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Ecological design of constructed wetlands in cold mountainous region: from literature to experience

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Abstract:	Constructed wetlands (CWs) are effective and sustainable engineered systems for domestic and/or municipal wastewater treatments. In the last half-century, CWs have become common solutions for small communities in remote mountainous areas. However, cold climate in mountain environment often causes a significant reduction of the pollutants removal performance compared to warmer environments. Therefore, in the present study, we aim to help build consensus on the best design practices for CWs in mountain environments. A meta-analysis of the scientific literature focusing on the CWs in cold climate was conducted. Meanwhile, several monitoring activities (chemical analysis on wastewater and treated water and analysis of changes in the plant communities) were carried out on 6 CWs observing the different conditions between immediately after the construction and 3-7 years later. The results showed an encouraging agreement between scientific studies and observations from the monitored case studies. Lack of plan space, low temperatures and supply meteoric inflows prompted the engineers, in the case studies, to design systems composed of septic tank and horizontal subsurface bed. Such a solution showed a good treatment efficiency (removal rates were more than 60% for most pollutants) in a harsh mountainous environment. A significant difference was evident in the choice of plants. Although the common reeds (*Phragmites australis*) remain an excellent solution, in plain and hilly areas, planting of tufted hairgrass (*Deschampsia cespitosa*) ensures

	similar average performance but is more suitable for the mountain ecosystems. In conclusion, the present study proposes technical and engineering recommendations and a sort of ecological design to increase wastewater treatment efficiency and adapt the systems to a natural and cold environment.
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Title

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Authors

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Abstract

Constructed wetlands (CWs) are effective and sustainable engineered systems for domestic and/or municipal wastewater treatments. In the last half-century, CWs have become common solutions for small communities in remote mountainous areas. However, cold climate in mountain environment often causes a significant reduction of the pollutants removal performance compared to warmer environments. Therefore, in the present study, we aim to help build consensus on the best design practices for CWs in mountain environments. A meta-analysis of the scientific literature focusing on the CWs in cold climate was conducted. Meanwhile, several monitoring activities (chemical analysis on wastewater and treated water and analysis of changes in the plant communities) were carried out on 6 CWs observing the different conditions between immediately after the construction and 3-7 years later. The results showed an encouraging agreement between scientific studies and observations from the monitored case studies. Lack of plan space, low temperatures and supply meteoric inflows prompted the engineers, in the case studies, to design systems composed of septic tank and horizontal subsurface bed. Such a solution showed a good treatment efficiency (removal rates were more than 60% for most pollutants) in a harsh mountainous environment. A significant difference was evident in the choice of plants. Although the common reeds (*Phragmites australis*) remain an excellent solution, in plain and hilly areas, planting of tufted hairgrass (*Deschampsia cespitosa*) ensures similar average performance but is more suitable for the mountain ecosystems. In conclusion, the present study proposes technical and engineering recommendations and a sort of *ecological design* to increase wastewater treatment efficiency and adapt the systems to a natural and cold environment.

Keywords

Wastewater treatment; common reed; tufted hairgrass; wetlands plants; pollutant removal.

Introduction

Wastewater treatment is an extensively explored practice that constantly requests methodological and technological developments for enhancing the efficiency in removing contaminants, reducing the costs, and for improving environmental sustainability. Constructed Wetlands (CW) are a suitable technique, widely adopted for their cost-effective, energy-efficiency, and environmental-friendly impact on treating various types of wastewaters (municipal-domestic, industrial, agricultural runoff, landfill leachate, polluted rivers, etc.) (Stefanakis and Tsihrintzis 2012; Flores et al. 2019). CWs are an integrated ecosystem that remove efficiently several pollutants such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total phosphorus (TP), and total nitrogen (TN), by a synergic process, involving plant uptake, microbe assimilation, and substrate adsorption (Wu et al. 2015; Jafarinejad and Jiang 2019). In addition, more than 25 years of experience showed that CWs assure lower cost, fewer operation and maintenance requirements than the traditional ones (Cooper 1999). Although these solutions bring evident advantages, the research is still ongoing, especially in remote mountainous areas (Schwitzguébel et al. 2011; Wang et al. 2017). Significant problems are related to i) the construction work where large and flat surface space and unrestricted accessibility are often missing, and ii) to the cold temperatures that reduce the pollution removal efficiency of the system (Varma et al. 2021). Many studies agree on how pollutants removal efficiencies are higher in summer than in winter (Kadlec et al. 2000; Tunçsiper 2009) and how the best nutrient removal rate occurs at a temperature of 30°C (Akpor et al. 2013). Low temperatures negatively affect phytodegradation, nitrification, denitrification, microbial degradation, and adsorption (Ji et al. 2020; Varma et al. 2021). Although some authors proposed solutions to overcome the impact of low temperature on pollutants removal, the limits of CWs in cold environment are evident and design and plant species selection remain a challenge (Yan and Xu 2014; Wang et al. 2017).

The designers could act over many parameters: hydrological and hydraulic characteristics of the system (subsurface or open water surface flow), flow path (horizontal or vertical), medium (grain size and additional filters), and type of plants (emergent, submerged, or free-floating) (Zhang et al. 2017). Three main types of phytoremediation beds can be found in literature: horizontal subsurface flow (HSF), vertical subsurface flow (VSF), and free-water surface (FWS-CW). In HSF and FWS-CW the bed is horizontal, dug in the ground at 0.5-1m-depth, whit in the first a wastewater flow that always is embedded, while in the second a free dispersion of water on the surface. In VSF, instead, vertical tanks are filled with the medium and vegetated, and the wastewater is inputted on the surface and moves vertically to the outlet.

In remote and cold mountainous areas, the selection of hydrological and hydraulic features and direction of flow is often subject to external conditions, such as topography and accessibility, thus the plant species begin a crucial design parameter (Mustafa et al. 2009; Brisson and Chazarenc 2009; Vymazal 2011a; Jain et al. 2020). In particular, the roots of plants play an indispensable role in the subsoil producing organic matter that is the energy source for heterotrophic activity by microorganisms and fungi, in their turn, responsible for transforming and decomposing the contaminants (Brix et al. 2007; Kadlec and Wallace 2009). Meanwhile, the plants cover the surface offering insulation and keeping substrate-free in colder periods (Vymazal 2011b). In addition, the right choice of plants is key to maintaining the integrity of the landscape and enhance the ecological and environmental value of a wetland ecosystem (Celewicz-Gołdyn and Kuczyńska-Kippen 2017). Stems, roots, and leavers serve as a substrate for microbes and bacteria, and a shelter for invertebrates and vertebrates (Rejmankova 2011).

In this context, despite the scientific communities making efforts to investigate the impact of different plant species on pollutants removal, few are the studies focusing on the selection of plant species that allow to balance the treatment performance and the ecological aspects in remote and cold climate areas (Põldvere et al. 2009; Cicero Fernandez et al. 2019). Exploring the experiences in high mountains is a necessity to address the design of new efficient systems.

In the present study, the main purpose is to provide some recommendations derived from a detailed literature review and a mid-term monitoring of some case studies in mountainous areas of the Alps, at low temperature. For this purposed, we organised the work into three main chapters and objectives:

- A meta-analysis of the wide literature on CW applications in cold climates to investigate which typology, medium, plant species and precautions can improve the performance in wastewater treatment.
- A field monitoring that focuses on the removal rate over time of 6 CWs built with different designs and plant species.
- The plant community evolution– the only design parameter that evolves over time – within the 6 studied CWs through the means of ecological criteria.

Furthermore, the present study provides an experience for an *ecological design* of new CW systems that, as well as being efficient, have to be properly adapted to a natural and precious mountainous landscape as in protected areas.

Case studies

The study sites are six CW systems situated in Camonica Valley (Lombardy, Northern Italy) in the municipalities of Cedegolo, Cevo, Edolo, Lozio and Sonico (Figure 1 and Figure 2) and five of them within the borders of Adamello Regional Park. These systems are situated at an altitude varying from 600 m to 2450 m a.s.l. and are in operation for at least 2 years (Table 1). Two of them treat municipal wastewater (50-1000 PE), while the others the domestic wastewater of four shelters (30-50 PE). The CWs are constructed with a similar scheme composed of a septic tank as primary treatment, connected to a horizontal subsurface flow system as secondary treatment, and in one case with a free water surface system. The horizontal beds were built with an average depth of 0.6-0.7 m, filled with medium-size gravel and zeolite, and covered by plants.

Table 1. Description of study sites: location, construction year, elevation, PE, system set-up, medium and planted plant species.

Figure 1. Location of study sites.

Figure 2. Photographs of case studies: (Table 1): [a] Cevo, [b] Tonolini, [c] Aviolo, [d] Gnutti, [e] Grevo, and [f] Lozio.

Material and methods

Meta-analysis

The study provides a meta-analysis of the recent scientific publication focused on the use of CWs for wastewater treatment in mountainous areas in cold climate. The selection includes all the studies conducted on sites with an average annual temperature of less than 10°C (and an average temperature in winter less than -5°C) and covers a wide range of developments in this field. In particular, the meta-analysis focuses on several factors such as the CW typologies (horizontal subsurface flow HSF, vertical subsurface flow VSF and free-water surface FWS-CW), the substrates used as a medium, the plant species, and the capacity to treat different pollutants.

Monitoring CWs

1.1.1 Water quality analysis

Inlet and outlet samples of domestic wastewaters were collected from inspection wells after the primary and secondary treatments. The water quality analyses were conducted for 3 out of the 6 case studies (Aviolo, Cevo, and Tonolini). Two replicates sampling were conducted in Tonilini and Aviolo shelter, and three in the Chevo phytoremediation system. The replicates sampling was conducted during the summer when the activity of the shelter is more intense. Samples were transported to laboratory and analysed immediately for BOD, COD, nitrate (NO_3^-), ammonium (NH_4^+), and phosphates (PO_4^{3-}) using conventional methods (American Public Health Association 2005).

1.1.2 Vegetation analysis

Floristic-vegetational data were collected in the 6 areas occupied by the CWs, immediately after the construction (t_0) and after several years of operation (t_x, from 2 to 7 years later). Some sampling plots of 2-16 m^2 were defined on the CW beds of each study area (Aviolo: 3; Tonolini: 3; Gnutti: 3; Cevo: 2; Lozio: 3; Grevo: 3) where the plants were planted during the construction. The plant species (tracheophytes) of each sampling plot were collected and identified in the months of July for some consecutive years (2019-2022) using "Flora d'Italia" dichotomous keys (Pignatti, 1982; Pignatti et al., 2017) and the percentage of coverage was estimated for each of them.

1.1.3 Ecological indicators

Six floristic-ecological indicators proposed by Landolt et al. (2010) were used to evaluate the environmental requirements of the plant species found in scientific literature and detected in the sampling areas: soil moisture (F), humus content (H), light needs (L), nutrients in the soil (N), soil reaction (R), and temperature (T). The values of these indexes range from 1 to 5 (Table 2). From the floristic-vegetational data collected, the mean values of each indicator were calculated by averaging the species values weighted on their abundance (percentage of coverage). Such indexes were used to compare the ecological differences and the evolution trajectory between the plant communities stabilized immediately after the CW construction and approximately 5-years later.

Table 2. Range of values for the Landdolt's indicators.

Results

Meta-analysis

The selected studies are 77 that investigated the removal performance of CWs in cold climates located in 27 different countries (Supplementary Materials – Table A). The meta-analysis focused on 4 different CW types: HSF, VSF and two hybrid systems, HSF+VSF and VSF+HSF. In fact, subsurface systems are more suitable for treating wastewater at low temperature because the heat loss is lower under the ground (Liang et al. 2020), whereas the free water surface systems are heavily affected by adverse conditions such as water icing and plant withering (Kadlec and Wallace 2009).

1.1.4 CWs typologies

CWs typology significantly influences the performance of pollutants removal (TSS, BOD, COD, TN, TP and NH_4^+). Among the scientific studies, the majority focused on HSF systems (55%), whereas hybrid systems (25%) and VSF systems (20%) were less investigated in mountainous areas. The efficiencies of each CWs typology showed wide variability in the function of pollutants (Figure 3). In general, the combination of VSF and HSF systems shows the best performance in reducing contaminants in wastewater, with more than 78% for TSS, BOD, COD and TP and more than 67% for nitrates and ammonia. The combination of HSF and VSF systems recorded the worst performance with five out of six pollutants removal rates less than 75% on average. HSF systems showed good performance over 77% of removal efficiencies for TSS, BOD, COD and NH_4^+, whereas moderate values for TN and TP, 52% and 66% removal rate respectively. Similar results were obtained for VSF systems that guaranteed the best performance in removing TSS concentration (-91% TSS concentration), good performance of over 80% of removal for BOD and COD, and a moderate performance for the other pollutants (<80% removal rate). Table 3 summarizes the efficiency of CWs typology in reducing some wastewater pollutants.

Figure 3. Distribution of removal efficiencies of CW systems in cold climate collected in the literature in function of CW's typology and pollutants.

Table 3. Average and standard deviation of removal efficiencies of CW systems in cold climate collected in the literature in function of CW's typology and pollutants

1.1.5 Medium

The choice of medium in CWs depends on hydraulic permeability and on the capacity in absorbing pollutants. In the scientific literature, the CWs substrates, frequently used and investigated, are numerous, grouped by natural material (sand, gravel, clay, calcite, marble, zeolite, bauxite, bentonite, etc.), industrial by-product (slag, fly ash, mineralized refuse, hollow brick crumbs, etc.) and artificial media (activated carbon, light weight aggregates, compost, biochar, calcium silicate hydrate, etc.). By restricting the selection of the widespread natural media, sand enhanced the best performance in terms of removal rates with all the pollutant removal rates higher than 70% on average (Figure 4). Conversely, despite the good performance in removal TSS, BOD and COD, gravel medium showed poorer results in reducing the concentrations of TN, TP and NH_4^+. Clay medium revealed the worst performance in reducing TSS and COD, but the best performance in reducing TP. Table 4 summarizes the efficiency of CWs in function of the medium.

Figure 4. Distribution of removal efficiencies of CW systems in cold climate collected in the literature in function of CW's typology and medium.

Table 4. Average and standard deviation of removal efficiencies of CW systems in cold climate collected in the literature in function of CW's typology and medium

1.1.6 Plant species

Approximately 60% of the analysed studies investigated CWs where the common reed (*Phragmites australis*) was exclusively planted without distinction for the typology (Figure 5). Approximately 13% of the CWs planted common reed in combination with other species. The second plant more used in CWs was the cattail (*Typha* spp.) for 6% of case studies. In addition, 20% of studies reported a wide spectrum of plant species (approximately 50), especially those of the genera *Carex* (sedges), *Iris*, *Schoenoplectus* or *Scirpus* or *Bolboschoenus* (bulrush) and *Salix* (willows). Among these genera, it was possible to identify 23 species of the Alps (Table 6Table 5). According to the Landolt's indicators associated with each species, all these 23 species were not tolerant to the alpine climate preferring the hilly climate (T=3.67±0.65) and were more suitable with a mid presence of humus content (H=3.52±1.08), of nutrients (N=3.52±0.67), and with an extremely wet soil (F=4.37±0.80). Moreover, such species prefer neutral soils (R=3.30±0.82).

The Landolt's indicators showed how the commonly used species such as *P. australis* and *Typha* spp. did not perfectly fit the cold climate features. In fact, *P. australis* grows well where the soil is rich in nutrients (N=4), and high level of humidity (F=4.5), suitable for HSF system. Conversely, this species requests mid-high temperature (T=4), light exposure (L=3) and moderate presence of humus in the soil (H=3). Landolt's indicators for *Typha* spp. (*T. angustifolia* and *T. latifolia*) are higher than for *P. australis*. Such species request alkaline soils (R=4), submerged water conditions (F=5) and high light need (L=4).

Figure 5. Distribution of plant species in CWs found in literature.

Table 5. List of the 23 plant species found in literature and commonly widespread over the Alps, with Landolt's indicators values.

Monitoring CWs

1.1.7 Chemical analysis

Chemical analyses were carried out for the first 4-5 years after the construction of CW. In Cevo shelter, the pollution removal rates were 86.74% for BOD, 89.18% for COD, 59.45% for NO_3^-, 78.37% for NH_4^+, and 74.28% for PO_4^{3-} (Figure 6). This performance in removing pollution was the best in the observed case studies. In Tonolini shelter, the pollution removal rates were 68.64% for

BOD, 60.66% for COD, 46.89% for NO_3^-, 75.59% for NH_4^+, and 60.09% for PO_4^{3-} (Figure 6). In Aviolo shelter, the pollution removal rates were 66.76% for BOD, 61.98% for COD, 24.40% for NO_3^-, 70.06% for NH_4^+, and 51.70% for PO_4^{3-} (Figure 6). Here, the performances were lower than the others but satisfactory over 60% for BOD and COD, and over 70% for NH_4^+. Scarce removal rates were observed for NO_3^- and PO_4^{3-}. All 3 monitored CWs did not show a trend of removal pollution rates over time, showing good performance already from the first year after the construction. The complete results of the chemical analyses were reported in Supplementary Materials - Tables B, C and D.

Figure 6. Removal pollution rates over the time for the case studies of Cevo, Tonolini and Aviolo.

1.1.8 Vegetation analysis

Once put into operation the CW, the plant species were few: in Tonolini, Gnutti and Aviolo shelters (>1900 m asl), the number of species varied from 2 to 6, whereas in the other CWs only *P. australis* was planted. In the first three case studies, tufted hair grass (*Deschampsia cespitosa*) was always present, whereas *Trichophorum cespitousum* and *Festuca rubra* were two on three times. The number of species sharply increased over the time as expected, while the plant coverage was approximately always higher than 90%, except for Grevo where it was around 60%. Where *P. australis* was planted, the number of species colonised the empty spaces among each other, benefiting from a wet and rich nutrient shallower soil layer (especially in the first part of the CW bed). In fact, 94 plant species were identified (Supplementary Materials – Table E). The maximum number of species was found in Aviolo (n=25), whereas the minimum one was in Cevo (n=5).

Considering the floristic-physiognomic changes of plant communities (Figure 7), in Aviolo, Tonolini and Gnutti, *D. cespitosa* was the dominant species increasing its coverage on the CW beds, whereas deergrass (*T. cespitosum*) and red fescue (*F. rubra*) were gradually replaced by several other species. In the other cases, *P. australis* remained the dominant plant of the community with a slight increase of other species (<20% of the coverage) where the position of the CW bed guaranteed a good brightness. Conversely, in Grevo, a poor brightness and a high humus content on the CW bed because of the coverage by chestnut foliage did not favour the growth of the *P. australis*. Among the 10 identified species, the common nettle (*Urtica dioica*) began the dominant species. Finally, in Lozio and Cevo, *P. australis* remained the dominant species approximately 80% of the plant community.

Figure 7. Plant community distribution over the time: t_0 is the beginning of the operation (after the construction) whereas t_x represents the time after 2-7 years after the construction; n.b. "other species" represents the species with a plant community distribution less than 10%.

1.1.9 Ecological indicators

Ecological indicators showed the plant evolution trajectories since the operations has been starting. The evolution of plant communities after 2-7 years is very similar in all the sites where only *P. australis* was planted (Table 6). In detail, the colonizing plant suits well towards an environment with low variations of soil moisture and temperature, and with an increment in light needs, nutrients, and humus concentration. Similar behaviour was observed in Gnutti, despite the elevation difference, except for humus content and light needs. In this case, the colonizing plant community seems to appreciate less humus content and light brightness. The remaining site showed a different trend in terms of ecological indicators. In Aviolo, all the indicators tend to increase especially in a wet and humus-rich environment. Conversely, in Tonolini, the results showed the highest discrepancies: a significant decrease in humus content, light and nutrient needs and a significant increase of temperature, soil moisture and soil reaction needed than the plant community planted during the CW construction.

Table 6. Variations of Landolt's indicators immediately after the construction (t_0) and 2-7 years later (t_x).

Discussion

Design key parameters from literature to experience

The criteria for CW design and operation include the selection of site, substrate, wastewater type, plant species, hydraulic loading rate, hydraulic retention time, water depth, operation mood and maintenance procedures (Kadlec and Wallace 2009; Akratos et al. 2009). In cold mountainous regions, the choice of the design key parameters should be done considering both the effects of the low temperature on the wastewater treatment performance (on phytodegradation, nitrification, denitrification, microbial degradation, and adsorption of the pollutants) and the impacts of the planted plants on the ecological landscape (including their ability to survive in a specific environment) (Varma et al. 2021).

1.1.10 Typology

This study conducted a detailed review that identifies the VSF+HSF systems as the best solution in terms of the reduction of water pollutants. However, this typology of CW requests wide and plain spaces that are rarely available. For these reasons, the most adopted solution was the combination between a Imhoff tank (or septic tank) and HSF. The first element settles the solids on the bottom, while the wastewater treatment is conducted through the horizontal subsurface flow. The subsurface flow is more suitable in cold climates as their wastewater treatment process is under the ground where heat loss is less (Liang et al. 2020). Conversely, all those systems including surface flow are strongly affected by wastewater disruption due to water icing and plant withering (Kadlec and Wallace 2009). For these reasons, the typology composed of septic tank and HSF is the most adaptable in cold mountain areas, as shown by the performance of our case studies. Both septic tank and HSF bed have to be designed in function of PE: Many authors recommend following standard designing criteria: 3-5 m^2 PE^{-1}, gravel-based with a mean grain size <10 mm, with a slope of beds of 1-2 % and mean depth of beds of 0.7 m (Masi et al. 2000). These designing parameters guarantee the best results in the removal of organic load, suspended solids, hygienic load, irrespective of the variations in hydraulic load, the characteristics of water treated and of seasonal temperature changes.

1.1.11 Medium

A design key parameter is certainly the medium that usually is selected in function of its hydraulic permeability and the capacity of absorbing different pollutants. Poor conductivity causes an increase of risk of clogging, whereas poor abortion by substrate means low long-term removal performance (Wang et al. 2010). In this context, this study underlined the good performance in removing pollutants provided by sand and fine gravel. However, these media increased the risk of clogging the first part of the CW bed where the wastewater flow is concentrated. For this reason, a reliable expedient is to fill the initial and outlet zones of the CW bed with coarse gravel to favour the wastewater flow. Moreover, it is evident how sand and gravel are poor candidates for long-term phosphorus and nitrogen storage; thus, the designers prefer to add other media supplements. For example, at low temperatures, the performance could be improved mixing sand and/or gravel with other materials such as zeolite, lightweight aggregates and carbonate that reduce all the main pollutants. Another interesting media supplement was the biochar: recent studies showed good performance in removing nitrates (Boehm et al. 2020) and was considered an effective alternative technology for its low cost. However, under low-temperature conditions, some authors noticed a decrease of microbial activity and as consequence nitrogen removal efficiency (Zhang et al. 2021). In all our systems, the choice fell on a 50-100 mm gravel with zeolite supplement; at an elevation higher than 1900 m asl the designers placed an additional layer of natural soil above the substrate.

1.1.12 Plant species

A challenge in designing CWs is to select plant species or better plant communities that can improve the pollutants removal rate. The most common plant used in CWs for wastewater treatment were *P. australis*, *Typha* spp., and *Scirpus* spp. (Reed and Brown 1992). Undoubtedly, *P. australis* is largely recognized as the “best plant” for treating wastewater and groundwater contaminated by organic pollutants (Fester 2012), even in a low-temperature environment. *P. australis* has a positive effect in removing organics, ammonia, phosphorus, and fecal coliforms, and in reducing heavy metal and per-polyfluoroalkyl substances concentrations (Schierup and Larsen 1981; Vymazal and Březinová 2016; Ferrario et al. 2022). This choice is confirmed also in our cast studies (Figure 2). In Cevo and Lozio (800-1100 m als), 5 years after the construction, *P. australis* has benefited from a good brightness and wet condition, remaining the dominant species with a plant cover of around 80%. Nevertheless, *P. australis*, used in a cold climate, is probably near close range to species ascension limit (Varma et al. 2021). In fact, *P. australis* (and *Typha* spp.) often turns yellow when the temperature fell below 5°C and completely withers when the temperature reached the freezing point (Yan and Xu 2014). In addition, *P. australis* generally suffered a shaded environment (L=4) and an excessive presence of humus on the ground (H=3). This fact was confirmed in Grevo, where the CW bed was degraded over time. The reasons were: (i) dense foliage of three chestnut trees that covered the CW bed; (ii) a clogging of the inlet zone due to the dense root network of the P. australis and the concentrated inlet wastewater flow; and (iii) the presence of wild animals such as boars (*Sus scrofa*). *P. australis* cannot be the optimum solution for high-altitude locations and/or for protected natural areas. As a potential alternative, the first systems were covered by a shallower soil layer with meadow species, collected in proximity. The monitoring conducted in the present study underlined how *D. cespitosa* was the dominant species inside the conditions of the HSF beds. *D. cespitosa* is a common species of the Alps, widespread in high-altitude meadows, marshes, and moorland (Davy 1980). Such species grows colonizes on soils with impeded drainage, low oxygen concentration, a wide range of pH (3.7-8.3) and poor nutrients (and also heavy metals) (Cox and Hutchinson 1979). Moreover, it has little sensitivity to atmospheric humidity, wind-exposure and a longer period of cold temperature (even producing more seed) (Davy 1982). As a tufted hairgrass plant, it was able to grow in a wide range of light intensities, also acclimatising to shade. In terms of water pollutants treatment, *D. cespitosa* tolerates high level of nitrogen and phosphorus especially ammonia and provides high capacity in nutrient fixation.

Problems, maintenance and possible solutions

The literature overview and the monitoring of some case studies showed some problems/solutions for the design of CWs in cold climate regions. This evidence can be resumed in the following points.

- *Improving the wastewater treatment performance*. Some recommendations are: (i) control the runoff flow and stormwater towards the system (directly or diluting the wastewater supply) that strongly reduces the hydraulic retention time; (ii) if there is empty space, designing a VSF upstream to HSF to promote nitrification and aerobic processes (Merlin et al. 2002; Mantovi et al. 2003; Jenssen et al. 2005; Sayadi et al. 2012); (iii) sizing the CW beds at least 6 m^2 PE^{-1} to reduce the impacts of external factors (Buchberger and Shaw 1995; Werker et al. 2002; Brix and Arias 2005; Tunçsiper et al. 2015).
- *Sizing properly the CW bed*. Some recommendations are: (i) the wastewater has to be pre-treated into a sedimentation tank (minimum volume 2 m^3 for a single household with up to 5 PE) (Brix and Arias 2005); (ii) the minimum length of the root-zone system is 10 m (Brix and Arias 2005; Vymazal 2007); (iii) the bottom slope should be around 1% from inlet to outlet; (iv) guarantee a minimum bed depth of 0.60 m at the inlet side of the bed and deeper towards the outlet; (iv) install a tight membrane (minimum 0.5 mm thickness) of polyvinyl chloride or polyester reinforced with glass fibers to avoid the infiltration below; (v) protect the membrane with sand or a geotextile layer; and (vi) the substrate should be uniform sand and fine gravel 0.5-8 mm.
- *Selecting the most adapt plant species*. This study emphasized the importance of an *ecological design* showing the potentialities of *P. australis* (as expected) and *D. cespitosa* in function of the environment where the CW has to be constructed. *P. australis* guarantees good performance especially at an altitude less than 1300 m a.l.s., making some few precautions: (i) after planting, a periodic eradication of invasive species is recommended for the first 3 years until complete colonization of the bed with a medium-high plant density (or plant cover) (Budelsky and Galatowitsch 2000); (ii) maintain a water level of 5-10 cm under the ground to

favor the plant growth; (iii) avoid the presence of excessive level of humus content in the shallower soil layer; and (iv) install a fence against wild animals (e.g. boars). Alternatively, for locations at higher elevations and cold climates, *D. cespitosa* is a good solution. Some recommendations are: (i) plant at the beginning of the growing season (end of the dormant period); (ii) maintain the water level of 5-10 cm under the ground to favor the plant growth; (iii) prevent stagnation in filtration bed that can degrade the plants, and (iv) ensure a good brightness removing or thinning the trees canopy, if necessary.

- *Preventing clogging*. Some recommendations: (i) install an oil separator (degreaser) to prevent flocculation, viscous layer and bulking and decrease solid waste floating (Perle et al. 1995; Vidal et al. 2000; Cammarota and Freire 2006); (ii) spread the wastewater over the entire width of the filtration bed; (iii) design inspection wells, in the proximity of the drainage pipes, accessible to air pumps/metal stick/brushes to allow de-clogging actions. If the system allows it (present a difference in ground level or it is raised compared to ground level) leave horizontal access to the pipe. If this is not possible, provide the drainage pipe with inspection manholes to insert an air pressure pump; (iv) design inlet and outlet zones as a transverse trench filled with stones ensuring that no wastewater is exposed to the atmosphere; and (v) use coarse and lightweight material (such as plastic media) for the inlet part of filtration bed to get easier the cleaning and replacing if necessary (Tatoulis et al. 2017).

Conclusions

In the last decades, CWs have become increasingly common solutions for wastewater treatment of small communities in remote mountainous areas. Although they enhanced good performance in pollutants removal rate and had low impact on landscape. However, in cold climates, low temperatures do not promote plant growth and reduced the removal performances of many pollutants. The literature review showed that the combination VSF+HSF filling the beds with sand and fine gravel guarantee a good performance also in cold climates. The plant that was largely used is *P. australis* in the previous studies. The monitoring results partially reinforced the outcome of the meta-analysis, observing a good treatment efficiency in the monitored sites also in harsh mountainous environments (average concentration reductions were BOD=61%, COD=42%, NH_4^+=76%, PO_4^{3}=61%). The lack of available space forced the engineers to design systems composed of septic tank and horizontal subsurface beds. The substrate that balances the requested dimensioning size of the bed and the performance is the fine gravel with a moderate percentage of zeolite that favours pollutant abatement. Moreover, a significant result was provided by the floristic-vegetational monitoring and the ecological indicators that showed as *P. australis* remains an excellent solution for most warm environments, but where the CW has to be integrated into natural and, sometimes, protected areas, planting *D. cespitosa* assurances similar removal performance and provides more eco-compatibility. Thus, *D. cespitosa* is a suitable phytoremediation species for the mountain environments of the Alps. In addition, the present study reinforced the importance of an ecological assessment of the plant communities, already present in the areas and able to colonise the empty space, that has to be inserted in the design process as a sort of *ecological design* of the CW. Finally, combining literature and experience is possible to provide technical, engineering, and botanical measures to improve the design and maintenance of the CWs, to increase the wastewater treatment efficiency and exploit the multi-functionality of these areas.

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Figures

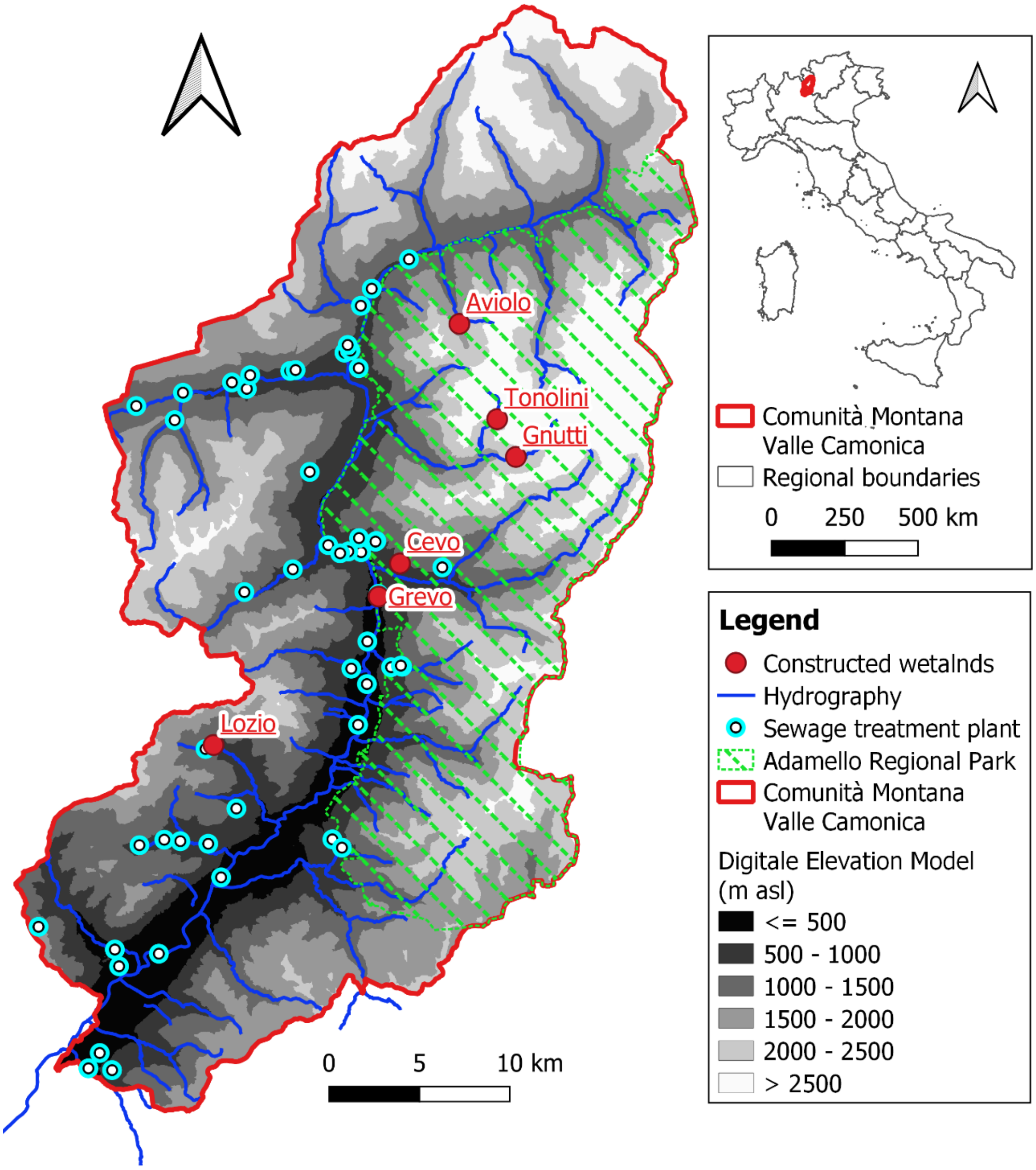

Figure 1. Location of study sites.

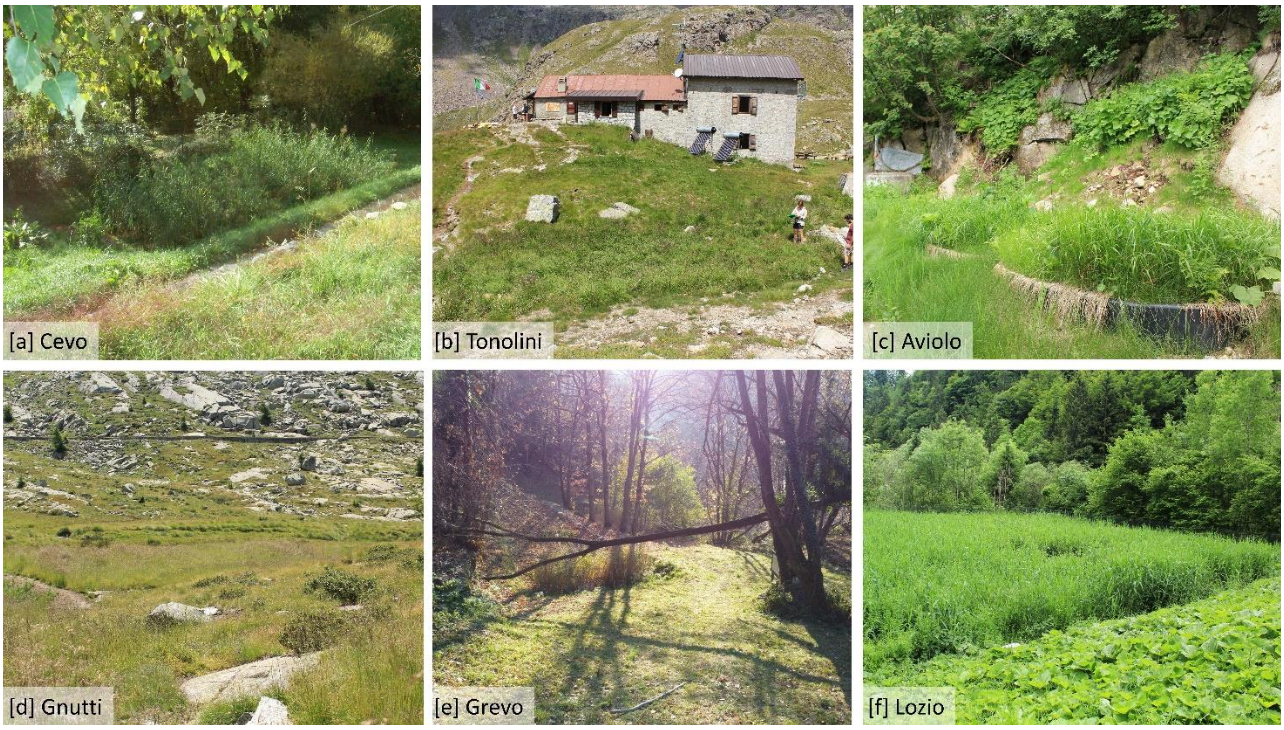

*Figure 2. Photographs of case studies: (**Error! Reference source not found.**): [a] Cevo, [b] Tonolini, [c] Aviolo, [d] Gnutti, [e] Grevo, and [f] Lozio.*

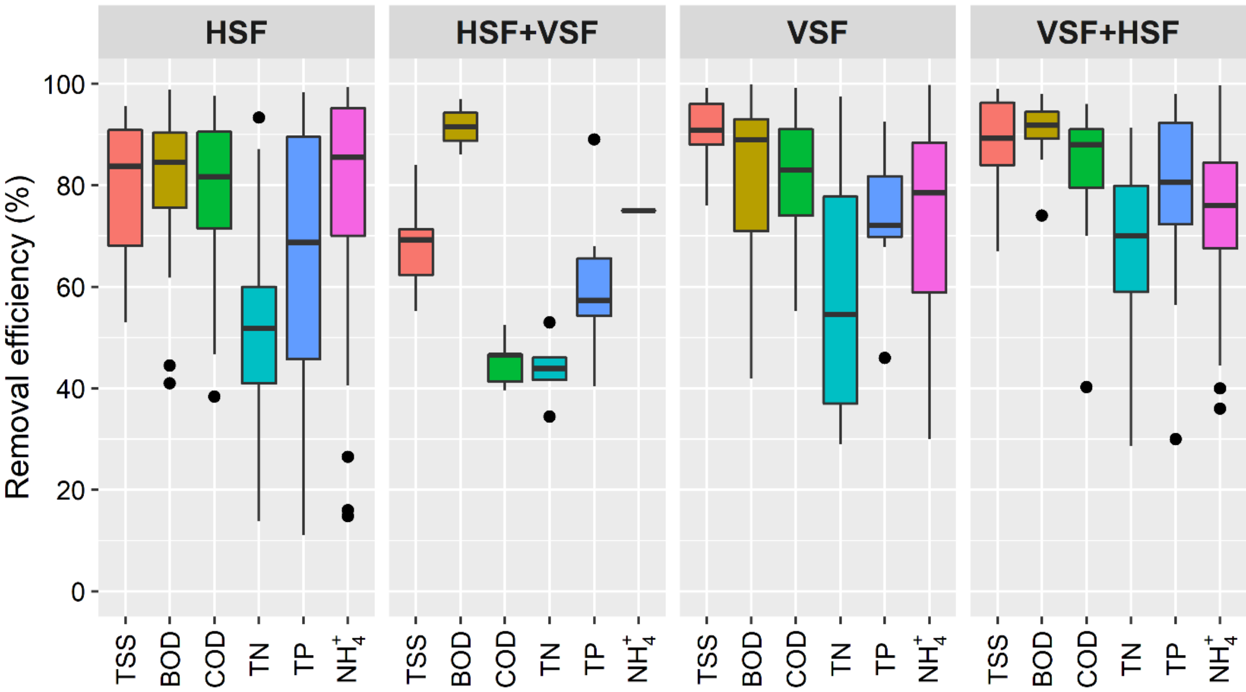

Figure 3. Distribution of removal efficiencies of CW systems in cold climate collected in the literature in function of CW's typology and pollutants.

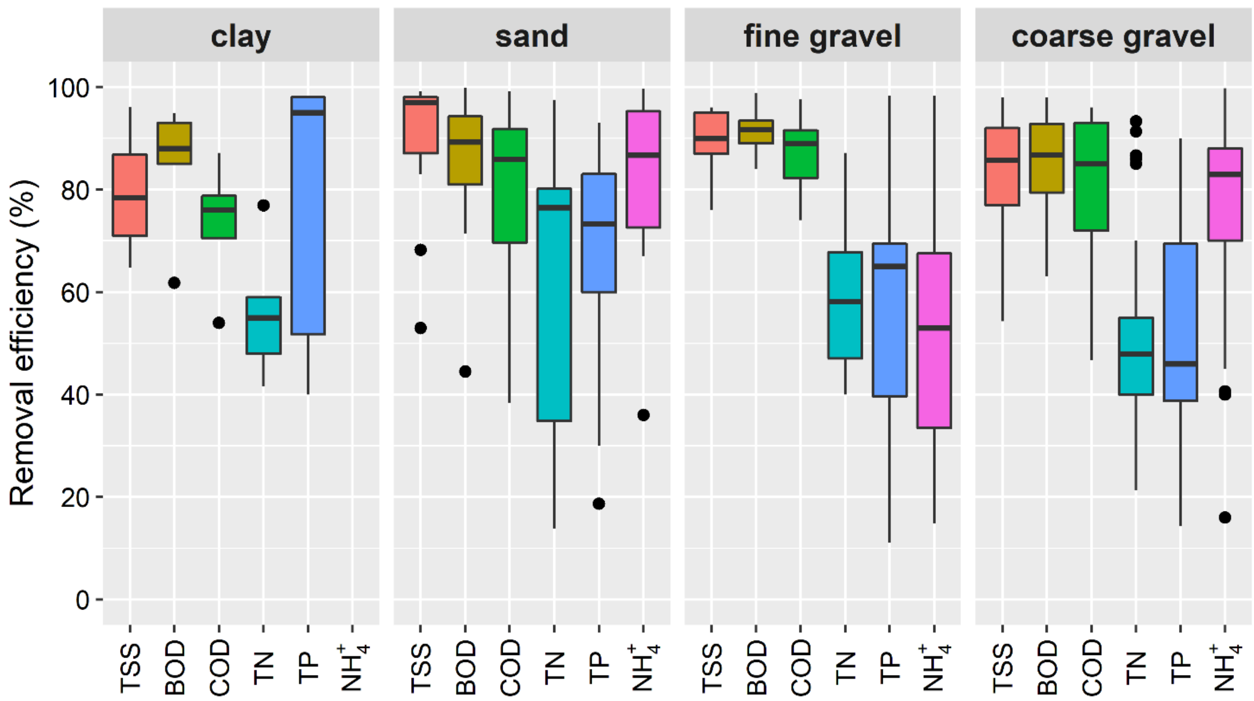

Figure 4. Distribution of removal efficiencies of CW systems in cold climate collected in the literature in function of CW's typology and medium.

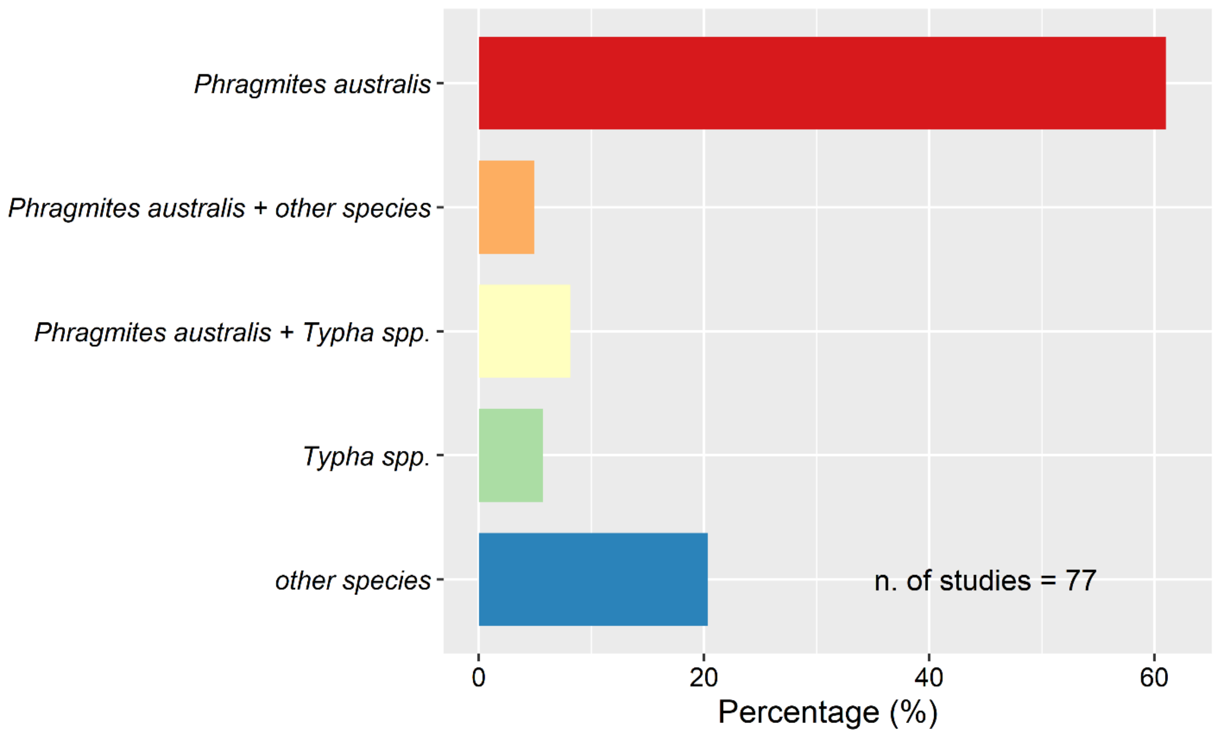

Figure 5. Distribution of plant species in CWs found in literature.

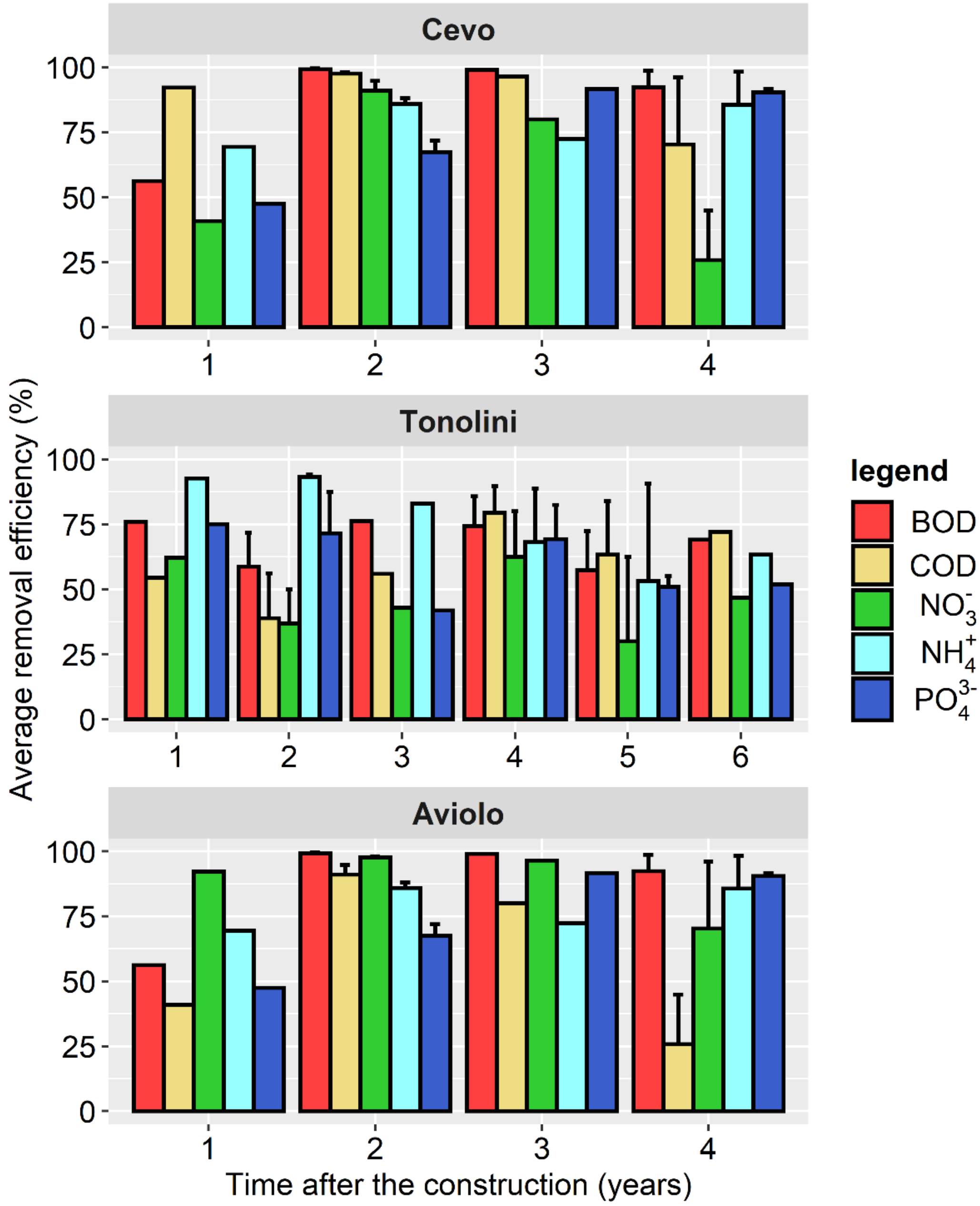

Figure 6. Removal pollution rates over the time for the case studies of Cevo, Tonolini and Aviolo.

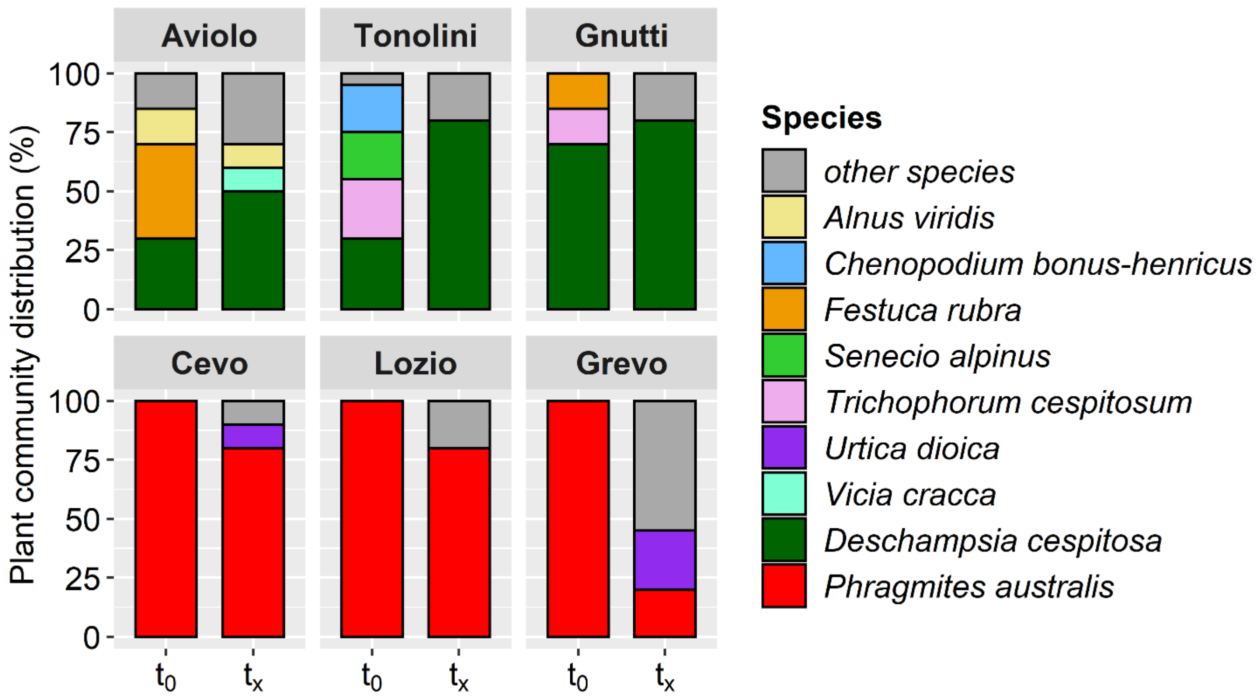

Figure 7. Plant community distribution over the time: t_0 is the beginning of the operation (after the construction) whereas t_x represents the time after 2-7 years after the construction; n.b. "other species" represents the species with a plant community distribution less than 10%.

Tables

Table 1. Description of study sites: location, construction year, elevation, PE, system set-up, medium and planted plant species.

Study site (Abbreviation)	**Location**	**Construction year**	**Elevation m a.s.l.**	**PE**	**CW description**	**Medium**	**Plant species**
"Casa del Parco" shelter (Cevo)	Cevo (BS)	2014	1100	50	Septic tank + 2 horizontal subsurface beds (4.7m x 15.3m)	70 cm: zeolite + 50-200mm gravel	• *Phragmites australis*
Franco Tonolini Shelter (Tonolini)	Sonico (BS)	2013	2450	20	Degreaser + Septic tank + horizontal subsurface wetland (6m x 10m)	60 cm: zeolite + 50-100mm gravel	• *Senecio alpinus* • *Leucanthemopsis alpina* • *Chenopodium bonus-henricus* • *Deschampsia cespitosa* • *Trichophorum cespitosum*
Occhi Sandro all'Aviolo Shelter (Aviolo)	Edolo (BS)	2015	1935	30	Degreaser + Septic tank + 2 parallel series of 5 horizontal subsurface wetlands (2m x 2.5m)	60 cm: zeolite + 50-100mm gravel	• *Festuca rubra* • *Deschampsia cespitosa* • *Senecio nemorensis*

						10 cm: natural soil	• *Alnus viridis* • *Vaccinium myrtillus* • *Rubus idaeus*
Serafino Gnutti (Gnutti)	Sonico (BS)	2019	2166	40	Degreaser + Septic tank + horizontal subsurface wetland (9m x 15m)	60 cm: zeolite + 50-100mm gravel	• *Deschampsia cespitosa* • *Trichophorum cespitosum*
Grevo-Cedegolo CW (Grevo)	Cedegolo (BS)	2013	510	50	Septic tank + horizontal subsurface wetland + open water surface wetland	70 cm: 50-100 mm gravel	• *Phragmites australis* • *Nymphaea alba* • *Iris pseudacorus*
Villa-Lozio CW (Lozio)	Lozio (BS)	2014	884	1000	5 Septic tanks + 2 horizontal subsurface wetlands	50 cm: natural soil 15 cm: 10-20 mm gravel 20 cm: 40-70 mm gravel	• *Phragmites australis*

Table 2. Range of values for the Landdolt's indicators.

Environmental factor	Indicator values [1-5]
Soil moisture (F)	Gradient from extreme dry soils (1) to plants growing underwater (5)
Humus content (H)	Gradient from humus-poor soils (1) to humus-rich soils (5)
Light needs (L)	Gradient from deep shade (1) to full light (5)
Nutrients (N)	Gradient from nutrient-poor soils (1) to nutrient-rich soils (5) mainly nitrogen
Soil reaction (R)	Gradient from acidic soils (1) to carbonate-containing alkaline soils (5)
Temperature needs (T)	Gradient from cold sites (alpine or nival belt) (1) to warm places (plain belt) (5) of the Alps

Table 3. Average and standard deviation of removal efficiencies of CW systems in cold climate collected in the literature in function of CW's typology and pollutants

Typology	TSS	BOD	COD	TN	TP	NH_4^+
HSF	80.16±13.60	81.59±13.06	78.37±15.72	52.64±17.29	66.31±24.51	77.06±22.97
VSF	91.38±5.87	81.94±17.76	80.79±13.83	58.19±24.32	73.99±12.86	74.85±20.56
HSF+VSF	68.29±10.04	91.50±7.78	45.31±5.10	43.83±6.18	60.92±16.40	75.00±0.00
VSF+HSF	88.44±9.58	90.67±5.90	84.11±13.66	67.54±18.44	78.63±18.27	72.52±18.90

Table 4. Average and standard deviation of removal efficiencies of CW systems in cold climate collected in the literature in function of CW's typology and medium

medium	TSS	BOD	COD	TN	TP	NH4
clay	79.4±13.54	84.54±13.31	73.29±13.89	56.1±13.4	76.56±28.32	±
sand	90.03±13.78	84.67±15.97	79.03±19.06	62.08±27.67	67.75±20.68	81.9±17.31
fine gravel	89.8±5.94	91.43±4.39	87.14±6.74	59.79±16.28	56.7±32.91	53.63±26.22
coarse gravel	82.66±12.24	86.13±9.15	81.46±14.06	51.56±19.85	52.48±21.48	77.28±20.01

Table 5. List of the 23 plant species found in literature and commonly widespread over the Alps, with Landolt's indicators values.

Plant species	**F**	**H**	**L**	**N**	**R**	**T**
Acorus calamus	5.00	5.00	4.00	4.00	4.00	4.00
Bolboschoenus planiculmis	4.00	3.00	4.00	3.00	4.00	4.50
Caltha palustris	5.00	5.00	3.00	3.00	3.00	3.00
Cardamine amara	5.00	3.00	4.00	3.00	3.00	3.50
Carex paniculata	5.00	5.00	4.00	4.00	4.00	3.00
Carex riparia	5.00	5.00	4.00	4.00	4.00	4.00
Carex rostrata	5.00	5.00	4.00	2.00	2.00	3.00
Deschampsia cespitosa	4.00	3.00	3.00	3.00	1.00	3.00
Glyceria maxima	4.00	3.00	4.00	4.00	4.00	4.00
Hippuris vulgaris	5.00	5.00	4.00	3.00	4.00	3.00
Iris foetidissima	2.00	3.00	4.00	3.00	3.00	5.00
Iris pseudacorus	4.50	5.00	3.00	4.00	3.00	4.00
Juncus effusus	4.00	3.00	3.00	4.00	2.00	3.50
Lolium perenne	3.00	3.00	4.00	4.00	3.00	3.50
Phalaris arundinacea	5.00	3.00	4.00	4.00	3.00	4.00
Phragmites australis	4.50	3.00	3.00	4.00	3.00	4.00
Rumex alpinus	3.50	3.00	4.00	5.00	3.00	2.00
Salix babylonica	3.50	3.00	4.00	3.00	3.00	4.50
Salix viminalis	4.00	1.00	4.00	3.00	4.00	3.50
Schoenoplectus lacustris	5.00	3.00	4.00	3.00	4.00	3.50
Schoenoplectus tabernaemontani	4.50	3.00	4.00	3.00	4.00	4.00
Typha angustifolia	5.00	3.00	4.00	4.00	4.00	4.00
Typha latifolia	5.00	3.00	4.00	4.00	4.00	4.00
Average value	**4.37**	**3.52**	**3.78**	**3.52**	**3.30**	**3.67**
Standard deviation	**0.80**	**1.08**	**0.42**	**0.67**	**0.82**	**0.65**

Table 6. Variations of Landolt's indicators immediately after the construction (t_0) and 2-7 years later (t_x).

Site	Time	T	F	H	L	N	R
Aviolo	t_0	2.83	3.45	3.20	2.95	3.20	2.75
	t_x	2.83±0.32	3.72±.022	3.37±0.18	3.05±0.44	3.15±0.10	2.82±0.48
Tonolini	t_0	2.58	3.68	3.50	3.55	3.25	2.65
	t_x	2.79±0.01	3.78±0.00	3.00±0.00	3.20±0.01	2.78±0.01	2.91±0.04
Gnutti	t_0	2.93	3.93	3.30	3.15	2.70	2.70
	t_x	2.86	3.77	3.06	3.13	2.93	2.91
Cevo	t_0	4.00	4.50	3.00	3.00	4.00	3.00
	t_x	3.85±0.04	4.26±0.02	3.00±0.00	3.08±0.02	4.10±0.06	3.06±0.07
Lozio	t_0	4.00	4.50	3.00	3.00	4.00	3.00
	t_x	3.84±0.48	4.28±0.47	3.00±0.01	3.07±0.17	4.08±0.04	3.07±0.42
Grevo	t_0	4.00	4.50	3.00	3.00	4.00	3.00
	t_x	3.64±0.17	3.65±0.43	3.00±0.11	3.18±0.11	4.01±0.03	3.20±0.09

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