KEY ASPECTS FOR SUCCESSFUL DESIGN AND IMPLEMENTATION OF PASSIVE WATER TREATMENT SYSTEMS

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INTRODUCTION

Water treatment has been implemented for decades to treat water supplies as well as "wastewater" from a variety of sources. Noteworthy are successes treating challenging contaminated waters, including industrial sources, mining influenced waters, and oil and gas produced waters. Passive water treatment is a process of simultaneously or sequentially mitigating contaminants and/or acidity and physicochemical properties in a man-made system. This is achieved by capitalizing on biological, geochemical, and coupled biogeochemical reactions, followed by the physical removal and sequestration of constituents. In its truest form, a passive water treatment system (PWTS) does not require power or chemicals after construction and can be designed as a sustainable system lasting for decades or longer with minimal intervention or maintenance. For waters that contain constituents of concern that are not amenable to treatment by naturally occurring biological, physical, or chemical pathways (e.g. sodium, chloride), hybrid or semi-passive systems can be developed that incorporate energy driven processes, such as reverse osmosis coupled with passive water treatment.

Today more than ever, with an increase in environmental awareness and corporate social responsibility, passive and semi-passive water treatment technologies are recognized as sustainable strategies for responsible operational and/or long-term closure water management. Accordingly, the state of the technology and scientific knowledge has advanced rapidly in recent years, far beyond what is readily available in commonly referenced textbooks and manuscripts. Through advances in microbial technologies, such as microbial community profiling through genetic methods (known as a microbiome), paired with proven process-driven approaches and scalable piloting methods, passive water treatment is no longer a 'black box' technology. In this paper, we provide a brief background on the principles of passive water treatment and emphasize key aspects for successful design and

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implementation of PWTS. Attention is focused on the advances in technology and piloting methods that contribute to the increased predictability and robustness of modern day PWTSs.

KEYWORDS
water treatment, constructed wetlands, process-driven design, bioremediation, microbiology, microbiome, metals, selenium, organics, closure planning, sustainability

PASSIVE WATER TREATMENT SYSTEM ESSENTIALS

Many different types of passive water treatment exist, and their foundational principles have been covered extensively in textbooks and review articles, and as such, will not be covered here. Instead, we will focus on key aspects of PWTS that are often overlooked, which can lead to failures and misconstrued information about the feasibility and success of passive treatment options.

It should be noted that in previous reviews or publications the complex classification and naming of technologies have contributed to a confusing technology landscape as practitioners have attempted to distinguish or differentiate their designs from those of others. Through experience, we recognize that most passive water treatment methods exist as a continuum rather than independently siloed or isolated technologies without overlap. Therefore, in this paper we use the term Passive Water Treatment System (PWTS) as a generic term encompassing a range of concepts and applications, whether designed to be aerobic, anaerobic, oxidizing, reducing, or with other specific design considerations to target functions such as alkalinity generation.

In general, there are numerous benefits to implementing a water treatment strategy that incorporates a PWTS (Rodgers and Castle 2008), including:

- low operation cost
- low maintenance
- driven by solar energy and gravity
- aesthetically pleasing
- predictable treatment effectiveness
- tolerance of deviations in flow rate and contaminant load
- sustained or increased effectiveness over time
- no need for transportation or handling of hazardous chemicals
- treatment of multiple contaminants simultaneously and more effectively than some costly chemical or physical treatment processes.

There are a variety of reactions and processes that occur naturally in wetland environments that can shape the design of a PWTS to specifically promote conditions that are conducive for certain types of reactions that 'treat' contaminants. In this manuscript, we use the term 'treatment' to typically mean one or both of two things: the contaminant of concern is either transferred or transformed (Table 1). In the first case, it is transferred to a site where it is removed from its aqueous or suspended state via processes such as filtration and settling, sorption to soils or dead organic material, and uptake into plants or biofilms. In comparison, transformation involves a reaction that alters the form of a contaminant to one that aids in its removal from the water column by complexation, degradation, mineralization, precipitation, volatilization, or changes in valence state. Each of these mechanisms serves a specific purpose in the context of passive water treatment.

It has been demonstrated in many cases that PWTSs can be specifically designed for targeted constituents and/or treatment pathways for contaminants in water, based on a meticulous site water characterization and understanding of treatment pathways (Hawkins *et al.*, 1997; Gillespie *et al.*, 1999, 2000; Huddleston and Rodgers, 2008; Murray-Gulde *et al.*, 2008; Rodgers and Castle, 2008). Constituents that can be treated by PWTS include but are not limited to acidity, algae, ammonia, biological oxygen demand, chlorinated compounds, chemical oxygen demand, metals, metalloids, nitrate, nuisance bacteria (e.g., coliforms), nutrients, oil and grease, organic compounds, pesticides, and total suspended solids (Bhamidimarri et al. 1991; Huddleston *et al.*, 2000; Ford 2003; Eggert *et al.*, 2008; Johnson *et al.,* 2008; Nelson and Gladden, 2008; Rodgers and Castle 2008; Dorman *et al.,* 2009; Spacil *et al.*, 2011; Horner *et al.*, 2012; Rutkowski 2013). Moreover, through the scientific process-driven approach described here, methods can be readily developed to treat new and emerging contaminants of interest (e.g., selenium, naphthenic acids).

TABLE 1. Treatment Processes of PWTS, adapted from Rodgers and Castle, 2008 (Environmental Geosciences), added microbial column.

Treatment Process	Biogeochemical Conditions in CWTS	CWTS Components: Hydrosoil	CWTS Components: Plants	CWTS Components: Microbes	Examples of Constituents Removed
Transfers					
Sorption*	Availability and generation of surfaces	Low ratio of sand to clay; high organic matter content; porous	Large mass of roots and shoots, incorporation of moss	Periphyton, microbial mats and biofilms	Hydrophobic chemicals (e.g. oil and grease, some pesticides, organometallics)
Volatilization	Presence of water surface and transpiration	Exposure to atmosphere (e.g. during drawdown)	Plants with high transpiration rates	Dissimilatory reduction	Chemicals with high vapor pressure or low solubility; low molecular weight organics
Precipitation, settling, and sedimentation	Low flow rate (less than approximately 10 cm/s conducive to settling (Stokes Law)	Not applicable	Flow baffles to maintain low flow rate and prevent short-circuiting	Not applicable	Solids and precipitates
Bioconcentration (plant uptake)	Prolific vegetation in contact with water	Favorable particle size and nutrients to support vegetative growth	Large mass in contact with water	Periphyton, microbial mats and biofilms	Hydrophobic chemicals (e.g. oil and grease, some pesticides, organometallics)
Transformations					
Photolysis	Sunlight intensity and light absorption	Not applicable	Minimize shading	Not applicable	Low molecular weight organics
Speciation and ionization	Presence of reactive ions or electrons (e.g. oxidation, reduction)	Refer to oxidation and reduction (below)	Refer to oxidation and reduction (below)	Refer to oxidation and reduction (below)	Metals and organics
Oxidation	Redox (Eh) > -50 (approximately); pH slightly acidic to near neutral	High ratio of sand to clay; low organic matter content	Rhizosphere aeration; large radial oxygen loss	Oxidizing bacteria	Organics (e.g. oil and grease); some metals (e.g. Fe); Ammonia
Reduction	Redox (Eh) < -150 (approximately); pH near neutral to slightly basic	Low ratio of sand to clay; high organic matter content	Small radial oxygen loss; root metabolism in anaerobic environment	Reducing bacteria; dissimilatory reduction; generate free electrons through decomposing plant matter	Metals (e.g. Hg, Cu, Pb, Se, Zn); Nitrate; Sulphate; organochloride chemicals subject to dehalogenation
Biotransformation and biodegradation	Presence of organisms capable of transforming targeted constituents	Favorable particle size and nutrients to support microbial growth	Plants that support periphytic and rhizosphere microbial growth	Catalyze reactions otherwise thermodynamically unfavorable	Biodegradable organics

*Adsorption to organic and inorganic surfaces; absorption by plants not used in these systems.

KEY ASPECTS FOR SUCCESSSFUL PWTS DESIGN

COMMUNICATION & DEFINING SUCCESS

In order to successfully implement a PWTS, the goals and objectives of passive water treatment must be pre-determined to define the design, feasibility, and functionality of the system. These goals and objectives are developed through discussions (sometimes in iterations) between the developer, client, regulators and local stakeholders in order to come to a mutually agreed upon definition of success for the PWTS. It must be recognized that it is impossible to meet a goal that does not exist, and it is not sufficient for a treatment system to simply "do something." Rather, a PWTS should be fully capable of meeting pre-determined performance objectives, with a well-defined design life and understanding of maintenance and monitoring requirements. As such these aspects must be clearly communicated and their feasibility discussed prior to execution.

PWTS goals and objectives should include quantifiable aspects such as:

- targeted outflow concentrations of contaminants or modifications in water quality,
- extent of removal in terms of total load versus outflow concentration,
- design life,
- time to performance,
- performance under extreme conditions or system upsets (e.g., freezing, high flow, drought, concentration fluctuations),
- maintenance and monitoring schedules, and
- changes over time.

Qualitative objectives of the PWTS should also be discussed, such as aesthetic design, educational opportunities for local institutions, or improved public perception of the facility. In all cases, the goals and objectives should be detailed to a sufficient level to be achievable, prioritized, and agreed upon by the owner, regulators, stakeholders, as well as the party developing the system. Finally, the feasibility of achieving pre-defined goals or changes in targeted goals should be revisited throughout the design and implementation process to ensure that objectives of the owner, regulators, and stakeholders are being met. Without this goal-oriented structure in place, the design and implementation of a PWTS can become extremely costly or even worse, result in failure.

PWTS COMPONENTS

Water

One of the first and most important steps in PWTS design is characterization of the quality, quantity, and periodicity of water needing treatment, as well as defining the outflow expectations and goals. While the flow rates, periodicity, and associated fluctuations in concentration of the constituent(s) of concern are obviously important to a water treatment system, there are a multitude of other characteristics that are critical to understanding the potential treatment processes for a site. A comprehensive and detailed water characterization is necessary to determine explanatory parameters and inventory the constituents in the water. With complex systems such as mining-influenced water or oil and gas produced waters, this full characterization is critical, as certain constituents (e.g., chloride) could interfere with wetland function, while other constituents may affect the treatability of other elements in beneficial or detrimental ways (e.g., iron, sulphate, ammonia). It is therefore important to evaluate the treatability of the water as a whole and to not focus solely on the constituents requiring treatment. Some parameters that are often included for characterization to understand the chemistry of the water that will influence treatability include:

- Acidity
- Alkalinity
- Biological Oxygen Demand
- Carbonate
- Chemical Oxygen Demand
- Chloride
- Conductivity
- Hardness
- Ion Balance
- Iron
- Manganese
- Metals
- Metalloids
- pH
- Sulphate
- Total Dissolved Solids
- Total Kjeldahl Nitrogen
- Total Organic Carbon
- Total Suspended Solids

Once water characteristics are defined, the treatment mechanisms and PWTS components can be selected to provide optimal conditions for constituent removal.

For certain contaminants, some treatment pathways are more desirable than others, both in terms of the rate of treatment, but also for long-term stability and decreased bioavailability. Accordingly, each treatment mechanism should be considered in the context of the constituents needing to be treated, as well as other constituents that are present in the water.

Process-Driven Treatment Mechanisms

PWTS can be designed to treat a range of constituents, sometimes sequentially as a treatment train, and at other times simultaneously. In some cases, simultaneous treatment of constituents is feasible in a PWTS when their respective treatment mechanisms require similar conditions to be effective. The conditions in this case are explanatory parameters that are quantifiable aspects of a PWTS environment. These parameters, which often include alkalinity, conductivity, dissolved oxygen, pH, redox, ion balance, available electrons (organic carbon), and temperature, can be used to predict, promote, and/or optimize the ability of the system to treat different constituents. For example, dissimilatory sulphate reduction may take place at the same time as dissimilatory selenium reduction, as the required conditions for these processes to occur have a range of overlap.

In other cases, sequential treatment, which is sometimes referred to as a 'treatment train', can be more effective and should be applied in two types of circumstances. In the first case, the targeted constituents require different conditions in order to be treated. In the second case, there are constituents or parameters other than those targeted for treatment that must be removed or adjusted before effective treatment can be achieved. For example, in some circumstances it may be necessary to remove dissolved iron through oxygenating steps before removing other elements through coupled biogeochemical reactions involving mineralization to sulphide from bacterially mediated dissimilatory sulphate reduction. In either case, just as with a conventional water treatment system, the water chemistry must be reassessed at the outflow of each step of the treatment train to confirm objectives have been met for that step and to ensure the functionality of the subsequent step. While scientifically more complex, a treatment-train approach is often more robust and can achieve better outflow concentrations of constituents of concern.

Once the theoretical process-driven design has been developed, the components can be brought together to achieve the PWTS objectives. There are typically four main components of any PWTS design: water, soil, plants, and microbes. Each of these must be given special consideration in the context of treatment objectives (Table 1), and have a range of options in their design and implementation. Characterizing the water is one of the first steps in defining the PWTS design, as discussed above, and the three remaining components are outlined below.

Soil

Here we use the term 'soil' in a loose way to refer to the soil, hydrosoil, substrate, and aggregates used to construct a PWTS. Once the desired processes have been identified, the soils can be modified in many ways to aid in achieving specific design objectives, some of which are outlined in Table 2. These aspects must not only take into account the desired processes, but also the pre-defined goals of the PWTS. While some amendments are only needed to 'kick start' processes that will become self-sustaining (e.g., organic carbon, nitrogen, or phosphorous addition), depending on the design and treatment objectives, other amendments may need to be supplemented on a scheduled basis and should be evaluated in a cost-benefit analysis for feasibility.

Plants

While plants are often thought of as a treatment pathway through uptake, this pathway is not sustainable for metals as they can be re-released upon decomposition. However, plants provide multiple other benefits to the function of a PWTS, and uptake of elements can be minimized through appropriate designs that target mineralization and decreased bioavailability.

TABLE 2. Considerations in selection of soil/aggregate for PWTS.

Aspect	Functions
Buffering capacity	Natural to borrow source, or added through amendments (oyster shells, lime)
Constructability	Structural stability of substrate, likelihood of channeling, re-suspension, ease of entry for monitoring, etc.
Nutrients	Natural to borrow source, or added through amendments (N,P,K and trace elements)
Organic content	Natural to borrow source, or added through amendments (straw, wood chips, peat)
Particle or aggregate size	Flow rates or diffusion of water through substrate
Procurement	Cost of procurement and transportation of desired soil/aggregates to site
Sorption capacity	Will only affect early treatment performance of system, must be accounted for in long-term treatment rates
Source mineralogy	Chemical properties natural to borrow source (e.g., source of iron, sulphate, alkalinity, hardness), or added as amendment (pelletized gypsum, iron, etc)

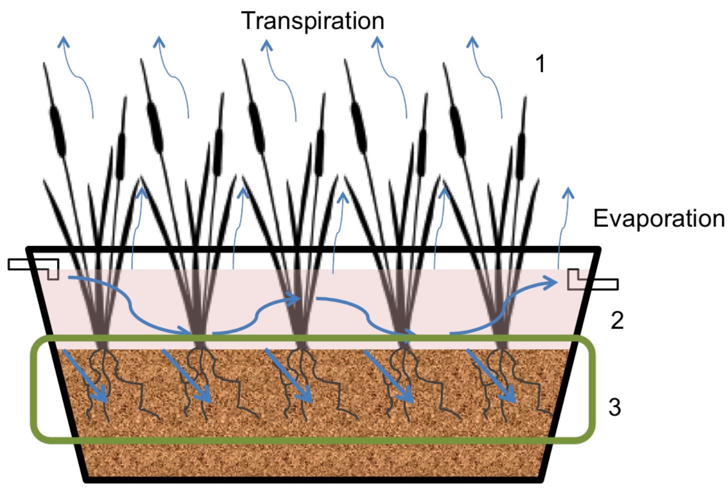
It is generally advisable to avoid planting a mixture of species in a treatment wetland. The purpose of using a monoculture planting is two-fold: plant diversity attracts wildlife which is often undesirable in a PWTS, and with increased plant diversity comes decreased certainty of functioning as designed. It is the latter of these two reasons that is most critical to the operation and planning of a PWTS. With a monoculture, it is possible to accurately pilot and model the behavior of the PWTS; however, when multiple plants are used, it is not possible to model how the PWTS will behave if one or another plant species becomes more dominant. Plant diversity is one of the reasons why natural wetlands often have a lower treatment capacity compared to constructed wetlands, since only some of the plant species contribute to treatment in a beneficial way. This is not to be confused with the use of different monocultures in specific cells within a treatment train to achieve desired conditions conducive to treatment.

Some of the key considerations for plant selection include: physiology (e.g., radial oxygen loss [ROL], water depth tolerance), biomass production per year versus decomposition rate (to allow for accretion), bioconcentration tendencies, effective plant density in the wetland cell (i.e., shoots per m^2 to aid in flow distribution), flow rate tolerance, structural capacity and prevention of sediment re-suspension (Figures 1 and 2), evapotranspiration rate (Figure 3), and provision for microbial habitat (Figure 4).

FIGURE 1. Roots of wetland plants showing ability to contribute to structural aspects of wetlands, as well as influence sediment redox states. Clockwise from top left: *Typha* roots with black coloration showing sulphate reduction and mineral plaque buildup on roots associated with reducing conditions; *Typha* roots without mineral buildup; Carex roots form in a peat building mat; *Schoenoplectus* roots form with linear structure.

FIGURE 2. Total suspended solids (TSS) removal by plants. Plants can aid in decreasing elemental concentrations through removal of TSS through filtration mechanisms, changes in flow velocities, and oxidation of water through radial oxygen loss (ROL). Left – *Schoenoplectus* roots have bound suspended solids (bottom right of picture), while the areas without roots (top left of picture) have not been successful in binding solids or settling precipitates. Right – visible difference in TSS of water exiting natural wetland (clear red/brown, right), compared to bypassed water (cloudy grey, left).

FIGURE 3. Overview of water movement in a PWTS cell. 1 – loss of water from system through transpiration and/or evaporation; 2 – movement of water through the water column; 3 – movement of water into the hydrosoil, with the root zone drawing water deeper into the hydrosoil and increasing the total area for microbially mediated treatment.



Credit: D.A. Beebe, J.W. Castle, J.H. Rodgers

FIGURE 4. Examples of redox conditions that exist around plant roots within a wetland. Black is indicative of sulphate-reduction and a negative redox, while the red is indicative of oxidized iron and a positive redox. Over time and with accretion, the red/oxidized regions can be sequestered into the sediment as reduced sulphidic minerals. This natural cycle must be considered in PWTS designs incorporating plants.

FIGURE 5. Pilot-scale PWTS cell constructed for copper and selenium treatment for the Minto Mine, Yukon Territory. Pilot system dismantling with plants exhibiting relatively low ROL. Regions of sulphate reduction are found at the sediment/water interface and in the root zone (black areas). In this system, copper treatment was highly correlated to sulphur deposition in soils and not correlated to iron concentrations.

Radial oxygen loss (ROL) can be defined as the flux of oxygen from the root material of plants to the immediate area surrounding the roots (Colmer 2003). Radial oxygen loss is a crucial parameter to consider when designing a wetland cell's targeted conditions (e.g., oxidizing vs reducing cell), as it can greatly affect soil redox, which in turn directly affects treatment mechanisms (e.g., dissimilatory sulphate reduction; Figure 5). For example, if reducing conditions are needed for treatment, wetland plants with a lesser degree of ROL should be chosen for that cell to avoid excessive oxygen transport to the root zone, which could increase redox levels and therefore inhibit treatment.

Evapotranspiration is another plant-mediated PWTS characteristic that must be considered. Evapotranspiration can be defined as the total sum of water removed from a PWTS by evaporation from surface water of the system and transpiration from plant leaves (Figure 3). The degree of evapotranspiration is dependent primarily on the plant species/ecotype and controlled by meteorological conditions such as air temperature, relative humidity, and wind. Evapotranspiration drives an important aspect of the hydrology of a PWTS, enhancing the effective treatment area of surface flow wetlands. Therefore, PWTS that are not vegetated are at a significant disadvantage in terms of treatment capacity, and may have a treatment zone only at the sediment-water interface (opposite effect demonstrated in Figures 3-5). Likewise, PWTS planted with submerged vegetation may benefit from increased plant-water interfaces that are beneficial in oxidizing reactions, but their processes will lack effective use of the root zone.

Evapotranspiration can also affect the perceived treatment of contaminants in a PWTS because removing water from the system concentrates the contaminants (as well as other constituents), but also results in a decrease of the hydraulic retention time (Allen *et al.*, 1998). Evapotranspiration can therefore be a very important consideration in attempting to meet the sometimes contradictory objectives of final outflow concentration versus total load reduction in a PWTS. That is to say, when evaporation and transpiration levels are high, an increased PWTS footprint may actually result in a higher outflow concentration of elements than is seen partway through the system, even though the total load of an element is lower at the outflow based on treatment. There are designs that can be used to decrease evaporation, such as a subsurface flow wetland design; however, these aspects must be balanced when considering the overall objectives for a treatment system.

Finally, accretion is the naturally occurring process of accumulation of wetland sedimentary material (soil, minerals, decaying plant material, etc.) over time. Once an accreting PWTS is established and mature, targeted constituents are sequestered into the sediment and covered over time by newly generated sediments and detritus. This essentially locks away the treated constituents under layers of sediment, decreasing bioavailability and re-suspension, which renders the constituents less susceptible to re-entry into the water column. Since PWTSs can be designed with this in mind, there is no need to dredge or harvest wetland plants; in fact, this type of activity would disrupt the treatment functions and re-expose the previously sequestered constituents. This process mimics what occurs in natural wetlands; therefore, it is the best option for long-term, efficient, and effective treatment. However, each plant species has a different decomposition rate, which varies with climate and freeze-thaw cycles. As such, decomposition and accretion rates must be considered as a site-specific aspect of a PWTS.

In addition to these physical, chemical, and physicochemical considerations, care should also be given to ecological and social aspects, such as whether the plant serves as an important food source for animals or if it has significant medicinal or cultural importance to local people.

Microbes

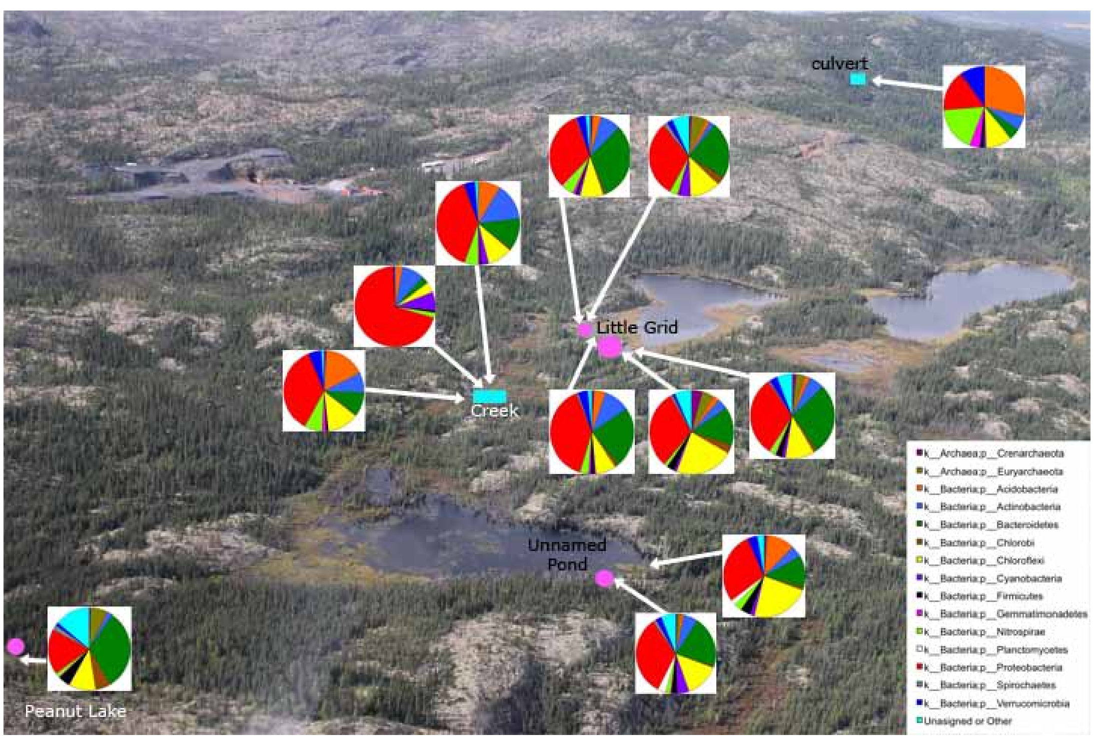
In order for a PWTS to function predictably and robustly, the interaction and foundation of treatment mechanisms must be understood and that knowledge properly applied. Microbes can be thought of as renewable catalysts in a PWTS that drive the removal of constituents from water through biogeochemical cycling. Careful PWTS designing can therefore mimic the environmental conditions that are known to enhance both the abundance and metabolic activity of beneficial microbes. Until recently, however, understanding of the biological contribution to such systems was lacking.

Traditional microbiological investigations involved growing organisms in a laboratory for characterization. However, microbes (algae, archaea, bacteria, cyanobacteria, and fungi) tend to survive and function better as part of a community in their natural environment, interacting and growing on substrates provided by other organisms in their niche (i.e., commensal relationship). Consequently, a very large proportion (often estimated at >99%) of environmental microorganisms cannot currently be grown in a laboratory setting, and it is difficult to understand their distribution and functions in the context of their influence on the environment. Additionally, the growth of an organism in a laboratory can result in the loss of functional abilities that are used by the microbes in their natural environmental setting, as the selection pressures are no longer present to maintain the activities. Moreover, single-organism studies can be misleading, as biogeochemical processes are often multi-organism or community driven. To understand biologically driven treatment mechanisms, microbes are best understood in the context of their natural community and environment.

Only recently has it become possible to analyze complex microbial communities in a cost and time-effective manner owing to advances in molecular biology and associated computational data analyses; what used to take years and tens of thousands of dollars, can now be done in weeks for only hundreds of dollars. Microbiome analyses through genetic sequencing can be used to gather information about the identity and distribution of microbes in a sample. With regards to PWTS, profiling the microbial communities associated with plant species that occur naturally on site (e.g., Figures 1, 2, and 4) can help identify the preferred niche of beneficial microbes (e.g., sulphate-reducing or ammonia oxidizing bacteria) along with environmental parameters that encourage their growth (e.g., pH, oxygen levels). This information can then be used to design a PWTS with plants and characteristics that enhance the microbial reactions by which constituents of concern are removed from the water (e.g., denitrification, nitrification, and sulphate, selenium, manganese or iron oxidation/reduction).

For example, microbiome analyses were applied to delineate shifts in microbial communities along a watershed that receives various seeps that are naturally high in arsenic (Figure 6). Treatment of arsenic was found to be occurring in this water system at several locations along the natural wetlands, while explanatory parameters and microbial populations dictated the mechanisms of treatment. Using this information, a PWTS was designed and a pilot-scale system constructed to mimic the natural treatment processes at the site. The PWTS design not only successfully achieved targeted reducing and oxidizing conditions and associated microbial complement, but also demonstrated stability of the key microbial communities through a freeze and thaw cycle (Figure 7). In the context of PWTS design, the information gathered through microbiome analysis is extremely valuable, as it can help delineate the target conditions and plants for effective constituent removal and guide process-driven design.

FIGURE 6. Aerial view of natural wetlands at Fortune Mineral's NICO site in the Northwest Territories that are receiving and treating water naturally elevated in arsenic. Pie charts indicate the composition of microbial communities at various sites, which were later correlated to water quality and physicochemical properties.



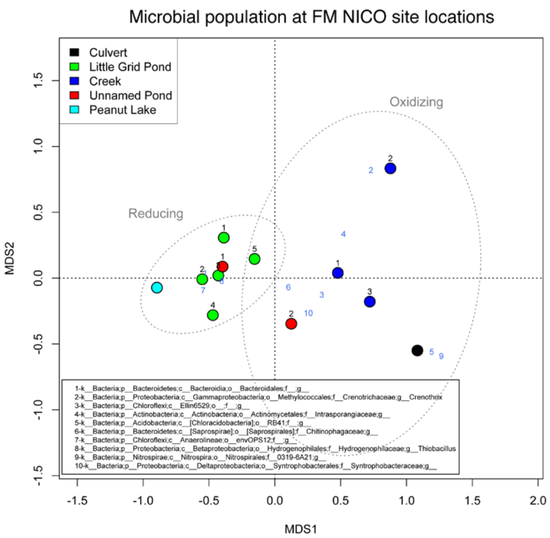
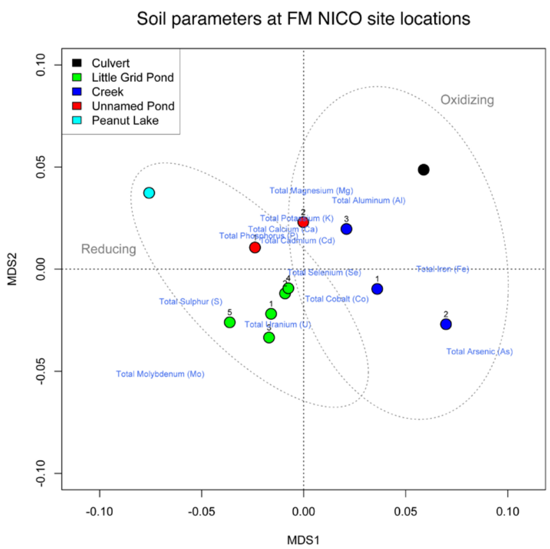
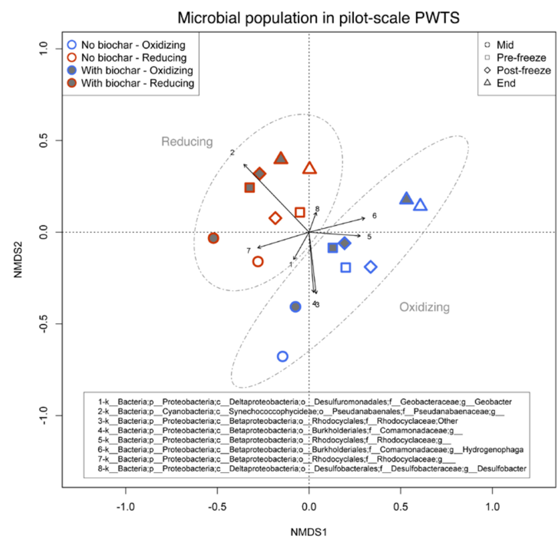


FIGURE 7. Multivariate statistical analysis can be used to suggest relationships in soil, water, and microbial populations in the context of physicochemical properties and explanatory parameters. The top and bottom left charts correspond to the microbes and soil from Figure 6. The bottom right chart corresponds to the microbial population in a pilot-scale PWTS designed to optimize the natural treatment mechanisms at the same site. The pilot-scale PWTS microbial population was monitored through a freeze and thaw cycle. Oxidizing and reducing conditions at the site and in the PWTS are outlined with dotted ellipses.





Ways microbiome analyses can aid PWTS design

- Identify which plants at site naturally host the most beneficial organisms
- Understand how microbial communities respond to changes in explanatory parameters or seasonal variances
- Identify co-factors, nutrients, or other conditions that could improve treatment performance
- Evaluate robustness and diversity of community members capable of desired reactions
- Confirm stability of microbial community over time (e.g., through freeze/thaw or after change in water chemistry)

In years past, a small number of microbes commonly studied as model organisms in laboratories were often used as examples of metabolic activities. For example, for years ‘common culprits’ such as *Acidithiobacillus ferrooxidans* were blamed for a wide range of acid/rock drainage issues. However, we now know through genetic profiling that this is only one among thousands of bacteria present in and influencing the environment of these acidic systems. Furthermore, owing to the oversimplification of applying microbiology to PWTS design and analysis, biogeochemical functions of such systems have sometimes been underestimated. In these situations, tolerances and preferred ranges of habitat were inferred from testing on laboratory strains of organisms, while in reality, many diverse organisms were capable of such a function.

In actuality, environmental microbial communities can be very tolerant to changes in their environment, with some capable of surviving through freezing, thawing, drying, fluctuations in temperature, and even thriving in some of the most extreme environments on Earth. Through microbial community analyses it is now understood that there are often multiple, different organisms capable of performing desired treatment reactions, and this contributes to the robustness of treatment capacity over a range of environmental conditions.

PWTS ecosystems can have highly diverse microbial communities with thousands of different microorganisms present and potentially competing for the same factors that promote growth. Therefore, shifts in environmental conditions on a microbiological scale (e.g., water, sediment, nutrient load, temperature) can drive the dominance of beneficial organisms or help specific groups of microbes thrive. If approached properly, this shift in microbial community composition will be beneficial to the treatment goals, based on the associated biogeochemical processes that the group can or cannot perform. By applying microbiome analysis to a PWTS, shifts in microbial communities that may be associated with improved and/or decreased treatment performance can be identified. Lastly, microbiome analysis can be used to monitor the stability of beneficial microbes through impactful events (e.g., drought, flooding, drastic temperature changes), particularly during the early phases of testing as outlined in later sections.

SITE SPECIFIC

Passive water treatment systems must be designed and implemented with site-specific considerations taken into account. This includes characteristics of the water requiring treatment (outlined above), inherent qualities of the physical site, ecology, and the natural latent capacity for treatment. In each case, these aspects must be evaluated in the context of the goals and objectives that have been set out for the PWTS through discussions with the owner, regulators, and local stakeholders. This site-specific approach is necessary in order to develop effective PWTS that function in a predictable manner and achieve predetermined water quality objectives. Accordingly, designs from textbooks and theoretical calculations based on data from other sites are a good starting point but cannot fully form the design basis for a system. The overall goal of a PWTS is to work **with** the site by using its inherent characteristics. Both intrinsic and extrinsic site characteristics can vary greatly, and there are several parameters that can affect PWTS implementation and efficiency. These include periodicity and characteristics of water, geology, topography, constructability, meteorology, latitude, freshet, and local ecology. While not exhaustive, the following sections outline some general considerations that must be taken into account.

It is not only the average flow rates and concentrations of the constituent(s) of concern, but also the *periodicity*, and associated *fluctuations* in water chemistry that are critical to understanding the potential treatment processes for a site. This is akin to understanding both the probability and magnitude of a given event, and the associated impacts the event may have on functionality of a PWTS. Recurring events (e.g., seasonal cycles) can be assessed through piloting and appropriately accounted for in the design. This is important to consider, as there are drastically different design considerations that need to be made for a condition of peak flow versus peak concentration. Accordingly, it must be known whether these events are likely to overlap.

The source rock *geology* of the area often dictates the character of the water and can aid, or hinder, efficiency and effectiveness of biogeochemical treatment pathways utilized within the PWTS. The geology must be evaluated in addition to the water quality itself, because it will influence how the water quality will change over time as the source ages.

In some cases, the *topography* and *constructability* (e.g., structural stability of a soil) within an area can result in a limited footprint. In such cases, it should be carefully vetted whether the available footprint is appropriate for the chosen technology, and special consideration should be given to hybrid or semi-passive options (e.g., bioreactors) that may provide greater treatment capacity in a smaller area.

Meteorological conditions include parameters such as average temperature and seasonal variations, precipitation (amounts, periodicity, and form), anticipated water loss via evaporation and transpiration from cells, and average wind speed, direction, and intensity. While *latitude* obviously plays a role in guiding climate, it also has influence in other ways, as northern regions have shorter growing seasons. However, at northern latitudes the daylight hours are longer during months with free-flowing water, enabling more plant growth and less diurnal fluctuation. Whenever working in cold climates where snow is present for any part of the year, the characteristics of the local *freshet* must be taken into consideration as spring thaw and snow melt occur at different rates and magnitudes in different areas, and they are also highly affected by altitude, geography, and latitude. Any and all of these aspects can affect treatment efficiency and effectiveness in a PWTS and consequently guide design choices.

If the PWTS design includes vegetation, a survey of the *local ecology*, including both flora and fauna, can aid in selecting suitable wetland plant species for use in the PWTS. Use of plants native to the area alleviates issues related to plant survivability and prevents the introduction of exotic plant species to the area. Although the literature can provide a strong basis for plant selection, for example, providing ranges of possible radial oxygen loss through roots or typical bioconcentation factors, it must also be recognized that there can be substantial difference between ecotype of the same plant species.

Lastly, the site assessment should determine if any natural treatment is ongoing at the site. This can be particularly beneficial for regulatory acceptance, providing preliminary proof-of-concept that passive treatment is feasible. Additionally, microbiome characterization of natural wetlands or potential treatment areas on site can elucidate the presence and preferred environment of beneficial microbes that can be used to optimize biogeochemical cycling and therefore treatment in a PWTS (Figure 7).

In summary, the design of an effective PWTS requires thorough vetting of aspects such as treatment goals, PWTS components, and site-specific considerations, all of which dictate the success of a design and therefore implementation of the treatment strategy. Table 3 summarizes, in brief, some of the key considerations for successful PWTS design.

TABLE 3. PWTS Design Considerations

Aspect
Passive Treatment Goals
Operational timelines (e.g., will PWTS operate during mine operations, closure - or both - and length of required operation)
Duration of operation required
Seasonality of treatment needed
Maintenance and monitoring schedules
Receiving system limits (water quality objectives, mixing zones)
PWTS Components
Water
Concentration and identity of constituents that will require a decrease in concentration (and their fluctuations)
Flow rates (including periodicity and fluctuations)
Water chemistry (cation/anion balance, metals, ions, conductivity, alkalinity, hardness, iron, sulfate, biological or chemical oxygen demand, total suspended solids, etc.)
Explanatory parameters (pH, Eh, temperature, nutrient availability, etc.)
Soil
Characteristics of local soil, including mineralogy, constructability, organic content, sorption capacity, buffering capacity, nutrients
Plants
Characteristics of native plant species, including uptake of constituents, microbial complement, radial oxygen loss, transpiration, flow rate tolerance
Decomposition/Accretion rates
Availability and borrow sites of local plants for PWTS planting
Microbiology
Establish baseline of microbial diversity in natural wetlands on site
Identify which plants or types of soils/environments beneficial microbes tend to be associated with at the site
Site Specific
Constructability (geology, topography, soil types)
Sources of organic material
Sources of borrow soil for substrate and associated chemistry
Sources of local plants for PWTS construction
Depth to groundwater (hydrogeologic regime: recharge or discharge area)
Proximity to permafrost
Wildlife deterrence requirements
Accessibility
North vs south-facing (shading)
Seasonal distribution of rainfall
Character of storm events
Snowfall
Freshet (break-up) character
Freeze-up character
Growing season
Temperatures (max, min, mean)
Growing-degree days
Evaporation and transpiration

SCIENCE- & EVIDENCE-BASED PWTS IMPLEMENTATION

A survey of literature and discussions with practitioners readily reveals that the success of PWTS is highly varied, even within a given industry. Unfortunately, this has led to the erroneous belief in some circles that PWTS are inherently variable and unpredictable in their function. We propose that while there are many different design factors that can be integrated into a successful PWTS, unsuccessful PWTS are typically lacking site-specificity, appropriate piloting and optimization, and a detailed understanding of microbial processes (Table 4).

TABLE 4. Features of successful PWTS designs

Critical Design Aspect	Warning Signs	Steps Towards Success
Site-specific	Design is based on calculation from other sites or textbook	Design incorporates consideration of data and experience from other sites with site-specific data
	Site-assessment has not been performed	Natural attenuation/treatment at site has been evaluated and characterized (e.g., testing through areas receiving effluent or seepage)
		See Table 3
	Water characterization is focused only on parameters needing treatment, and does not consider total water chemistry that will affect treatability	Detailed water characterization has been performed in the context of passive treatment
		Potential treatment pathways have been identified in context of entire water chemistry (not just constituent of concern)
Appropriate process-driven piloting and optimization	Implemented based on calculations only	Calculations form a conceptual basis, but are revisited through phases of piloting and optimization
	Pilot PWTS implemented directly on site	Phased approach taken to piloting, allowing for optimization of design prior to implementation
		Often would involve bench and/or pilot-scale testing in a controlled facility, pilot/demonstration on site, then full-scale implementation
	Short duration (<3months)	Sufficient length to test actual treatment beyond initial sorption capacity of system
		Timeline allows for plant acclimation and system maturation
Detailed understanding of microbial processes	Plant uptake is considered main treatment mechanism	Plant uptake should be minimized in most cases, actual uptake quantified, and subsequent cycling evaluated to prevent re-release through decomposition
	'Common culprits' listed, but no microbiological testing performed	Most-probable number growth-based testing for processes of interest, such as reduction of iron, molybdate, nitrate, selenate, selenite, sulphate; oxidation of ammonia, iron; decomposition of organic compounds
		Baseline testing of microbial communities to identify diversity and robustness of natural community capable of performing treatment reactions
		Key plants at site have been characterized for associations with beneficial microbes for needed processes

When a design has been established for a PWTS, it needs to be tested to verify successful operation. To start this process, a series of bench- and/or pilot-scale experiments are initiated to confirm specific treatment mechanisms, and since these are conducted at a smaller scale, making corrections and adjustments to the design, uncovering unforeseen complications, and other unexpected problems can be remedied very quickly and cost-effectively. This facilitates the scaling-up process and potential troubleshooting when demonstration or full-scale PWTSs are implemented. In most cases, a simulated version of the site water in question, formulated from the detailed site water characterization, is used in the pilot-scale study. This is more cost-effective, as the use of sufficient volumes of the actual site water, rather than simulated water, to undertake a longer-term pilot-scale study is rarely feasible.

A phased approach to PWTS design and implementation is critical to effectively treat contaminants at any site. While the approach taken will vary depending on site-specific considerations, there are four separate phases that are typically used (Table 5):

A) bench-scale experimentation
B) pilot-scale testing and optimization
C) on-site demonstration
D) full-scale implementation and operation

These four phases are now discussed in the order they would be undertaken to develop a site-specific PWTS, after information has been gathered through a site assessment.

TABLE 5. Phases of PWTS testing and optimization following a site

Aspects and Parameters	Phase			
	Bench/ Laboratory	Pilot (off-site)	Demo (on site)	Full
Test various water chemistries (e.g., average, worst case, long-term closure)	+	+		
Test different sediment compositions	+	+		
Test different plant efficacies/properties	+	+		
Environmental parameter control	+	+		
Develop required retention times and water depths		+		
Develop rate coefficients and kinetics		+		
Acquire proof-of-concept for design		+		
Intensive monitoring	+	+	+[2]	
Determine parameters for proper sizing		+	+	
Measure removal extent		+	+	+
Evaluate cold weather performance		+[1]	+	+
Compare demo/full scale data to pilot data (e.g., rate coefficients)			+	+
Confirm removal rates/extents			+	+

[1]if conducted outdoors in cold climate facility.
[2]Intensive monitoring may or may not be possible on-site.

A) Bench-Scale Experiments

Bench-scale PWTS are small-scale experiments that can take place on a laboratory bench/counter in beakers, buckets, or jars. They can be used to test the behavior of water chemistry parameters, contaminant interactions, and reactions with different hydrosoils, wetland plants, potential amendments, and specific treatment mechanisms. The bench-scale PWTS can provide initial proof-of-concept, preliminary designs, and explanatory parameters for a subsequent pilot-scale PWTS, which will further refine the operation and serve as a more detailed and representative depiction of real-world conditions that a full-scale PWTS would experience.

B) Pilot-Scale Testing and Optimization

Pilot-scale PWTS testing and optimization are medium-sized experiments that should take place in dedicated facilities (Figure 8). In some cases it can be possible to conduct pilot-scale testing on-site, however, these opportunities are the exception. In most cases, it is advisable to conduct the pilot-scale testing in a dedicated facility where individual variables within a system can be controlled and rigorous supervision and testing can be performed. This is normally not possible on site, and the multivariate nature of changes that occur with outdoor pilot-scale testing can make it impossible to optimize the designs or removal rate coefficients for appropriate full-scale sizing.

For example, temperature or flow rate fluctuations can be imposed and system upsets triggered purposefully (e.g., drought or flooding) to test the effects on treatment. Moreover, a range of water chemistries can be tested to simulate the various conditions or long-term scenarios that the PWTS might be exposed to, but for which the actual water does not currently exist (e.g., post-closure water treatment). Finally, when pilot facilities have cold-climate capabilities (Figure 8), systems can be operated and tested at cold temperatures, with ice cover, through freeze-thaw cycles (Figure 7), and even in conditions similar to freshet.

Pilot-scale systems are typically built using large tubs or tanks to represent individual treatment cells (Figure 8). Each cell can be built differently as the process-driven steps of a treatment train that are designed to promote different biogeochemical reactions targeting specific contaminants. It is possible to build several cells of a similar design in a series, which enables removal rate coefficients to be developed across a range of concentrations as treatment occurs, and allows for appropriate sizing of the full-scale system. The pilot-scale phase can last as short as several months or as long as a few years, depending on the goals and scope of the study. Regardless of the location or design of the PWTS, it should be cautioned that a period of three or more months is often necessary not only for plant acclimation, but also to observe actual treatment within a system beyond that which is attributable to sorption.

FIGURE 8. Examples of pilot-scale PWTS testing in a controlled indoor (top left and middle figures) and outdoor (top right and bottom figures) setting.

C) On-site Demonstration-Scale Testing

The demonstration-scale (demo-scale) PWTS experiment is the last phase before full-scale implementation. The demo-scale system is built at the site in a similar manner as a full-scale PWTS, but it is smaller in size and receives a lesser amount of influent (Figure 9); at this phase, the demo-scale PWTS receives water from the site and not simulated water. Sometimes the demo-scale can be the first series of a full-scale PWTS that has several series to be built in parallel.

The demo-scale testing allows for final site-specific optimization of the design without building a full-scale system (Table 5). This is important, as it can often be difficult and costly to implement changes to a system once it has been constructed fully. Furthermore, on-site demonstration-scale testing is indispensable for adaptive management and operational decision trees to be finalized, which are necessary in order to effectively operate the full-scale PWTS in a predictable manner as would be expected with any traditional water treatment system.

FIGURE 9. On-site demonstration-scale PWTS. Clockwise from top left, demonstration-scale PWTS being planted with *Carex* and moss at the Minto Mine in the Yukon Territory for copper and selenium treatment; same PWTS, being filled with water; established demonstration-scale PWTS, planted with *Schoenoplectus* in the United States.

D) Full-scale implementation and operation

A full-scale PWTS is the culmination of all previous testing and experimentation scaled up from the pilot system and designed to operate efficiently and effectively. Using rate coefficients gathered from the piloting and on-site demonstration, sizing is calculated, and final installation takes place (Figure 10). As with the pilot and demonstration systems, there is a period of acclimation and maturation during which all of the explanatory and performance parameters are monitored to prevent excessive deviations from final design characteristics. Once this period has passed and the PWTS is sufficiently acclimated and mature, monitoring can be less frequent and intensive, and the system can more effectively manage fluctuations in these parameters and provide robust and predictable treatment performance.

As would be expected for any water treatment facility, a PWTS should come with an operating manual that includes routine monitoring and maintenance schedules, expected operating parameters, design specifications, and the range of operating conditions. Additionally, a decision matrix for the adaptive management of the system should be available in case any explanatory parameters deviate from those specified for optimal treatment.

When designed with sustainable processes in mind, and using the phased approach described here, PWTS can have sustained or improved performance over time and function for decades and longer. For example, a PWTS built over 15 years ago for the treatment of copper and mercury has shown sustained or improved treatment over time (Figure 10; Nelson 2010). This PWTS functions with consistent and predictable performance with little or no operational interventions and has achieved a decreasing monitoring frequency over time.

FIGURE 10. Full-scale PWTS. Left, Savannah River Site A-01 (South Carolina) has been in operation since 2000 treating for copper, zinc, and mercury (Nelson 2010). Right, PWTS treating flue gas desulfurization waters (Eggert et al., 2008; Dorman et al. 2009).

SUMMARY

Building upon decades of work in the area of passive water treatment, the state of knowledge in PWTS design has matured substantially in recent years as a response to increased demand for the technologies, as well as the application of scientific advances. Accordingly, the predictability, robustness, effectiveness, and efficacy of these systems have also undergone significant improvements and PWTS can now be designed to effectively treat a wide range of constituents, often with improved performance over time.

In order to successfully design and implement PWTS, several key aspects need to be taken into consideration and revisited throughout the project. This starts with having a clear outline of the goals and objectives for water treatment, which should be aligned with those of the owner, regulators, and stakeholders. A process-driven design involving rigorous testing and a phased optimization strategy is crucial for the effective operation of a full-scale PWTS in a predictable manner. Owing to recent advances in technology, the process-driven design can now be guided by a deeper understanding of the microbiological components driving the biogeochemical pathways of a PWTS, meaning that these systems are no longer the 'black box' they once were. This allows for not only more accurate design and optimization, but also for long-term operation, management, and maintenance.

The process-driven design should be developed and assessed for feasibility in a site-specific context, evaluating PWTS components, such as plants, soil, and microbes. Site-specific considerations must always be taken into account as they can drastically affect PWTS success, but with proper consideration can contribute to success if incorporated early in the planning and design.

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