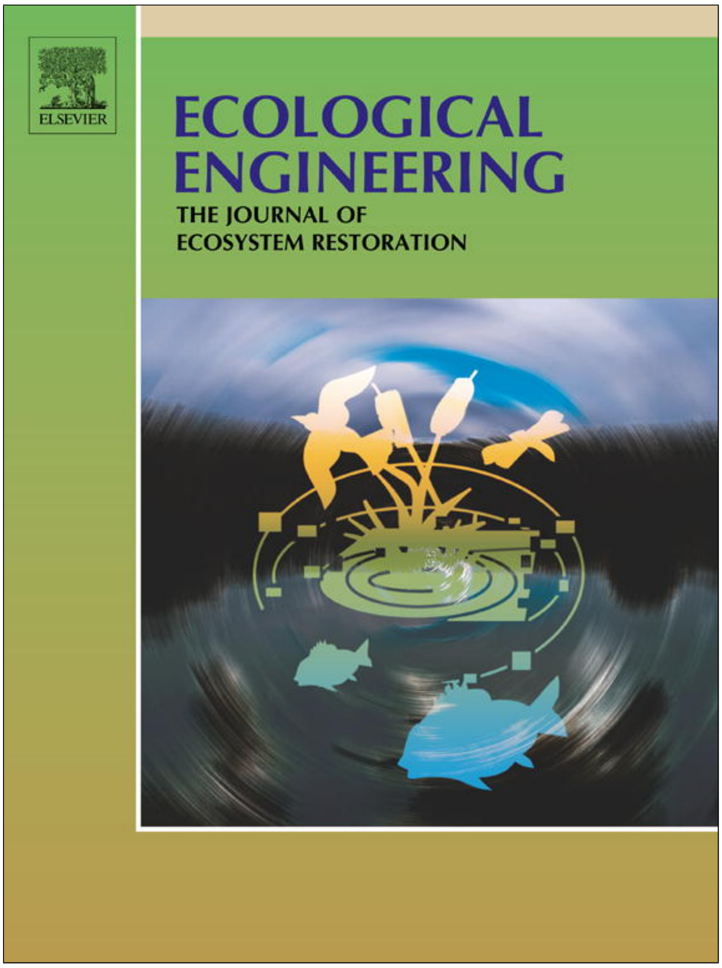

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The taxonomy of treatment wetlands: A proposed classification and nomenclature system

Nat Fonder[a,*], Tom Headley[b,1]

[a] Epuvaleau, npo, ULG, Gembloux Agro-Bio Tech, Soil Water System Department, Passage des déportés, 2 B 5030 Gembloux, Belgium
[b] Helmholtz Centre for Environmental Research (UFZ), Permoserstrasse 15, D-04318 Leipzig, Germany

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ABSTRACT

This paper proposes a structure for classifying and naming different treatment wetland (TW) design alternatives, based on physical design traits. A classification hierarchy is organised like a polychotomous key, from general classification criteria to wetland type identification. Three characteristics are typical of all TWs: the presence of macrophytic vegetation; the existence of water-logged or saturated substrate conditions for at least part of the time; and inflow of contaminated water with constituents to be removed. Treatment wetlands are further classified based on hydrology and vegetation characteristics. Hydrological traits relate to water position, flow direction, degree of saturation and position of influent loading. Based on the predominant position of water in the system, two main groups are identified: those with surface flow above a benthic substrate and those with subsurface flow through a porous media. The systems with surface flow are divided into three standard types, differentiated by vegetation type: Surface flow (SF), free-floating macrophyte (FFM), and floating emergent macrophyte (FEM) TWs. Subsurface flow systems always contain sessile emergent macrophytes and are divided into four standard types, based on flow direction: horizontal sub-surface flow (HSSF), vertical down flow (VDF), vertical up flow (VUF) and fill and drain (FaD) TWs. Standard types are described with their main applications. Associated variants are identified. An overview of intensified variants, which have elevated energy, chemical or operational inputs in order to increase efficiency or overcome process limitations, is also provided.

1. Introduction

While some systematic approaches for classifying and naming treatment wetland (TW) types currently exist (e.g. Fonder and Headley, 2010; Vymazal and Kropfelova, 2008; Wallace and Knight, 2006), a wide range of terminology is used inconsistently throughout the literature. Numerous names are used almost interchangeably to describe any given wetland variant, even if the physical design and operational characteristics are essentially the same. In other cases, the same name has been used for systems with very different design configurations. The applied terminology often varies by region, culture, discipline-base or the author's desire to give the impression that their design is new or innovative.

The new classification and nomenclature system here presented is the updated version proposed by Fonder and Headley (2010), with new figures and tables. It takes into consideration feedback provided by practitioners in the field who have worked with the first iteration nomenclature system. The purpose is intended to be a standardised classification and terminology system that can provide a clear framework for consistent nomenclature for any given treatment wetland.

2. The classification system

The basis for wetland terminology is easily definable and observable physical traits of TW design, which leads to the identification of a series of "standard" design types. These standard types form a central part of the proposed nomenclature system and are assigned a root-name and abbreviation. Design variants, which are considered to be modified versions of the standard types, are subsequently identified. In some cases, a third level of common design variants can be defined either because they receive a very specific waste type (application-based variants) or have been intensified via elevated energy, chemical or operational inputs (intensified variants).

* Corresponding author. Permanent address: ENEE sprl, Environment Economy Ecology, Rue Baron Fallon, 38, B-5000 Namur, Belgium. Tel.: +32 495 77 52 08.
E-mail addresses: Natfonder@gmail.com (N. Fonder), tom.headley@ufz.de, tom.headley@bauerenvironment.com (T. Headley).
[1] Present address: BAUER Nimr LLC, Muscat, Oman.

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2.1. Wetland definition

The first step in the classification hierarchy is to define whether or not the system in question is a wetland. Wetlands can be defined as areas of land where the water table is at or near the surface for at least part of the year and are characterised by the presence of vegetation types and soil characteristics that have developed in response to the wet and saturated conditions (Kadlec and Wallace, 2009; Mitsch and Gosselink, 2007). In the context of this article, closely related aquatic ecosystems that do not include higher plants (macrophytes), such as phytoplankton dominated ponds, are not included within the definition of wetlands.

2.2. Wetland genesis

Wetlands can be first split into the two major types of natural and constructed wetlands. Natural wetlands are only defined here as those wetland areas that exist in the landscape due to natural processes rather than having been created either directly or indirectly as a result of anthropogenic influences. Classification or terminology for natural wetlands is not developed here, as several systems already exist (see related references, e.g. Wetzel, 2001; Mitsch and Gosselink, 2007), but rather focuses on terminology related to constructed wetlands.

Constructed wetlands are artificially created ecosystems that would not otherwise exist without significant human intervention, such as earthworks or hydrologic manipulation. They are generally designed to mimic many of the conditions and/or processes that occur in natural wetlands (Vymazal and Kropfelova, 2008).

2.3. Purpose of the constructed wetland

The next level of classification is based on the main purpose of the constructed wetland system. Constructed wetlands can be split into three categories according to their purpose.

- Restored wetlands: areas which were formerly natural wetlands that were lost or heavily degraded in the past and which, through human intervention, now support a near-natural wetland ecosystem.
- Created wetlands: non-wetland areas which have been converted to a wetland ecosystem by civil engineering works for purposes other than water quality improvement.
- Treatment wetlands: artificially created wetland systems designed to enhance and optimise certain physical and/or biogeochemical processes that occur in natural wetland ecosystems for the primary purpose of removing contaminants from polluted waters.

The focus of this article is on the third purpose, which is the removal of pollutants in treatment wetlands (TWs); firstly introduced in the text book ‘Treatment Wetlands: theory and implementation’ by Kadlec and Knight in 1996. Although the term “constructed wetland” is widely used to describe wetland systems built for water treatment purposes, the term TW is considered to be more specific and technically accurate.

Natural wetlands are in some cases used as receiving bodies for polluted waters and often provide important treatment functions and those systems could also be considered “TWs”. However if such systems were not intentionally designed or modified with a pollution control function in mind, then they would be described as “natural treatment wetlands”, in opposition to “constructed treatment wetlands”.

3. Treatment wetlands

Two characteristics are issued from natural wetlands' definition which are:

1. The presence of macrophytic vegetation, and
2. The existence of water-logged or saturated substrate conditions for at least part of the time.

   The third additional one, specific to TWs is:
3. The inflow of contaminated waters with constituents that are to be removed.

The first criterion excludes ponds and lagoons that consist primarily of microscopic algae (microphytes) without higher plants (macrophytes). However, it is acknowledged that ponds and TWs are closely related technologies often used in combination. One exception to the second requirement is within the context of research, where “unplanted” versions are sometimes included to distinguish the effect of the plants in the system. Outside of this context, treatment units that do not include wetland vegetation, such as gravel or sand filters, should not be classified as a TW. Vertical down flow systems intermittently loaded which are intended to operate in a primarily free draining (unsaturated) mode are encompassed by the second criteria, as they typically experience, at least localised and temporary, water-logging of the substrate.

3.1. Classification of treatment wetlands

As TWs can be constructed in a variety of hydrologic modes (Kadlec and Wallace, 2009), numerous design variations have been developed for a large array of pollutant removal mechanisms. The classification hierarchy presented is based on physical design traits rather than the application of the TW. The various TW designs can be categorised based on two main physical attributes: the hydrology and the vegetation characteristics. The hydrological and vegetative attributes can be sub-divided into four and two specific traits respectively, in order to classify different TW design types, as shown in Table 1, which includes updates from the system originally proposed by Fonder and Headley (2010).

3.1.1. Water position

Surface flow TWs (SF TW) are defined as aquatic systems in which the majority of flow occurs through a water column overlying a benthic substrate. Hence, they have an exposed water surface similar to a natural marsh or swamp. This is in contrast to sub-surface flow TWs where the majority of flow is through a porous media. The term “surface flow” is a clear antonym for “sub-surface flow” and is therefore preferred here to the previous term: *free water surface TW*.

3.1.2. Flow direction

The flow direction is governed by the position of inlets and outlets, being either horizontally or vertically opposed. By virtue of design, all surface flow TWs have flow in a predominantly horizontal direction. In contrast, sub-surface flow TW units can be designed with a range of different flow directions, with horizontal and vertical down flow being the most common to date. Systems with up flow also exist along with an increasing number of design variants where the flow alternates between an upward and downward flow direction (“mixed”).

3.1.3. Media saturation

The saturation or moisture status of the media is relevant for systems with sub-surface vertical flow. Systems with an outlet structure designed to hold water in the bed and maintain the media

Table 1
Traits used to define the different classes of treatment wetlands.

Physical attribute	Specific trait	Description	Defined classes for each trait	Sub-class
Hydrology	a. Water position	Position of water surface relative to soil or substrate	Surface flow	–
			Sub-surface flow	–
	b. Flow direction	Predominant direction of flow through system	Horizontal	–
			Vertical	Down
				Up
				Mixed
	c. Saturation of media	Degree of saturation in media-based systems	Free-draining	–
			Intermittent	–
			Constant	–
	d. Influent loading type	Position and type of influent distribution in media-based systems	Surface inflow	–
			Subsurface inflow	–
			Basal inflow	–
Vegetation	a. Sessility	Location of the roots: attached in the benthic sediments or floating	Sessile (benthic bound)	–
			Floating	–
	b. Growth Form	Dominant growth form of the vegetation in relation to the water	Emergent	Herbaceous
				Woody
			Submerged	–
			Floating leaved	–
			Free-floating	–

in a continuously saturated state are classed as having “constant” media saturation. By virtue of the design, all surface, horizontal sub-surface and vertical up flow systems have a constantly saturated substrate. Vertical down flow TWs most commonly operate in a “free-draining” mode, with a permanently open outlet at the bottom of the bed. In between constantly saturated and free-draining systems lay those TWs where the media saturation varies periodically or seasonally due to a pulsed loading or operational strategy.

3.1.4. *Influent loading type and surface flooding*

The influent discharge level refers to the degree to which the surface of the bed is flooded (inundated) during a loading event. A clear distinction should be made between this classification trait and the water position trait, especially for horizontal sub-surface TWs which are designed with the intention of avoiding surface flooding, but can have influent introduction either above (surface and exposed inflow) or below the media (subsurface and covered inflow). In vertical down flow TWs, Surface inflow encompasses those systems in which influent distribution is accomplished by ephemeral flooding of the media surface, whereas subsurface inflow refers to those systems where a network of pipes is used to distribute the influent uniformly beneath the upper surface of the media without intentionally inducing flooding. A third type of influent loading is the “basal inflow” category, which is typical of TWs with vertical flow in an upward direction.

3.1.5. *Vegetation sessility*

Sessile is a term used in the field of limnology to refer to vegetation that is anchored to the benthic environment, as opposed to floating. This trait is only relevant to surface flow TWs because sub-surface flow through a porous media precludes floating plants.

3.1.6. *Vegetative growth form*

This classification trait is intended for surface flow systems only, as sub-surface flow TWs always consist of emergent macrophytes growing on top of the porous matrix due to the lack of an exposed water surface. The TW type is classified based on the growth form of the dominant vegetation as defined by Brix and Schierup (1989) as emergent, submerged, floating leaved and free-floating plants. Emergent macrophytes typically grow in a sessile form (rooted in a benthic substrate). However, they can also grow on a buoyant mat that floats on the water surface.

3.1.7. *Emergent vegetation variants*

The majority of emergent wetland plants are herbaceous macrophytes and are the default type of emergent vegetation within the classification system. However, some TWs are dominated by woody emergent macrophytes, which are identified as a non-standard design variant.

3.2. *The treatment wetland classification tree*

Applying the classification system to the diverse range of TW designs currently in use leads to the polychotomous classification tree presented in Fig. 1, adapted from Fonder and Headley (2010). The standard types and their design variants are keyed out with bold lines at the base of the tree along with the proposed nomenclature.

Considering the current status of TW applications around the world and the fundamental design differences between the TW units identified using the classification system, seven ‘standard types’ of TW are distinguished, corresponding to a number above the nomenclature boxes at the base of Fig. 1.

The three standard types with surface flow are:

1. Surface flow (SF) TW, dominated by emergent herbaceous macrophytes.
2. Free-floating macrophyte (FFM) TW containing free-floating vascular aquatic plants growing on the water surface.
3. Floating emergent macrophyte (FEM) TW with emergent macrophytes growing on a buoyant structure.

The four standard types with sub-surface flow are:

4. Horizontal sub-surface flow (HSSF) TW, with subsurface loading (without intentional surface flooding).
5. Vertical down flow (VDF) TW, with free-draining substrate and subsurface loading (without surface flooding).
6. Vertical up flow (VUF) TW with a flooded surface for outflow

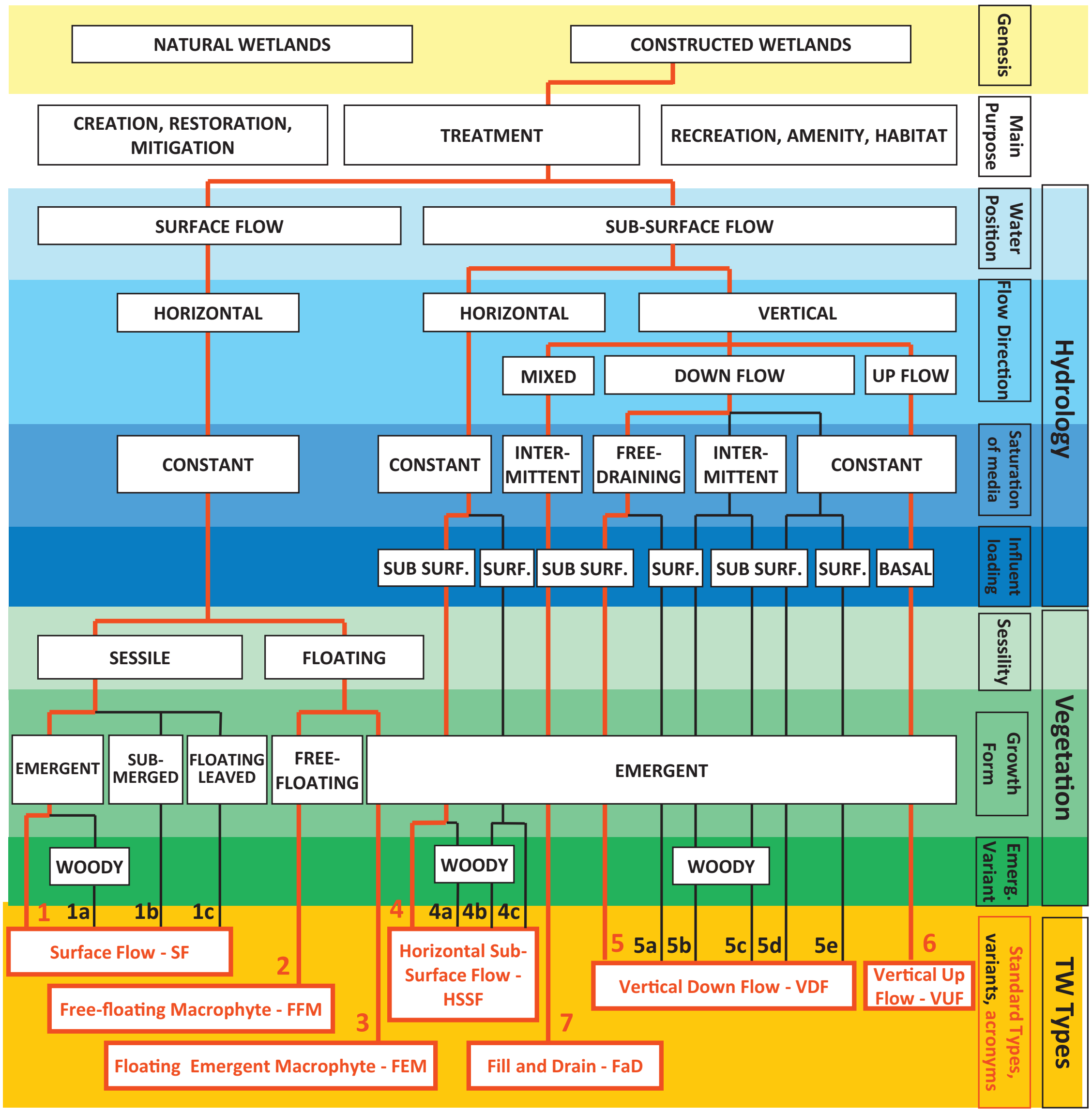

Fig. 1. Treatment wetland polychotomous classification tree.

7. Fill and drain (FaD) TW in which the flow direction is mixed, often periodically alternating between up and down flow.

There are also numerous design variants that are in common use and are identified in Fig. 1. Variants are generally differentiated based on atypical vegetation types, degree of saturation or position of the influent loading. They are not abbreviated. An additional sub-set of variants can be identified based on specific applications within the grouping of systems with vertical flow in a downward direction. Subtle variations in design and operational strategies have been developed to deal with various types of wastes, such as raw wastewater, sludge, effluents after primary or secondary treatment or stormwater.

3.3. *Intensified treatment wetland sub-variants*

Intensified TWs are specific designs to increase the efficiency and/or overcome process limitations (such as oxygen availability) of conventional zero- or low-energy input, extensive wetland designs. The term 'intensified' is preferred to 'engineered' (a term previously used in references such as Wallace and Knight, 2006), as it can be opposed to 'non intensified' (or extensive) TWs. In principle, intensification represents a range of design or operational modifications that can be applied to virtually any of the TW types that have been classified in Fig. 1.

Intensification is generally achieved through increased inputs of electricity, physicochemical amendments, added operational effort or complexity to increase the treatment efficiency of the TW for certain target contaminants (Table 2). System designs incorporating specialised or synthesised media, such as those with exceptionally high sorption capacities, are also considered to be intensified.

Another form of intensification are identified as system-based intensification, where different TW units are coupled together in various ways to form a treatment train with the aim of optimizing the treatment efficiency of the overall system or of mixing different purposes. Such systems are commonly referred to as *hybrid* or *integrated* systems. Intensification is an attribute that cuts across the final level of the standard and variant types in the classification hierarchy (Fig. 1).

Table 2
Intensification classes currently applied to enhance the performance of standard treatment wetland units.

Type of intensified input	Intensification class	Examples
Energetic	Aeration	Aerated subsurface flow TWs
	Pumping[a]	Fill and drain TWs with reciprocation
Physicochemical	Sorptive media	Expanded clay, zeolites, bauxsol, chitinous material
	Chemical dosing	Alum, ferric chloride, oxidizing agents
Operational	Frequent plant harvesting	Duckweed systems, biomass production
	Cyclical resting	Routine alternation between multiple TW units in parallel
	Recirculation of flow	SF, VF or HSSF TW with recirculation

[a] Energetic intensification is accompanied by modification of the physical design of the unit.

4. Definition and nomenclature for standard treatment wetland units and their variants

Standard TW types and their variants identified through the classification process are briefly described, as well as currently used intensified variants.

4.1. Systems with surface water position of the flow

The group of TWs with a surface water position are defined as having the majority of flow occurring through a water column above the surface of a benthic substrate. This group is divided into three standard types: the surface flow TW, the free-floating macrophyte TW and the floating emergent macrophyte TW. They are depicted in Fig. 2.

4.1.1. Standard type 1: surface flow TW (SF TW)
The surface flow TW have water flowing above the surface of a permanently saturated soil substrate in a horizontal direction, with the predominant vegetation type being herbaceous emergent macrophytes which have their roots bedded and anchored in the benthic substrate (sessile) as depicted in Fig. 2(a). This represents one of the most widespread and commonly used TW design worldwide.

All variants of the standard SF TW differ based on the vegetation growth form of their dominant vegetation, with the major distinction being between those with woody-emergent, submerged or floating leaved macrophytes.

4.1.1.1. SF variants.

1a The woody emergent SF TW has woody, rather than herbaceous, emergent vegetation. This variant is typically limited to very large applications, often for tertiary polishing of effluents. They typically resemble natural wooded wetlands such as swamps, and are often associated with zones dominated by other vegetation types. Examples exist in the southern regions of the United States such as Florida and Louisiana (dominated by *Cypress* tree species) and on the east coast of Australia (dominated by *Melaleuca* tree species).

1b The submerged macrophyte SF TW contains predominantly submerged macrophytic vegetation, having their photosynthetic tissue entirely submerged and typically only grows well in oxygenated water with good clarity. They are often used for treating stormwater where the submerged leaves and associated biofilms provide an effective filter for removing fine suspended sediments.

1c The floating leaved macrophyte SF TW is dominated by plant species which are rooted in the benthic substrate (sessile) with their leaves floating on the water surface, such as water lilies and some *Potamogeton* species. Floating leaved macrophytes are often used in combination with other emergent and submerged macrophytes (Kadlec and Wallace, 2009) either by accident or to create a more diverse ecosystem. To date, full scale application is rare (Vymazal, 2009).

4.1.1.2. SF applications. The most common application is to polish secondary treated wastewaters. They are suitable in all climates, including very cold regions. They are also a popular choice for the treatment of urban, agricultural, and industrial stormwaters because of their ability to deal with higher inflow velocities and temporary changes in water levels compared to TWs with sub-surface flow. They are a frequent choice for treatment of mine waters, groundwater remediation and leachate. SF TWs are also typically the preferred design variant for large-scale applications (greater than 1 ha) because at such scales the sand or gravel substrate used in TWs with sub-surface flow becomes prohibitive due to cost and hydraulic limitations.

Significant ancillary benefits in the form of recreation and wildlife habitat can be provided by SF TWs. Operating costs are typically low and are usually capital cost-competitive with other treatment technologies (Kadlec and Wallace, 2009).

4.1.1.3. SF intensification. Surface flow TWs are intensified in rare cases where effluent is recirculated to the front of the system or where aeration is included at the inlet or in deepened zones which exclude macrophytes. Intensification of SF TWs has also been attempted in the form of harvesting farms where the macrophytes are grown with the goal of biomass production (e.g. food for animals, energy biomass or production of ornamental flowers) (Verijken et al., 2007).

4.1.2. Standard type 2: free floating macrophyte TW (FFM TW)
The free-floating macrophyte TW has free-floating aquatic vegetation (rather than sessile), with surface flow, primarily in a horizontal direction, and remain permanently saturated (Fig. 2(b)). The buoyant vegetation means that these systems have more flexibility with regards to water depth as they are not limited by the flooding tolerance of the plants (as with sessile emergent macrophytes) or light penetration through the water column (as with submerged macrophytes).

4.1.2.1. FFM applications. FFM TWs are most commonly used for the treatment of municipal or industrial wastewaters. Some large-scale systems exist in the United States which have been designed specifically to facilitate regular harvesting of the rapidly growing biomass. There are also numerous examples of their use in tropical countries where suitable species occur naturally and productivity is particularly high. The adoption of this type of TW unit is hampered in many countries by the fact that many of the commonly used free-floating macrophyte species typically present significant weed problems outside of their natural range. Their free-floating nature can make them difficult to contain and easily transportable by waterfowl or flooding.

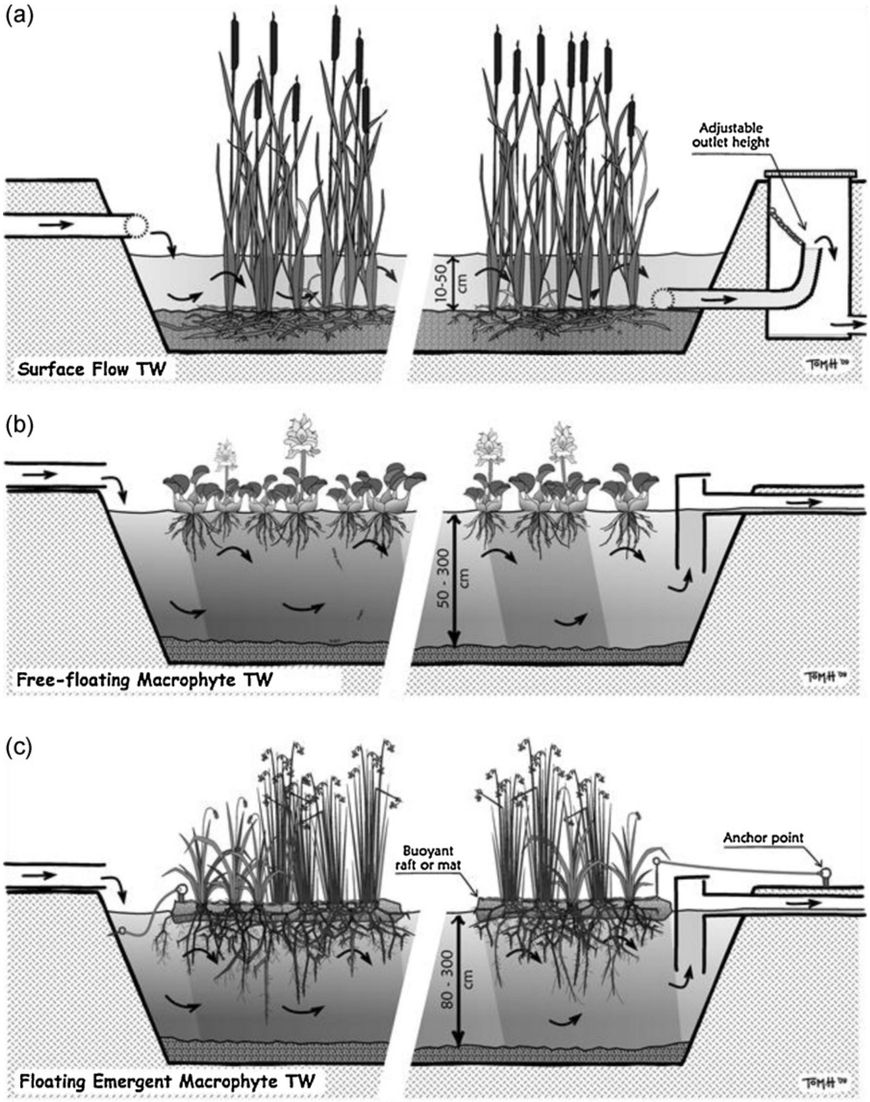

Fig. 2. Standard types of TW systems with surface flow.

4.1.2.2. FFM intensification. A common form of intensification is the inclusion of regular vegetation harvesting in order to keep the floating plants in an active growth phase and optimise biomass production and uptake and removal of nutrients or other elements. This often requires specially developed harvesting machinery and adapted basin configurations.

4.1.3. Standard type 3: floating emergent macrophyte TW (FEM TW)

The floating emergent macrophyte TW is distinguished by having emergent macrophytes growing on a buoyant human-made mat or raft floating on the surface of a pond (Fig. 2(c)). They have a predominantly horizontal flow direction, with the inlet and outlet horizontally separated, combined with the capability to tolerate significant vertical water level variations due to the buoyant structure which holds the emergent macrophytes that would not otherwise survive deep water levels. Water is treated as it moves through the floating mat and root-biofilm network that hangs in the water column beneath the mat. They are commonly named floating TWs.

4.1.3.1. FEM applications. FEM TWs are particularly suitable for drainage and runoff applications that are characterised by fluctuating flow regimes, such as treatment of urban stormwater, combined sewer overflows and agricultural drainage and runoff. This is due to their ability to tolerate variable and relatively deep water levels. They can represent a relatively easy and inexpensive retro-fit option for upgrading existing aquatic systems, such as urban waterways and detention ponds. They are added as buffer pond before intensive urban wastewater treatment plants, fed by combined sewers. They absorb stormwater events, avoid by-pass of the station, deliver constant inflow and reduce hydrocarbon contents by breaking chains and trapping the greasy floating film at surface. Another potential application is the upgrading of existing waste stabilisation ponds, where the root-biofilm network provides additional surface area for attached-growth processes and filtering of particulates. The shade provided by the floating mat can also be of benefit in preventing the excessive growth of phytoplanktonic algae. They have also been used for the remediation of eutrophic lakes and reservoirs.

4.1.3.2. FEM intensification. FEM TWs have been intensified through the inclusion of aeration, inclusion of media with high sorption capacity within the floating mat or pumping of water from below to above the floating mat in order to enhance contact between water and the mat-root system. Systems are being developed in China for improving the water quality in polluted canals using commonly edible plants such as Water Spinach and Watercress with the dual aims of enhancing the harvesting of nutrients while providing an incentive for local people to implement and maintain the FEM TW systems.

4.2. Systems with sub-surface water position of the flow

This group gathers together all TWs where the majority of flow occurs through a porous media within which most of the treatment processes take place. The key difference compared to SF TWs is that sub-surface flow systems are media-based systems. According to the type of influent loading (exposed flood-loading or covered dispersion beneath the substrate surface), or due to operational modes, there may be ephemeral or permanent flooding of the surface of the media, but the majority of treatment still occurs within the porous media. Sub-surface flow systems are subclassified based on flow direction into those with a horizontal flow path and those where the flow is in a vertical direction, as depicted in Fig. 3.

4.2.1. Standard type 4: horizontal sub-surface flow (HSSF TW)

This standard TW type is characterised by flow in a horizontal direction with the inflow being covered beneath the media surface (subsurface loading) and planted with emergent herbaceous macrophytes. They are typically comprised of lined gravel, sand or soil based beds. The inlet and outlet are horizontally opposed and the wastewater flows through the rhizosphere of the plants with a subsurface water position (Fig. 3(a)). Such systems generally have smaller surface areas (<0.5 ha) and higher hydraulic loading rates than SF TW (Xanthoulis et al., 2008).

4.2.1.1. HSSF variants.

4a and 4b	The woody emergent HSSF TWs utilise woody rather than herbaceous emergent vegetation, such as Melaleuca trees (Australia) or Willows (Europe). Variants 4a and 4b have subsurface and surface influent loadings, respectively.
4c	The surface loading HSSF TW has loading of the inflow above the media surface (surface or exposed Inflow), rather than subsurface, and often develop a flooded surface in the inlet region of the bed leading to some distinctly different operational conditions compared to the standard HSSF TW. The influent is distributed on the top surface and is intended to reach the subsurface level of the beds within the first few meters. This design is widely used in the UK and commonly named *reed beds*. Some of the earlier TWs with horizontal flow that were built in Germany and Denmark with a soil-based medium could also be considered to fall into this category, due to clogging of the substrate and ponding of effluent over time.

4.2.1.2. HSSF applications. HSSF TWs are typically used to treat primary or secondary treated sewage. In Europe, the systems are commonly used to provide secondary treatment for village-sized communities of up to about 2000 population equivalents. In North America, they have been used to provide tertiary treatment for larger populations. However, they are also commonly used in small on-site systems following a septic tank and there are many other applications for specialty wastewaters from industry and acid mine drainage. In general, HSSF TWs have been utilised for smaller flow rates than SF TWs, mainly because of cost and hydraulic limitations associated with flow through the porous media. These systems are capable of operation under colder conditions than SF TW, because of the ability to insulate the top surface and the thermal buffering provided by the substrate.

4.2.1.3. HSSF intensification. The current intensification processes to boost the efficiency of HSSF TWs is done by means of aeration lines on the bottom of the bed (intensified aerated HSSF TW), or specific substrates to enhance reactions like chemical precipitation, pH adjustment, or adsorption.

4.2.2. Standard type 5: vertical down flow (VDF TW)

Vertical down flow TW consists of a bed of porous media (sand or gravel) through which the water moves in a vertical direction (inlets are located vertically above outlets) which is free-draining (open outlet at the base of the bed) and remains unsaturated for most of the time (Fig. 3(b)). The vegetation is typically herbaceous emergent macrophytes (*Phragmites australis*) in Europe. A network of pipes with multiple emitters, located within the granular media bed or under a layer of insulating mulch, is used to intermittently distribute the flow across the upper surface of the bed in a way that avoids surface flooding or exposure of the influent ("sub-surface inflow"). The bottom-most layer of media usually consists of coarse media with a network of perforated drainage pipes (Cooper et al., 1996), which are sometimes ventilated to the atmosphere to promote passive aeration of the substrate.

4.2.2.1. VDF applications. Vertical down flow TWs are similar to intermittent sand filters (Liénard et al., 2001), which are widely used throughout the United States, Australia and New Zealand for decentralised wastewater treatment, except that VDF TWs are planted with wetland vegetation. They are used in many European countries particularly for achieving secondary treatment of primary settled sewage. Due to their higher oxygen transfer rates, VDF TWs are becoming more common where discharge regulations require removal of ammonium and for effluents with a high carbonaceous or nitrogenous oxygen demand, such as landfill leachates and agricultural wastewaters.

4.2.2.2. VDF variants. Variants of the VDF TW are based on the degree of media saturation and the occurrence of surface flooding due to the surface discharge of the influent.

5a The surface inflow VDF TW is free-draining and operates with ephemeral flooding of the upper media surface as a means of achieving distribution of the influent on the top surface of the bed. This variant is traditionally used in the UK and relates back to the original TW designs proposed by Seidel and co-workers in Germany during the 1960s. The distribution of the influent over the surface is achieved via point discharges which flood-load the wastewater across a surface layer with restrictive permeability (usually sand), rather than the use of a network of distribution pipes with multiple emitters. Two important application can be identified based on the type of inflow they receive:

- (i) The raw wastewater VDF TW, developed and commonly applied in France, receives unsettled raw wastewater and is often name the *French style system*. In order to manage the organic sludge layer that accumulates on the surface and maintain permeability, they typically have multiple beds in parallel with a rotationally rested operation, and can therefore be considered as operationally intensified systems.
- (ii) The sludge drying VDF TW receives sludge and operates with the purpose to dewater and mineralise the sludge. After each load, a dewatering period is allowed before a new layer of sludge is flood-loaded on top of the dewatered sludge. The plants progressively grow upwards as the stabilised sludge is gradually accumulated in the system. The roots provide drainage channels through the accumulated sludge and also contribute organic matter and enhance the physical structure of the dewatered sludge, thereby

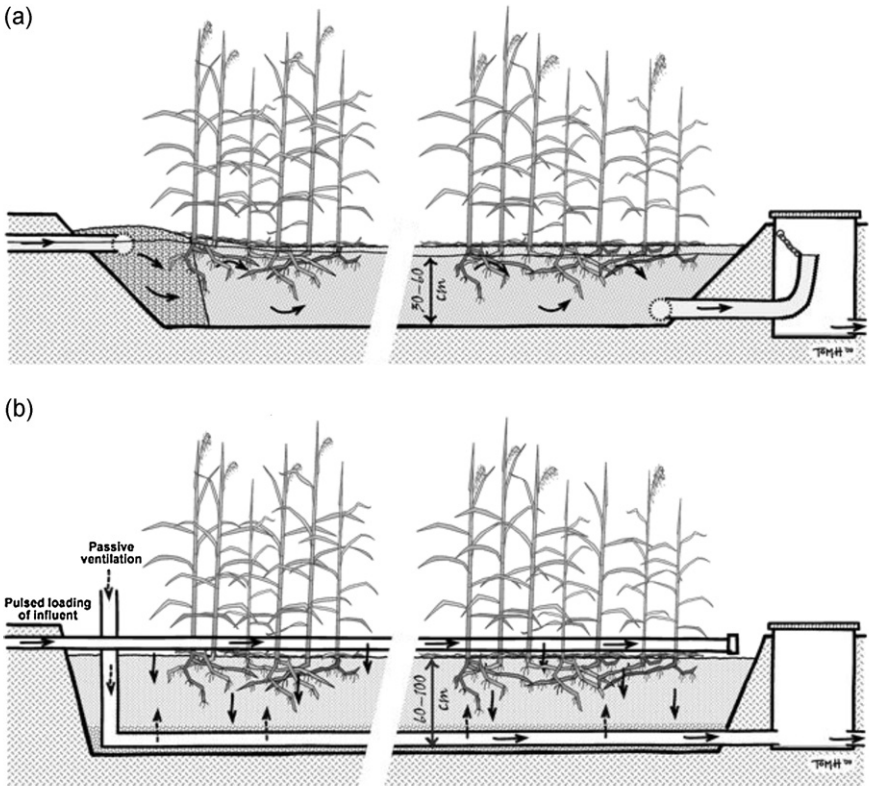

Fig. 3. The two major standard types of subsurface flow TW systems.

facilitating composting and stabilisation processes (Nielsen, 2003). They are commonly named *Sludge Drying Reed Beds*, which can cause confusion with the common *Reed Beds* term in the UK as they refer to two very different design configurations.

5b The stormwater retention VDF TW has an intermittent saturation level and ephemeral surface flooding. It accumulates runoff during rainfall events which then slowly percolates downwards through the porous substrate of sand or gravel. Woody emergent vegetation is often used because it tends to be more tolerant of the dry conditions that can develop within the filter between rainfall events. They are commonly referred to as a *Bio-retention*, *Bio-filtration* or *Rain Garden* systems within the stormwater management industry.

5c The evapotranspirative TW has an intermittent saturation level of the porous media and uses fast growing woody vegetation with a high evapotranspiration (ET) rate, such as willows, with the aim of evapotranspiring all of the wastewater on an annual basis. The water level within the media varies seasonally depending on the balance between inflow, rainfall and evapotranspiration. The media is typically deeper (approximately 2 m) than in other VF TWs, in order to provide storage capacity to accumulate water during periods of wet weather and low evapotranspiration. They are commonly referred to as *Zero-discharge Willow Systems*.

5d The saturated VDF TW has a constantly saturated media (rather than free-draining) as the water level in the bed is maintained slightly below the upper surface of the media. These systems are very similar to HF TWs with regards to the biogeochemical conditions that develop within the wetland. However, because the influent is distributed across the entire upper surface of the wetland, the influent loading rate of organics and solids in the cross-sectional plain perpendicular to the flow direction are greatly reduced when compared to HSSF TWs.

5e The anaerobic VDF TW has a constantly saturated media and a permanently flooded surface. It is still classed within the subsurface flow group of TWs because the majority of flow and important treatment processes occur within the porous media. These systems are similar in application to vertical up flow TWs and are often used to promote anaerobic treatment processes for mining and industrial applications. They are not always planted.

4.2.2.3. VDF intensification.

- Vertical down flow TWs are often intensified operationally by the inclusion of recirculation of a portion of the effluent back to the pre-treatment stage in order to enhance treatment stability or achieve denitrification. Such systems are called recirculating VDF TWs.
- Intensification can be made by the selection of media, such as materials with a high sorption capacity for fixation of problematic contaminants such as phosphorus, or a mixture of compost and limestone in order to promote anaerobic conditions and the production of alkalinity for the treatment of mine waters.
- Saturated VDF TWs are commonly intensified through a network of aeration lines installed at the base of the bed in order to overcome oxygen transfer limitations. These systems can be termed aerated saturated VDF TWs. They are sometimes further intensified through the use of pumping to recirculate a portion of the effluent back through the aerated bed and can be named recirculating aerated saturated VDF TWs. They are often used for treatment of waters with a particularly high oxygen demand, either due to high concentrations of organic compounds (e.g. airport de-icing runoff) or total kjeldahl nitrogen (e.g. landfill leachates) (Wallace et al., 2006).

4.2.3. Standard type 6: vertical up flow (VUF TW)

The vertical up flow TW is similar in design to the VDF TW with the key difference of the upward flow direction. The standard type is defined as having a constantly saturated media with a permanently flooded surface, even if sometimes the outlet collection pipes are configured in a way to avoid flooding of the upper surface of the media. Wastewater is introduced at the bottom of the media bed via a series of distribution pipes and moves slowly upwards to the substrate surface. While these systems may periodically experience a flooded media surface to facilitate effluent collection, they are still classified as having sub-surface flow because the majority of important treatment processes are intended to occur within the saturated bed of media. These systems are sometimes referred to as *Anaerobic Beds* (Younger et al., 2002).

4.2.3.1. VUF applications. Vertical up flow TWs are commonly applied mining or industrial applications, where anaerobic treatment conditions are required.

4.2.4. Standard type 7: fill and drain (FaD TW)

The fill and drain TW is similar in design to the standard VDF TW except that the flow direction is mixed direction and cyclically alternates between upward and downward flow. The media in these systems has an intermittent saturation level as it alternates between being saturated and unsaturated as a result of the filling and draining sequences. Normally the upper surface of the media is not flooded. The system has high rates of oxygen transfer and provides the conditions necessary for complete nitrogen removal within the one reactor, with ammonia adsorption on the media during the filling stage, nitrification under aerobic conditions while the bed is drained, and denitrification with anaerobic condition and carbon source provided by the second filling sequence (Austin, 2006). Their application at full scale is increasing. Common names for this design are *Tidal Flow* and *Fill and Drain wetlands*.

4.2.4.1. FaD applications. Fill and drain TWs are being increasingly applied for wastewaters with a high oxygen demand or where removal of total nitrogen is required. They tend to have a smaller foot-print than other TW alternatives which makes them potentially suitable for arid regions where water loss via evapotranspiration can be a limitation.

4.2.4.2. FaD intensification. FaD TWs can be intensified by the elevated input of energy for pumping of the water. The reciprocating FaD TW is intensified by repeatedly transfer the water in a fill and drain fashion between two partnered beds using pumps. A reciprocation cycle typically involves the pumping of the majority of water from one bed to an adjacent drained bed, followed by a rest period. After the rest period, the majority of water is pumped from the full bed back to the original bed which has been resting in a drained state. The number of reciprocation cycles per day is largely dependent on the oxygen demand of the wastewater and is commonly in the order of one complete cycle every one or two hours. They are currently developed at full scale in Israel and the United States.

5. Summary

The paper proposes a standardised classification and terminology system for TWs. The three criteria identified to name TWs are the presence of macrophytic vegetation, the existence of water-logged or saturated substrate conditions for at least part of the time, and the inflow of contaminated waters with constituents to be removed. The classification hierarchy presented is based on the two physical design traits which are the hydrology; and the vegetation characteristics. The classification hierarchy and terms are organised as a polychotomous key, based on opposite functioning modes. Six major types are identified; their applications are described; variants and intensified versions are summarised.

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