk of cross-contamination between samples, internal samples are generally collected sequentially starting from the outlet end of a given bed and working up-stream, hence sampling along a gradient from lowest to highest pollutant concentration. Approximately 500 mL of clean tap water was pumped through the tubing between samples to further minimize cross-contamination. The purged “waste volume” previously discussed ensured that a sample was not affected by the tap-water rinse of the tubing.

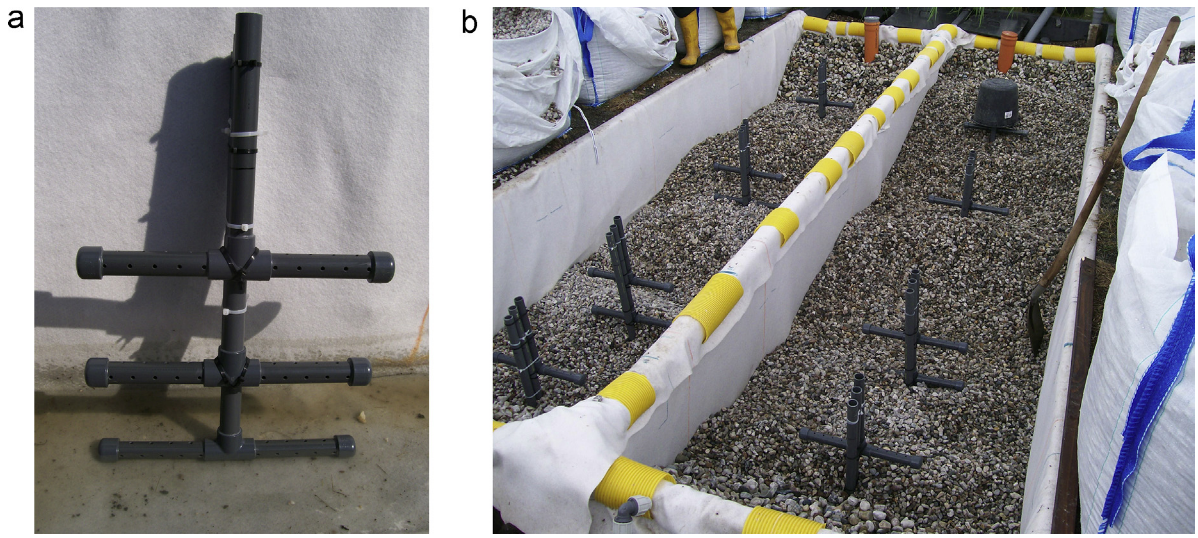

Fig. 12. Internal sampling tees for saturated beds: (a) before and (b) during installation.

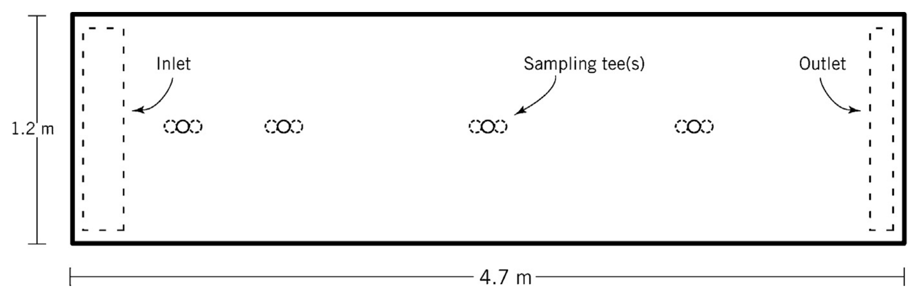

Fig. 13. Plan view of internal sampling locations for horizontal flow beds.

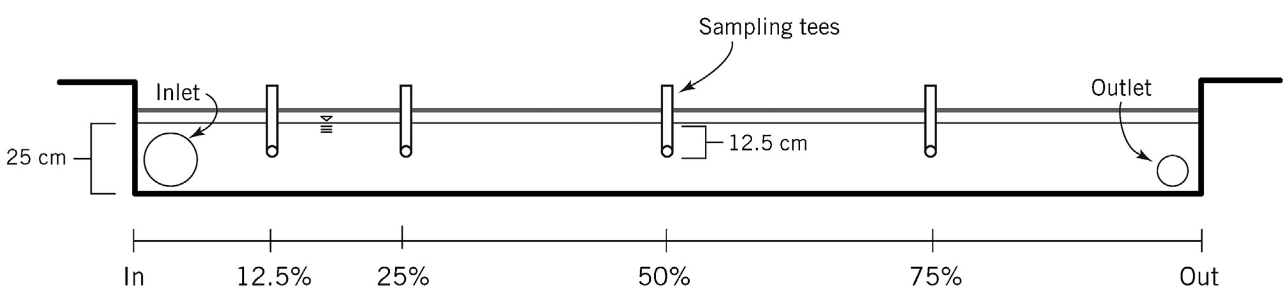

Fig. 14. Longitudinal cross-section showing location of internal sampling tees within the 25-cm deep horizontal flow beds (H25, H25p).

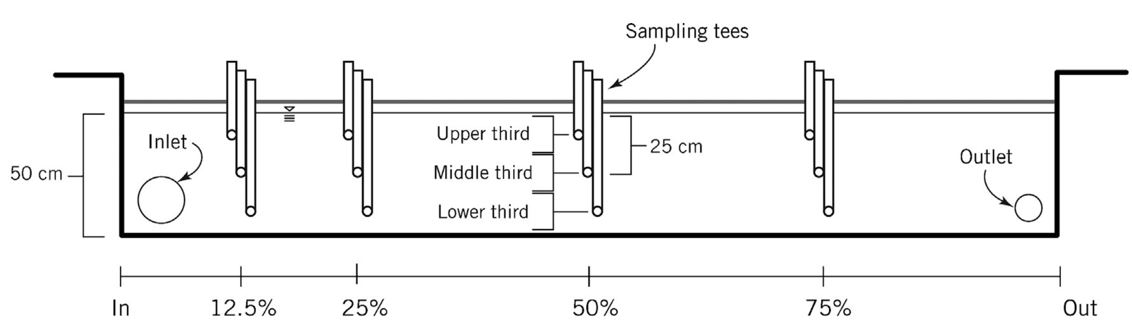

Fig. 15. Longitudinal cross-section showing location of internal sampling tees within the 50-cm deep horizontal flow beds (H50, H50p).

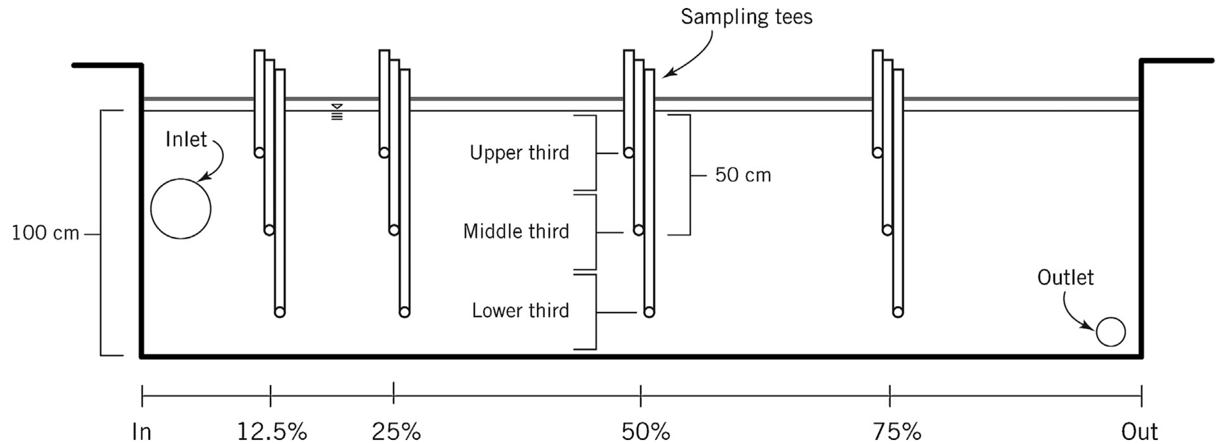

Fig. 16. Longitudinal cross-section showing location of internal sampling tees within the 100-cm deep horizontal flow beds with aeration (HA, HAp).

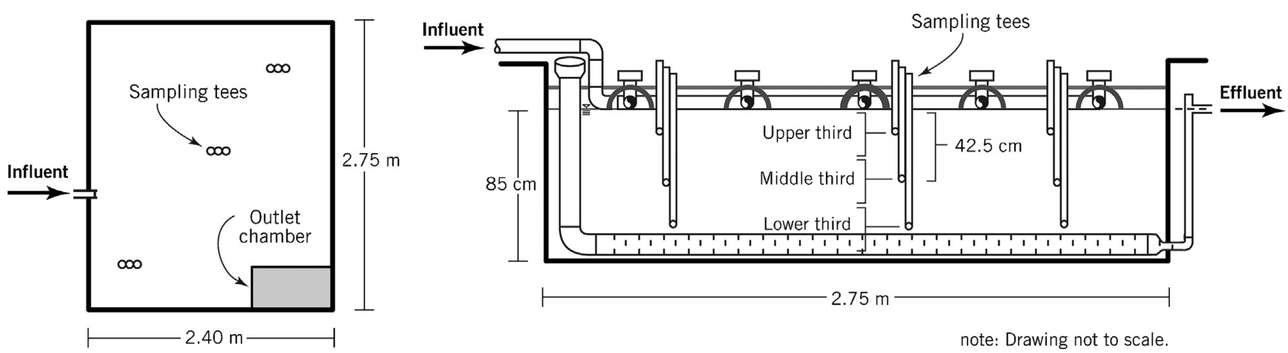

Fig. 17. Plan (left) and profile (right) views of internal sampling tees within the vertical flow beds with aeration (VA, VAp).

3.2. Unsaturated systems

Interception pans were designed for internal sample collection from the unsaturated beds (VS1, VS1p, VS2, VS2p, VG, and VGp). The pans, which were installed during construction (Fig. 18), were placed at 10 cm, 20 cm and 40 cm depths, and are situated perpendicular to the flow distribution pipes (Fig. 19). The pans were constructed of stainless steel, measuring 12 cm in diameter and 50 cm in length. One interception pan has an area of 0.06 m^2, which represents approximately 1% of the total surface area the bed. The pans were filled with coarse gravel to prevent washout of the main filter material and prevent clogging of the pans while minimizing the potential for further treatment of the collected water. A polyethylene pipe connects the pans to a sample collection point within the outlet chamber.

Inside the outlet chamber was a hose that can be placed into the mouth of a sample bottle during sample collection. It generally takes between one and three hours to collect 200–500 mL of sample. Fresh samples are therefore collected in the morning on the day of sampling. During regular operation, the water collected by the pans is allowed to drain freely into the effluent pipe (shown in Fig. 19). A bottlebrush connected to a length of wire is used to periodically remove biofilm buildup in the pipe between the pan and outlet chamber. Such maintenance activities were conducted prior to the sampling day so as not to contaminate samples the day of collection.

4. Water quality sampling and analysis

Scheduling water quality sampling for Langenreichenbach presented somewhat of a logistical challenge. Due to the abundance of internal sampling points within each system, to sample everything on one day would result in nearly 90 samples. The time required for sample collection alone could potentially take an entire day. Moreover, sampling all possible points on a single day would make it impossible to conduct water quality analysis on the same day as sampling, which is not ideal. Ideally, samples should be analyzed on the same day on which they are collected.

It was desirable to sample each system at Langenreichenbach as often as possible. With uncertainties such as emergency maintenance and/or severe weather events, scheduling monthly sampling would not guarantee that every system would be sampled each month. In order to maximize the frequency of sample collection, we developed a flexible three-week sampling rotation that could be modified as necessary. The first week in the rotation was for the four horizontal flow systems (H25 and H50; internal sampling at the mid-depth tees, resulting in 20 samples plus one influent sample). The second week in the rotation was dedicated to the six unsaturated vertical flow systems (VS1, VS2, and VG; internal sampling at three depths within each system, resulting in 25 samples plus one influent sample). The third week in the rotation included internal sampling within the four intensified systems (VA, HA) and outlet samples from all 15 systems at the site (29 samples plus one influent sample).

Routine inlet and outlet water quality analysis included $CBOD_5$, TSS, TOC, Total Nitrogen, NH_4-N, NO_3-N, NO_2-N, Turbidity, and *E. Coli*. Due to logistical limitations internal samples were not analyzed for $CBOD_5$ and TSS. These tests required large volumes of water, which could not always be collected from each interception pan (in unsaturated systems), and the extra laboratory personnel that would be required for these analyses was not available.

Normally, a minimum of three people was needed to conduct sample collection. One person would collect outlet samples (the building that can be seen in the center of Fig. 1), another would

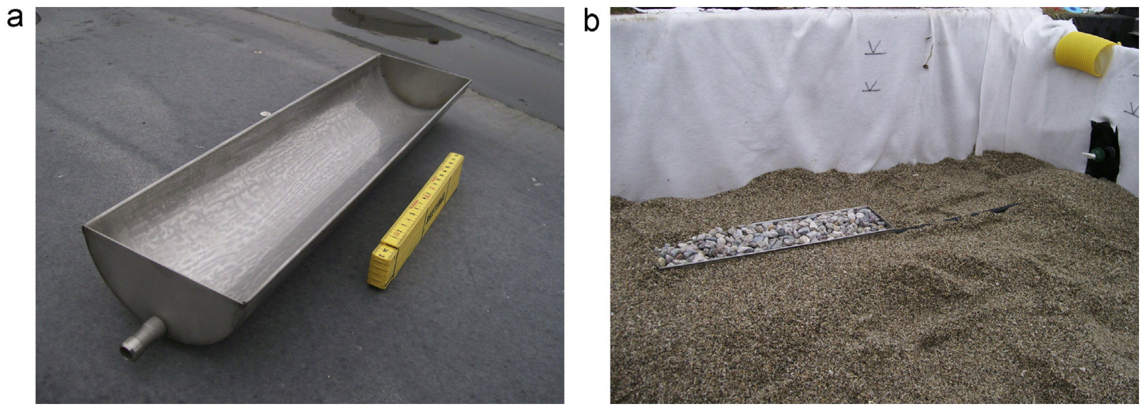

Fig. 18. Internal interception pans in the unsaturated vertical flow beds (VS1, VS1p, VS2, VS2p, VG, and VGp): (a) before installation and (b) during installation.

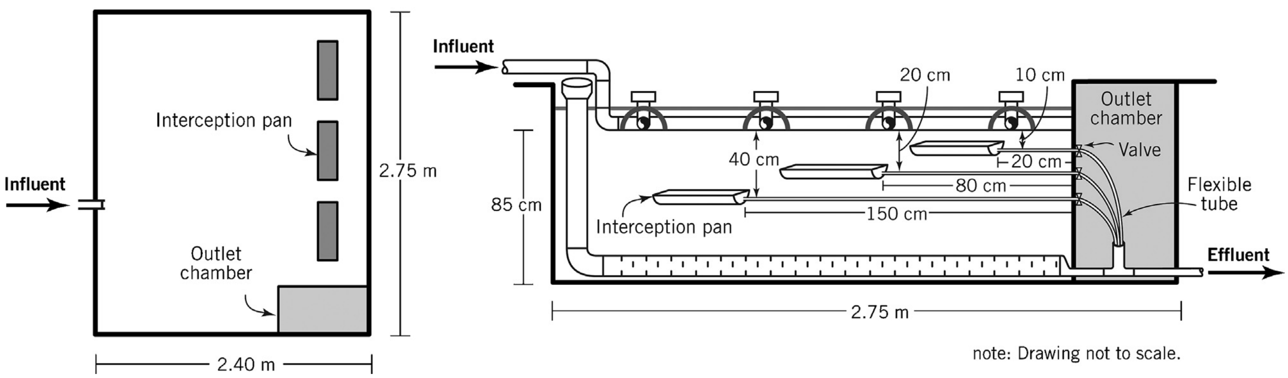

Fig. 19. Plan and profile views of interception pans in the unsaturated vertical flow beds (VS1, VS1p, VS2, VS2p, VG, and VGp).

collect internal samples (from horizontal, vertical, or intensified beds), and a third person would measure the physico-chemical parameters (temperature, dissolved oxygen, redox potential, electrical conductivity, and pH) at the onsite laboratory. Field water temperatures were measured as the samples were collected (e.g., by the person collecting the sample). After all measurements were made, the samples were brought back to Leipzig and analyzed immediately upon arrival. Routine analysis for $CBOD_5$, TSS, TOC, Total Nitrogen, NH_4-N, NO_3-N, NO_2-N, Turbidity, and *E. Coli* generally required a minimum of three people for the entire afternoon, with one person solely dedicated to *E. Coli* analysis.

5. Biomass sampling and plant establishment

Aboveground biomass estimates were made for the first two growing seasons, once in September 2010 and again in September 2011. In 2010, a non-destructive method based on the relationship between the height and dry mass of dried shoots was employed. Each horizontal flow bed was divided into four quarters, and a representative 20 cm section within each quarter was delineated (0.2 m wide by 1.2 m long) in order to account for spatial heterogeneity of plant growth in these beds. The stems within the delineated section were counted according to height class; twine wrapped around the rods at each corner of a section was used to designate each 20 cm-height increment. Shoots were measured from the gravel surface to the tip of the longest extended leaf. Representative shoots from each height class were harvested, dried in a ventilated oven (70 °C) until a constant mass. A power-curve relationship between shoot height and mass was developed from the harvested stems (215 stems in total); this relationship was subsequently applied to the stem counts for each section in order to obtain an estimate of total aboveground biomass in each bed. One larger section (0.2 m wide by 2.75 m long) was evaluated in each vertical flow bed using the same method. The 2010 aboveground biomass measurements occurred on 29–30 September 2010.

In 2011, the plants were too dense to use the non-destructive method, so 20-cm wide sections were harvested in order to estimate shoot density and biomass. The plants were cut at the gravel surface, sorted into 20-cm increment height classes, and counted. The harvested plant material was fractionated into leaves, stems, rhizomes and roots and their dry mass (DM) measured after drying to constant weight in a 70 °C ventilated oven. Subsequently, the dried plant samples were finely ground with a ball mill grinder and used for chemical analysis. The 2011 aboveground biomass measurements took place on 28–29 September 2011.

Belowground biomass sampling was conducted using a 20-cm diameter stainless steel corer that was inserted into the wetland bed. The coring device had handles at the top, and the bottom edge was sharpened to facilitate cutting through rhizomes. Four cores were taken from each horizontal bed, and two from each vertical bed. The biomass within a single core was excavated by hand, rinsed with tap water, and dried to a constant weight in a 70 °C ventilated oven. The dried plant samples were subsequently ground with a ball mill grinder and used for chemical analysis. Belowground biomass sampling occurred on 25–26 October 2010 and 4–5 October 2011.

As mentioned earlier, the systems were originally planted at a density of five plants per square meter. At the end of the first growing season (2010), *P. australis* showed positive growth in every system, but to varying degrees. At the end of the first growing season, aboveground biomass of *P. australis* was estimated to be 1110 g/m^2 and 1100 g/m^2 for H25p and H50p, respectively.

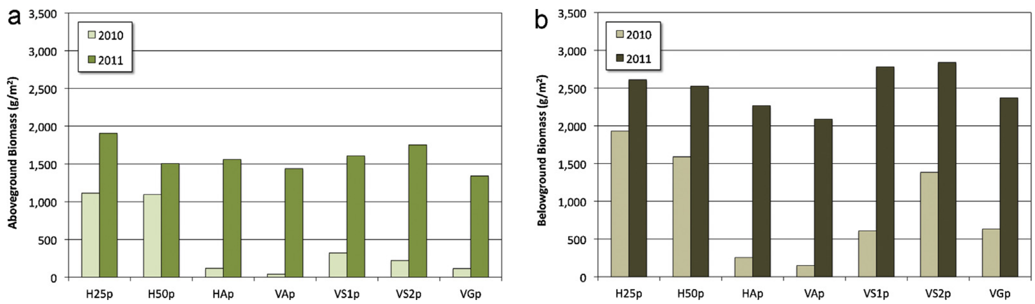

Fig. 20. Above (a) and belowground (b) *P. australis* biomass of the seven planted treatment wetlands at the end of the first and second growing seasons.

Aboveground biomass for vertical flow beds was much lower; estimated at 320, 220, and 110 g/m^2 for VS1p, VS2p, and VGp, respectively. The intensified systems showed the lowest growth rates at the end of the first growing season: HAp with an average aboveground biomass of 120 g/m^2, and only 40 g/m^2 for VAp. It is important to note that biomass in the HA bed was not uniformly distributed over the surface of the bed (refer to Fig. 1, planted system in the uppermost right corner of the photo). The first 50 cm of the bed (closest to the inlet) had an estimated aboveground biomass density of 1000 g/m^2, which is in stark comparison to the average growth of 40 g/m^2 for the remaining 75% of the bed. Taking this into account, the aboveground biomass density for the majority of the HAp bed was similar to that of the other aerated bed (VAp), indicating that aeration may play a role in the lower growth rates of *P. australis* in these systems. Belowground biomass at the end of the first growing season displayed similar trends to aboveground biomass, with values ranging from 40 g/m^2 (VAp) to 1930 g/m^2 (H25p) (Fig. 20).

Overall, the aboveground biomass densities at the end of the second growing season (2011) were much higher and more consistent than they were at the end of the first growing season. Aboveground biomass densities ranged from 1340 g/m^2 (VGp) to 1910 g/m^2 (H25p); belowground biomass densities were between 2090 g/m^2 (VAp) and 2840 g/m^2 (VS2p). The ratio of belowground to aboveground biomass (BG:AG) was also relatively consistent, ranging from 1.4–1.8 for the seven treatment systems. This ratio is similar to the BG:AG of the *P. australis* stands investigated by Tanner (1996), which was reported to be 1.29.

The HAp system exhibited a strong gradient in plant growth again in 2011. The densely vegetated area near the inlet expanded by the end of the 2011 growing season to cover the first half of the bed. The *P. australis* in the inlet half of the bed was taller and had thicker stems than the *P. australis* in any other system in the study, which is reflected in the density of the standing crop in the first half of the bed (3500 g/m^2) compared that of the other beds (around 1500 g/m^2 on average). The density in the second half of the HAp bed was considerably low (170 g/m^2) and these plants showed extreme signs of stress. During the field work at the end of the growing season, long runners were found in the aerated beds HAp and VAp. These runners were not taken into account for the biomass density estimates, but the total length of runners was measured: 20 meters of runners in HAp and 30 meters of runners in VAp. Runners were not observed in the other systems.

6. Conclusions

Ecotechnologies such as treatment wetlands bridge the gap between “hard engineering” and natural science. Because of this, professionals in this field are widely scattered amongst the various disciplines of engineering and natural sciences. The treatment wetland discipline can be characterized by pockets of intense research based on locally accepted design or basic discipline of the professionals. In 2009–2010, a small group of engineers and scientists constructed an ecotechnology research facility in Langenreichenbach, Germany. This research facility, which is the first of its kind, contains 15 individual pilot-scale treatment systems from eight of the most commonly implemented designs. The designs differ in terms of flow direction, degree of media saturation, media type, loading regime, and aeration mechanism. Seven of the systems were constructed as planted and unplanted pairs; in order to better elucidate the role that common reed (*P. australis*) plays in treatment performance. Plant biomass measurements showed that conventional horizontal flow designs developed the most biomass in the first growing season (ca. 1000 g/m^2). Vertical flow systems and aerated systems did not establish a thick canopy until the second growing season. At the end of the second growing season, all planted systems had a mean aboveground biomass density between 1300 and 1900 g/m^2. We also provide insight into the design, construction, and operation of such a unique ecotechnology research facility. Wetland treatment systems are dynamic systems, however, so this research facility should be monitored for several years in order to characterize the steady-state performance and optimization of the ecotechnologies.

Acknowledgements

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