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Master Thesis

CONSTRUCTED WETLANDS, A BIOLOGICAL ALTERNATIVE WASTEWATER TREATMENTS AND ITS ROLE IN THE NEW CIRCULAR ECONOMY

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ABSTRACT

The climate changes, the natural resources depletion, the population number increase are alarm bells for the future that must push the humanity to turn on more sustainable use of the natural resources, particularly the water. The water management must shift towards solutions acted to protect, safeguard, and sustainably use the available water resources. A new water scheme must be implemented, in which the waste paradigm must be overtaken and substituted with resource-oriented one.

The Thesis aims to present the Constructed Wetland (CW) technology, an attractive green solution for wastewater treatment that nowadays is consolidated as a efficient and valid Natural Based alternative to the conventional systems. The different typologies of CWs are exposed as well as their advantages, disadvantages, and applications. The removal pollutant processes (biological, physical, and chemical processes) occurred within, are deeply analysed and the choice of the suitable vegetation species depending on the wastewater characteristic discussed. Furthermore, I give a brief overview on the European and Italian regulations before explaining in details the design (preliminary and empirical) methods. The treatment goodness and effectiveness are discussed and commented with helping of working applications. Finally, the future role of the CWs systems in circular economy approach is clarified and an overview on the water management scheme modification (from waste paradigm to resource-oriented concept) is provided. The potential applications of CWs within this new scheme are outlined and an in-depth study on recreative applications of CW (Natural Swimming Pools technology) are presented.

Key words: Phytoremediation, Constructed Wetland, Natural Swimming Pools, Circular Economy, Wastewater Treatment

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INTRODUCTION

Water is one of the biggest concerns for the future of the earth and the human rice. It could be defined as “tomorrow’s gold”, a precious and fundamental resource for human life that can be a source of conflicts and wars.

Every year, on twenty-second of March the World Water Day (WWD) is celebrated, created by the United Nation in 1992 within the guidelines of Agenda 21, for highlighting the importance of management of freshwater resources. The Agenda 21 guided the sustainable development governance until 2015, when Agenda 2030 substituted it. In the latter, it presents a new specific Sustainable Development Goal, SDG n°6 , regarding the topic of water, and it is called “clean water and sanitation” (ONU, 1992) (ONU, 2015).

The WWD 2020 was dedicated to the topic of climate change and its links with the water resources. The climate changes increase the water cycle variability: every year extreme meteorological events, like floods and droughts, are more frequent and they cause issues of water pollution and water scarcity. As a consequence, the assessment of water availability is more complicated, and the sustainable development, the ecosystem and the biodiversity of the globe are threatened.

Moreover, issues such as the world population growth, which is expected to exceed nine billion by 2050 , urbanization, rapid industrialisation, and intensifying food production are putting pressure on water resources and leading to a rise in water demand (United Nation, 2019). The world is facing a water crisis.

To thwart the crisis, we must face the problem with a new vision. The protection of existent global water resources from pollution and the application of efficient water managements methods are fundamental steps but are no longer enough. There is the need to enlarge the prospective, to consider all the resource cycles together and to change the economy structure, from linear (‘take-make-use-dispose’) to circular. The use of resources must be thrifty, the efficiency of industrial processes must be improved and the waste valorised and considered as new precious secondary raw material to be recycled to the process and reused.

The wastewater treatment is one of the most important aspects to face due to the high growth of wastewater collection systems, which nowadays brings more and more wastewater to treat. Hence, it is necessary that the urban wastewater treatments in the future become more economically sustainable systems, exploiting their great potential of integration with energy production and resource recovery. In fact, the wastewaters are rich sources of valuable primary chemicals which can be converted into marketable products (bio-plastic, biofuel, fertilisers, etc.) as well as a source of new water (Masi, et al., 2017). The reclaimed water could be used for irrigation of gardens or agricultural fields, for replenishing surface water and groundwater, but may also be directed toward fulfilling certain needs in residences (e.g. toilet flushing) or in industry field.

In this prospective, besides the conventional wastewater treatment systems, such as bar screening, degreasing, air floatation, primary/secondary sedimentation, biofilm processes/activated sludge processes, nature-based solutions (NBS) are becoming more and more popular. The phytoremediation together with lagooning and sub-irrigation systems, is part of these unconventional treatments. The design and construction simplicity, the high pollutant removal efficiency, the reliability also in extreme operating conditions and the low cost-effectiveness ratio (they almost require no energy consumption), make nature-based systems the future wastewater treatment solutions, perfectly compatible with the circular economy concept.

In this thesis work, I will expose and discuss one of the most promising nature-based techniques for wastewater treatment, the Constructed Wetlands (CWs), which is part of the phytodepuration solutions.

After the introduction and brief comparison with natural wetland environment, the CW technique is presented and its efficiency as a treatment system discussed. Then, the different typologies and configurations are analysed, and the possible applications exposed.

Subsequently, the treatment functioning is explained and all the physical, chemical, and biological processes which occur within it are deeply analysed, with single paragraphs dedicated to the removal of each pollutant.

The central part of the thesis is aimed to clarify the role of CW systems in the frame of the circular economy, in which the concept of wastewater changes, from a waste to a possible resource. I will discuss the transition from the waste paradigm to a resource oriented one which it is necessary to apply to respond to the sanitation worldwide and future needs. The transition from the conventional wastewater treatment scheme to the new one, more sustainable, nature-based and resource oriented, is discussed and the CW potential applications within this new paradigm are presented.

Finally, a brief in-depth study on the Natural Swimming Pools (NSP), a modern application of phytodepuration system for creating recreative areas, is made. The NSP typologies and the water quality guidelines are outlined, and some examples of existing structures in Italy are provided.

CHAPTER 1 CONSTRUCTED WETLAND AS TREATMENT SYSTEM

The phytoremediation is emerging as one of the most efficient unconventional alternative technology for the wastewater treatment. The etymology of the word phytoremediation (from the Greek phito = plant) can be misleading in far believe that plants are the main actors in the mechanisms of pollutants removal. Actually, plants have the role of promoting the creation of microhabitats suitable for the growth of the microbial flora, true protagonist of biological purification.

In nature the phytoremediation zone are wet environment like lagoon, mashes, bogs, swamps, floodplains, wet meadows and ribbon wetlands (Davis, 1995). Until few decades ago, these zones have been considered as unhealthy and unsuitable for the human life, whereas lately they have been revalued for their self-adjusting capacities.

The Constructed Wetland system (CW) is one of the most effective solution proposed in the field of phytoremediation (Kadlec & Brix, 1995). It is an engineered ecosystem that aims to copy the natural wetland both in form and function. The environment condition and the biological processes which characterize the natural wetland, are artificially reproduced for exploiting the self-adjusting capacities (auto-depurative) to treat wastewater (Davis, 1995).

Based on physical and biological processes CW uses natural functions vegetation, soil, and organism to treat water. It consists of a properly designed basin which contains water, substrate, and plants. It is feed with controlled flow of wastewater that is spread among the plants. The slow flow and the shallow water depth allow the sedimentation of suspended solids and heavy metals. The substrate is saturated and provides a filter functions while the plants have the task to absorb trace metal and, most important, supply through the roots the oxygen for the microorganisms to live and grow. They use the organic material and nutrient as food, reclaiming as the same time the wastewater, that, after a proper retention time, flow out to the wetland and can be discharge into water body or be reused for different purposes (Davis, 1995).

The high reliability and low cost of construction, operation, and maintenance (O&M), make CW a valid sustainable alternative with low energy process and minimal operational attention to the traditional treatments.

Generally used as secondary treatment, CWs can treat municipal or industrial wastewaters, greywater, stormwater runoff. They may also be used for land reclamation after mining, as a mitigation step for natural areas lost to land development, or as polishing stage for secondary effluent treatment.

Depending on the type of wastewater the design of the Constructed Wetland must be adjusted accordingly (Langergraber, et al., 2019).

1.1 FROM NATURAL TO CONSTRUCTED WETLAND

The first studies and experiments on use wetland for treat wastewater, were made in 1950s (Vymazal, 2010). However, the natural treatment of domestic wastewaters has ancient origins. In Rome, during the imperial period, it was used to unload the maximum cloaca in the Pontine Marshes with the precise purpose of exploiting their self-purifying power. In China, the custom is still common today the millenary tradition to create lagoons for fish farming where, in order to increase fish production, appropriate quantities of domestic sewage, containing a high concentration of nutrients (phosphorus and nitrogen) are periodically released in.

Hence, for centuries, the natural wetlands were considered and used merely as storage basins for sewage before the discharge to the final receiver water bodies and not as a real depuration plant. In many cases, uncontrolled discharge of wastewater into these natural wetland and incorrect valuations of the environmental impact of wastewaters, led to irreversible damages and degradation for the ecosystems. (Vymazal, 2010)

In common culture, in fact, wetlands have historically been considered insane and not proper for human life, thus, till anthropocentric vision of the world has prevailed, they have been completely set aside also by the scientific world.

In the early 1950s, many studies on the wetland’s ecosystems and on the complexity of biological reaction that characterized them, led to change of this negative perception (Vymazal, 2010). Natural wetlands are characterized by an extreme variability of their functional components, which led to observed good improvements in the quality of wastewater after a transition in natural wetlands, even if it was still not possible to give a precise quantification of their depurative capacities (Brix, 1993). So, on this basis have developed numerous experiences of planned and controlled utilization of the auto-depurative capacity of some natural wetlands to obtain precise water quality goals. It was noted that if the wastewater inflow is properly controlled, the wetland treatment could become a useful natural treatment plant. Between the 1970s and 1980s, following the idea of preserve the existent natural wet area, it started to study the possibility of realization appropriate wet system designed to purification of wastewater (Vymazal, 2010).

In respect to natural wetlands, the constructed ones offer a great grade of control, allowing a precise valuation of their efficiency. Moreover, the possibility to choose the site, the flexibility in dimensioning and the control of the path and the retention time, are additional advantages that led during the 1990s to spread the technologies around the world. Two different configurations were studied and invented (vertical and horizontal flow), but the need of more efficiency in removal nitrogen and ammonia led to combine them to complement each other. (Vymazal, 2010)

In the last 30 years, we have assisted to a real increase of the interest on CW technologies. In fact, the numerous different benefits of wetlands have been identified, such as possibility of water supply (e.g. refill of underground waters, potable and irrigation use), good work for hydraulic control (expansion basins for prevention of floods), exploitation for extraction activities (sand and gravel), utilization of plants present in the wetlands (prime materials for alimentary, cosmetic and medical products, forage, timber, production of paper, fertilizers), presence of free animals (migratory birds, beverage for many species), presence of fishes and invertebrates, possibility of utilization for integrated productions (for example fish raising combined with rice cultivation), control of erosion and desertification, and a great contribution to bio-diversity, possibility of utilization as energy sources (hydroelectric, sun, heat pumps, gas, biomasses) and finally educative and recreative activities (Whigham & Brinson, 1990).
Nowadays, even if in some part of the world, natural wetland are still used to dispose wastewaters, though under controlled conditions, the use of phytoremediation technologies for treat wastewaters have been become a common choice at world level, particularly in which areas affected by water scarcity (Stefanakis, 2020).

1.2 CONSTRUCTED WETLAND TYPOLOGIES

Constructed wetlands are engineered systems with high versatility for treatment of wastewaters. They are constructed in function of the characteristic of the wastewaters and the lands. The typologies of configuration are several and they depend on three main factors:

- Hydrology (open water-surface flow or submerged flow)
- Flow path (horizontal or vertical and or hybrid)
- Type of macrophyte growth (emergent, submerged, free-floating)

When higher removal efficiency is required, hybrid configurations are possible in order to combine the specific advantage of each component system (Vymazal, 2008).

As follows, the different types of configuration are presented starting from the subdivision based on the flow water direction.

1.2.1 Constructed wetland open water-surface flow (FWS or SF)

Constructed wetland with surface flow is known also with the acronym of FWS CWs, that stands for Free Water Surface Constructed Wetlands. They consists of shallow basins or channels, where the water surface is always exposed at the atmosphere and the substrate is constantly submerged (Kadlec & Wallace, 2008). These areas, which can contain floating, submerged, or emerged plants, are the best reproductions of the natural wet zones and exploit the self-adjusting capacity to treat the effluents. The treatment processes that occur into the FWSCWs are physical (sedimentation, filtration, UV exposure), chemical (precipitation, adsorption, volatilization) and biological (microbial degradation, microbial nutrient transformations, bacterial die-off). The shallow water depth, the plant's roots and litters allow to regulate and maintain the slow flow inside the wetland (Brisbane, 2000).

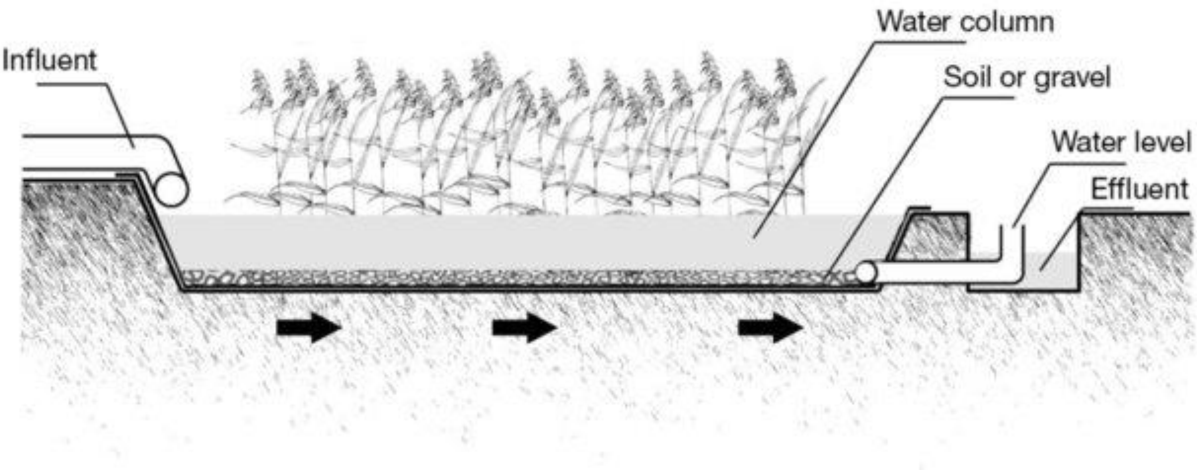

Figure 1: Free Water Surface Constructed Wetland (FWS CW or SF) (Avila, 2013)

In this type of configuration, the filtration and sedimentation processes are very effective and leads to a high removal of suspended solids. Moreover, thanks to consistent microbial degradation, FWS is also very efficient in organic matter removal (Kadlec, et al., 2000). Instead, the nitrogen removal yield results variable and depends on inflow concentration, chemical form of nitrogen, dissolved oxygen concentration and water temperature (Kadlec & Wallace, 2008). In FWS CWs, the contact between water column and soil is limited, and as consequence adsorption and precipitation result penalized. This fact has repercussions on the removal of phosphorus, that results quite slow (Kadlec, et al., 2000). As far as the removal of ammonia concerned, the present of an upper aerobic water zone allows the nitrification processes, followed by denitrification of nitrate occurred at the bottom level in anaerobic conditions (Vymazal, 2001). Even if FWS wetlands are suited in all climates, the present of ice can condition remarkably and reduce the rate of nitrification and removal (Kadlec & Wallace, 2008).

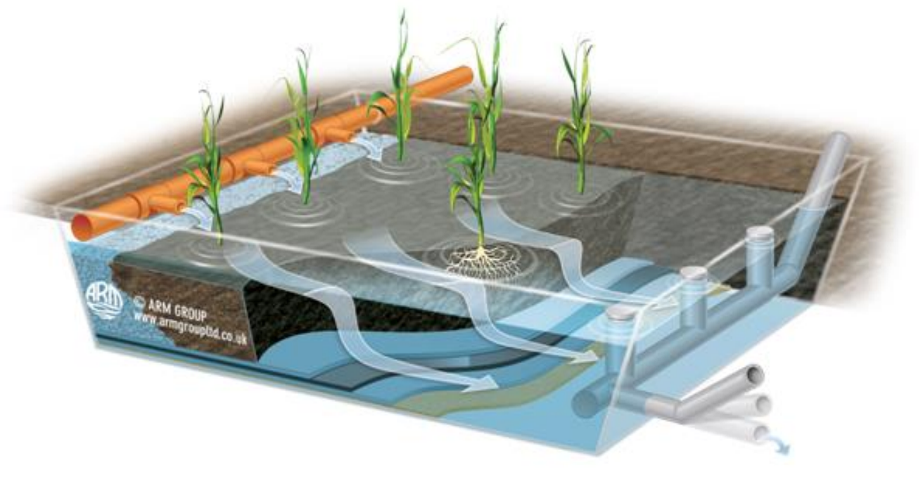

Figure 2: Free water surface constructed wetland (Globalwettech, s.d.)

For all these reasons, FWS CWs are commonly used for tertiary treatment of municipal wastewater, but also of mine drainage effluent and stormwater runoff (Kadlec & Wallace, 2008). Their use as secondary treatment is less common due to the few attachment sites for microbial biofilms, for which other typologies are more convenient. The initial investment and the operating costs are low, and the construction and maintenance operations are very simple and low time required. The main disadvantage of FWS systems is that the ratio between the volume of treated water and the required land area are small compared to other systems (Davis, 1995).

1.2.1.1 <u>Constructed Floating Wetland</u>

Surface flow systems also include phytoremediation with floating barriers, which allow to intercept and treat pollution flows directly inside surface water bodies, whether natural or artificial (fig. 3). The barriers are installed perpendicular to the flow of water, using floating or non-floating plants, but inserted on floating supports (Pavlineri, et al., 2016).

The use of floating plants can present difficulties of realization, because it is not easy to find suitable species, the settlement and colonization are not always uniform and the plants can invade sectors not dedicated to purification and disperse, up to becoming dangerous weeds for the water bodies.

The use of floating platforms allows the use of aquatic macrophytes that do not float, but which are specifically used and effective for purification purposes.

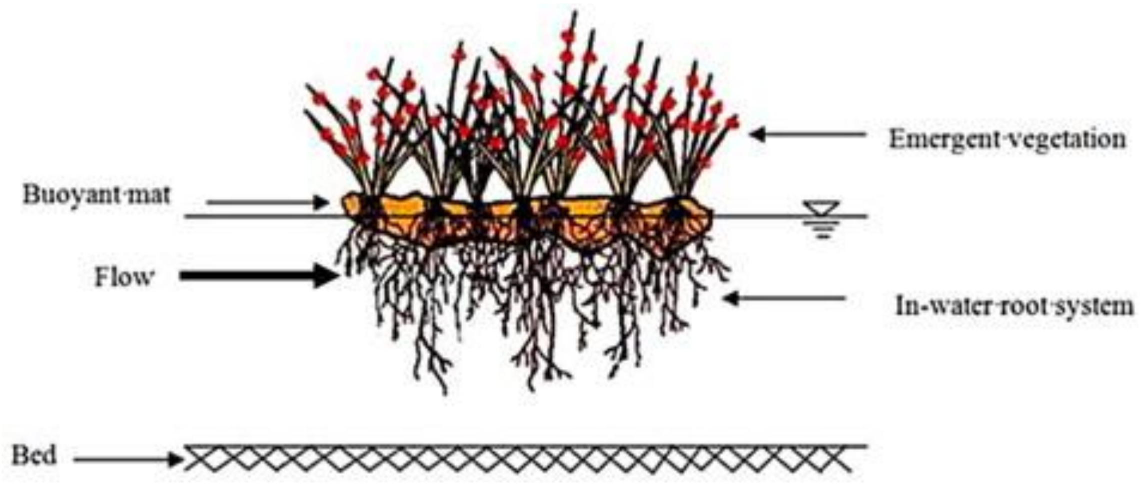

Figure 3: Constructed floating wetland scheme (Pavlineri, et al., 2016)

The advantages of this system are (Pavlineri, et al., 2016):

- Wider range of choice of species
- Uniformity of settlement and behaviour of the barrier
- Confinement of vegetation in the assigned sector
- Adaptation to water level changing
- Managerial versatility.

By using suitable species, plant root development can reach and exceed one meter in depth. Deep and dense roots play an important role in physical filtration as well as nutrient absorption and support for the microbial communities that develop in the biofilm that surrounds them.

Furthermore, the dense intertwining of roots that develops under the surface water level can offer suitable habitat for various forms of aquatic life. For instance, fishes can find shelter, food, and spawning sites.

CFWs are ideal for sludge lagoons to aid settlement of solids and for the treatment of surface water run-off, as the rafts can withstand fluctuating water levels caused by storm events.

1.2.2 Constructed wetland with subsurface flow (SSF)

The Constructed Wetlands with subsurface flow are sealed basins with porous substrate, that supports the roots of emergent plants, and where the water surface is never in contact with the atmosphere and it remains always below the top of the substrate. For this reason, these systems can operate also under colder condition than FWS ones, avoiding the ice formation on the water surface and the slowdown of treatment processes (Davis, 1995).

Based on the direction of the flow, they can be divided in three groups:

- HF CWs, horizontal flow Constructed Wetlands
- VF CWs, vertical flow Constructed Wetlands
- Hybrid or multistage Constructed Wetlands

1.2.2.1 Horizontal flow Constructed Wetland (HF CWs)

In this configuration the wastewater flow is horizontal. The flow enters at the inlet point, runs slowly under the surface through the substrate pack where the purification processers occurred (see fig. 3). The bed, permanent saturated, is characterized for the majority by anoxic/anaerobic zones and by few small aerobic zones around the roots of the plants and rhizomes. In fact, the plants, which emerge up to the bed surface, have their roots sunk into the porous medium. They have the task to carry the oxygen from the leaves to the roots and provide it for aerobic microbial activity. After the passage along the whole substrate pack, the purified effluent goes out at the outlet where is collected before be discharged in the water bodies (Brix, 1987).

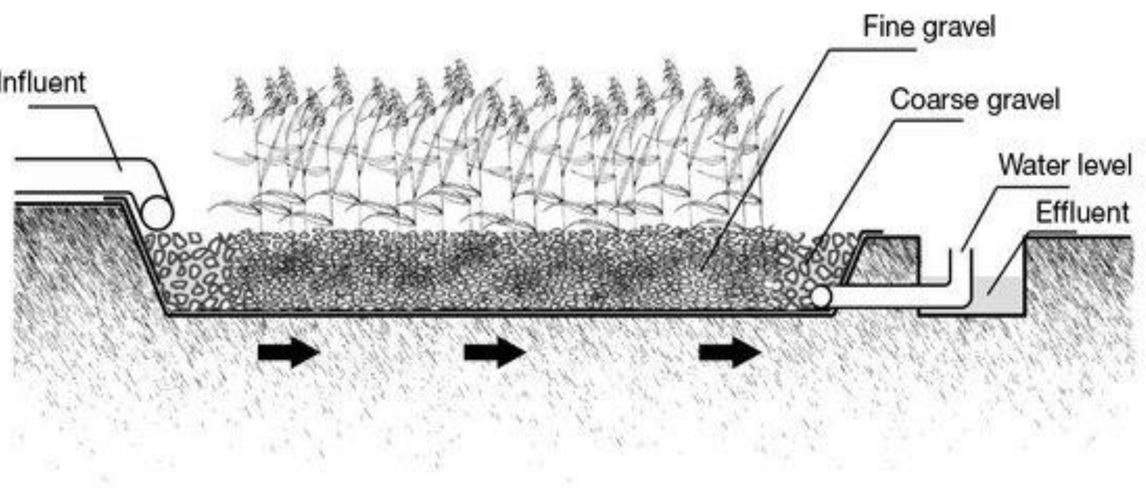

Figure 4: Horizontal Flow Constructed Wetland (Avila, 2013)

The most common application for HF CWs is for secondary treatment of municipal wastewater. The presence of aerobic, while in few parts, and anaerobic zones allow to have great result in the removal of organic matter and pollutant compounds. Not the same efficient it is noted for the removal of phosphorous and ammonia-N. The scarce oxygen presence limits the nitrification process, though suitable condition for denitrification are provided (Vymazal & Kropfelovà, 2008). To face this issue, in 2000s in North America some studies was conducted for understanding the impact of aeration system addition in terms of treatment performance and costs (fig. 4 and 5). It was noted that the removal yield, mostly for ammonia, was incremented, but also the costs of operation and maintenance was significantly increased. ”From the economic viewpoint, aeration is only justified when the lifecycle cost of aeration is sufficiently offset by the reduction in capital costs as the net saving of reduced wetland size less the cost of aeration equipment” (Kadlec & Wallace, 2008).

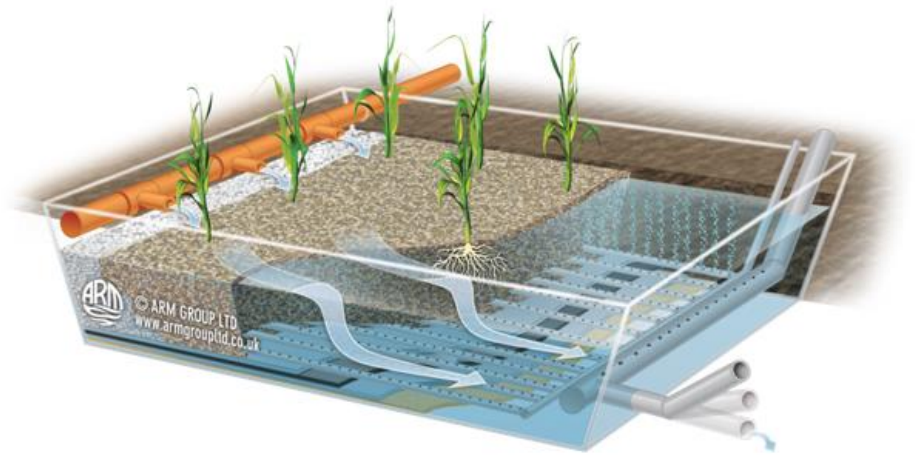

Figure 5: areated Horizontal SubSurface Flow Constructed Wetland (Globalwettech, s.d.)

Generally, HF CWs result not appropriate system to treat wastewaters rich of ammonia and phosphorous. On the other hand, they have the advantage to be able to treat diluted wastewater form combined sewer systems, such as activated sludge, which is impossible to process by conventional treatment systems (Vymazal & Kropfelovà, 2008).

The major problem that characterizes HF wetlands is clogging. It can be eliminated by addition of pre-treatment to filter most of suspended solids.

1.2.2.2 Vertical flow Constructed Wetland (VF CWs)

VF wetlands consist of a flat bed, composed by a graded gravel layer and an upper sand one, where the macrophytes are planted (fig. 6 and 7). Unlike HF where the wastewater is continuously feed, the vertical flow configuration is characterized by batch sequences. The water is uniformly released at the surface, and it percolates through the medium strata. The bed remains completely saturated for the retention time requested. At the end, at the bottom the water is collected by a drainage network, the bed is totally drained and it allows air to refill the pores providing oxygen for the nitrification of the next sequence (Mander, et al., 2002). On the other hand, the condition for denitrification, and therefore complete the Nitrogen cycle and release N gaseous are not provided. Anyway, as the HF systems, for the removal of organics and suspended solids VF CWs are very efficient, and also they require less land for treating the same volume (Vymazal & Kropfelovà, 2008) (Cooper, 2005).

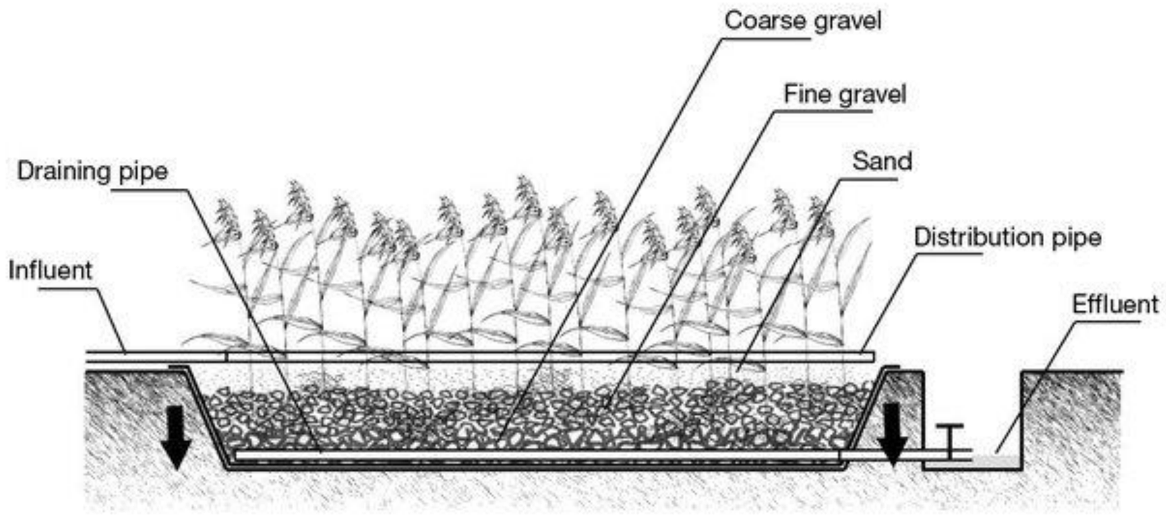

Figure 6: Vertical Flow Constructed Wetland (VF CW) (Avila, 2013)

Recently, a new vertical flow configuration has been development, and it is called "Tidal" CW (Kulshrestha, 2019). The main difference is that the bed is fed with wastewater from the bottom of the wetland. The water percolates upward until the bed is completely saturated and stands in contact with bacteria for the retention time required. After that, the bed is drained downward, and the air can substitute the water inside the pores and the system is ready for another treatment cycle (Cooper, et al., 2005).

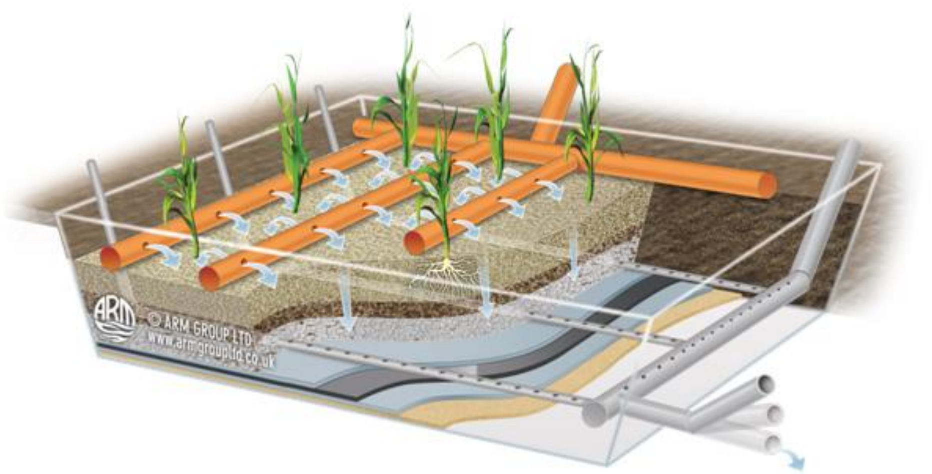

Figure 7: Vertical Flow Constructed Wetland (Globalwettech, s.d.)

The main disadvantage that characterized them, is clogging of the filtration substrate, hence it is useful to choose carefully the proper one and select the suitable hydraulic loading rate.

The vertical flow systems find applications at urban level for treatment of domestic wastewater (on-site) or sewage from small communities, but also in industry or for stormwater runoff (Vymazal & Kropfelovà, 2008).

1.2.2.3 Hybrid Constructed Wetlands

To achieve higher level of purification and improve the treatment effects, especially for nitrogen removal, it is possible to combine HF and VF wetlands in a unique hybrid or multistage system, where different cells are designed for different type of reactions (aerobic and anaerobic) (Davis, 1995).

VF-HF is the most common configuration and consist of several parallel VF beds followed by 2 or 3 HF beds in series. In the first stage, part of organics and suspended solid are removed, and the nitrification process happen due to the oxygen refilling at the end of the drainage step. Then, the water flows into HF beds, where anaerobic/anoxic conditions help the denitrification, maximizing the nitrogen removal and, also a further removal of suspended solids and organics happen (Brix, et al., 2003).

An alternative can be found by inverting the configurations and putting the HF step before VF ones. In this case only one large horizontal flow bed is placed for provide denitrification and first part of removal of organics and suspended solids. Subsequently, the water is intermittently discharged and loaded into small VF beds, where additional removal of organics and suspended solid happen, together with nitrification. However, the nitrified effluent must be recycled to the sedimentation tank (Vymazal, 2005).

1.3 CONSTRUCTED WETLAND FUNCTIONING

Wastewater are defined the waters that contain excess substances, or that are in a state of natural biological and chemical-physical balance altered, hence they can generate inconvenient conditions for humans and other living beings (toxicity, pathogenicity, unpleasant smells) (Romagnolli, 2000).

The purification of the polluted water has the purpose of removing solid substances, both suspended and dissolved, harmful chemicals and to eliminate or inactivate pathogenic microorganisms and stabilize the organic substances. The removal mechanisms, occurring in Constructed Wetlands, exploit capacity of self-cleaning typical of aquatic environments: pollutants are removed, transformed, or stored through a combination of physical, chemical, and biological processes. The efficiency of all these processes will obviously vary with the retention time. Long times will have positive effects on the removal of pollutants, although they have not to become too long, by causing the change in the redox potential of sediments and the return of the nutrients and pollutants into to the water column (Romagnolli, 2000).

Upstream of the phytoremediation plant it is advisable a pre-treatment stage with the function of retaining part of the organic load (pollutant) and most of the suspended solids (e.g. one Imhoff type pit). This improves the purification efficiency of the downstream system and its average life. The effluent leaving the primary treatment (pre-treatment) flows inside the wetland bed. Here the pollutants are naturally removed through physical, chemical, and biological processes, in which the main responsible is the bacterial activity. The macrophytes planted on the bed have multiple tasks. The penetration of their roots inside the substrate allow the creation of aerobic micro-zones in anaerobic environment, that help the bacteria growth. In fact, the plants have the natural ability to capture oxygen through the leaf apparatus and move it, through the stem, to the roots. The roots' surface, few months after start-up of the plant, will be coated with a bacterial film of microorganisms, the real ones responsible for the purification process. Depending on the medium (sand / gravel) used, and technical precautions used, the film bacterial can also extend onto the substrate itself. Moreover, the large roots system helps to keep constant the hydraulic permeability of the substrate, while no contribution in pollutants removal is made by them (Favotto, s.d.).

The limit of these types of treatment is the external temperature, which is a factor that influences the kinetics of the chemical and biological reactions responsible for purification. The major successes for annuity and continuity of this type of treatment are recorded in the warmer countries (Favotto, s.d.).

1.3.1 Biological processes

The main pollutant removal mechanisms are the biological, and they are described in the following list:

- Chlorophyll Photosynthesis: process made by plants and algae that provides carbon and oxygen useful for nitrification and respiration
- Respiration: the organic carbon, coming from polluted compound dissolved in water, is oxidized by the bacteria, and transformed to easier compounds, water and carbon dioxide
- Fermentation: anaerobic microorganisms, fungi and bacteria, degrade the organic matter in absence of oxygen and produce methane, ammonia, alcohol and fatty acids
- Nitrification/denitrification: Ammonia is oxidized to Nitrate by aerobic bacteria and this latter is degraded under anaerobic condition to Nitrogen gas, which is released in atmosphere
- Phosphorus removal: biofilm and macrophytes absorb the dissolved pollutants and nutrients, and used them for creation of new biomass (Cooper, et al., 1996).

1.3.2 Chemical processes

In the following sub-paragraph the chemical mechanisms are described:

- Precipitation: though chemical reactions, substances like heavy metals can precipitate in insoluble compounds
- UV light exposure: organic compounds coming from pesticides are broken in simple substances, while pathogen microorganisms can dead if under persistent sunlight exposure
- Volatilization: some organic compounds dissolved in water can directly volatilize in the atmosphere
- Redox reaction: they change the redox potential of nutrients or heavy metals, which acquire or lose electrons. The redox potential determines the solubility or insolubility of a substance. Redox reactions occur in water or sediments and depend on the oxygen concentration (Cooper, et al., 1996).

1.3.3 Physical processes

At least but not the least, important contributions in pollutant removal are provided by physical processes. The suspended solids can be blocked by mechanical filtration in pre-treatment steps or they can settle down by sedimentation due to the low waterflow velocity inside the Constructed Wetland (Cooper, et al., 1996).

1.3.4 Removal components processes

Following the main component of effluent and their removal processes, which occur inside the wetland environment, are exposed. At the end of the section, a summarized table is present (tab.1).

1.3.4.1 ***Suspended solids*:** represents a significant component (approximately 25-30%) of the load pollutant present in the wastewater. For avoiding the occlusion, the porous medium, its removal must occur for the majority in the pre-treatment (septic tank, tricameral sedimentation tank, Imhoff, etc.). The suspended particles that are not separated in this preliminary phase, left the water fluid by filtration and sedimentation in the gravel layer. Sedimentation capacity is related to the flow speed within the medium and acts synergistically with the filtration process by the biological film (bacterial film) formed on the filling material

1.3.4.2 The *organic matter* consists of carbohydrates, fats, proteins, soaps, detergents, etc. They may be in solid form, in suspension, in solution, in the sediment or partially metabolized. The dissolved organic compounds present in the wastewater undergo a decomposition process, mainly aerobic, by microorganisms (bacteria, fungi) attached to the surface of the rhizomes or of the plant's roots. The oxygen needed for these processes comes from both directly from the atmosphere by diffusion and indirectly from the plants through the release by the roots. In sub-surface flow systems, the removal efficiency is significantly higher compared to other types of Constructed Wetlands, due to the presence of a high contact area between slurry and the bacterial film attached to the surface of the medium. Anaerobic degradation predominates over aerobic degradation when the amount of oxygen it comes to be limiting, for example in the presence of high organic loads (Cooper, et al., 1996). Since this process is linked to bacterial activity, it strongly depends on the climatic conditions and therefore the temperature of the wastewaters. For this reason, the sub-surface flow systems result to be the most stable since the substrate layers act as insulation, keeping the internal temperature always higher than 0 ° C, even when outside the air temperature is much lower (Cooper, et al., 1996)

1.3.4.3 *Nitrogen* (N) is present in wastewater in form of ammonia for the majority, but it can be present also in other chemical forms. They derived from degradation of proteins presented in wastewaters by bacteria activities (ammonification). Through oxidation processes (nitrification) ammonia is transformed in nitrate compounds, which in anaerobic conditions undergo a reduction process (denitrification) for being transformed in Nitrogen gas, released in the atmosphere. Bacteria that use the nitrogen compounds as energy source carry all these processes. In VF systems, the environment conditions are prevalent aerobic, due to the discontinuity in feeding that allow a recharge of air and oxygen from outside. Hence, in these configurations, nitrification processes predominate. On the other hand, in system with horizontal flow, the porous media is always saturated, and the conditions are anaerobic. Only closed to the roots, the environment is aerobic. Furthermore, even if in minority, the removal of nitrogen can occur through absorption by the plants or adsorption by the substrate (Cooper, et al., 1996)

1.3.4.4 Another dangerous element presents in wastewater is the *phosphorus (P)*. It may be in form of phosphate or in organic form and it is present in high concentration in industrial effluents. The bacteria can oxidize and convert all the phosphorous form in the phosphate. The removal of the latter occurs manly through adsorption by the substrate, if rich of iron and aluminium, or by calcium and other minerals present in clay. Hence, the substrate has a big role in the P removal, and the quality and quantity of substrate can help it. Furthermore, P can be removed also through precipitation and absorption by plant, although it results significant only in case of low load per unit of area (Cooper, et al., 1996)

1.3.4.5 *Heavy metals* are present in high concentration in industrial effluent, but it is possible to find significant concentration of copper, nickel, zinc, lead, and cadmium in domestic and urban wastewaters. The removal of heavy metals, which is dangerous in high concentration, occurs through sedimentation, filtration, precipitation, and adsorption. The conventional wastewater treatments have not sufficiently efficient in removal of heavy metals. On the other hand, the phytoremediation systems, particularly the subsurface ones, have a great capacity to remove heavy metals. The plant can absorb a certain quantity of metals, but as consequence they show irreversible damage of tissues. Moreover, the substrate can retain metals in functions of its cation exchange capacity (Volterra & Mancini, 1994) (Romagnolli, 2000). Recently, Phytoremediation techniques, by using special plants, are used to reclaim old industrial areas, former landfill, or polluted zones by heavy metals. When the plants are at the end of the cycle, they are dehydrated and then treated as special waste. Moreover, it is possible to extract by exhausted plant the accumulated metals and reuse them as industrial feedstocks (Brooks, 1998)

1.3.4.6 The *micro-polluted organic compounds*, as benzene, trichloroethane, PCP pentachlorophenol, chloroform, etc. are present in the industrial effluents and normally they can resist to the treatment of traditional systems. Hence, they persist in the environment for long period and they are accumulated in the ecosystems (Giger & Roberts, 1978). The mechanisms to their removal are biological degradation by bacteria, sedimentation, chemical and physical adsorption. In natural systems, like wetland, the present of complex and heterogeneous microbial population allow to degrade also the more stable compounds like tar. The subsurface flow Constructed Wetlands, the most efficient system of micro-polluted organics removal, can remove the 99% of these compounds (Reed, et al., 1987)

1.3.4.7 Constructed wetlands have great efficient in *pathogen* removal with reduction values around 99%. The flow though aerobic microenvironment alternating with anaerobic zones, induces a high stress level for pathogen microorganism. They suffer this continuous change of oxygen concentration that lead them to the dead. Moreover, filtration and sedimentation mechanism, occurring during the flow inside the substrate, help to further reduce the concentration (Gresberg, et al., 1987). The removal's yield results directly proportional with the retention time, which must be higher than 1 or 2 days until 6 days, and the air moisture level, for which in dry condition the removal processes are more efficient (Green, et al., 1997)

POLLUTANT	REMOVAL PROCESSES
Suspended solids	Filtration Sedimentation
Organic matter (BOD)	Aerobic respiration Fermentation
Nitrogen (N)	Ammonification / Nitrification / Denitrification

	Adsorption By substrate Absorption by plants
Phosphorus (P)	Adsorption By substrate Absorption by plants Precipitation
Heavy metals	Sedimentation Filtration Adsorption Precipitation Redox reactions
Micro - polluted organic compounds	Biological degradation Chemical and physical adsorption Sedimentation Evaporation Volatilization
Pathogen microorganism	Sedimentation Filtration UV sunlight exposure Adsorption Natural death Predation

Table 1: Pollutants and relative removal processes (Cooper, et al., 1996)

1.4 APPLICATION

The Constructed Wetlands are commonly used to treat municipal and domestic wastewaters. Nowadays, all around the world there are many systems applied for treatment of wastewaters coming from municipal or domestic centres, hence a lot of data and information about the efficiency and purification yield are available for evaluation the goodness and feasibility of investments.

The low operation and maintenance cost, and simple management, coupled with efficient capacity of pollutants degradation, make the Constructed Wetlands a valid alternative solution to conventional systems (Filter beds, activated sludge, sequencing batch reactors), which also allow the decentralization of the depuration systems.

Constructed wetlands are mostly used as secondary treatment of wastewaters, but also as tertiary treatment of secondary effluent for producing high quality waters. In both cases, CWs ensure excellent removal capacities, particularly for COD, BOD, suspended solids, and nitrogen, and, at the same time, they have a weak environmental impact and a small carbon footprint due to the low energy requirement.

The wetland size is calculated by using the Population Equivalent number (PE), defined in Italian Regulation by Legislative Decree No. 152 of 3 April 2006. PE is defined as "the organic biodegradable load which has an oxygen request at 5 days (BOD5) equal to 60 gr/d" and represents the pollution load produced by resident inhabitants (D.Lgs 152/2006, 2006). The specific area value (m^2/PE) depends on the wastewater characteristics and the treated water destination type (discharge into superficial water bodies or directly to soil surface, reuse).

Figure 8: Constructed Wetland for treatment of small community municipal wastewater (32000 PE, 3 ha) (Lajo, s.d.)

Their most applications are for treating domestic wastewaters coming from small communities or isolated houses, which cannot be collected and conveyed into urban sewage networks. Some examples are showed by fig. 8, a CW system designed for treatment municipal wastewaters coming from a small community of 32000 PE, and by fig. 9, a small wetland system at the service of a private isolated house (2 PE).

Figure 9: Constructed wetland for treatment of domestic wastewaters coming from isolated house (2 PE) (Lajo, s.d.)

Other possible applications are for treatment of wastewaters produced by agricultural or industrial activities (food industry, butchers, distilleries, paper industry, chemical and petrochemical industry) and for treatment of soil leachate or run-off wastewaters. The fig. 10 shows SSF system sited in Salto di Moltese, Modena province, which has been designed for treatment of wastewaters produced by a cheese factory.

Figure 10: constructed wetland for treatment of dairy's wastewaters (Salto di Moltese MO) (Lajo, s.d.)

Constructed wetland systems are successfully used for treating wastewaters coming from tourist activities, as camping, hotels, tourist villages, farmhouses, mountain refuges. Their high flexibility and adaptability allow to efficiently receive and treat oscillating and inconstant organic and hydraulic loads. An example is displaied by the following figure (fig.11), a CW system located in the Zoldana valley (1498 a.s.l.) for the treatment of an alpine refuge wastewaters.

Figure 11: Constructed wetland for alpine refuge (Zoldana valley 1498 a.s.l.) (Lajo, s.d.)

CWs find important application also for tertiary treatment, as polishing stage of secondary effluent coming from physicochemical treatment systems and/or oxidation systems as activated sludge, biofilm reactor. Generally, for these purposes the free water surface systems are the most used and they are often in combination with aquaculture and agriculture irrigation, allowing the optimization of the local water and nutrient cycle. An example is reported in the figure 12 that shows a constructed floating wetland system (CFW) designed in Brescia, to treat urban secondary effluents and reuse for agricultural irrigation.

Figure 12:CW as tertiary treatment of urban secondary effluent for agricultural water reuse (BS) (Lajo, s.d.)

CHAPTER 2 REGULATIONS

The regulations regarding the phytoremediation systems and technologies is explained in the European, national, and regional laws of wastewater treatment.

2.1 EUROPEAN DIRECTIVES

The first law that I want to mentioned is the European directive 91/271/EC (Urban Waste Water Treatment Directive) which treats the collection, the treatment and the discharging of urban and industrial wastewaters, with the purpose to protect the environment from pollution damages. The law defines that, in function of geographical position, urban area size, system treatment potential and effluent load (PE), every agglomeration must have collection and treatment systems. These latter must be built following specific rules and be licensed by the local authorities. Moreover, the law divides the receiving waterbodies in sensible (freshwater resources) and less sensible ones. The European countries must locate the sensible waterbodies inside their administration to monitor their biological conditions and the effluent loads (Directive 91/271/EC, 1991).

Another important European Directive is the Water Framework Directive WFD (directive 2000/60/EC. It is inspired by community environmental policies and it is based on the principle of prevention and responsibility. The member states must locate all the watersheds inside their territories and assign them to single river basin districts, which control the condition of watershed through management plans. The law purpose is to protect and maintain or improve and restore the qualitative state of the waterbodies to natural condition (before the human impact) (WFD 2000/60/EC, 2000).

2.2 ITALIAN REGULATIONS

In Italy, the first law about water resources protection, was the Merli's Law (L. 10 May 1976, n. 31911) in which it was introduced the obligation to treat the wastewaters before discharging in the waterbodies. Reference tables of pollutant concentrations were provided and set the limit values for the treated wastewater to be discharged into the waterbodies. The impossibility to consider the cumulative effect produced by many effluent point sources on one single receiving waterbody was the main limitation of this law (Merli's Law n. 31911, 1976).

The overall condition (qualitative and quantitative) of the waterbodies was taken into account by the D. Lgs.152/99, that anticipated the European law WFD by one year. It confirmed the necessity to treat every wastewater but proposed new dispositions for the achievement of environmental quality targets. They were based on the pollutant effect of single effluent, and on the capacity of the receiving waterbodies to endure loads coming from all points and diffuse effluent sources. Furthermore, the law set new limit values of pollutants concentrations: they were not static but dynamic (more restrictive) in function of the characteristic of the receiving waterbody and of the pollutant sources (D.Lgs. 152/99, 1999).

The new environmental code (D.Lgs. 3 April 2006, n. 152) was issued with the purpose to reorder the laws regarding the environmental protection. It abrogates the previous law even if it maintains its normative structure and adds and updates new subjects with reference to 2000/60/EC, with particular attention to wastewater discharging.

The law locates the areas, which require particular pollution prevention measures or environmental remediation measure: the sensible areas (waterbodies), the agricultural nitrate vulnerable zones release, the zones with desertification predisposition and protected area.

Moreover, the D.Lgs. 152/06 set the fundamental principles of managing and treating the wastewaters that must be followed by the regions for the writing of “water protection plans”. These latters are the technical tools though which achieve the quality and quantity goals requested by the law. The regions must write a water protection plan referring to one single watershed.

The discharge regulation provides that:

- Urban Agglomerations bigger than 2000 PE must be equipped with sewage network
- All discharges must be authorized to quality targets of the waterbodies, expect for domestic wastewater discharged into sewage networks. In this case, they are always allowed as long as respect the regulations issued by water service
- The regions can set limit values of pollutants maximum concentrations (more restriction) different by table attached to the law
- All discharges, except the domestic ones, must be accessible for sampling activity by the authorities
- It is forbidden to discharge wastewater directly on the land surface or underground. Only specific case, previously authorized can be allowed by derogations

Specific cases, like wastewaters coming from urban agglomerations with a population lower than 2000 PE discharged into freshwaters or wastewaters coming from urban agglomeration with population lower than 10000 PE discharged into salt waters, require to be subjected to "appropriate treatments" (D.Lgs 152/2006, 2006).

In the following paragraphs, some key concepts and definitions used for comparing different water protection plans written by regions.

2.2.1 Population Equivalent (PE)

The Population Equivalent (PE) is the number that expresses the sum of pollution loads produced by resident inhabitants, by floating population (commuters and tourists) and by the inhabitant number equivalent to economic activities.

The reference national legislation (Legislative Decree 152/2006), in article 74 paragraph 1 letter a), defines the population equivalent as the biodegradable organic load having a biochemical demand for 5-day oxygen (BOD_5) equal to 60 grams of oxygen per day.

When the organic load analytical data is not available, some regions consider 200 litres of wastewater as the pollution load produced by one person, some others calculate the equivalent load considering the total residential volume (D.Lgs 152/2006, 2006).

2.2.2 Urban Agglomerations and Appropriate treatment system

In article 74, letter n) of Legislative Decree 152 of 2006, the definition of urban agglomeration is provided as follow: "An agglomeration is the area in which the population and productive activities, are concentrated and for which the collection of its wastewaters into a sewer network and the conveyance to a treatment systems is technically and economically admissible".

The identification and delimitation of agglomerations are closely linked to development urbanization of the territory, to the interconnection programs of the sewage-treatment systems, as well as to specific territorial needs.

The term "agglomeration" should not be confused with administrative entities (such as municipalities or others local authorities). The borders of an agglomeration can match or not on the borders of an administrative entity or a watershed. In fact, a single agglomeration can have one (1: 1 ratio) or more

(1: n ratio) wastewater treatment plants or it can have multiple collection sewer network, each of which connected to one or more treatment systems.

The pollution load (in terms of Population Equivalent PE) produced by an agglomeration, the receiving waterbody typology (freshwaters, estuaries and coastal waters) and the characteristic of discharging area (sensible area, insensible area) are the factors used for choosing the type of suitable treatment system.

As reported in the paragraph 1.2 of national legislation, for agglomerations with population equivalent number lower than 2,000 the use of “appropriate treatment systems” is imposed. The term was first introduced by Directive 91/271 / EEC, with the meaning of "urban wastewater treatment through which can guarantee, after the discharging of treated waters, the respect of the receiving waterbodies quality targets requested by this and other directives". Three parameters define an “appropriate treatment systems”:

- Easily maintain and manage of the systems
- Tolerance to high hourly organic and hydraulic load variations
- Low investment, management and maintenance costs.

The “appropriate treatment” can be primary or secondary ones in relation to the technical solution chosen and purification targets requested. For agglomerations with population equivalent in the range of 50 and 2000 PE, it is advisable to use phytoremediation systems like lagoons and Constructed Wetlands or other techniques like percolates filters.

For urban centres with population equivalent between 2000 and 25000 PE, phytoremediation treatments can be integrated to activated sludge treatments (secondary step) as tertiary step (D.Lgs 152/2006, 2006).

2.2.3 Criteria for identification of equivalent domestic wastewaters

The national law declares that wastewaters, coming from industrial and agricultural activities, can be treated as domestic wastewaters if the qualitative characteristics are equivalent. In article 101, subsection 7, letter e) of D.Lgs. 152/2006, a list of criteria for the identification of wastewaters equivalent to domestic one is provided:

a. Wastewaters coming from agricultural industry
b. Wastewaters coming from breeding industry

c. Wastewaters coming from industrial activities as the ones described at point a and b, which also perform activities of transformation or valorisation of agricultural products
d. Wastewaters coming from aquaculture and fishing farming that produce discharged wastewaters and that are characterized by breeding density of 1 kg or less per square meter or that use a water flow equal to 50 litres per second or less
e. Wastewaters having equivalent qualitative characteristic to domestic ones and described inside the normative
f. Wastewaters coming from spa activities.

Therefore, on the basis of what is established by the regional legislation, wastewaters that have equivalent qualitative characteristics to domestic ones but that come from non-residential buildings (artisanal or industrial or commercial), can be treated as these latter. In addition to the individuation criteria of equivalent domestic wastewaters, certain regions have set emission limit values that wastewaters must satisfy upstream of any purification treatment (D.Lgs 152/2006, 2006).

CHAPTER 3 GENERAL DESIGN

The Constructed Wetlands are engineering systems, which are designed for attempting to mimic the natural wetland structures and to foster the biological processes that contribute to the improvement of water quality. High flexibility and adaptability of these systems allow to deal with different types of wastewaters, but a standard design cannot be determined. Every site is unique, and the CW system must be preliminary studied, planned and designed specifically for fulfilling the required objectives. The site topography, geology, hydrology, and land availability provide important information and limitations to have to take into account, and the system should be designed to minimize the environmental impact and to take advantage of the natural site features.

Mitsch suggested some general guidelines in the book “Landscape design and the role of restored, restored and natural riparian wetlands in controlling nonpoint source pollution” (Mitsch, 1992):

- Simple design
- Mimic natural wetlands (avoid over-engineering)
- Minimal maintenance
- Design the system to use natural energies (gravity flow)
- Integrate design within nature
- Design for the extremes of weather and climate (floods, droughts, storms)

3.1 DESIGN ASPECTS

To design an efficient Constructed Wetland system, some main factors must be taken into account. Following they are listed and then briefly explained:

3.1.1 Objectives and processes
3.1.2 Hydraulic retention time
3.1.3 Hydraulic load
3.1.4 Substrate
3.1.5 Pre-treatment and Primary treatments
3.1.6 Inlet/outlet structures
3.1.7 Beds configuration

3.1.1 Objectives and Processes

A Constructed Wetland system can be designed for a single objective (treating and making water suitable for other purposes) or multiple ones, but water treatment is always included. Beside the wastewater treatment, as we have seen in the chapter 4 "Constructed Wetland in the frame of circular economy", CW secondary objectives can be:

- Water reuse
- Water retention/storing or flood waves attenuation
- Biomass production
- Nutrients recovery
- Energy production
- Recreational purposes

The purpose for which treated water should be used, defines the treatment objectives (Langergraber, et al., 2019). For instance, if the treated water is to be used for flushing the toilet, it makes less sense the complete removal of pathogen microorganisms.

However, in various countries some purposes, that require a particular quality effluent to be accomplished, are obstructed by restricted regulations. For example, water reuse for agricultural irrigation would not require water quality in which pathogen concentration is close to zero. Nevertheless, Italian regulation require the application of zero-risk approach, therefore the spreading of CW system for agricultural reuse is limited (Langergraber, et al., 2019). Instead, The World Health Organization propose the adoption of a pragmatic approach, in which an assessment of microbial risk, an evaluation of the suitable pathogen reduction level and how to achieve this, must be made case by case (Licciardello, et al., 2018).

In that countries governed by these restrictive guidelines, it is therefore appropriate a revision of the regulations in order to exploit the full potential of circular management of water and substances (Langergraber, et al., 2019).

The definition of the purposes, hence consequently objectives, is carried out through the main water quality parameters concentration setting:

- Oxygen demand (BOD and COD)
- Phosphorus
- Nitrogen ($N\text{-}NH_4$, $N\text{-}NO_3$, $N\text{-}NO_2$)

- Pathogen microorganisms (Total Coliforms, Escherichia coli)

Once the objectives are defined, the designer must carry out the identification of the suitable processes (physical, chemical, biological) needed to accomplish the goals. The following table (tab.2) summarizes the objectives and the processes required to reach them.

Objective	Processes
Improve water quality	
Removal of solids	Filtration Sedimentation
Removal of dissolved organic matter	Aerobic degradation Anaerobic degradation
Removal of ammonia	Nitrification Adsorption
Removal of nitrogen	Denitrification after nitrification Plant uptake
Removal of phosphorus	Adsorption Precipitation Plant uptake
Removal of microbial contamination	Filtration Disinfection
Removal of organic micropollutants	Biological degradation Adsorption
Removal of metals	Sorption Plant uptake Precipitation
Remove water/reduce water content	Evaporation Evapotranspiration
Recover energy from biomass	Biomass production
Enhance biodiversity	Creation of habitats

Table 2: Processes required to reach the specific objectives (Langergraber, et al., 2019)

As it was explained in the first chapter, second paragraph "Constructed Wetland typologies", different configurations can perform different processes. Hence, the identification of the processes needed is linked with the choice of the CW typology. In the table 3 there are summarized the processes occurring in the main CW types. Each typology is ranked according to the goodness in carrying out a specific process. Double plus '++' indicates that this process is a primary process in the CW type. For instance, if we want to obtain anaerobic degradation, only HF CW can be used. Moreover, '+' or 'o' indicate that by using that CW type, the process occurs even though it is not primary one (Langergraber, et al., 2019).

		Processes												
		Sedimentation	Filtration	Aerobic Degradation	Anaerobic Degradation	Nitrification	Denitrification	Adsorption	Sorption	Precipitation	Plank uptake	Evaporation	Biomass production	Creation of habitats
CW types	Vertical Flow		++	++		++		+	+				+	+
	Horizontal Flow		++	o	++		o	+	+	o		+	+	+
	Free Water surface	++	+	+	+	+	+			o	+	o	+	++
	Aerated		++	++		++		+		o			o	o

Table 3:Processes in Constructed Wetland types (Langergraber, et al., 2019)

3.1.2 Hydraulic retention time

The retention times can vary from few hours to days. When we are designing a CW, the maximization of the contact between wastewater and the ecosystem components (biofilm, plants, etc.) is important because microorganisms cause the majority of removal activities. The contact efficiency depends on the water path inside the system and it is strictly related with the dimensioning and retention time calculation phases. Hence, the designer should try to optimize the theoretic retention time and should make sure that this latter is as much close as possible to the real retention time.

The retention time depends on the bed slope, the vegetation density, the bed area width, and the bed shape. (DLWC, 1998)

During the summer period, the evapotranspiration can significantly increase the retention time, whereas the winter freezing can decrease it.

In CW with surface water flow, the water flows through the filling medium and the retention time is in function of hydraulic conductivity of medium itself (Nuttal, et al., 1997).

3.1.3 Hydraulic load

The hydraulic load, which the Constructed Wetland is subjected, is another important factor to consider during the design and dimensioning phases. It must be able to tolerate sensible daily or seasonally variation of load due to changing in climatic conditions, infiltration, or simply more wastewater production.

The load is strictly related to the site hydrological factors (climate conditions, hydraulic conductivity of medium, organic load, etc.), and together with the removal percentage that we want to achieve, they are the factors which determine the geometry and depth of the CW system (Romagnolli, 2000).

Another time it is highlighted the importance to know the chemical composition of the treating wastewater, for the calculation of retention time and the system dimension.

For containing and limiting the effects of hydraulic load variations, it is frequently used to put in place in parallel another bed.

3.1.4 Substrate

Another important factor to consider in the design phase is the substrate. It has multiple roles in the system, not only it guarantees the support of the vegetation, but also it acts as an important mechanical and chemical filter for some substances contained in the wastewater (Romagnolli, 2000). For this reason, the substrate choice depends on the characteristic of inlet wastewaters.

Usually, the substrate is a mixing of clean and washed inert (fine or coarse gravel, sand) that is tested in laboratory before putted in place. Its porosity, hydraulic conductivity, and granulometric curve are calculated, whereas the thickness is determined considering the max depth of vegetation species planted (Romagnolli, 2000). The following table (tab.4) summarizes the most used substrate for filling the Constructed Wetland beds.

Typology	Grain dimension (mm)	Porosity (%)	Hydraulic conductivity (K_f = m*d^{-1})
Sand	1-2	30-32	420-480
Fine gravel	8-16	35-38	500-800
Coarse Gravel	32-128	4045	1200-1500

Table 4: Main geologic parameters of type of substrates (Romagnolli, 2000)

Furthermore, artificial mediums can be used as substrate, even if their use is still uncommon. The most known are LECA (Light Expanded Clay Aggregate), very light expanded clay with grain size between 1 – 32 mm and created in special high temperature hover, and BIOBLOCK, polyethylene matrix with high porosity where the plants are rooted. Instead, the use of waste materials as ashes, sawdust, mining and building wastes, is still little experienced (Romagnolli, 2000).

In Constructed Wetland systems with subsurface flow, the substrate choice is particularly important. The first SSF systems used soil (hydraulic conductivity 0.86 m*d^{-1}) as substrate, since the designers thought that after 2 or 3 working years the soil would have increased its conductivity value due to the plants and roots growth. On the contrary, it occurred the creation of stagnant zones and flow surface areas due to this such low soil permeability. In some part of the bed, the vegetation grew with difficulty for the lack of water, and the performance of the systems did not meet the expectations (EC/EWPCA, 1990). Hence, the designers changed the material used to fill the beds and have been chosen the sand and the gravel. Moreover, putting in place coarse gravel layers (grain size 50 – 100 mm) at inlet and outlet, high permeability is provided and possible clogging phenomena are avoided (Romagnolli, 2000). In conclusion, particularly attention must be taken during the building phase of the systems, avoiding the entrance of the soil inside the bed that could compromise the hydraulic conductivity of the medium and the system efficiency.

3.1.5 Pre-treatment and primary treatments

In Constructed wetland systems the main biological treatment stage is the second and occurs inside the planted bed. As all biological treatments, to obtain a correct functioning of the treatment beds, pre-treatment and primary stages are needed.

The objective of pre-treatment is the removal of coarse solids and other large materials often found in raw wastewaters. Basing on the wastewater characteristics, the suited pre-treatment typologies is chosen. The typically operations used include coarse screening and grit removal (ISPRA , 2012).

The next stage is the primary treatment, where the settleable organic and inorganic solids are removed by sedimentation, in order to avoid the possible risks of clogging in the second stage. It is commonly used put before the beds an Ihmoff Tank" or septic tanks with two or three chambers.

3.1.6 Inlet/outlet structures

An important aspect for obtaining an efficient treatment system is the inlet wastewater system, which has the function to regularize the water level and uniformly distribute the inflow into the bed.

For a SWF CWs, the wastewater is distributed through a superficial channel, superficial T shape pipes or free entrance. Same methods are preferentially used (cleaner, low clogging risk) in HF CW, even if the flow distribution can be made also through submerged pipe. For these typologies of CW, it is common to create coarse gravel layers (1 m width) upstream and downstream to the remediation zone, to avoid preferential paths inside the bed (Pergetti, 1994).

Instead, in VF CW the wastewater superficial distribution is uniformly obtained by using perforated PVC or PE pipes. They are placed inside the upper substrate layer or 10 cm above the surface level, and normally provide a discontinuous flow alimentation, controlled by pumps.

The outlet structure is equal for every typology and consists of a drainage pipe that has the function of collect the treated water and regularize the water level inside the bed. In this way, it is possible to completely empty the bed for maintenance operations, as change substrate or remove undesired weeds.

3.1.7 Beds configurations

As it has been explained in the previous paragraphs, a Constructed Wetland system can be composed by more than one bed or cell. The cell disposition and configuration depend mainly on the treatment objectives defined in the preliminary design phase, on the hydraulic regime and on the inflow and outflow waters quality.

The single cell can be disposed in series, in parallel or in a combination of these two.

The parallel disposition is used to obtain more flexibility in order to easily exclude cells which need maintenance or limit the discharge variation effects. In these cases, it always is important to control that the flow is appropriately divided between cells (it does not necessarily have to be proportionate).

On the other hand, the disposition in series has the advantages to reduce the hydraulic short-circuit, to increase the treatment efficiency, and to physically separate the treatment zones for each pollutant (Romagnolli, 2000). In this latter case, the disposition can be designed in the way to have organic removal in the first cell, then nitrification in the second one (where aeration is provided) and concluding with denitrification in the last cell.

The combination of parallel and series cell disposition is always the best option in terms of efficiency, flexibility, and adaptability, even if the building and maintenance cost obviously increase (Romagnolli, 2000).

3.2 PRELIMINARY DIMENSIONING

Considering all the aspect above explained, the dimensioning of the Constructed Wetland cells is the next stage.

The cell sizing is made by using different methods, empirical or mathematical, based on the kinematic equations. For a preliminary study, an initial idea of needed area is provided. The superficial dimensioning is calculated considering the surface value for population equivalent (m^2/PE) in relation to the wastewater sources and the objective that it wants to obtain. This approach is simple and fast, and it is useful for a first rough dimensioning and as a final check.

To verify the acceptability of preliminary sizing and calculate what will be the theoretical purification yields, you need to use mathematical models.

3.2.1 HF wetlands

The most common CW typology used is the horizontal subsurface flow (HF CWs). They have high removal efficiency of BOD and TSS, but low capacity to reduce the nitrogen and phosphorus compounds, due to the predominantly anaerobic environment created. However, the HF wetlands can be very effective at denitrification if the nitrate and carbon presences in water column are sufficient.

For the preliminary dimensioning of surface area, the specific surface area requirement (m^2/PE) is used. The following table (tab.5) summarizes the main design parameters of HF wetlands for secondary or tertiary treatment of domestic wastewaters, including the specific surface area requirements.

	Czech Republic	Spain	US	UK
Treatment Step	Secondary	Secondary	Secondary	Tertiary
Pre-treatment	Screens + Imhoff tank	Screens + septic tank	Septic tank	Primary settling + biological treatment
Specific surface area requirement (m^2/PE)	5	10	5 – 10	0.7
Maximum areal organic loading rate (g $BOD_5/m^2 \cdot d$)	–	6	4 – 8	2 – 13
Maximum cross-sectional organic loading rate (g $BOD_5/m^2 \cdot d$)	–	–	250 [a]	–
Hydraulic loading rate (mm/d)	–	20	20 – 40	200
Gravel size (mm)	< 20	5 – 6	> 4	10 – 12
Distribution system	Subsurface pipes	Subsurface pipes	Subsurface pipes	Surface trough
Reference	Vymazal (1996) Vymazal and Kröpfelová (2008)	García and Corzo (2008)	Wallace and Knight (2006)	Cooper *et al.* (1996) Griffin *et al.* (2008)

[a] This value has been reduced to 100 g $BOD_5/m^2 \cdot d$ in a recent proposal by Wallace (2014).

Table 5: HF CW design parameters for domestic wastewater treatment (Dotro, et al., 2017)

For the dimensioning of the transversal area, the Darcy equation (eq.1) is applied:

$$A_T = \frac{Q_m}{k_f * \frac{dH}{ds}} \qquad (1)$$

Where:

A_T = transversal bed area (m^2)

Q_m = average wastewater flow (m^3/s)

k_f = hydraulic conductivity (m/s)

dH/ds = hydraulic gradient approximated with the bottom bed slope (m/m) (dH = water depth, ds = bed length)

In this equation, Cooper advices to use type of substrate with hydraulic conductivity value higher than 10^{-3} m/s, in order to limit the clogging. Moreover, the average bed depth should be 0,6 m and the slope should not be higher than 1% (Cooper, 1993).

Once the transversal area is obtained, the minimum bed length can be calculated (eq.2). A suitable value of this parameter can remove the risk of hydraulic short-circuit, the creation of surface flow path and stagnant zones that negatively influence the remediation yield of the system. Generally, the length-to-width ratios is between 2:1 and 4:1 for secondary systems, while for tertiary ones the width is typically higher than length to maximise the cross-sectional area and reduce the clogging possibility (Dotro, et al., 2017).

$$w = \frac{A_T}{0{,}95 * d_m} \qquad (2)$$

Where

w = minimum bed width (m)

A_T = transversal area (m^2)

0.95*dm = 95% of minimum wet depth of the medium (m)

Regarding the bed depth the guidelines are not rigorous. In Europe, most HF CWs present a bed depth of 60 cm (Cooper, et al., 1996), whereas in America it use to design horizontal flow wetlands with bed depth between 30 and 45 cm (Steiner & Watson, 1993). Moreover, in 2004 Garcia carried out an experiment in which efficiency of HF wetlands with an average depth of 27 cm was compared with the one of HF wetland with 50 cm average water depth. The results showed how the shallow wetlands have been more efficient that the other (Garcia, et al., 2004).

In general, it is recommended to use an average depth of 40 cm, considering the possible rainfall contribution, which could cause surface flows.

3.2.2 VF wetlands

The vertical flow configuration is commonly used for secondary treatment of domestic wastewater where ammonia nitrogen concentration is the main concern. The highly oxidising conditions and the intermittent loading give to VF wetlands extremely high efficiency in organic compound removal and suitable conditions for the occurring of nitrification processes. Thanks to these properties, VF CWs can be also used for treating landfill leachate and food wastewaters, which are characterized by high ammonium nitrogen and organic compound levels, and agro-industrial wastewater as olive mill effluents, animal farm effluent (Kadlec & Wallace, 2008).

For surface area preliminary dimensioning, two methods can be used: the empirical one, multiplying the specific surface area requirements to the population equivalent, or the Platzer method, based on the oxygen demand.

The table 6 summarizes the main design parameters for domestic wastewater treatment and guidelines in Denmark, Germany, and Austria, providing the specific surface values.

The second design model, proposed by Platzer in 2000, is based on the oxygen requirements for the aerobic processes (COD oxidation, nitrification).

The superficial area is calculated by the following equation (eq.3):

$$A_S = (1 + 0{,}25) * \frac{OD}{K_a} \qquad (3)$$

Where:

A_S = superficial wetland area (m^2)

OD = oxygen demand (g/d)

K_a = superficial aeration coefficient (gr O_2/g COD)

The superficial aeration coefficient has values between 30 – 56 gr O_2/g COD (Romagnolli, 2000) and depends on the oxygen input mechanism (diffusion and convention) (Dotro, et al., 2017).

Design Parameter	Denmark [a]	Germany	Austria
Minimum size	5 PE	4 PE	4 PE
Primary treatment (septic tank)	2 m^3 for a single household (5 PE)	0.3 m^3/PE (min. 3 m^3)	0.25 m^3/PE (min. 2 m^3)
Specific surface area requirement (m^2/PE)	3	4	4
Max. organic loading rate (g COD/m^2·d)	27	20	20
Main layer			
Filter material	Sand	Sand 0.06 – 2 mm	Sand 0.06 – 4 mm
Depth (cm)	100	> 50	> 50
d_{10} (mm)	0.25 – 1.2	0.2 – 0.4	0.2 – 0.4
d_{60} (mm)	1 – 4	-	-
$U = d_{60}/d_{10}$	< 3.5	< 5	-
Distribution System	-	Minimum one opening hole per m^2	Minimum one opening hole per 2 m^2
Reference	Brix and Johansen (2004) Brix and Arias (2005)	DWA (2017)	ÖNORM B 2505 (2009)

[a] for VF wetlands up to 30 PE, the Danish guidelines require recirculation of 50% of the effluent to the 1st chamber of the septic tank.

Table 6: main design parameters for VF CWs in Denmark, Germany, and Austria (Dotro, et al., 2017)

The Total Oxygen Demand (OD) for organic matter decomposition and nitrification, taking into account the oxygen recover by denitrification, is calculated with the equation 4. It is assumed a complete nitrification (eq.6), about 10 % denitrification (eq.7), and average 85% COD removal efficiency (eq.5) (Dotro, et al., 2017).

$$OD = OD_{COD} + OD_{nitrification} - OD_{denitrification} \qquad (4)$$

$$OD_{COD} = 0.85 * 0.7 \frac{g\ O2}{g\ COD} * COD_{in} \qquad (5)$$

$$OD_{nitrification} = 4.3 \frac{g\ O2}{g\ TKN} * \ TKN_{in} \qquad (6)$$

$$OD_{denitrification} = 0.10 * 2.9 \frac{g\ O2}{g\ TKN} * \ TKN_{in} \qquad (7)$$

Where:

OD_{COD} = oxygen demand due to decomposition of organic matter (g/d)

$OD_{nitrification}$ = oxygen demand due to nitrification (g/d)

$OD_{denitrification}$ = decreased oxygen demand due to partial denitrification (g/d)

COD_{in} = COD influent load (g/d)

TKN_{in} = TKN influent load (g/d)

Once the OD is known, the treatment area is calculated by the ratio with Ka, and then increasing the value to 25% as precautionary factor (Romagnolli, 2000).

Regarding the water depth, the VF system are built with larger values than HF systems. In UK the recommended depth is between 50-80 cm values (Cooper, et al., 1996), in Germany greater than 80 cm (ATV, 1998), in Austria around 95 cm (ONORM B 2505, 1997), while in Denmark is often higher than 100cm (Brix, 2004).

3.2.3 FWS wetlands

The FWS Constructed Wetlands are the simplest configuration, the lowest cost required and the first to be implemented in history. They are commonly used as tertiary treatment for polishing non-point sources (urban stormwater, municipal wastewaters, agricultural runoff, etc.) but also as secondary treatment with only solid separation objective.

To preliminary design a free water surface system, you can refer to the following average values of main parameters (tab.7), taken from references (Vismara, et al., 2000) (Crites, 1994):

PARAMETER	AVERAGE VALUE
Retention time (d)	5 – 14
Maximum organic load, BOD (kg/ha per day)	80
Water depth (m)	0.15 – 0.8
Superficial bed area (m^2/PE)	4 – 40 (> 20 for secondary treatment)
Bed Length/Width (-)	2:1 – 10:1
Superficial area/vegetated area (%)	40 - 60

Table 7: Main design parameters for FWS CW design (Vismara, et al., 2000) (Crites, 1994)

Kadlec provides another important guideline for preliminary design. He fixed between 4 – 20 m^2/PE the specific superficial area requirement value for the treatment of domestic wastewaters with polishing objective or BOD and suspended solids removal (Kadlec & Knight, 1996). However, this approach is not suitable for nitrification objectives, for which value higher than 20 m^2/PE are needed.

3.3 MATHEMATICAL MODELS

The preliminary sizing approaches must be confirmed by using mathematical models. The most used models are: Kadlec & Knight model (K – C*) (1996), Reed, Crites & Middlebrooks model (1995) and EPA model (1993;1999). All of these are based on simplification of phytoremediation systems in which the CW systems are approximated with an adherent biomass plug-flow reactors, and where the polluting substances are degraded with a first order kinetics.

3.3.1 Kadlec & Knight model

The Kadlec & Knight model, also called K-C*, simulates the removal of BOD, suspended solids (TSS), total phosphorus (TP), total nitrogen (TN) and faecal coliform (FC) as first order kinetic degradation. The system is approximated to a plug-flow reactor (ANPA, 2002)_(APAT, 2005) (EC/EWPCA, 1990).

The model is an amendment to the older Kickuth equation and differs to its for two aspects:

- It is a reversible first-order reaction equation rather than the irreversible one

- It includes a non-zero background concentration

The irreversible equation did not satisfactorily describe the pollutant removal from the wetlands. In facts, the pollutant concentrations can never reach zero due to the subsequent release of pollutants resulting from transformation processes within the sediments and sediment water interaction (Frazer & Williams, 2010). These concentrations are called non-zero background concentrations (C*). Sometimes these can be higher than the influent ones (ANPA, 2002), hence, their knowledge and consideration are important to avoid too optimistic calculations.

The K-C* model is almost independent from the temperature. For this reason, it is easy to apply, but it is not very sensitive to the climatic condition variations, especially because the biological processes are strongly temperature dependent.

The general equation (eq. 8) is:

$$\ln \frac{C_e - C^*}{C_i - C^*} = \frac{-K}{q} \qquad (8)$$

Where:

C_i = influent concentration (mg/l)

C_e = effluent concentration (mg/l)

C* = non-zero background concentration (mg/l)

K = areal rate constant (m/y)

H = water depth (m)

q = specific flow rate (m/y)

From the specific flow rate definition q (m/y), the superficial area can be obtained (A_S):

$$q = \frac{365 * Q}{A_S} \qquad (9)$$

Where:

A_S = superficial area (m^2)

Q = average flow rate (m^3/d)

$$A_S = \frac{365 * Q}{K} * \ln \frac{C_i - C^*}{C_e - C^*} \qquad (10)$$

In case, the temperature is considered, the value of K becomes K_T temperature dependent, and its value is calculated by the following equation (eq.11):

$$K_T = K_R * \theta_R^{(T_W - T_R)} \qquad (11)$$

Where:

K_T = temperature dependent removal rate constant at T_W (d^{-1})

K_R = removal rate constant at T_R (d^{-1})

T_W = water temperature (°C)

T_R = reference temperature (°C)

θ = temperature factor (-)

Kadlec & Knight (1996) test the model for different systems and they affirm to carefully used the global parameters determining from data recorded by North American Data Base. The authors suggest to locally determine such parameters. The table 8 summarizes the average global parameters calculated by NADB for the K-C* model at T_R 20 °C:

Surface flow	BOD	TSS	Organic N	Sequential NH_4–N	Sequential NO_x–N	TN	TP	FC
K (m/year^2)	34	1000[a]	17	18	35	22	12	75
θ	1.00	1.00	1.05	1.04	1.09	1.05	1.00	1.00
C^* (mg/L)	$3.5 + 0.053C_i$	$5.1 + 0.16C_i$	1.50	0.00	0.00	1.50	0.02	300[b]

[a] Rough unsubstantiated estimate, settling rate determination preferred.
[b] Central tendency of widely variable values.

Table 8: K-C model parameters at reference temperature 20 °C (Kadlec & Knight, 1996)*

3.3.2 Reed, Crites & Middlebrooks model

The Reed et al. model is based on first order cinematic and the assumption of a plug-flow model, for the removal through biological processes of some main wastewater parameters (BOD, Ammonia, Nitrates) (ANPA, 2002)_(APAT, 2005)_(Reed, et al., 1995). Reed suggest different equation for suspended solids (TSS) and total phosphorus (TP), based on regression analysis by NADB (North American Data Base) (Kadlec & Knight, 1996) .

For BOD, NH4 and NO3 removal, the equations used to calculate the treatment area are (eq.12, 13, 14):

$$\ln\left(\frac{c_i}{c_e}\right) = K_T * t \quad (12) \qquad K_T = K_R * \theta^{(T_W - T_R)} \quad (13) \qquad t = \frac{V_f}{Q} = \frac{A_S * y * n}{Q} \quad (14)$$

Where:

t = retention time (d)

Ce = effluent concentration (mg/l)

Ci = influent concentration (mg/l)

K_R = rate constant at reference temperature (d^{-1})

K_T = rate constant at temperature T (d^{-1})

θ = temperature factor at reference temperature

T_W = average water temperature in wetland (°C)

T_R = reference water temperature (°C)

A_S = treatment area (bottom area) of wetland (m^2)

Q = average daily flow in the wetland (m^3/d) = (Qi -Qo)/2

V_f = wetland volume (m^3)

y = average depth of water in the wetland (m)

n = porosity of the wetland (% as a decimal)

L = bed length (m)

W = bed width (m)

K_R and θ are parameters that depend on wastewater characteristics and temperature, and which are necessary to calculate the superficial area. The authors propose some reference values for temperatures between 1 and 10 °C and temperatures higher than 10°C., which are summarized in the table 9:

$1<T_W<10$				
PARAMETER	**BOD**	**NH4-N**	**NO3-N**	**FC**
T_R	20	10	10	20
C*	6	0.20	0.20	-
K_R	1.104	K_{10}	1.000	2.6
θ_R	1.06	1.15	1.15	1.19

$T_W>10$				
PARAMETER	**BOD**	**NH4-N**	**NO3-N**	**FC**
T_R	20	20	20	20
C*	6	0.20	0.20	-
K_R	1.104	K_{NH}	1.000	2.6
θ_R	1.06	1.048	1.15	1.19

Table 9: Reed Model parameters (Reed, et al., 1995)

K_{NH} is the nitrification rate constant and depends on the bed height percentage occupied by roots (rz):

$$K_{NH} = 0.01854 + 0.3922 * rz^{2.6077} \qquad (15)$$

K_{10} is obtained by the following equation:

$$K_{10} = K_{NH} * 1.048^{-10} \qquad (16)$$

From the definition of retention time (eq.14), it is possible to calculate (eq.17) the superficial area A_S (bottom area) of the Constructed Wetland bed.

$$A_s = L * W = \frac{Q * t}{y * n} = \frac{Q * \ln\left(\frac{C_i}{C_0}\right)}{K_T * y * n} \qquad (17)$$

For the suspended solids removal (TSS), Reed suggests different equations to calculate the influent and effluent concentration (eq.18 and 19):

$$C_e = C_i * (0.1139 + 0.00213 * q) \qquad (18)$$

$$C_e = C_i * (0.1058 + 0.0011 * HLR) \qquad (19)$$

Where:

Ce = effluent concentration (mg/l)

Ci = influent concentration (mg/l)

q and HLR = hydraulic load rate (cm/d) = 100*Q/A_S

Q = average flow (m^3/d)

A_S = superficial area (m^2)

The background concentration C* is equal to 6 mg/l.

For the faecal coliform removal, the author approximates the removal processes occurred into the CWs to the removal model of stabilized ponds. Some experiments confirm the validity of this approximation, that uses the following equations (eq.20):

$$\frac{N_e}{N_i} = \frac{1}{(1 + K_T * t)} \qquad (20)$$

Where:

N_e = E.Coli number in 100 ml of effluent

N_i = E.Coli number in 100 ml of influent

K_T = rate constant at temperature TW (d^{-1})

t = retention time (d)

Instead, the model that better describe the phosphorus removal (TP) is:

$$C_e = C_i \, e^{\frac{-K_P}{q}} \qquad (21)$$

Where:

C_e = Phosphorus effluent concentration (mg/l)

C_i = Phosphorus influent concentration (mg/l)

K_P = Phosphorus rate constant at reference temperature = 2.73 cm/d

q = hydraulic load (cm/d)

3.3.3 EPA model

The Environmental Protection Agency of United States proposes in 1993 and then a revision in 1999, another mathematical model, based plug-flow reactor with first order kinetic too (ANPA, 2002) (APAT, 2005).

The suggested equation (eq. 22) is:

$$\frac{C_e}{C_i} = e^{(-K_T * t)} \qquad (22)$$

Where:

C_e = BOD effluent concentration (mg/l)

C_i = BOD influent concentration (mg/l)

K_T = rate constant dependent to temperature and vegetation density (d^{-1})

t = retention time (d)

The retention time is calculated by the equation (eq. 23):

$$t = \frac{n * L * W * d * 0.95}{Q} \qquad (23)$$

Where

n = porosity (-)

W = bed width (m)

0.95*d = 95 % of bed depth (m)

L = bed length (m)

Q = average flow (m^3/d)

Combining the previous equations (eq.22 and 23), the treatment area A is obtained as follows:

$$A = L * W = \frac{Q * \ln \frac{C_i}{C_e}}{n * 0.95 * d * K_T} \qquad (24)$$

The K_T value is calculated by substituting the constant values (K_{20} = 1.104, θ = 1.06) reported by authors inside the equation (eq.25):

$$K_T = K_{20} * \theta^{(T-20)} \qquad (25)$$

3.3.4 Monod model and simulation software

The previous mathematical models based on first kinetic order, are commonly used to practical applications. In the last years, simulation software has been diffused and preferred for designing and removal prediction activities. They describe the biological processes (degradation and transformation processes), the hydraulic condition, the transport processes, the biofilm, and microbial growth occurred inside Constructed Wetland areas by using simultaneous implementation of models (Rousseau, et al., 2003) (Saeed & Sun, 2011) (Langergraber, et al., 2019).

One of these models is called Monod, and it used to describe the BOD, COD, and nitrates (NO_3) removals. It corrects the first kinetic order models that provide a continuous increasing of pollutants removal rate with the increase of hydraulic loads. This non-realistic phenomenon was corrected Monod, suggesting a new equation (eq.26):

$$C_i - C_e + C_{half} * \ln \frac{C_i}{C_e} = -\frac{k}{q} \qquad (26)$$

Where:

C_e = effluent concentration (mg/l)

C_i = influent concentration (mg/l)

C_{half} = semi-saturation constant (mg/l)

k = first order constant rate (m/y)

q = hydraulic load (m/y)

The C_{half} represents the concentration measured at semi-saturated substrate. Saeed & Sun in their article " Kinetic modelling of nitrogen and organics removal in vertical and horizontal flow wetlands" suggest some C_{half} values for BOD (60 mg/l), COD (20 mg/l), and NO_3 (0.14 mg/l) removal (Saeed & Sun, 2011).

3.4 VEGETATION SPECIES

The vegetation species used in phytoremediation systems are plants (aquatic and hydrophilic plants) that live normally in natural humid environment (lakes, wetlands, marshes) and be adapted to grow in soils partially or perpetually saturated.

In the natural lake ecosystem, the aquatic plants live in different zones depending on the water depth. The lake environment can be divided in three main zones (fig.13):

- Littoral zone
- Limnetic zone (euphotic zone, characterized by passive fluctuant microorganism or plankton)
- Benthic zone (aphotic zone, corresponding to the bottom of the lake with absence of solar light and lived only by macrobenthos animals).

The Constructed Wetland environment looks like the littoral zone, where we can find three types of aquatic plants:

- Emergent macrophytes
- Floating hydrophytes
- Submerged hydrophytes

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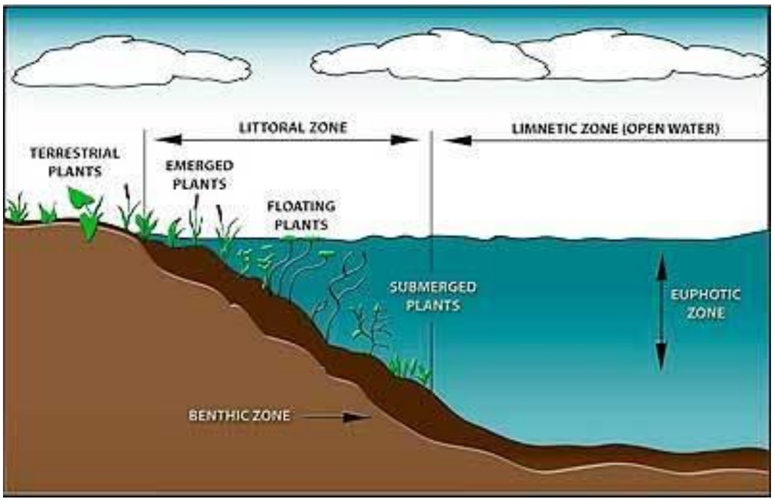


Figure 13: transversal lake section and its zoning based on depth (Lakeaccess, s.d.)

These plants play a key role in biological processes that occur in aquatic environments. Thanks to the chlorophyll, they can transform the solar energy in chemical one, which is usable by every life being for growth and reproduction. To fulfil this essential function, the plants need an environment which ensures all the elements (solar light, water, nutrients) required to make the organic synthesis.

In the phytoremediation systems, the main function of these plants is the oxygen production through photosynthesis process and the motion of the O_2 molecules from the leaves to the stem and to the roots. Fundamental elements that influence the growth and life of used vegetation species, are the substrate, the chemical composition of wastewaters, and the climate conditions (ISPRA , 2012).

Different types of aquatic plants can be used inside the Constructed Wetland, and we can choose the most suitable species basing on the CW configuration. The vegetation species used are usually perennial and native plants that can adapt themselves to saturated and eutrophized conditions (ISPRA , 2012).

We will enter more in details and will name some more common and suitable plants for phytoremediation systems, after the next paragraph where it will explain the vegetation function in the remediation processes.

3.4.1 Vegetation function:

In the Constructed Wetlands the plants play an active role for the depuration processes, as well as aesthetic. The wastewater treatment is based on the cooperative actions of macrophytes and microorganisms, which are the main responsible of organic matter degradation.

The main function that the plants provide in the remediation process, is the transfer of oxygen from the aerial parts to the rhizosphere. Developing a dense and intertwined root system, the macrophytes stabilize the substrate, ensuring the physical filtration processes and avoiding the clogging phenomena of the medium. Moreover, they provide, through oxygen transportation, the optimal conditions for the creation of suitable environment for the microbial growth. Thanks to a special spongy tissue, called parenchyma, that composes the internal structure of the stem and the roots of aquatic plants, the oxygen is moved from the leaves and stem to the rhizosphere (Romagnolli, 2000) (see fig. ??8).

Usually, the macrophytes roots are immerged into the sediments, which are environment characterized by lack of oxygen. As consequence the plant has difficult to respire and to get needed energy for the ions adsorption and metabolism. Therefore, the plant can survive by using the oxygen flows though the channels network of parenchyma (Romagnolli, 2000).

The excess of this supplied oxygen that is not used for plant metabolism, is transported to the roots and the rhizosphere. Here, aerobic microzones are created in a predominantly anaerobic environment which allow the growth of different microorganism species (Camuccio & Barattin, 2001). These latter are responsible for the oxidation of organic compounds, the ammonification and nitrification. Moreover, the nitrogen cycle is completed by the anaerobic bacteria that perform the denitrification (fig.14).

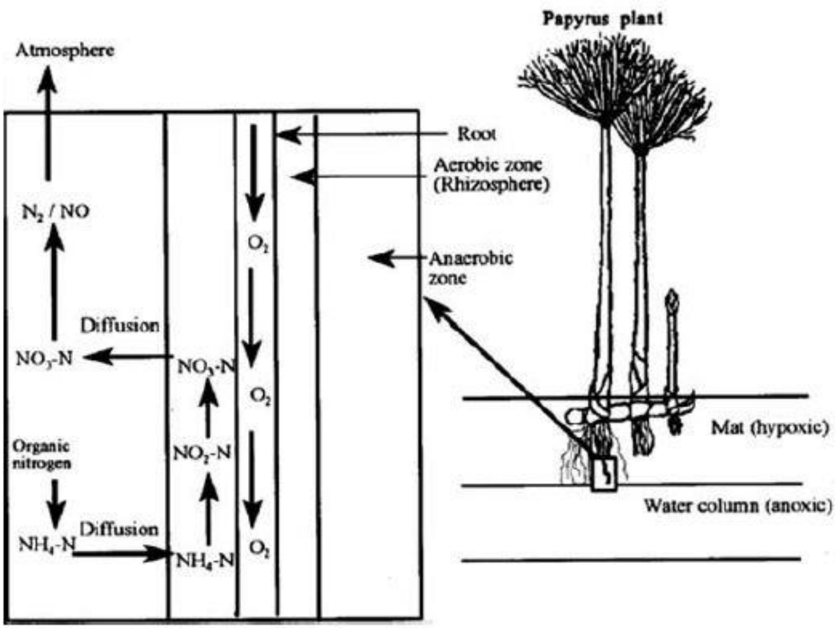


Figure 14: Oxygen translocation scheme into the rhizosphere and its subsequent use in nitrogen cycle (Kansiime, et al., 2007)

The oxygen translocation inside the plants occurs for passive diffusion under gas concentration gradient and for convective flux under pressure gradient that is generated by different physical processes. The causes of the pressure gradient are not clear. Some authors identify as the cause the difference in temperature and vapour tension between porous septa of vegetal tissues, some others indicate the induced Venturi ‘s effect generated by the wind velocity gradient around the plant (Brix, 1993) (Amstron_J. & Amstrong_W., 1990).

About the amount of oxygen transported to the roots, in literature uniform values does not exist, due to the different conditions under which the experiments were made. Reed and Brow in 1992 conduced an experiment in which they studied a species of macrophytes called *Pharagmites australis*. They affirmed that the oxygen released by the roots varied from 0.02 $g/m^2/d$ to 45 $g/m^2/d$, depending on the vegetation density, the saturated soil oxygen request and the roots permeability values (Reed & Brown, 1992).

For the choice of vegetation species to use in the Constructed Wetland, the type and the extension of root system result important parameters. In fact, they influence the depth of which the oxygen can be transported and the contact surface between wastewater and rhizosphere, and therefore the remediation yields. *Pharagmites australis* results particularly efficient in the oxygen transportation because its rhizomes can penetrate on average between 70 – 80 cm in depth (Gesberg, 1986).

In addition to the oxygen transportation function, the macrophytes have other important intrinsic properties that make them essential components for the wastewater treatment in CW:

- Stabilize the beds surface
- Provide good condition for physic filtration
- Change the hydraulic conductivity of the medium
- Avoid clogging phenomena in vertical flow systems
- Provide wide superficial area as substrate for the microbial growth
- Remove nitrogen, phosphorus, and other dangerous compounds through roots adsorption (ISPRA , 2012).

3.4.2 Vegetation choice:

The choice of vegetation species to plant in the CWs must consider multiple aspects, including climate condition of the phytoremediation system location, wastewater composition and the required effluent quality.

A suitable vegetation must be chosen in relation to:

- Adaptability to the soil saturation conditions
- Root system potential growth and extension
- Root system oxygen translocation capacity
- High photosynthetic capacity
- Resistance to high pollutants concentration
- Resistance to disease
- Simplicity in management (planting, propagation, harvesting) (ISPRA , 2012).

Moreover, it is important to consider the velocity and methods of plant propagation. Some species can have an excessive growth and propagation and can infest the aquatic environment and compromise their natural cycles.

The vegetation species used in phytoremediation systems are predominantly herbaceous species, and they can divide in **macrophytes or helophytes** and **hydrophytes**.

These latter are aquatic perennial plants with submerged or floating buds. Some authors can further subdivide in other two subcategorize: **pleustophytes** which have not roots inside the substrate and freely float on the water surface, and **rhizophytes** that have roots inside the substrate (Romagnolli, 2000).

The rhizophytes can live totally submerged in the water (submerged hydrophytes, fig.16) or can be rooted into the substrate and have flowers or leaves emerged and floated on surface (floating hydrophytes, fig.15). Their use in phytoremediation systems is limited to clean and oxygenated waters due to their sensibility to the anaerobic conditions, or to combination with other emergent plants (ISPRA , 2012).

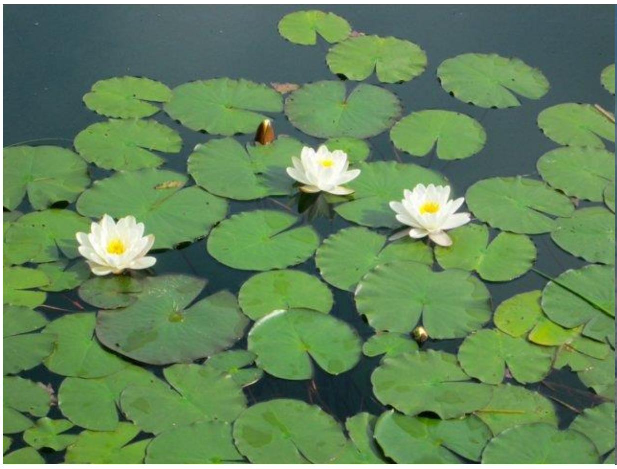


Figure 15: Nymphaea alba, floating hydrophytes (Cheshire, 2019)

Figure 16: Myriophyllum spicatum, submerged hydrophytes (Pondsuperstore, s.d.)

On the contrary, the pleustophytes (fig.17 and 18) are plants not rooted into the soil and freely floating on the water surface. They are characterized by high efficiency in nutrient absorption, which makes them suitable for tertiary treatments (effluent polishing or nutrient removal). Their root system extends along all the water column so that the probability of direct nutrient absorption is increased. Furthermore, also the surface where the biomass grow is increased, with the consequence the filtration and adsorption processes of the colloidal substances are improved. An important aspect that it must be considered is the possible wide propagation and extension of their leaves, which can totally cover the water surface. As consequence, the solar light penetration and the oxygen diffusion along the water column are limited, favouring the growth of photosynthetic algae and the anaerobic condition establishment (ISPRA , 2012) (Pignatti, 1982).

Figure 17: Lemma spp., pleustophytes (Wikipedia, s.d.)

Figure 18: Eichornia crassipes, pleustophytes (Fishinnet, s.d.)

The other type of plants used in phytoremediation systems are the macrophytes or helophytes (fig.19 and 20). They are terrestrial vegetation that over time have adapted to the life in partially or totally saturated soils. Their roots settle into the soil and the plant grows in height and emerge over the water surface with the leaves. The majority of emerged macrophytes species have an extended aerial tissue system (aerenchyma) which allow the transport from the leaves to the roots and the surrounding soil (Brix, 1993).

The macrophytes are often used in free water surface CWs and, also in Vertical and horizontal subsurface flow CWs.

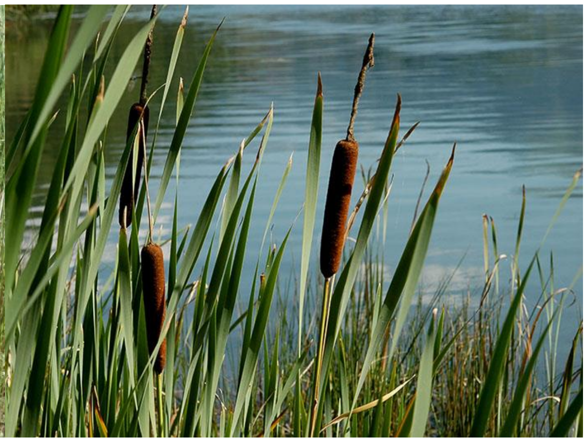


Figure 19: Juncus spp., emerged macrophytes (Wikipedia, s.d.) *Figure 20: Typha latifolia, emerged macrophytes (Vivai Valverde, s.d.)*

The vegetation species used in Constructed Wetlands are several. In general, to obtain better results in terms of vegetation growth, it is advisable to choose native plants, adapted to the environmental conditions yet. The choice of the vegetation species depends mainly on the type of configuration system. In the following tables are summarized the vegetation species names mostly used in Italy, based on the CW configuration as visible in Table 10 and 11:

FREE WATER SURFACE CONSTRUCTED WETLANDS (FWS CWs)	
HELOPHYTES or MACROPHYTES	**HYDROPHYTES**
Phragmites australis (o communis)	**Submerged Hydrophytes**
Thypha minima	Myriophyllum spicatum
Schoenoplectus lacustris	Patomogeton natans

HELOPHYTES or MACROPHYTES	HYDROPHYTES
Juncus spp.	Ceratophyllum demersum
Butomus umbellatus	**Floating Hydrophytes**
Carex fusca	Nimphaea alba
Carex hirta	Nimphaea rustica
Carex elata	Nuphar lutea
Iris pseudacorus	Nymphoides peltata
Alisma plantago acquatica	**Pleustophytes**
Lythrum salicaria	Hydrocaris morus – ranae
Gliceria maxima	Lemma spp.

Table 10: most used vegetation species in water free surface CWs (FWS CWs) in Italy (ISPRA , 2012)

SUBMERGED FLOW CONSTRUCTED WETLANDS (HF or VF CWs)
HELOPHYTES or SUBMERGED MACROPHYTES
Phragmites australis o communis
Typha latifolia
Thypa minima
Typha angustifolia
Shoenoplectus lacustris o Scirpus lacustris
Juncus spp.

Table 11: most used submerged macrophytes in Subsurface flow Constructed Wetlands (HF or VF CWs) (ISPRA , 2012)

When we are dealing with subsurface flow systems (HF or VF CWs), the roots penetration depth is the main aspect to consider for calculating the suitable height of the bed. As it has been explained in the previous paragraphs, the root system depth and extension are important parameters which influence the oxygen translocation and the contact surface extension between wastewater and rhizosphere, thus the treatment efficiency (tab.12).

PLANT	ROOT PENETRATION DEPTH (cm)
Phragmites australis (o communis)	70
Typha latifolia	30 – 40

PLANT	ROOT PENETRATION DEPTH (cm)
Schoenoplectus lacustris	80
Juncus effuses	60 - 90

Table 12: root penetration depth of aquatic species used in HF CWs (ISPRA , 2012)

For the design of Free Water Surface Constructed Wetlands (FWS CWs), the water depth is the most important parameter to consider for the vegetation species choice (tab.13).

HELOPHYTES		HYDROPHYTES	
PLANT	**WATER DEPTH (cm)**	**PLANT**	**WATER DEPTH (cm)**
Phragmites australis	0 – 100	Myriophyllum spp.	10 – 20
Thypha minima	0 – 40	Patomogeton spp.	>50
Schoenoplectus	0 – 100	Ceratophyllum dem.	>50
Juncus spp.	0 – 30	Nimphaea alba	70 – 110
Butomus umbellatus	10 – 30	Nimphaea rustica	70 – 110
Carex spp.	0 – 10	Nuphar lutea	30 – 50
Lythrum salicaria	0 – 30	Nymphoides peltata	30
Alisma plantago aq.	10 – 20	Hydrocaris m.-r.	Floating
Iris pseudacorus	0 - 20	Lemma spp.	Floating

Table 13: Suitable water depth for aquatic plants in FWS CWs (ISPRA , 2012)

In addition to these parameters (roots penetration depth, water depth), other aspects must be taking into account during the design phase:

- Sale and installation costs
- Maintenance coasts
- Aesthetic features
- Availability.

In Europe, the most common plants used in Constructed Wetlands belong to *Phragmites* family, due to their low maintenance and high growth and diffusion rates. In Italy, *Phragmites australis*, *Schoenoplectus lacustris* (or *Scirpus lacustris*) and *Typha latifolia* are the most used (ISPRA , 2012).

3.4.3 Vegetation planting and propagation

The plants present in phytoremediation systems can be sowed or be directly planted in the substrate. In this latter case, the plants can come from natural wetlands with similar climate condition than the destination area, where they grow spontaneously or can be bought at the plant shop. The planting is preferred than sowing because the latter requires longer time to reach a totally and uniform cover of water surface.

In the specific case of *Phragmites macrophytes,* if the planting operations are made during spring, they consist of the young plants transplantation into the substrate, with density of 3-4 plants/m^2,while during the autumn it is preferred to bury rhizomes (4-5 m^2) of 15-20 cm length. Moreover, the rhizomes must be placed at 20 cm in depth and 25-30 cm apart from each other (ISPRA , 2012).

The best period for planting is the spring season, where the buds of the rhizomes can germinate immediately, avoiding freezing and premature death, which can occur during autumn.

In general, the plants need a period of 2-3 years for reaching the maximum growth and root extension. The alternation of hydraulic regime (humid/dry) favours a higher roots growth rate. The horizontal growth of rhizomes allows the total cover of the Constructed Wetland at the start of second year (Romagnolli, 2000).

Once the plant is grown, rooted macrophytes are more resistant to any drought periods compared to the other plant species considered. The biggest problem is the presence of other vegetation species that compete with macrophytes for nutritional resources: the most frequent are *Urtica dioica*, *Convolvolus arvensis*. For this reason, at least every 6 months in the first 3 years and then when it need, maintenance operations and manual elimination of weeds should be done (Romagnolli, 2000).

3.5 OPERATION AND MAINTENANCE ASPECTS

Operation and maintenance can be classified in three aspects:

1. Start-up operations
2. Routine operations
3. Long-term operations

3.5.1 Start-up operations

The start-up requirements are characterized by site-to-site variability. Its duration depends on the type of design, the wastewater features, and the season of year, and mainly consists of making sure that the vegetation uniformly grows and begin to root. For make this, the primary concern is the adjustment of water level in the wetland. The water must fill the wetland to the surface and saturate the substrate until the plants are rooted. After that, the water level can be lowered to design operating level.

3.5.2 Routine operations

The routine operations are affected by design details. They do not take long time and big interventions, due to the natural capacity of the wetland to self-adjust. The main aspects that an operator must take under control are the water level and the flow control.

Significant changing in water level could be an alarm bell for clogging phenomena, leaking and breached berms.

The clogging at inlet and outlet structures can affect the Constructed Wetland performances, reducing the hydraulic detention times. Particularly attention must be paid in HF CWs, where the inlet clog could create a short-circuit, determine the substrate clog and the water rising at the surface and the formation of stagnant zones.

Therefore, a constant control of the flow uniformity inside the wetland must be provided and, debris removal and manifolds cleaning should be periodically made.

One of the most common cause of clogging is the pre-treatment malfunctioning. Hence, the septic or Imhof tanks should be emptied and cleaned one or two time per year, whereas the residual sludge should be disposed in accordance with national regulations.

Regarding the vegetation maintenance, for FWS wetlands the operator must mow the plants, remove, and dispose the biomass generally one time per year. For the SSF systems the cutting operation are not required since the plant communities are self-maintaining. The suitable water level maintaining and constant undesired plants (weeds) harvesting, provide the conditions for having a balance plant life cycle (growth, death, regrowth).

3.5.3 Long-term operations

Beside the routine operations, which are essential to maintain perfectly functioning the wetland systems, data monitoring (flow rates, water level, water quality) and performance evaluation should be regularly performed. However, sampling and analysis activities of inflow and outflow waters, the pollutants concentrations (TSS, BOD, COD, NH_4, NO_3, TN, TP, TF) are monitored and the removal yield of system deduced.

The operation and maintenance requirements are classified by frequency of action and listed in the tables 14 to 16:

Berm/Wall	• Visual inspection for weeds, erosion and damage
Inlet	• Visual inspection for adequate and uniform inflow and identification of blockages and damage • Maintain and adjust as required
Outlet	• Visual inspection for blockages and damage, and visual check of water level and outflow quality and quantity
Vegetation	• Visual inspection for any weed, plant health or pest problems. Take remedial action as necessary

Table 14: Fortnightly Operation and Maintenance action list (UN-HABITAT, 2008)

Berm/Wall	• Visual inspection for weeds, erosion and damage. Take remedial action as necessary
Outlet	• Check functioning of discharge system and apparent health of receiving water • Where appropriate, mow or graze (sheep only) grass on outer embankments and wetland surrounds
Vegetation	• Control weeds in wetland by handweeding, herbicide application, and/or temporary water level increase
Primary treatment	• Visual inspection of upstream primary treatment for structural integrity, quantity and quality of effluent

Table 15: Two monthly operation and maintenance action list (UN-HABITAT, 2008)

Substrate	• Check clogging of the substrate, remove the substrate, clean it and replace if necessary
Inlet	• Remove end caps from inlet pipe and distribution network and flush out and clean thoroughly to remove slimes and blockages
Outlet	• Clean and remove plants around outlet pipe to provide access and guard against blockages.
Vegetation	• Harvest vegetation and replant if necessary
Primary treatment	• Check sludge levels in primary treatment and desludge as necessary to maintain treatment performance and avoid sludge drift into wetland

Table 16: Yearly operation and maintenance action list (UN-HABITAT, 2008)

CHAPTER 4 CONSTRUCTED WETLAND IN THE FRAME OF CIRCULAR ECONOMY

Water management is included in the 17 Sustainable Development Goals (SDGs), precisely in the 6^{th}, Clean Water and Sanitation. It aims at ensuring water access for all and guarantee sustainable management of water and sanitation. Despite the progress, billion people around the world still lack water and sanitation services. In 2017, 2.2 billion people have not access to safety managed drinking water and 4.2 billion lacked safely managed sanitation. Nowadays with Covid-19 implications, the issue become more relevant. Three billion people worldwide lack the basic handwashing facilities at home which is the most effective method for Covid-19 prevention (United Nation - Department of Economic and Social Affairs - Sustainable Development, 2020).

In 2019 World Economic Forum listed the water scarcity, defined as the lack of freshwater resource to meet the standard water, as one of the largest global risk in term of potential impact over the next decade. Even if the amount of freshwater on a global scale is sufficient for satisfying the needs of worldwide people, half a billion people live under condition of severe water scarcity all year round. It is expected that water scarcity, caused by the unequal distribution around the globe of the freshwater resources (exacerbated by climate change), will displace more than 700 million people by 2030 (United Nation - Department of Economic and Social Affairs - Sustainable Development, 2020).

Unfortunately, the lack of available freshwater in several regions of the world is only one of the current and future environmental issues that worries the humanity at global level. There is the need of decoupling the human well-being from resource demand; hence a list of general challenges was identified:

- Cut greenhouse gas emission to 4% of present levels globally
- Consume all but no fossil fuels
- Eliminate mined phosphorus demand within the next 80 years
- Drastically reduce reactive nitrogen production and release into the biosphere
- Massively cut biodiversity loss
- Deal locally with lack of available freshwater in several regions of the world (Masi, et al., 2017)

Starting from the industrial revolution, the anthropogenic activities, with the increase of carbon dioxide CO_2 and dinitrogen monoxide N_2O release in the atmosphere and the production and use of fertilizes in intensive agriculture, have conditioned and changed the natural cycles of carbon C and nitrogen N. The change in fixation, mobility and speciation of C and N lead to unbalance and the decoupling of these cycles, which have remarkable consequences also on natural water resources, like ocean acidification and increase of the net primary productivity in water bodies (Masi, et al., 2017).

It is possible to note how all challenges above identified, are linked and interdependent. Hence, we cannot face every problem individually, but we need a largest and comprehensive vision to find solutions that includes more problems.

For instance, talking specifically about water resources, problem solving activities cannot be focused on only drinking water and basic sanitation availability, but the entire water cycle must be accounted, including management of water, wastewater, and ecosystem resources. The problem of limited freshwater resources leads to put more effort on protection of those, in term of quality and quantity. As consequence, the wastewater issue becomes urgent, especially if we think that 80% of worldwide wastewater are untreated or not correctly treated and directly discharged into the water bodies (Masi, et al., 2017). Referring to the circular economy approach, where source one substitutes the concept of waste, a new approach in water management, resource-oriented, must be adopted. The wastewater flows must not be considered anymore as waste to treat and dispose but as a resource, a carrier of valuable primary chemicals, which can be converted to marketable products (fertilisers, biofuels, bio-plastic, soil conditioners, etc.), or a relevant source of "new water" to be reused for different purposes.

In this scenario, the Constructed wetlands CWs (or treatment wetlands) with their flexibility, adaptability, little maintenance, and low operation cost, can play a key role in the wastewater treatment, sanitation, and resource recovery.

4.1 FROM WASTE PARADIGM TO RESOURCE ORIENTED AND CIRCULAR ECONOMY

The current common scheme of water management in urban areas is based on combined sewer systems (fig.21). They are designed to collect rainwater runoff, domestic sewage, and industrial wastewater in the same pipe. Most of the time, combined sewer systems transport all of their wastewater to a sewage treatment plant (Waste Water Treatment Plant), where it is treated and then discharged safely into a receiving water body. The treatment principle consists of "eliminating" as much of the pollutant substances contained as possible, in order to preserve the environmental quality of the receiving water bodies (Masi, et al., 2017).

During periods of heavy rainfall or snowmelt, however, the wastewater volume in a combined sewer system can exceed the capacity of the sewer system or treatment plant. For this reason, combined sewer systems are designed to overflow occasionally and discharge excess wastewater directly to nearby streams, rivers, or other water bodies. These overflows, called combined sewer overflows (CSOs), contain not only storm water but also untreated human and industrial waste, toxic materials, and debris. The picture followed shows a sketch of current common scheme of water management in an urban settlement (EPA, s.d.).

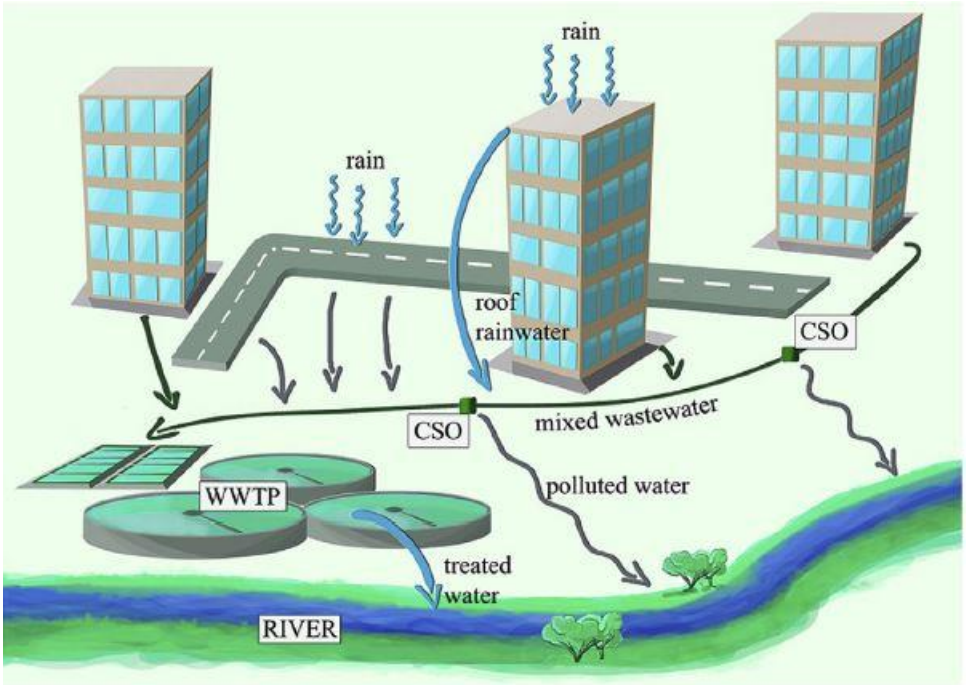


Figure 21: Current common scheme of water management in an urban settlement (Masi, et al., 2017)

Turning toward more sustainable water management systems is necessary to accomplish the challenges and the goals of Agenda 2030 signed by ONU. The future urban water systems will be resource oriented, sustainable, and integrated with different nature-based systems (as Constructed Wetlands, ponds, vertical garden, sustainable urban drainage systems SUDs). The waste becomes a resource and the main target is not wastewater treatment anymore, but the production of goods. An unique optimised system with multiple purposes (wastewater treatment, production of fertiliser, provision of urban green, production of renewable energy) substitutes a plurality of separate infrastructures with single purposes (Masi, et al., 2017).

In this idea, the current scheme of water management (collection, treatment, and release) is substituted with one more complete service chain from production to reuse (from cradle to cradle) (Braungart, 2007), characterized by smart collection and resource processing. Upstream prevention and sources separation result fundamental to avoid a unique mixed wastewater flow, and allow, downstream to treat and, when is possible, valorise all substances (usable and harmful) contained through suitable treatments for future reuse and marketability. Every treatment system must be tailored to a specific source (domestic, hospital or industrial wastewater) and reuse purpose (e.g. irrigation, toilet flushing), and the level of satisfy requested will depend on the type of source and reuse (Masi, et al., 2017).

As all substance flow management systems, the water one must satisfy the triple criteria of sufficiency, consistency, and efficiency (Sachs, 2008). “Sufficiency stands for the reduction of flows and volumes to necessary levels and uses, consistency is to be seen with respect to the environment and efficiency of systems is only sought once the other criteria are met” (Masi, et al., 2017).

The table 17 summarizes the differences between the actual and the future water systems.

Water systems from present	To future
treatment of waste	manufacturing of products: water, fertiliser (N, P, K), soil conditioner (compost, bio-char, substrate, ...), heavy metals,...
single purpose, e.g. water treatment, water supply, water evacuation...	multifunctional approaches
linear, disrupted and disconnected cycles	closing and reconnecting loops
centralised	distributed, optimised between sites of production of raw material and use of products
largest possible, claiming economy of scale	all sizes
remote, out of sight	integrated everywhere in the urban fabric and in buildings
technical	ecosystems
repulsive	attractive
static	flexible
vulnerable	resilient, robust
unaffordable for a large part of the global population	affordable for all because of multiple purposes
high-tech	smart
end-of-pipe	source control
based on a city-wide piping network	all options from no network to multiple smaller and larger networks to present situation
all-in-one solution	source separation where helpful for product quality
evacuating “stormwater”	harvesting rainwater
dealing with different kinds of water in the urban fabric in distinct, unconnected ways and systems: supply water, wastewater, stormwater, natural waters... or combining them in ways making their further use difficult, e.g. in a combined sewer.	integrating all kinds of waters in a unique system, a network with many nodes in order to use all possible sources but keeping flows separate where necessary for further use
ineffective for any kind of new pollutant	responsive to new pollutants through source control, systemic adaptation and diversity
selecting resistant germs	preventing the selection of resistant germs through systemic response, e.g. isolation of hospital wastewater

Table 17: current and future water systems features (Masi, et al., 2017)

An example of possible future scheme of sustainable water management in an urban settlement is showed in the figure 22. Safe evacuation of sanitary wastewaters, water saving, rainwater retention, maximising resource and water recover and reuse, maximising crops production and reduction of non-renewable energy use are the main targets set.

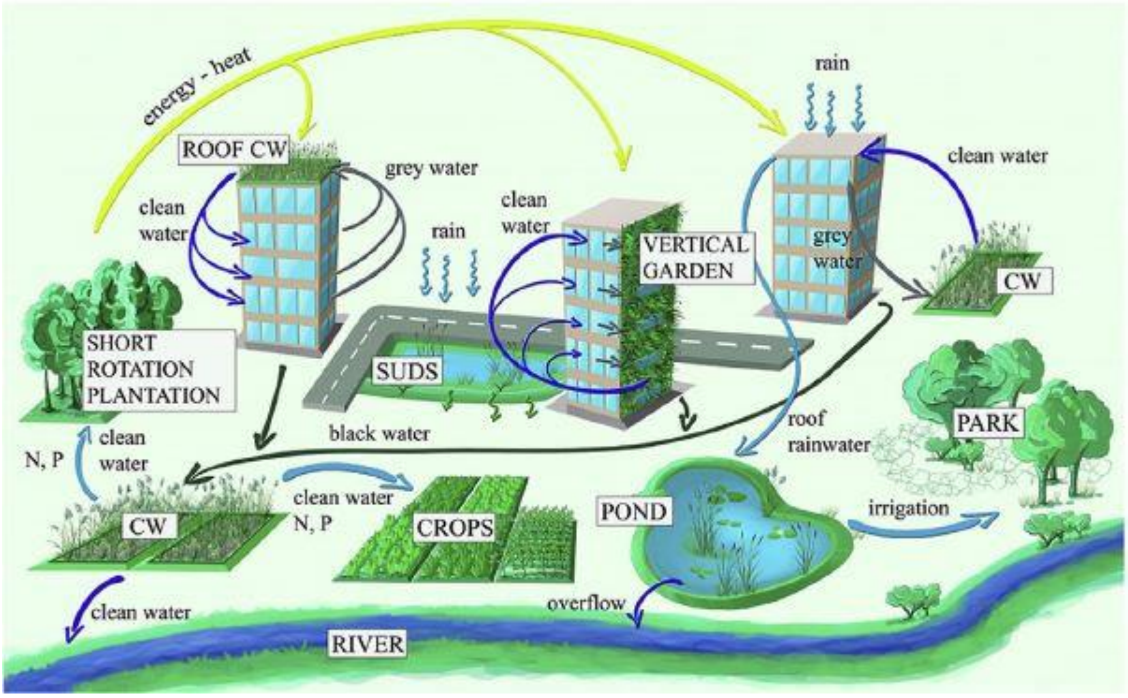


Figure 22: Future scheme of sustainable water management in an urban settlement (Masi, et al., 2017)

Firstly, the wastewaters must be separated between useable (greywaters) and harmful substances (black waters), characterized by pathogen present. The grey waters feed apposite Constructed Wetlands built on the roof or close to the buildings, where the biological processes purify them, reducing the organic content, nitrogen, and phosphorus concentration. The clean water resulted will be undrinkable, but it could be reused to irrigate the gardens or flush the toilet.

The black part wastewaters, due to the richness in nutrient and the high content of suspended material, must be treated in different ways. Special CWs are built with the purpose of recover the N and P present into urine and faeces and use them to fertilize the crops or short rotation plantations. In these latter the trees grow fast due to the high nutrient availability. The woody biomass produced is used as a renewable and clean fuel for heat and power generation, or for further processing into liquid biofuels.

The unnecessary clean water, treated by CWs, is discharged into the closest receiving water bodies, without cause quality problems.

As far as the rainwater concerned, they are collected by sustainable urban drainage systems, capable of mitigate the effects of human development has had or may have on the natural water cycle, particularly surface runoff, and water pollution trends. The collected waters feed ponds where they are treated and prepared for irrigation of parks or garden. The possible overflow is discharged into the receiving water bodies.

These sustainable water managements are part of a future idea of green, sustainable and energy independent town. To create this new water scheme and build the blue and green area, large space is needed. Appropriate solutions within the urban fabric must be found, with attention to the improvement of urban aesthetic aspect. To make this, a collaboration between administrations and different professionals (engineers, architects, biologist, and agronomist) that work together with synergy, is needed. Moreover, for a well-functioning of the entire system, the contribution of users is essential, as must adapt their behaviour and habits to the new system (Luthi, et al., 2011).

4.2 POTENTIAL APPLICATION OF CWS WITHIN NEW WATER MANAGEMENT SCHEME

Nowadays, Constructed Wetlands are considered a reliable and efficient biological treatment technology for mixed domestic wastewaters but the transition to the new water management system fixes new different targets (water reuse, nutrient recovery, energy production, ecosystem services) which requires some design adaptations.

In the following paragraphs, they will be analysed the most promising new CW applications and the best configuration which are required to accomplish the single goals.

4.2.1 Water reuse

Water reuse is the most important new target and the most influent in the new water management scheme, in which finds application in agriculture, for irrigation of field and gardens but also at domestic level for flushing the toilets. Many potential water sources for reuse are available, but the easier to collect and treat is the rainwater. Despite the inconstancy of its availability, its collection/storage result quite simple. Due to its low concentration of pollutants, a single CW will be enough to reach the standard of reuse. Even though vertical subsurface flow configuration (VF) needs the use of pumps, it is more appropriate and efficient to treat rainwaters, due to its higher flexibility in the bed geometries (Gross, 2007).

Same consideration can be made for greywater (GW) treatment. They are characterized by low concentration of nitrogen (commonly less than 5 mg/L of NH_4), but significant levels of total suspended solids (TSS) and Organic Matter (OM). Hence, single horizontal/vertical subsurface flow beds, with small footprint (between 0.5 and 1 m^2/PE) can be enough for reaching the quality standard required for reuse (Masi & El_Hamouri, 2010).

Different speech must be made if the wastewaters are featured by high level concentration of pathogen microorganisms. In this case a single system is unable to reach the standard level required by the law (tab.18), that are quite strict, hence a multiple barrier approach is needed.

Parameters	Italian limits	European guideline	
		Quality requirements	Water quality class
BOD_5 (mg/L)	20	10	$A^{a,e}$
		25 (according to Council Directive 91/271/EEC)	B^b, C^c and D^d
COD (mg/L)	100	–	
TSS (mg/L)	10	10	$A^{a,e}$
		35 (according to Council Directive 91/271/EEC)	B^b, C^c and D^d
NH_4 (mg/L)	2	–	
TN (mg/L)	35	–	
TP (mg/L)	10	–	
Escherichia coli (CFU/100 mL)	10 (80% of samples)	≤10 or below detection limit	$A^{a,e}$
		≤100	B^b
	100 (max value)	≤1000	C^c
		≤10,000	D^d

[a] Crop category irrigable with water quality of Class A: All food crops, including root crops consumed raw and food crops where the edible part is in direct contact with reclaimed water. All irrigation methods allowed.

[b] Crop category irrigable with water quality of Class B: Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops to feed milk- or meat-producing animals. All irrigation methods allowed.

[c] Crop category irrigable with water quality of Class C: the same for the class B but only drip irrigation is admitted.

[d] Crop category irrigable with water quality of Class D: Industrial, energy, and seeded crops. All irrigation methods allowed.

[e] Performance targets for the treatment chain (log10 reduction) only required in class A: *E. coli* ≥ 5.0; Total coliphages/F-specific coliphages/somatic coliphages/coliphages ≥ 6.0; *Clostridium perfringens* spores/spore-forming sulfate-reducing bacteria ≥ 6.

Table 18: Italian and European reclaimed water quality standard for agricultural reuse (Russo, et al., 2018)

Different types of configurations were tested by the department of agricultural, food and environment of Catania University for a research study made in 2018 and titled "Constructed wetland combined with disinfection system for removal of urban wastewater contaminants”, in order to understand which is the best configuration to reach the Italian quality standards for reuse in agriculture. They tested the efficiency of two configurations, a three full-scale horizontal sub-surface flow (H-SSF) working in parallel and planted with different macrophytes species, combined in series with a UV device and a lagooning system. The experiment results showed how the combination of different treatment mechanism are essential to satisfy the law limits. Significant reduction of microbiological indicators was obtained by H-SSF CW + UV system, that resulted the best efficient configuration in the treatment of secondary effluent of WWTP for future reuse in agriculture. In the following figure (fig.23) the results are summarized.

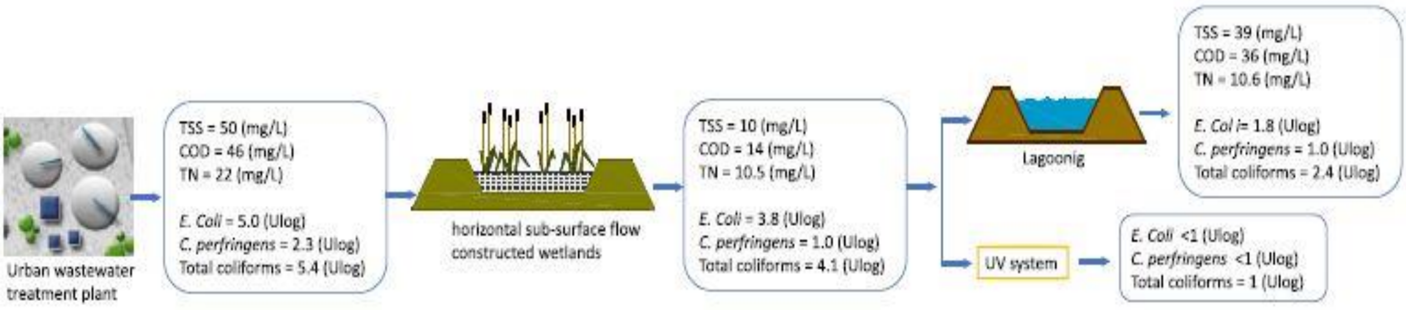


Figure 23: pathogen removal from secondary effluent by CWs, lagoonig and UV systems (Russo, et al., 2018)

Another interesting and important CWs application is the polishing of secondary treated wastewaters for reuse, as long as these still exist (Alyaz, 2008). The secondary effluents are characterized by persistent organic pollutants content (POPs), which previous treatments could not remove. The most efficient configuration is the free water surface system (FWS). The high biodiversity and the abundance of biomass (litter, plant stem, microalgae) favour the adsorption and degradation of POPs (Matamoros, et al., 2016). As in all other case, the removal efficiency of pollutants depends mainly on the hydraulic retention time (Masi, et al., 2017).

4.2.2 Nutrient recovery

Another interesting application of Constructed Wetlands is the nutrient recovery and special configurations are required. The French Redd Beds (FRBs) is one of these, and it consists of two stages. In the first stage raw wastewaters are fed in batches with a resting period of 4-8 days. In this way, drying and aerobic oxidation of the sludge layer forming on the top (growth rate 1-2 cm per year) is guaranteed. This organic layer dehydrates and degrades over time and after about 10-15 years humified biomass, rich in macronutrients, is well stabilized and suitable for reuse in agriculture as fertiliser (Paing & Guilbert, 2015). The second stage has the purpose to improve the TTS and OM removal, complete the nitrification, mostly fulfilled in the previous stage, and achieve denitrification. It can be both a conventional horizontal, or vertical flow wetland, function of water quality target to be met (IRIDRA, s.d.).

If coupled with the circular economy principle, it is possible to propose only the first FRB stage, where the effluent rich in nutrients is well suited to irrigate non-edible crops or to produce biomass for energy purposes (IRIDRA, s.d.).

In general, the FRB systems FRB does not require typical primary treatment of conventional Constructed Wetland solutions (septic or Imhoff tanks) and they needs an occupation area of 2 to 3 m^2/PE, as a function of different water quality target to be met. It notes that this range is lower in comparison to conventional Constructed Wetland solutions (usually 3-5 m^2/PE) (IRIDRA, s.d.).

Similar configuration exists to treat directly stabilized sludge, coming from activated sludge plants, and it is called Sludge Drying Reed Beds (SDRBs). The processes implemented and the final products are the same of FRB, but different is the type of inlet load. It was demonstrated that SDRBs represent the cheapest solution to treat excess sludges , and the final dewatering sludge can be potentially reused as conditioner in agriculture (Nielsen & Bruun, 2015).

4.2.3 Energy production

Regarding the energy production integration in the water cycle, CWs can play a significant role and can provide great opportunities.

As it was mentioned in the previous paragraph, CWs find application in the production of biomass. The first stage of FRB produces not only effluent rich in nutrient, but also humus. Both can be directly used for fertigation on crops fields and Short Rotation Plantation (SRP). The high nutrients availability of effluent and humus allow the rapid growth of the plants and trees. They are cut at frequent intervals and used for woody biomass production (wood chips). It is a renewable and clean fuel which is be used for heat and power generation, or for further processing into liquid biofuels. These configuration CWs + SRPs is widely diffused in the countries where the warm climate helps the vegetation growth and the biomass yields result extremely interesting (Barbera & Cirelli, 2009) (Barbagallo & Barbera, 2014).

An alternative way to producing clean energy is the biodegradation of wastewaters in anaerobic reactor. The domestic and industrial wastewaters can be collected to feed bioreactors, where under anaerobic environment microbial activity (digestion and fermentation) degrades the organic compounds and produces biogas. It can be used directly as fuels in combined heat and power gas engines or upgraded to natural gas-quality biomethane. The secondary effluent produced can undergo a polishing stage in a CW or be used for nutrient recovery.

4.2.4 Ecosystem services

Finally, in this new vision of green, sustainable cities, CWs find great potential number of applications in retention systems, too. Particularly, if the retention concept is not reduced to flood risk reduction only, the CWs can play a key role to drain runoff water and reduce the pollutant loads discharged into waterbodies (Ballard, et al., 2015). Moreover, they can work as a sponge and trap nutrients and persistent organic pollutants (POPs) that can be dangerous for the environment, and slowly degrade or transform in fertilizers (Masi, et al., 2017).

In conclusion it cannot underestimate the contribution of CWs for the quality and aesthetic improvement of the urban environments. In addition to the technical functions discussed above, they create enjoyable spaces and fruition opportunities for the citizens, raise the local biodiversity and the presence of wildlife and, not less important, they can mitigate the impact of climate change, helping to reduce the air pollutant loads and release oxygen in the atmosphere. “The concepts of ecosystem services should therefore become a basic strategy in every urban planning procedure, inserting multi-purpose green and blue infrastructures in a diffuse way in our cities” (Masi, et al., 2017).

CHAPTER 5 NATURAL SWIMMING POOLS

In this last chapter, entitled “Natural Swimming Pools – NSPs” I want to report modern applications examples of phytodepuration inside the new scheme of water management, particularly the use of Constructed Wetland systems with the purpose to water reuse, improvement of aesthetic environment and create recreative areas.

The concept of NSP is relatively new and starts to diffuse at the early 80’s mostly in German, Austria and Switzerland. It was born with the purpose to create swimming areas (pools or artificial lakes), which reproduce the self-adjusted natural characteristics of a lake, giving the possibility of bathing in completely natural purified water and also guaranteed an aesthetic improvement of the site.

The constant water quality is ensured by physical and biological treatments, which substitute the most dangerous for the human health based on chlore use. As in chlorinated pools, the water treatment and disinfection are reached by internal (in-situ) and external (ex-situ) procedures.

The in-situ mechanisms are based on the zooplankton filtration, considered to be the major factor contributing to water purification (Bruns & Schwarzer, 2013), whereas the ex-situ treatment occurs by using bio-filter and hydro-botanic plants (Constructed Wetland technique).

Hence, we can define the NSPs as living places in which perfect balance between microorganism population that inhabit it, must be achieved. On the contrary, the traditional chlorinated pools are aseptic environments in which bathing is achieved totally through artificial way.

The NSPs are distinguished from chlorinated swimming pools by:

- Total absence of chemical products and / or treatments
- Absence of washing of artificial filters
- No drain in the sewer (therefore connection is not required)
- There is no need for winter emptying and subsequent spring filling (with significant savings in water resources)
- Excellent environmental integration and aesthetic site improvement.

Figure 24: Natural Swimming Pool (ChagallGiardini, s.d.)

Their shape can be classic rectangular, like a traditional pool, or more irregular, which can replay the natural lake shape and where the vegetation is contained inside the pool (fig.24). It is also possible to convert traditional chlorinated pools to natural ones, by implementing few changes, adding the regeneration area and recirculating mechanisms, and without upset the entire system.

5.1 NSP TYPOLOGIES

The advantage of these natural systems is above all identifiable in the ease and cost-effectiveness of management. The treatment and disinfection of the water is done naturally, thanks to the aquatic plants, microflora, and microfauna presences, and without the use of chemical products that often prove to be, in addition to being expensive, harmful to health.

To obtain a suitable water treatment and filtration, the swimming area and regeneration area must be separated, and suitable ratio calculated.

The NSP can be designed as single unit (regeneration area is within the swimming area) or as a series of two or more waterbodies (regeneration area is partly or completely outsourced) (Kircher & Thon, 2016).

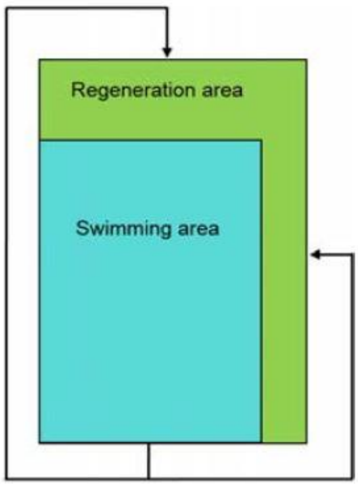
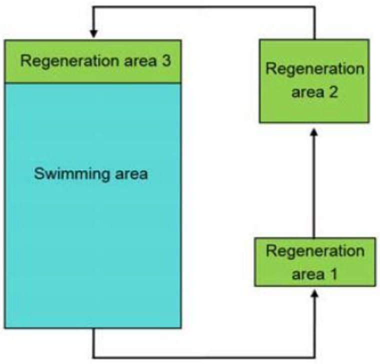


Figure 25: NSP single unit (Ecoprospettive, s.d.) (Kircher & Thon, 2016)



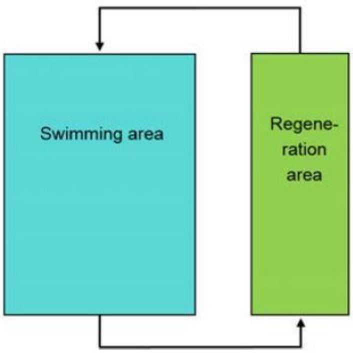


Figure 26: NSP double units (Agriverde, s.d.) (Kircher & Thon, 2016)

The appearance of the water differs considerably depending on the NSP type chosen. The different typologies of NSP are mainly based on the level of technology applied for the treatment of water. From totally naturalistic systems without any use of technique, passing from systems with low and medium techniques, up to systems with the use of various types of circuits, filtering, and mechanical suction. The less technique is used, the higher the ratio of the regeneration areas to the swimming area must be. They can be distinguished in (Spieker, et al., 2013):

- Natural pool: the easiest solution, without any implementation of pumps or filter. The water is treated only by natural systems (CW) hence the water condition is similar than a natural lake. This is the most cost-effective model, but you will need quite a large area for it to work effectively. The ratio between regeneration and swimming area is 1:1 and the vegetation species must be differentiated (emerged, submerged and floating plants). The maintenance must be regular for ensuring bathing conditions for long time.

- Low technology natural pool: in this typology skimmers or overflow gutters are added for filtering the water before entering in a pump. This latter provides a constant nutrient flow for the plants and allows to recirculate the 20% of total water volume in 24 hours. The regeneration/swimming area ratio is the same as the natural pools (1:1)

- Medium technology natural pools: it is the most common solution used, since best water quality is provided, maintaining at the same time a high natural level at relatively low costs. A pump is placed outside the pool and allows to recirculate the total water volume in 24 hours. The water must go back into the pool in a way to create flow path for encouraging and helping the filtration. Skimmers are added to increase the suspended solid removal and improve the water limpidity. The regeneration area must occupy the 40% or the total pool surface. The maintenance is mainly concentrated to the skimmer tools, which everyday have needed to be cleaned. Moreover, the vegetation growth must be controlled, and mowed when it is needed, and once a year the bottom-pool must be cleaned.

- High and very high technology natural pools: filtration and water recirculation are more efficient than the previous cases, and require more powered pumps, higher efficient organic or mineral filters using. The pumps work all day to allow the total water volume recirculation two times per day. Obviously, the energy, operation and maintenance costs are greater, but proportionated to the quality and limpidity water levels, which are the same as the traditional pools. The regeneration/swimming area ratio is reduced to 30-35 % of total surface.

5.2 INTERNATIONAL GUIDELINES

The IOB, the International Organization for natural bathing waters, provides the guidelines for the design, the maintenance of the pools and the control of water quality. They are based on the existent regulations of some European countries, like German, Austria, and Switzerland where the first NSP systems were built. However, these guidelines represent a reference to be used by other countries for defining national guidelines, which take into account the different climate conditions.

The natural swimming pools stability depends essentially on its trophic state, on the complex biocenosis and the food chains within it, hence the water quality must be regularly controlled.

The IOB proposes some threshold values of physical, biological, and chemical parameters for the swim and fill waters, with the main purpose to protect the human health, safeguard the life and the stability of the natural ecosystem, and guarantee an high comfort level.

Generally, the water analysis and threshold values control of chemical and hygienic parameters must be carried out every 14 days.

5.2.1 Physical parameters

For the bathing waters, the following parameter values are recommended (IOB, 2011):

- Water temperature: the values must be referred to the natural lake (located at the same latitude level) temperatures, measured at 30 cm depth
- Oxygen saturation: 80 – 120 %
- Limpidity: the pool bottom must be visible.

The Bolzano province have been provided through the resolution of the provincial Concilium n. 974 of 20 June 2011 (Resolution of provincial Concilium n. 974, 2011) more details about the physical requirements to respect (tab.19).

PHYSICAL REQUIREMENTS	
Oxygen saturation	60 % – 120 %
Transparency	Almost 2 m. At less depth, the bottom visible
Total Phosphorus (TP)	< 15 ug/l

PHYSICAL REQUIREMENTS	
pH	6 - 9
Temperature	≤ 24 °C

Table 19: Physical requirements for bathing water, threshold values parameter (Resolution of provincial Concilium n. 974, 2011)

5.2.2 Biological parameters

The NSPs cannot be lived by fishes, birds, snails, etc, for hygienic and microbiological reasons.

The fitoplankton (suspended algae) which should be composed by only green algae species (Chlorophyta, Bacillariophyceae, Cryptophyceae), must not cause problem of water turbidity (the pool bottom might be always visible). Its concentration, such as suspended particles one, are regulated by the zooplankton through biological filtration and other processes (IOB, 2011).

5.2.3 Chemical parameters

Different threshold values are proposed by IOB for fill water and for bathing/treated water and they are showed respectively by table 20 and 21.

Referring to the fill water, it must be taken from the aqueducts, wells or water springs, or superficial water bodies. If it comes from the latter, it must be filtered before to be used to fill the pool. Moreover, the water cannot contain chemical substances in such a concentration that can harm the human health, and any traces of faecal bacteria are not permitted. Particularly attention must be taken for the total amount of phosphorous, which cannot exceed the 0.015 mg/L (Resolution of provincial Concilium n. 974, 2011).

CHEMICAL REQUIREMENTS – FILL WATER	
pH	6 – 9
Conductivity	< 1000 VS / cm (20°C)
Total Phosphorus	< 0.015 mg/L
Nitrates	< 50,0 mg/L
Ammonia	< 0.5 mg/L

CHEMICAL REQUIREMENTS – FILL WATER	
Iron	< 0.2 mg/L
Hardness	> 1 mmol/L

Table 20: Chemical requirements for fill water (IOB, 2011)

Slightly different values are requested for bathing and the treated waters (tab.21).

CHEMICAL REQUIREMENTS – BATHING WATER	
pH	6 – 8,5
Conductivity	1500 VS / cm (20°C)
Total Phosphorus	< 0.01 mg/L
Nitrates	< 30,0 mg/L
Ammonia	< 0.3 mg/L
Hardness	> 1 mmol/L

Table 21: Chemical requirements for fill water (IOB, 2011)

5.2.4 Hygienic parameters

The guiding values for hygienic/microbiological parameters are showed in the table 22.

HYGIENIC/MICROBIOLOGICAL REQUIREMENTS	
Escherichia coli	< 100 ufc (MNP) / 100 ml
Enterococci	< 50 ufc (MPN) / 100 ml
Pseudomonas aeuruginosa	< 10 KbE / 100 ml

Table 22: Microbiological requirement, bacteria threshold values

Generally, Escherichia coli and Enterococci represent the microorganism indicators. They are not pathogen, but they can indicate the presence of microorganism pathogen (IOB, 2011).

5.3 NSP DIFFUSION – APPLICATION EXAMPLES

The concept of NSPs born in the 80’s, have been largely diffused in Europe, particularly in German and Austria. Nowadays, over than 20000 natural pools are present, mostly of them used privately, in houses, hotels or bed & breakfast, even if the public systems have been increased (Bruns & Schwarzer, 2013).

In 2009, the IOB was founded at the 5th international congress of natural swimming pools in Merano, Italy. The IOB is an organisation that groups eleven national associations (IOB, 2011) and form the international federation. The purpose is to promote the diffusion of natural swimming pools with totally biological depuration, through information activity and project and experience sharing between the single national association.

In 2011, IOB took a census of the natural swimming pools inside the eleven participating countries.

Germany and Austria, the first countries in which natural pools built, still today remain the leaders for the promotion and diffusion of NSPs. Germany has more than 500 public natural pools, on which some with accommodation capacity of 3000 people, and few thousands of private systems, whereas Austria is the country with the highest ratio population – number of NSPs. Moreover, it is the only country that has adopt standards and approved specific laws for the design, control, operation, and maintenance activities.

Quite same speech can be made for Switzerland, whereas in Spain, Portugal, Great Britain and Belgium the natural pool market has been started few years ago, with good diffusion of private systems, particularly as recreation activities of hotels, camping and farmhouse, while less common are the public systems.

Talking about our country, in Italy the situation differs from region to region. In the North the diffusion of natural swimming pools is higher than the South, in which the presence of beautiful sea places, make less important and urgent the need and desire of artificial high-water quality pools. In Tuscan, Emilia-Romagna, and Umbria, there are lot of hotels, farmhouse and resort sited in the hills and immersed in nature which offer to their customers the possibility to swim in natural pools. Trentino – Alto Adige is the region which now have invested most of all in the natural pool market. In 2014 the Public NSPs were nine in all Italian territory and sited all in Trentino - Alto Adige.

Figure 27: Dobbiaco natural pool – Pusteria Valley (BZ) (VivoAltaPusteria, s.d.)

Between these, the most famous are the Dobbiaco biolake (fig.27), inaugurated in the summer of 2008 and locate in the “Grieswaldile” recreative area, and the natural pool built in Campo Tures (fig.28), which has an area of 4500 m^2 split in half between regeneration and bathing areas.

Figure 28:Campo Tures biolake – Pusteria Valley (BZ) (Val-Pusteria.net, s.d.)

During the last July, in Rendena Valley (Trentino), a new biolake was inaugurated (fig. 29). Located in the middle of the valley and surrounded by the Alps, it provides an important and strategic bathing recreation area in a geographic zone naturally unprovided of lakes.

Figure 29: Pinzolo Biolake - Pinzolo, Rendena Valley (TN)

The artificial lake, with 5000 m^3 of water contained, has 3200 m^2 of bathing surface with 3,5 max depth, in which a portion of 100 m^2 is used for a little children pool. The shape of the lake is irregular in order to replay the natural lake shape.

Figure 30: Regeneration area with emerged macrophytes - Pinzolo Biolake

The three regeneration areas included within the swimming area provide the main treatment stage and are planted with emerged macrophytes (fig. 30), floating and submerged hydrophytes (fig. 31).

Figure 31: Floating and submerged hydrophytes - Pinzolo Biolake

Skimmers tools are placed for pre-filtering the back water before inflows into the pumps, which works 24 hours per day for providing recirculation. A final UV treatment is placed for improving the water quality and totally remove the dangerous microorganisms.

Figure 32: Skimmer tools for pre-filtering - Pinzolo Biolake

Contrary on the natural lake, any torrent or river feeds the bio-pool, except of a constant little inflow, coming from the aqueduct, which has the purpose to replace the water amount lost for evaporation. For this reason, the water inside the pool, filtered and naturally regenerated, has better water quality (low bacterial load) and more comfortable temperature (around 25°C) than natural lake.

The lake is surrounded by grass beaches, provided with beach chair and three piers from which it is possible to dive, embellishes its. Showers sited on the shore and locker rooms, energetically independent thanks to solar panels, complete the whole, providing to the tourists and customers, the comfort of a swimming pool and at the same time the natural beauty of a lake.

CHAPTER 6 CONCLUSIONS

Climate change, the depletion of natural resources and the increase in world population are alarm bells for the future that must push humanity to turn to a more sustainable use of natural resources, particularly water. Water management must shift towards solutions focused on protecting, safeguarding, and sustainably using available water resources. A new water scheme must be implemented, in which the waste paradigm must be substituted with a resource-oriented paradigm; one unique system which aims to reach multiple targets and to substitute the current scheme based on separate infrastructures for every purpose. It must be sustainable and integrated, composed of smart collection and natural-based processing of all resources contained in wastewaters (water, contained substances, energy) with the purpose of further reuse and marketability.

In this thesis work, I have analysed and deeply described one typology of Natural Base Solutions, the Constructed Wetland, which can play an important role in this scenario of prospective change. Multiple potential applications have been identified and discussed, trying to evaluate the effectiveness, the feasibility and reliability of each.

Firstly, the high efficiency of pollutant removal as well as the simple design and management, lead the CWs to be an attractive, and nowadays consolidated, alternative to conventional wastewater treatments. Completely build using natural or recycled materials, they are green and eco-friendly also in economic terms, due to their low cost and minimal time requirements for the maintenance and the operation.

Currently they already find applications as secondary treatments of domestic/industrial/agricultural wastewaters or as tertiary treatments for polishing secondary effluents. The great adaptability to any climatic condition, flexibility of enduring discontinuous and high hydraulic load variations, and the possibility to combine more different CW cells in series or parallel configurations, allows us to reach the same, or higher, treated water quality results also for small or medium communities, rural and remote regions for which it is economically infeasible to be connected with conventional sewage networks. In a prospective of urban expansion and sustainability, CWs allow for the decentralizing of wastewater treatment, decreasing the loads to the existing WWTPs, and reducing the sanitation costs.

Moreover, the ability to treat different types of wastewaters and the high efficiency of pollutant removal, give them the possibility of also being applied to other scopes: water reuse (irrigation, flushing toilets, heat exchange), nutrient recovery (fertilizers production, crops irrigation), energy production (irrigation and fertilization of short rotation plantation), and ecosystem services (recreative or green areas creation, run-off waters retention).

A significant aspect emerged by my thesis work is the creation and development of recreational applications in urban ambience, which replay the Constructed Wetland environment with the dual purpose of aesthetic improvement and water reuse. Particularly, in the last part of the thesis, I have presented and illustrated Natural Swimming Pools as natural alternative to chlorinated pools, which are nowadays a technology widely applied and developed in many European countries. The capability of CWs to reach high water quality level combined with their aesthetic contribution, allow us creating beautiful natural recreation areas with a low energy and environmental footprint and meeting spaces that, through this type of Natural Based Solution, strengthen the environmental resilience of the sites.

In conclusion, I affirm how the Constructed Wetlands are already a valid alternative for treating the wastewater of conventional systems, due to the high efficiency, the low costs and great adaptability. The eco-friendliness and energy effectiveness make them even more attractive solutions. The removal yields for water treatment or reuse are almost the same as for conventional systems, but the same cannot be said for other purposes, where improvements in reliability are needed. Furthermore, the large area required, as well as the not very good immediate yield remain drawbacks which the scientific community must further investigate.

In a prospective of green, sustainable and energy independent future cities, based on the circular economy concept, we expect that Constructed Wetland systems, thanks to their great treatment potential and plurality of applications, play an increasing and fundamental role in the future of resource-oriented, integrated water management scheme.

References:

Agriverde, n.d. *Agriverde.net.* [Online]
Available at: https://agriverde.net/biopiscine

Alyaz, 2008. Post-treatment and reuse of tertiary treated wastewater by constructed wetlands.

Amstron_J. & Amstrong_W., 1990. Light-enhanced convective throughflow increases oxygenation in rhizomes and rhizosphere of Phragmites autralis.

ANPA, 2002. *Linee guida per la ricostruzione di aree umide per il trattamento di acque superficiali - manuali e linee guida.* s.l.:Università di Padova.

APAT, 2005. *Linee guida per la progettazione e gestione di zone umide artificiali per la depurazione dei reflui civili.* s.l.:s.n.

ATV, 1998. *Principles for the dimensioning, construction and operation of plant beds for communal wastewater with capacities up to 1000 Total number of inhabitants and population equivalent,* Bonn, Germany: s.n.

Avila, 2013. Effect of design and operational factors on the removal efficiency of emerging organic contaminants in constructed wetlands for wastewater treatment.

Ballard, Woods & Wilson, 2015. The SuDS Manual.

Barbagallo & Barbera, 2014. Reuse of constructed wetland effluents for energy crops.

Barbera & Cirelli, 2009. Growth and biomass procution of different plant species in two different constructed wetland system in Sicily.

Borin & Tocchetto, 2007. Five year water and nitrogen balance for a constructed surface flow wetland treating agricultural drainage waters.

Braungart, 2007. Cradle-to-cradle design: creating healthy emission - as trategy for eco-effective product and system design.

Brisbane, 2000. Guidelines for using free water suface costructed wetlands to treat municipal sewage.

Brix, 1987. Treatment of wastewater in the rhizosphere of wetland plants. *Water Sci.Technol..*

Brix, 1993. Macrophyte mediated oxygen transfer in wetlands: transport mechanisms and rates.

Brix, 1993. Wastewater treatment in constructed wetlands: system design, removal processes, and treatment performance.

Brix, 2004. *Danish guidelines for small-scale constructed wetland systems for onsite treatment of domestic sewage,* Avignon, France: s.n.

Brix, Arias & Johansen, 2003. Experiments in a two-stage constructed wetland system: nitrification capacity and effects of recycling on nitrogen removal.

Brooks, 1998. Plants that hyper accumulate heavy metals.

Bruns & Schwarzer, 2013. Performance of publich swimming ponds - An overview of hygiene in pools with biological water purification. *Internationale organisation fur naturnahe Badegewasser (IOB),* Volume I.

Campo Tures Municipality, n.d. *Campo Tures.* [Online]
Available at: https://www.campotures.eu/it/

Camuccio & Barattin, 2001. La fitodepurazione: manuale tecnico divulgativo.

ChagallGiardini, n.d. *ChagallGiardini.* [Online]
Available at: https://www.chagallgiardini.com/biopiscine.php

Cheshire, 2019. Plant series, Nymphaea alba. Manuscript MS408(3).

Cooper, 1993. *The use of reed bed systems to treat domestic sewage: the european design and operation guidelines for reed bed treatment systems.* Tokio: Lewis Pubblisher.

Cooper, 2005. The performance of vertical flow constructed wetland systems wuth special reference to the significance of oxygen tranfer and hydraulic loadinf rates.

Cooper, Griffin & Cooper, 2005. Factors affecting the longevity of sub-surface horizontal flow system opearting as tertiary treatment for sewage effluent.

Cooper, Job, Green & Shutes, 1996. Reed beds and constructed wetlands for wastewater treatment.

Crites, 1994. *Design criteria and pratice for constructed wetlands,* s.l.: Wat.Sci.Tech.

D.Lgs 152/2006 (2006).

D.Lgs. 152/99 (1999).

Davis, 1995. A Handbook of constructed wetlands. Volume 1.

Directive 91/271/EC (1991).

DLWC, 1998. *The constructed wetlands manual,* New South Wales, Australia: Department of land and water conservation.

Dotro, et al., 2017. *Treatment wetlands vol 7.* 7 ed. s.l.:Iwa publishing.

EC/EWPCA, 1990. European design and operation guidelines for reed bed treatment systems. *Report U1.17 Water research center.*

EcoBnB, 2014. *Ecobnb.* [Online]
Available at: https://ecobnb.it/blog/2014/09/piscine-naturali-biolaghi/

Ecoprospettive, n.d. *ecoprospettive.com.* [Online]
Available at: http://ecoprospettive.com/progettare-biopiscina-natural-pool/

EPA, n.d. *EPA - United States Environmental Protection Agency.* [Online]
Available at: https://www3.epa.gov

Favotto, n.d. La fitodepurazione: come depurare l'acqua con le piante.

Fishinnet, n.d. *fishinnet.* [Online]
Available at: https://www.fishinnet.net/Eichornia-crassipes

Frazer & Williams, 2010. A review of the influence of design parameters on the performance of constructed wetlads. *Journal of chemical engineering,* ChE.25(1).

Garcia, Morator, Bayona & Aguirre, 2004. *Performance of horizontal surface flow constructed wetlands with different depths.* Avignon, France, s.n.

Gesberg, 1986. Role of aquatic plant in wastewater treatment by artificial wetlands.

Giger & Roberts, 1978. Characterization of persisten organic carbon. *Water pollution Microbiology.*

Globalwettech, n.d. *globalwettech.com.* [Online]
Available at: https://globalwettech.com/en/about-constructed-wetlands.html

Green, Griffin, Seabridge & Dhobie, 1997. Removal of bacteria in subsurface flow wetlands.

Gresberg, Lyon, Brenner & Elkins, 1987. Fate of viruses in artificial wetlands.

Gross, 2007. Recycled vertical flow constructed wetland (RVFCW) - a novel of recycling greywater for irrigation in small communities and household.

IOB, 2011. *International guidelines (LG),* s.l.: s.n.

IOB, 2011. *International Organization for natural bathing waters,* s.l.: s.n.

IRIDRA, n.d. *IRIDRA, natural-based solution, sustainable water management.* [Online]
Available at: http://www.iridra.eu/

ISPRA , 2012. *Guida tecnica per la progettazione e gestione di sistemi di fitodepurazione per il trattamento delle acque reflue urbane,* s.l.: Istituto Superiore per la Protezione e la Ricerca Ambientale.

Kadlec, 2009. Wastewater treatment at the Houghton Lake wetland.

Kadlec & Brix, 1995. Wetland systems for water pollution control. *Water science technology,* p. 32:3.

Kadlec & Knight, 1996. *Treatment Wetlands.* Florida: Lewis Publisher CRC press.

Kadlec, et al., 2000. Constructed wetlands for water pollution control: processes, performances, design and operation.

Kadlec & Wallace, 2008. Treatment wetlands. Volume 2.

Kansiime, Saunders & Loiselle, 2007. Function and dynamic of wetland vegetation of lake Victoria: an overview. *Wetland Ecology and Management.*

Kircher & Thon, 2016. *How to build a natural swimming pool.* London: Filbert Press.

Kulshrestha, 2019. Treatment of domestic wastewater in pilot vartical flow constructed wetland with recycle and with Tidal flow constructed wetland in India.

Lajo, n.d. *La fitodepurzione: esperienze realizzative nel mondo e presso Allevamento Master. La riduzione dell'azoto di origine zootecnica,* s.l.: artec ambiente.

Lakeaccess, n.d. *Lake access an empatic metro project.* [Online]
Available at: https://www.lakeaccess.org/ecology/lakeecologyprim9.html

Langergraber, et al., 2019. *Wetland technology, Pratical inforamation on the design and apllication of treatment wetlands.* s.l.:IWA Pubblishing.

Licciardello, et al., 2018. Wastewater tertiary treatment options to match reuse standards in agriculture. *Agricultural water management.*

Luthi, Morel, Tilley & Ulrich, 2011. Community-led Urban Environmental Sanitation Planning.

Mander, Jenssen & Eds, 2002. Natural wetlands for wastewater treatment in cold climates.

Masi & El_Hamouri, 2010. Segregated black/grey domestic wastewater treatment by Constructed Wetlands in the Mediterranean basin.

Masi, Rizzi & Regelsberger, 2017. The role of constructed wetlands in a new circular economy, resource oriented, and ecosystem services paradigm.

Masi, Rizzo & Regelsberger, 2017. The role of the constructed wetland in a new circular economy, resource oriented, and ecosystem services paradigm. *Journal of environmental management.*

Matamoros, Rodriguez & Albaigès, 2016. A comparative assessment of intensive and extensive wastewater treatment technologies for removing emerging contaminants in small communities.

Merli's Law n. 31911 (1976) Merli.

Mitsch, 1992. Landscape design and the role of created, restored and natural riparian wetlands in controlling nonpoint source pollution. *Ecological Engineering 1*, pp. 27-47.

Moshiri, 1993. Constructed wetlands for water quality improvement.

Nielsen & Bruun, 2015. Sludge quality after 10-20 years of treatment in reed bed systems.

Nuttal, Boon & Rowell, 1997. Review of the design and management of constructed wetland. *CIRIA.*

ONORM B 2505, 1997. *Subsurface flow constructed wetlands - application, dimensioning, installation and operation,* Vienna, Austria: s.n.

ONU, 1992. *Agenda 21 ONU,* Rio de janeiro: s.n.

ONU, 2015. *Agenda 2030 ONU,* s.l.: s.n.

Paing & Guilbert, 2015. Effect of climate, wastewater composition, loading rates, system age and design on performances of French vertical flow constructed wetlands.

Pavlineri, Skoulikidis & Tsihrintzis, 2016. Constructed floating wetlands: a review of research, design, operation and management aspects, and data meta-analysis. *Elsevier.*

Pergetti, 1994. *Criteri progettuali e costruttivi di un sistema a flusso sub-superficiale per piccole comunità,* Politecnico di Milano: XLI corso di aggiornamento ISA: piccoli impianti di depurazione.

Pignatti, 1982. Flora d'Italia. *Edagricole.*

Pondsuperstore, n.d. *pondsuperstores.* [Online]
Available at: https://pondsuperstores.com/

Reed & Brown, 1992. Constructed wetland design - the first generaton.

Reed, Crites & Middlebrooks, 1995. Natural systems for waste management and treatment. *McGraw-Hill,* Volume 2nd .

Reed, Middlebrooks & Crites, 1987. Natural systems for waste management and treatment. *McGraw-Hill book Co..*

Resolution of provincial Concilium n. 974 (2011) Bolzano province.

Romagnolli, 2000. *La fitodepurazione: manuale tecnico divulgativo per una gestione sostenibile del ciclo delle acque.* s.l.:ReggioEmiliaComune.

Rousseau, Vanrollenghem & DePauw, 2003. Model-based design of horizontal surface flow constructed treatment wetlands. *Elsevier.*

Russo, et al., 2018. Constructed Wetland combined with disinfection systems for removal of urban wastewater contaminants. *Elsevier - Science of the total environment.*

Sachs, 2008. Zukunfsfahiges Deuschland in einer globalisierten Welt.

Saeed & Sun, 2011. Kinetic modelling of nitrogen and organics removal in vertical and horizontal wetlands. *Elservier.*

Spieker, et al., 2013. Freibader mit biologischer wasseraubereitung - Outdoor swimming pools with biological water treatment. *Handbook of applied limnology.*

Stefanakis, 2020. Constructed wetlands for sustainable wastewater treatment in hot and arid climates: opportunities, challages and case studies in the middle East. *Water - open acces journal.*

Steiner & Watson, 1993. *General design, construction and operation guidelines: constructed wetlands wastewater treatment systems for small users including individual residences.* Chattanooga, TN, United States, s.n.

TuttoGreen, 2018. *TuttoGreen - guida pratica alla green economy.* [Online]
Available at: https://www.tuttogreen.it/biopiscine-arriva-la-piscina-naturale-che-non-contiene-cloro/

UN-HABITAT, 2008. *Constructed wetlands manual. UN-HABITAT water for Asian cities Programme Nepal.* Kathmandu, Nepal: s.n.

United Nation - Department of Economic and Social Affairs - Sustainable Development, 2020. *Sustainable Development Goals.* [Online]
Available at: https://sdgs.un.org/

United Nation, 2019. *www.un.org.* [Online]
Available at: https://www.un.org/development/desa/en/news/population/world-population-prospects-2019.html

Val-Pusteria.net, n.d. *Val-Pusteria.net.* [Online]
Available at: https://www.val-pusteria.net/it/sport-e-tempo-libero/attivita-sportive/nuotare/laghetto-naturale-balneabile-campo-tures/

Vismara, et al., 2000. *Linee guida per il dimensionamento degli impianti di fitodepurazione a macrofite radicate emergenti: gli esempi internazionali ad una proposta italiana,* s.l.: s.n.

Vivai Valverde, n.d. *Vivai Valverde di Ester Cappadonna.* [Online]
Available at: http://www.vivaivalverde.it/typha-latifolia/

VivoAltaPusteria, n.d. *Vivo Alta Pusteria.* [Online]
Available at: https://www.altapusteria.com/sport/estate-attiva/piscine/piscina-naturale-dobbiaco/

Volterra & Mancini, 1994. Fitodepurazione e riuso successivo delle macrofite.

Vymazal, 2001. Types of constructed wetlands for wastewater treatment: their potential for nutrient removal.

Vymazal, 2005. Horizontal sub-surface flow and hybrid constructed wetlands systems for wastewater treatrment.

Vymazal, 2008. Constructed wetlans, suface flow. *Encyclopedia of ecology,* Volume 1.

Vymazal, 2010. Constructed wetlands for wastewater treatment: five decades of experience.

Vymazal & Kropfelovà, 2008. Wastewater treatment in constructed wetland with horizontal sub-surface flow.

WFD 2000/60/EC (2000).

Whigham & Brinson, 1990. Wetland and shallow continental water bodies: wetland value impact.

Wikipedia, n.d. *Wikipedia.* [Online]
Available at: https://en.wikipedia.org/wiki/Juncus

Wikipedia, n.d. *wikipedia.org/wiki/Lemnaceae.* [Online]
Available at: https://it.wikipedia.org/wiki/Lemnaceae

Figures contents:

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