Journal of Water Sustainability, Volume 7, Issue 1, March 2017, 17-67

2 Decades Constructed Wetland Experience in Treating Municipal Effluent for Power Plant Cooling at the Shand Power Station, SaskPower Part I: A Review on the Rationale

Emmanuel K. Quagraine
Saskatchewan Power Corporation, Shand Power Station, Estevan, Saskatchewan, S4A 2K9, Canada

ABSTRACT

With increasing water shortages, power plants in particular are pinged and are being compelled to consider the reuse of treated municipal wastewater (MWW) for steam condenser cooling. The use of such reclaimed water however poses its own challenges including operational issues such as scaling, corrosion and biofouling that have serious cost implications as well as environmental and health concerns. Post-treatment of the usually permitted secondary effluent for reuse applications is typically required or otherwise to operate with these consequences. Constructed Wetland (CW) is a relatively new technology that holds promise for such post-treatment to make the effluent more fit for the cooling water application and minimize such associated risk, but its actual commercial-scale application within the power industry is still wanting, although there are recent intense interests for such application. The Shand Power Station of SaskPower, is one Canadian example, which has since 1994 been using CW as tertiary treatment of municipal effluent, which constitutes a dominant portion of the Cooling Tower (CT) re-circulating make-up water during the warmer months. The paper is the first of a series of publications that seek to broadly outline experiences and lessons learnt with CW as treatment technology in polishing municipal effluent for reuse in power plant cooling, whilst also highlighting other capabilities inherent in the technology for enhancement in this application. Specifically, this current paper reviews the literature on municipal effluent quality and the concerns and limitations associated with its reuse in power plant cooling; CWs performance in treating various municipal effluent qualities; current CW treatment applications within the power industry; and lastly discusses the associated benefits as rationale for why SaskPower would have adopted this technology 2-decade ago.

Keywords: Constructed wetlands; treatments; municipal effluent; power plant cooling; benefits

1. INTRODUCTION

Fresh water demands are on the rise and are expected to be more extreme with time (Veil, 2007). Many traditional sources such as surface and groundwater may be over-allocated, too costly, or unavailable due to periodic droughts or regulatory considerations. Non-traditional sources including acid mine drainage, surface runoff capture, and municipal or industrial wastewater treatment plant effluents are therefore now under more serious consideration. Considering its abundance and reliability as a supply source, municipal wastewater (MWW) treatment seems to be the main current dominant focus with respect to reclaiming such wastewaters for reuse (Cooper, 2012). Steam electric power plants are industrial examples that require vast quantities of water each day for cooling and therefore constitute one of the main sectors pinched for available and reliable water resources and

*Corresponding to: equagraine@saskpower.com

DOI: 10.11912/jws.2017.7.1.17-67

hence driven to consider MWW reuse (Cooper, 2012;USEPA, 2004; Veil, 2007).

In Canada, over a decade ago, water reuse was remarked as being practiced only on a relatively small scale and mostly in isolated cases (Marsalek et al., 2002). Reuse examples such as agricultural cropland irrigation, golf course and landscape irrigation and at isolated facilities such as resorts and truck stops were recognized then, but Canadian examples of industrial reuse and recycling did not seem to have been well acknowledged by experts in the field (Marsalek et al., 2002). Industrial uses (particularly for thermoelectric power plant cooling) have however been one of the biggest applications of wastewater reuse in other countries especially since the 1990s (Merz, 2000; USEPA, 2004; Veenstra, 1998). It is noteworthy that SaskPower's Shand Power Station, a 305 MW coal (lignite)-fired single unit Power Plant is one Canadian example, which has since 1994 been using treated MWW effluent as a significant portion of a Cooling Tower (CT) re-circulating make-up water for steam condenser cooling.

Reclaimed water by definition is any treated wastewater to be reused for beneficial purposes, but more commonly the term is used with reference to treated MWW and so is it used hereafter in this paper. Depending on the water quality desired for a reuse application, additional treatment of reclaimed water to surpass the widespread regulatory secondary effluent standard(s) for reuse or discharge is usually vital. In California (USA), the standard is higher; MWW treatment to tertiary standard and post disinfection is required for reclaimed water reuse in industrial cooling that creates a mist (e.g. cooling towers) (USEPA, 2004; Veil, 2007). Although occupational health and safety concerns are undeniable with the reuse of reclaimed water (Veil, 2007), quality criteria for industrial cooling systems are usually associated to scaling, corrosion, and bio-fouling potential of reclaimed water (Barcelo and Petrovic, 2011; Puckorious, 2015; Rebhun and Engel, 1988; Selby et al., 1996; Veil, 2007). Therefore, more often than not (irrespective of regulatory standards), polishing of lagoon effluent, conventional secondary or advanced secondary effluent, and even tertiary effluent is required by the user to make the reclaimed water more suitable as make-up for industrial cooling unit(s). Generally, the additional treatment steps may be performed at the wastewater treatment plant or onsite and they include chemical addition, clarification, disinfection, pH adjustment and biological treatment (Lahnsteiner et al., 2007; Veil, 2007). Tertiary lime treatment, for example, is one of the familiar methods applied to remove scale forming constituents such as phosphate, calcium, and alkalinity (Rebhun and Engel, 1988; Scherer and Alexander, 1959; Scherer and Terry, 1971); whilst biological nitrification can also eliminate ammonia (a corrosive chemical to copper and its alloys) (Lahnsteiner et al., 2007; Osborne, 1964; Rebhun and Engel, 1988) to make the municipal effluent fit for cooling purposes. Wetlands have the capability to post treat secondary effluent to standards that can address the scaling, corrosion and bio-fouling concerns, which are so critical for cooling water reuse. Reuse applications for CW effluent such as agricultural, golf courses, parks and garden irrigation, and toilet flushing have been common in Europe on small scales (Rousseau et al., 2008; Veenstra, 1998), but have been practised on larger scales especially in Australia and United States (Greenway, 2005; Merz, 2000;Rousseau et al., 2008; USEPA, 1993). Industrial reuse applications of CW effluent are however very limited, although the potential is usually theoretically presumed based on the effluent quality from mainly pilot-scale treatability demonstration of CW (Peng et al., 2006; Rousseau et al., 2008; Wang et al., 2005).

Specifically with reference to CW and their application in the power plant industry (particularly coal-fired power plants), feasibility studies and pilot/full scale demonstrations of CW for treating industrial wastewaters are quite recent and have been reported for cooling tower blowdown (Bayley et al., 2009; USEPA, 1993), flue gas desulfurization (FGD) wastewater (Duke Energy, 2012; Eggert et al., 2008; Iannacone et al., 2009; Mooney and Murray-Gulde, 2008;Reitenbach, 2014; Rodgers et al., 2005; Snider et al., 2012;Wylie, et al., 2008), and coal combustion by-product (CCB) ash-leachate (EPRI, 1998; USEPA, 1993). The overall objective for such applications has been to treat the wastewater for some targeted constituents to achieve concentration levels that allow for discharge into streams, rivers, underground aquifers, etc. Feasibility of using CW effluent for industrial cooling has typically been presumed (Peng et al., 2006; Rousseau et al., 2008). Despite the current interest and propositions for it (Apfelbaum et al., 2013; Bengston, 2010; Duke Energy, 2012), search for actual examples both from scientific and general publications on reuse of CW effluent for power plant cooling purposes are very hard to come by. The following are few examples noted from quite an elaborate literature search of projects that somewhat relate to CW treated effluent for power plant cooling reuse.

A wetland complex (~9.5 acres) commissioned in 2007, whose influent is typically a combined surface water from an agricultural ditch system and storm water (not municipal wastewater), is reported to have been constructed to supply partial cooling water to a natural gas fired plant in Faribault, Minnesota (USA) (Sparks and Dougherty, 2009). Although it continues to serve its water conservatory purpose, current use of the CW effluent primarily for cooling could not be confirmed. However, this CW continues to be used as source make-up water for steam generation (MMPA, 2007); i.e. after passage through sand filtration and RO processes. In Europe, effluent from the Fusina Treated Wetlands sited near Venice, Italy (said to be the largest of its kind in Europe) is reused by nearby industrial complex for cooling or discharged to the Adriatic Sea (Albano et al., 2014; Frank et al., 2011; Zaffaroni et al., 2016;Zanovello et al., 2003). Between April 2006 to October 2007, a pilot scale CW treatment system was evaluated for its treatment of a cooling pond water from a power generating station (Hines Energy Complex in Florida, USA) (Lazareva and Pichler, 2010). Favorable outcome from the pilot project has led to development of a commercial scale, 250-acre wetland for cooling at the Hines Energy Complex that was anticipated to be completed in 2014 (Apfelbaum et al., 2013). More recently (March 2015), a project again in Florida (named Regional Reclaimed Water Project) was commissioned that supplies a CW (i.e. Lakeland Wetland) treated effluent to a power station (i.e. Tampa Electric Company's-TECO's Polk Power Station) for reuse as cooling water (TECO, 2015).

Commissioned in 1992, the Shand Power Station (SaskPower), which is located in Estevan of the Province of Saskatchewan, Canada received the Power Magazine Power Plant award in 1993 for its advanced design and environmental control processes (Lavender, 1993). Notable features recognized for the award included Zero Liquid Discharge (ZLD) water management system, LIFAC-which involves limestone and wastewater injection to capture SO_2, burners utilizing in-burner staging to minimize NO_x formation, and an on-site Greenhouse utilizing waste heat from the power station. At onset, the plant used mainly groundwater as the source of CT re-circulating make-up for condenser cooling. However, and as part of an earlier agreement between SaskPower and the City of Estevan to use all the city's year round treated municipal effluent for condenser cooling, a 23.5 hectare CW was completed in 1994 to polish the city's Wastewater Treatment Plant (WWTP) effluent for reuse at the power station. In the initial stages (first 2 years) of the wetland operation, influent to the CW was the city's lagoon effluent until the city's WWTP was upgraded to a conventional secondary treatment standard. It is now over twenty years since the station has been using CW for polishing municipal effluent for reuse in power plant cooling. Much knowledge has already been gained in the application of this low energy demand and relatively cheaper technology solely as treatment process for power plant cooling, whilst the industry seeks to break further grounds for this technology in power plant cooling with renewed focus to exploit also the cooling effect inherent in the process (Apfelbaum et al., 2013; Bengston, 2010; Duke Energy, 2012). It is hoped that the sharing of 2-decades commercial experience in this field will significantly contribute to the knowledge gap required for proper assessment of the viability of such new endeavors.

The paper is the first of a series of publications in attempt to fill this knowledge gap. It focuses on the rationale for use of CW to post-treat municipal effluent for power plant cooling reuse. It provides a literature review on the following: water quality requirements for power plant cooling; parameters of concern for reclaimed water reuse in power plant cooling application; performances of CWs around the world used in treating municipal wastewaters of different pre-treatment standards to indicate how CWs fit in addressing concerns in the reuse application for power plant cooling; and the various CW treatment applications within the power plant industry. It concludes with description of the experience at the Shand Power Station and enumerates the driving factors and/or benefits that motivated the partnership between SaskPower and the City of Estevan in adopting this technology-even 20 years ago to polish municipal treated wastewater to supplement the cooling needs at this power station.

2. WATER QUALITY FOR POWER PLANT COOLING

Reclaimed water quality guidelines for various water reuses including industrial reuse have been provided by various countries, states or provinces e.g. (Marsalek et al., 2002; USEPA, 2004; Victoria University, 2010). Water quality requirements for irrigation, recreational and some other purposes are however different from industrial requirements, which themselves may vary from one industry to another, and even within one single industry (Barcelo and Petrovic, 2011). Available reclaimed water quality guidelines for generic industrial uses are usually specified with respect to human and environmental health concerns and do not necessarily address parameters of concern to the industrial process. Parameters such as pH, total suspended solids (TSS)-mg/L, biochemical oxygen demand (BOD)-mg/L, faecal coliform-cfu/100 mL, and free (and/or total) chlorine residual-mg/L are what are usually specified and they do vary from region to region and depending on likely exposure to humans. For example, and in the respective order for pH, TSS-mg/L, BOD-mg/L, faecal coliform-cfu/100mL, and free (and/or total) chlorine residual-mg/L: 6-9, <30, <30, <200 and ≥ 1 is specified by USEPA (2004); 6-9, <5, <10, not specified, and ≥ 1 for Victoria in Australia when human contact is likely (Victoria University, 2010); and 6-9, <45, <45, <200 and $\geq(0.5)$ for British Columbia in Canada (Marsalek et al., 2002).

2.1 Cooling tower guidelines

Quality requirement for cooling water is related mainly to 3 common operational issues, which can affect the power plant performance: scaling, corrosion and bio-fouling (Barcelo and Petrovic, 2011;Puckorious, 2015; Rebhun and Engel, 1988;Selby et al., 1996; Veil, 2007). Stricter criteria are therefore required for power plant cooling water than for example when used in refineries, where these issues are of less concern (EPRI, 2012). Table 1 shows water quality criteria for cooling towers as they relate to power plants and refinery cooling systems.

2.2 Reclaimed water quality for cooling purposes

Some recommended reclaimed water limits as make-up for circulating cooling in power plants are also shown in Table 1. The reclaimed water qualities from the City of Estevan's WWTP employing facultative lagoon and conventional secondary treatment prior to CW polishing for cooling at the power station are also provided for comparison. It is noteworthy that effluents from municipal WWTPs do vary much. The variation is usually influenced by the wastewater sources, treatment technology-which is usually dictated at the design state by the locality's discharge standards for particular parameters, and the treatment efficiency-which is influenced also by site-specific operating (e.g. operator's skills) and environmental (e.g. seasonal or weather) conditions. In the United States, the federal requirement for discharges of treated wastewater is a minimum of secondary treatment that complies with the following discharge water quality: pH of 6-9, and BOD_5 and TSS each of $\leq$30 mg/L for a 30-day average. Water quality limits may however be set by various states with more stringent BOD and TSS standards and set standards for other parameters such as metals, organic compounds, nutrients, microbial pathogens (e.g. faecal and total coliforms), disinfection limits, etc. (EPRI and CEC, 2003; USEPA, 2004; Veil, 2007). For example, a discharge limit for environmental reuse of 1.0 mg/L limit for total phosphorous (TP) is required in some states in USA (USEPA, 2012), but not in others (USEPA, 2004, 2012; Veil, 2007; Vidic et al., 2009).

More often than not, the discharge limits set at the federal, state (or province), or the local level are governed by environmental and health/safety concerns and may have less or no consideration for the reclaimed water reuse application-in this case power plant cooling. For example, free chlorine minimum limit of 1 mg/L is usually stipulated for most state discharge permits as disinfection standard, with less consideration to corrosion issues that may result in the reuse application. Operational objectives of water criteria should however also focus on minimizing mineral scaling, corrosion and bio-fouling (as mentioned earlier) of heat transfer surfaces as well as other components of the cooling systems (e.g. nozzles, cooling tower filling materials, screens). For power plant cooling reuse, the secondary to tertiary reclaimed wastewater quality is usually only a starting level of treatment from WWTPs and further treatments are required to address any operational concerns (USEPA, 2004; Veil, 2007). For example, the Palo Verde Nuclear Generating Station, which uses the secondary effluent from the City of Phoenix's (Arizona, USA) 91st Avenue WWTP for cooling, subjects the effluent to tertiary treatment before reuse application (Lotts, 2014;NPDES, 2010). This further treatment includes the use of trickling filters (for biological nitrification/de-nitrification), lime and soda ash softening and mixed media gravity filtration. Through these processes, influent alkalinity (189 mg/L $CaCO_3$), Ca (73.2 mg/L), Mg (29.9 mg/L), SiO_2 (19 mg/L), and PO_4^{3-}(10 mg/L), for example, can be reduced to 27, 29.2, 3.6, 3.5 and <0.1 respectively and allow higher CT cycles of concentrations (Lotts, 2014).

2.2.1 Parameters of health concerns with reclaimed water uses

Traditionally, parameters in reclaimed water of health concerns in industrial cooling applications include BOD, TSS, and faecal coliform. Of notable concern in power plant cooling are the levels of bacteria and other microbial pathogens (including Legionella) that could potentially be released to the atmosphere through a CT plume (e.g. aerosols and windblown spray)(Lee, 2012; Veil, 2007). CT plume containing Legionella can potentially cause Legionnaires' disease to employees and members of the public who come in contact (Lee, 2012).

Organics (especially the biodegradable fraction usually measured in terms of BOD) also serve as food for microorganism and together with nutrients in the reclaimed water (e.g. P and N compounds, and even some inorganic minerals such as Fe and Mn) do promote biological growth and therefore pose health concerns when in high levels of concentration. To alleviate the health risks associated with microbial growth, disinfectionof treated MWW (reclaimed water) is usually required before the reuse application and in the case of power plant cooling also during the cooling process. Chlorination is the most widely used disinfection program (EPRI and CEC, 2004; Lee, 2012; Veil, 2007; Weber and Legge, 2008). For industrial reuse applications where human contact is likely, a free chlorine minimum of 1 mg/L is required in the reclaimed water (USEPA, 2004; Victoria University, 2010). However, high levels of organics in reclaimed water do react with chlorine and may lead to the formation of trihalomethanes (THMs) as disinfection by-products, which are known carcinogens. In a study involving two power plant sites (EPRI and CEC, 2004): one using well water (fresh water) as CW makeup and the other using a blend of well water and reclaimed municipal effluent; whereas no significant amount of total THM (TTHM) concentrations was anticipated in the makeup for former, relatively high TTHM concentration (average of~19.4μg/L) was observed for the latter site which uses reclaimed water as part of the CW makeup. Apart from concerns with cancer, THMs can also cause liver and kidney damage, retard fetus growth, birth defects, and possibly miscarriage (EPRI and CEC, 2004). The known exposure routes into humans include ingestion, inhalation and dermal contact (Dyck et al., 2011); although the first exposure route is less likely for power plant cooling process.

2.2.2 Parameters of operational concerns with reclaimed water uses

The above listed parameters of health concerns in Section 2.2.1 are also of operational concerns as they lead to biofilm formation impacting the efficiency of heat exchanging equipment within cooling systems (e.g. steam condensers and CTs). Other parameters of operational concerns that also impact on cooling efficiency include o-phosphate (PO_4^{3-}), pH and/or alkalinity (HCO_3^- and CO_3^{2-}), hardness (i.e. magnesium and calcium content), silica and/or silicate as they may cause scale deposition on heat exchanger surfaces and also block screens and other filtration units, nozzles, etc. within the cooling system.

There are also parameters in reclaimed water used for power plant cooling that pose corrosion challenges depending on the metallurgy of equipment exposed to the recirculating water including pumps, nozzles, valves, expansion joints, condenser tubes, tubesheets and waterboxes, etc. (SDCWA, 2009). Copper alloys are susceptible to corrosion from ammonia and high total dissolved solids (TDS). Mild steel is prone to corrosion from high TDS, suspended solids, biomass, scale and heavy metals. Galvanized iron (Cu and Zn coating) is vulnerable to corrosion from high TDS and pH

Table 1 Water quality requirements for cooling towers and recommended reclaimed water limits as make-up for power plant circulating cooling water; along with facultative lagoon (L2^o) and conventional secondary treated (2^o) municipal wastewater (MWW) quality prior to CWpolishing for cooling purposes at the Shand Power Station

Parameters	**Units**	**Cooling Towers**		**Make-up max (Reclaimed water)**			**MWW**	
		Power Plant	Refinery				L2^o	2^o
Mg	mg/L	56	-	20	-	40	86	63
Ca	mg/L $CaCO_3$	≤900[a]	≤1,500	175	-	250[i]	100	91
Ca × SO_4^{2-}	$(mg/L)^2$	500,000[g]	-	N/A	N/A	N/A	N/A	N/A
Mg × SiO_2	$(mg/L)^2$ [j]	35,000	-	N/A	N/A	N/A	N/A	N/A
M-Alkalinity	mg/L $CaCO_3$	30-50[b]; 200-250[c]	-	200	350	-	451	417
Total Hardness	mg/L $CaCO_3$	-	-	-	450	417[i]	-	479
SO_4^{2-} and (S)	mg/L	(5)	≤5,000 (10)	300	-	50	825	667
Cl^-	mg/L	-	-	-	250	250	239	231
SiO_2	mg/L	150	300	20	-	20	-	-
PO4 (TP)	mg/L	<5a	≤50	0.5	(1)	-	10.4	10.4
Fe (total)	mg/L	<0.5	≤10	0.2	0.3h	0.3	-	0.16
Mn	mg/L	<0.5	1	0.05	0.2h	-	0.10	0.25
Cu and Al	mg/L	<0.1 (<1)	0.5 (1)	0.1	-	1	<0.002	<0.002
NH3 (NH4+-N)	mg/L	<2d	≤40	-	(10)	(2)	(6.9)	(7.4)
pH	-	7.8-8.4a	7-9	6-8	6-9	7.0-8.5	8.0	8.3
TDS	mg/L	70,000	-	750	1,000	1,200	2,074	1,817
TSS	mg/L	<100e; <300f	200	10	-	5	86	41
BOD and (TOC)	mg/L	-	200	20 (5)	10	-	27 (40)	10 (21)
Feacal Coliform	MNP/100 mL	-	-	150	2,000	(126)k	7 × 104	2 × 102
Total N (TKN)	mg/L	-	-	8	-	5	(11.9)	(10.0)
Ni and (Pb)	mg/L	-	-	0.5 (0.05)	-	-	-	-
		(Eble and Feathers, 1993; EPRI, 1982; EPRI, 2012; EPRI and CEC, 2003; Schimmoller, 2012)		Schimmoller, 2012)	(Lahnsteiner et al., 2007)	(Hansen and Harder, 2006)		

Note: [a]Earlier guideline (EPRI, 1982)-all others in column are current standards (EPRI & CEC, 2003);[b]Without scale-inhibitor;[c]With scale-inhibitor;[d]When Cu bearing alloys (but not 70-30 or 90-10 Cu-Ni) are present;[e]System with film fill;[f]System with open fill; [g]GC3(2016) suggests that with phosphonate scale inhibition treatment, recommended product for without scale inhibitor could extend up to~3x;[h]metal ion cited in +2 state;[i]Calculated based on reported data; [j]mg/L $CaCO_3$× mg/L SiO_2; [k]E-coli count outside the range 6.5-8.5. Stainless steel (304- and 316-SS)is susceptible to both chloride-and microbiological induced corrosion (MIC) when deposition occurs on the metal surface (SDCWA, 2009). The mechanisms of MIC are diverse and often rely on both organic and inorganic materials to metabolise (Victoria University, 2010). Inorganic parameters whose presence are implicated to accelerate MIC include sulphates (and related species), Fe^{2+} and Mn^{2+} when the right microbes capable of assimilating them are present.

Deposition corrosion is a special case of galvanic corrosion that takes the form of pitting. It occurs when particles of a more cathodic metal is plated out of solution unto the surface of a less cathodic metal to set up local galvanic cells (Davis, 1999). For aluminium, the ions aggressive to it are copper, lead, mercury, nickel and tin (often called heavy metals). The effect of heavy metals is greater in acidic solutions, as they tend to be less soluble in more alkaline solutions. Of the heavy metals, mercury can cause the most corrosion damage to aluminum (Davis, 1999). Precipitation of copper ions from solutions on aluminium alloys 6061 and 3003 caused pitting corrosion of these alloys (Hack, et al., 1998). A copper ion concentration of 0.02-0.05 mg/L in neutral or acidic solutions is generally considered to be the threshold value for initiation of pitting on aluminium (Davis, 1999). Copper (and nickel) can plate out also on steel causing localized galvanic corrosion that can rapidly penetrate thin steel heat exchanger tubes (SDCWA, 2009). Although the effect of heavy metal ions on corrosion behaviour of carbon steel is quite pronounced, there is negligible effect of these ions on corrosion rate of 316SS (Mobin et al., 2007).

3. CONSTRUCTED WETLAND TREATMENT OF MUNICIPAL EFFLUENT

In the previous sections, parameters of concern in reclaimed water that may make them unsuitable for power plant cooling were discussed. Parameters characteristic of reclaimed water (from municipal sources) include high nutrients, organic matter, and bacteria content. These are variously measured and reported sometimes in terms of their biological or chemical stability (to include biological oxygen demand (BOD) and chemical oxygen demand (COD)) or as total of the element/component of interest or its speciated forms. For example, nitrogen may be expressed as total nitrogen (TN) to include organic nitrogen and inorganic nitrogen comprising ammonia, nitrate, and nitrite; phosphorous as total phosphorous (TP) to include organic phosphorous and inorganic fraction usually expressed as phosphate; carbon content (as dissolved and/or total organic carbon or as inorganic carbon in the form of carbonates or bicarbonate); and bacteria (more commonly measured generically as fecal/total coliform and heterotrophic plate count or in rare cases as specific bacteria type(s)). There are bountiful treatment options for these parameters-individually or collectively and most times may require multiple treatment processes to remove multiple contaminants of concern from the wastewater.

3.1 Constructed wetlands vs. conventional wastewater treatment

Conventional wastewater treatment systems are promising but involve high capital and maintenance costs and in most cases require high level of expertise and training (not forthcoming in all regions or difficult to retain) to ensure adequate, consistent and sustainable treatment. In comparison, CW technologies are low cost, have low external energy requirements, easily operated and maintained (Gray, 2008; Mustafa, 2013; Wu et al., 2014). CW for wastewater treatment is a more environmental friendly and sustainable technology; it minimizes the amount of carbon dioxide released into the atmosphere. Carbon dioxide released via microbial decomposition is reused by macrophytes in photosynthesis (Mthembu et al., 2013).

Despite the reliability and effectiveness of conventional MWW treatment methods in removing pathogens (Vymazal, 2005b), post-disinfectionis usually still necessary to meet requirements for discharge and reuse applications, with chlorination being the most widely used (Weber and Legge, 2008). Chlorination however can produce the carcinogenic THMs when natural organic matter is present in the wastewater. CWs can provide alternative treatment for the removal and inactivation of pathogens in the conventional treated wastewater (Vymazal, 2005b; Weber and Legge, 2008), whilst also reducing further the organic content to minimize THM concerns in reuse applications, such as in power plant cooling. Pathogen removal efficiencies upwards of 99.99% have been reported from multiple studies employing a number of different CW designs (Weber and Legge, 2008).

Both at pilot and commercial scale, CWs have shown to successfully remove organic material, nutrients and pathogens at rates comparable if not better in some cases to conventional wastewater treatment (Gray, 2008;Mthembu et al., 2013; Mustafa, 2013). The demonstrations have been on varied types of wastewaters including storm run-offs, MWW, landfill leachates, paper and pulp wastewaters, refinery process water, agricultural drainage, animal wastes, acid coal and metal ores mine drainages, etc. (Vymazal, 2010). Here, the literature is reviewed on the performance of CWs to polish MWW at different levels of treatments (i.e. lagoon effluent, secondary and advanced secondary or tertiary effluent).

Apart from treatment improvements in an easy to manage and cost effective manner, CW based technologies have numerous other beneficial qualities their conventional treatment counterparts do not offer in the reuse application of MWW effluent for power plant cooling. These include (Apfelbaum et al., 2013); the cooling effect they provide, amenability for water harvestingand storage to augment water resources for makeup supply and improve the makeup quality, as well as providing various socio-economic and ecosystem benefits including wildlife habitation.

3.2 Types of constructed wetlands

CW technologies can be divided into different types based on various parameters, including the types of plants, the water flow regime, flow direction, etc. By the water flow regime, CWs may be classified as surface flow or sub-surface flow (SSF). The latter may be further classified according to flow direction as horizontal subsurface flow (HSSF) and vertical subsurface flow (VSSF) (Vymazal, 2010, 2011). The former, which is more dominant in North America and Australia, is referred to also as free water surface (FWS) flow (Vymazal, 2010). FWS CWs are mostly used for treating secondary treated wastewaters including those of domestic or municipal and agricultural sources (Kadlec and Wallace, 2009). The SSF systems may be vegetated or non-vegetated, but are not distinguished as such in this manuscript although most, if not all, of the referenced systems herein are vegetated. HSSF CWs are mostly used for secondary treatment of domestic and municipal wastewater (Vymazal and Kröpfelova, 2008).

Various CW configurations may be combined so as to increase their treatment efficiency, especially for nitrogen and phosphorous compounds. Such combinations are called hybrid systems. Herein, a combination of

VSSF and HSSF CWs is referred to as hybrid-subsurface flow (HYSF) CW; a combination of FWS and SSF CWs is referred to simply as hybrid (HY) CW, whilst three or more stages of same type of CW is described by the prefix "Multi" (e.g. 3-stage FWS is referred to as MultiFWS). A combination of FWS, HSSF, or VSSF with soil filters, ditches, etc. as part of the treatment system [e.g. (Obarska-Pempkowiak and Klimkowska, 1999)] is also referred herein as hybrid (HY) system. Unlike conventional treatment systems, which usually involve multiples of single processing units either in tandem or as separate units to treat multi-contaminants; CWs offer the advantage of utilising various treatment principles in a more comprehensive fashion to remove multi-contaminants.

3.3 Processes involved in constructed wetland treatment

Wetlands (both natural and constructed) employ 3 main processes (physical, biological and chemical) for removing various contaminants from the wastewaters (Choudhary et al., 2011). The physical processes involved are sedimentation and/or filtration to remove parameters such as TSS, BOD, COD, metals and nitrogenous/phosphorous compounds; volatilization to remove more volatile compounds such as some petroleum hydrocarbons, synthetic organics, ammonia, and nitrogen (N_2)/di-nitrogen oxide (N_2O) from denitrification process, etc.; and filtration for pathogen removal.

The chemical processes comprise adsorption and precipitation to remove dissolved phosphorous and nitrogenous compounds, metals and some organic compounds; ion exchange (soil media) for removing dissolved metals; and redox reactions to include photolytic oxidation (from UV ray exposure) to destroy pathogens and biochemical oxidation of organic compounds under aerobic conditions (i.e. reduction of BOD, COD and total organic carbon (TOC).

The biological processes involved in wetlands operation include biodegradation of organic compounds (via fermentation-under anaerobic conditions and microbial respiration-under aerobic conditions); nitrification and denitrification processes to remove nitrogenous compounds; plant and/or microbial uptake of metals, phosphorous and nitrogenous compounds; phytovolatilization of hydrophilic compounds such as acetone and phenol through the root system and transfer to the atmosphere via the plant's transpiration stream, and natural die-off or predation to remove pathogens (Horner, 2015).

3.4 Treatment efficiencies of constructed wetlands

Tables 2 to 4 show influent, effluent, and removal efficiency (%) of various parameters typically reported as averages during the respective study periods. The results indicate significant variations in treatment efficiency for different parameters from the various reports. This should be expected considering differences in CW types, design, wastewater characteristics, weather and climatic conditions, and differences in operational conditions even for same CW (i.e. differences in for example hydraulic and mass loads and the season of operation).

Although significant site specific variations in efficiency do exist, there are consistent improvements of the wastewater quality in terms of certain parameters (e.g. BOD, COD, TSS, TN and TOC). CWs demonstrate removal of many other parameters, but there seem to be less consistency amongst the various types of CWs, the size of the CW and/or the quality of wastewater being treated. Details of such consistency or inconsistency in efficiency of CW as a treatment process for various parameters as discussed below.

3.4.1 Removal of organic matter and suspended solids

Organic matter removal efficiency of CW may be evaluated based on measurement of BOD, CBOD (carbonaceous biochemical oxygen demand), COD and TOC as shown in Tables 2 to 4. As shown in the tables, CW(irrespective of the type) have been used successfully, both at pilot- and full-scale levels, in removing various forms of organic fractions from municipal wastewaters of various shades (quality) and of a wide range of inflow concentrations. Although significant site specific variations in efficiency do exist, there are consistent improvement of wastewater quality in terms of BOD (or CBOD), COD, and TOC-irrespective of the type of CW; the improvement being more manifested in the treatment of raw or primary municipal effluent (Table 4).

Average removal of BOD(as BOD and/or CBOD) from secondary and tertiary MWW is 53.3 ± 21.7% and 65.3 ± 19.1% respectively for small scale and large scale CWs; whilst the general (both large and small scale CW) removal from primary or raw MWW was significantly higher at 82.8± 15.0%. The reader is also being referred to another comprehensive review of data on the performance of FWS CW in BOD removal from secondary effluent, where an average removal of 49.6% was reported (Ghermanhi et al., 2007). Similarly, 48.8 ± 14.1% and 58.2 ± 22.4% removal of COD fraction of organic matter is respectively realized from small scale and large scale CWs on treating secondary and tertiary MWW in comparison to 74.6 ± 14.7% when treating primary or raw MWW. Data on TOC is scanty, but is consistent with that of BOD and COD: 31.5± 3.5% removal on treating secondary and tertiary MWW as compared to 86.2 ± 8.6% when treating primary or raw MWW. CW treatment of raw MWW has however not been recommended (Horner, 2015); this is likely because of potential clogging of the wetlands due to high organic and suspended loading rates in the raw wastewater (Liu et al., 2015).

Suspended solid removal efficiency is also shown in Tables 2 to 4 from TSS measurements. From these tables, CWs-irrespective of the types is generally effective in removing suspended solids from wastewaters. Apart from two FWS sites (Kadlec et al., 2010; USEPA, 1993) with TSS removal of less than 20%, which incidentally are the two largest CW from the data survey and one HYSF CW (Pan et al., 2012) with removal of only ~39%, the TSS removal efficiency of CWs irrespective of the type and the quality of the wastewater being treated is estimated as 80 ± 14%. From another comprehensive data review on TSS removal, but restrictively on the performance of FWS CW treating secondary effluent, 19 out of 36 sites were reported to remove >60% TSS (Ghermanhi et al., 2007). Although an average removal of only 23.1% was reported, the value does not seem to be a good representation of the performance of even FWS CW in removing TSS; being distorted by data from 6 sites with significant export of TSS from the wetland.

Table 2 Performance of small (<405 m^2 or 0.1Acres) field pilot or laboratory scale constructed wetlands for tertiary (3^o)/secondary (2^o) municipal wastewater (including lagoon or stabilizing pond effluent ($L2^o$)) treatment (to be continued)

	Unit	Influent conc.	Effluent conc.	Eff. (%)/Δ [diff] = Inf.-Eff.	CW Type and influent quality	Years in Operation	References
BOD_5	mg/L	68.8	34.0	50	FWS-2^o	<1	Mustafa (2013)
		19	12	36.8	HSSF-$L2^o$	~3	Steinmannetal. (2003)
		80.51	62.80	22.0	HSSF-$L2^o$	½	Katsenovich et al.(2009)
		11.0	3.85	65	HSSF-3^o	3	Ayaz (2008)
		11.0	3.96	64	FWS-3^o	3	
		78.7	14.0	82.2	^{n}HY-2^o	3 + 2¼	de la Varga (2013)
COD	mg/L	122.9	68.3	44	FWS-2^o	<1	Mustafa (2013)
		77	53	31.2	HSSF-$L2^o$	~3	Steinmann et al. (2003)
		33	16.5	50	HSSF-3^o	3	Ayaz (2008)
		33	18.15	45	FWS-3^o	3	
		20.9	12.6	39.7	VSSF-3^o	1	Martin et al.(2013)
		335.9	147.13	56.2	HSSF-$L2^o$	½	Katsenovich et al.(2009)
		141.0	34.7	75.4	^{n}HY-2^o	3 + 2¼	de la Varga (2013)
TSS	mg/L	201.4	45	78	FWS-2^o	<1	Mustafa (2013)
		202.7	32.13	84.15	HSSF-$L2^o$	½	Katsenovich et al. (2009)
		15	3.0	80	HSSF-3^o	3	Ayaz (2008)
		15	5.25	65	FWS-3^o	3	
		41.3	5.3	87.2	^{n}HY-2^o	3 + 2¼	de la Varga (2013)
TP	mg/L	(7.6)	(3.7)	52	FWS-2^o	<1	Mustafa (2013)
(PO_4^{3-})		8	7	12.5	FWS-2^o	~3	Greenway(2005)
TP (PO_4^{3-})	mg/L	0.2 (0.06)^l	<0.05 (<0.03)	>75 (>50)	FWS-2^o	~2?	Greenway (2005)
		7	7	0	FWS-2^o	-	Greenway (2005)
		1.52	1.28	15.8	HSSF-$L2^o$	~3	Steinmann et al. (2003)
		0.64(0.52)	0.15 (0.13)	76.1 (76.0)	VSSF-3^o	1	Martin et al. (2013)

Table 2 Performance of small (<405 m^2 or 0.1Acres) field pilot or laboratory scale constructed wetlands for tertiary (3^o)/secondary (2^o) municipal wastewater (including lagoon or stabilizing pond effluent ($L2^o$)) treatment

	Unit	Influent conc.	Effluent conc.	Eff. (%)/Δ [diff] = Inf.-Eff.	CW Type and influent quality	Years in Operation	References
TN	mg/L	6	1.5	75	FWS-2^o	~3	Greenway (2005)
		25	6	76	FWS-2^o	~2?	Greenway (2005)
		32	7	78.1	FWS-2^o	-	Greenway (2005)
		9.9	7.9	25.3	HSSF-$L2^o$	~3	Steinmann et al. (2003)
		19.8	12.0	39.3	HSSF-$L2^o$	½	Katsenovich et al.(2009)
		8.9	7.5	15.7	VSSF-3^o	1	Martin et al. (2013)
NH_3-N	mg/L	19.2	9.7	49	FWS-2^o	<1	Mustafa (2013)
		0.3^m	0.2	33.3	FWS-2^o	~3	Greenway (2005)
		13	1	92.3	FWS-2^o	~2?	Greenway (2005)
		11	2	81.8	FWS-2^o	-	Greenway (2005)
		3.76	3.10	17.6	HSSF-$L2^o$	~3	Steinmann et al. (2003)
		1.91	0.20	89.5	VSSF-3^o	1	Martin et al. (2013)
NO_3^--N	mg/L	9.0	0.1	98.9	FWS-2^o	~3	Greenway (2005)
		8	1	87.5	FWS-2^o	~2?	Greenway (2005)
NO_3^--N	mg/L	16	0.3	98.1	FWS-2^o	-	Greenway (2005)
		0.80	1.01	-26.3	HSSF-$L2^o$	~3	Steinmann et al. (2003)
		5.69	6.67	-17.2	VSSF-3^o	1	Martin et al. (2013)

Table 2 Performance of small (<405 m^2 or 0.1Acres) field pilot or laboratory scale constructed wetlands for tertiary (3^o)/secondary (2^o) municipal wastewater (including lagoon or stabilizing pond effluent ($L2^o$)) treatment

	Unit	Influent conc.	Effluent conc.	Eff. (%)/Δ [diff] = Inf.-Eff.	CW Type and influent quality	Years in Operation	References
TOC	mg/L	11	8.7	29	HSSF-3^o	3	Ayaz(2008)
		11	7.3	34	FWS-3^o	3	
TC	cfu/100mL	2.1×10^6	8×10^3	93	FWS-2^o	<1	Mustafa (2013)
		2.1×10^4	1.24×10^3	94	HSSF-3^o	3	Ayaz (2008)
		2.1×10^4	1.24×10^3	94	FWS-3^o	3	
FC or (E-Coli)	cfu/100mL	1.1 × 106	3×10^3	98	FWS-2^o	<1	Mustafa (2013)
		8.48×10^4	1.23×10^4	85.52	HSSF-$L2^o$	½	Katsenovich et al.(2009)
		2.3×10^3	1.4×10^2	94	HSSF-3^o	3	Steinmann et al.(2003)
		2.3×10^3	1.4×10^2	94	FWS-3^o	3	
pH	-	7.8	7.9	[-0.1]	FWS-2^o	< 1	Mustafa (2013)
		7.2-11.3	6.5-8.9	[0.7-2.4]	HSSF-$L2^o$	~ 3	Steinmann et al. (2003)
		7.13	7.12	[0.1]	VSSF-3^o	1	Martin et al. (2013)
Temp	^oC	12.2	11.3	[0.9]	HSSF-$L2^o$	~3	Steinmann et al. (2003)
		21.2	20.0	[1.2]	VSSF-3^o	1	Martin et al. (2013)
		14.8	14.0	[0.8]	[n]HY-2^o	3 + 2¼	de la Varga (2013)
BOD_5 (CBOD)	mg/L	31.7	6.0	77.8	FWS-15-2^o	~3	USEPA (1993)
		27	6	77.8	FWS-15-$L2^o$	8	USEPA (1993)
		3.88	3.12	19.6	FWS-1400-2^o	~4	USEPA (1993)
		3.62	2.38	34	FWS-0.77-L 2^o	<1	Cameron et al. (2003)

Notes: [l]Alum dosing pre-treatment to remove PO_4^{3-};[m]Oxidation ditch pre-treatment for nitrification of NH_3;[n]an up-flow anaerobic sludge bed (UASB) serves as pre-treatment in a combined hybrid system of FWS-HSSF

Table 3 Performance of full-Scale or large field Pilot (>405 m^2 or 0.1acres) constructed wetland for Tertiary (3^o) and Secondary (2^o) municipalwastewater (including facultative lagoons ($F2^o$)) treatment (to be continued)

	Unit	**Influent conc.**	**Effluent conc.**	**Eff. (%)/Δ [diff] = Inf.-Eff.**	**CW type, size (acres) and influent quality**	**Years in Operation**	**References**
BOD_5 (CBOD)	mg/L	(28)	(8.2)	(70.7)	HSSF-15.2-L 2^o	~2	TWDB (2000)
		(40.4)	(11.3)	(72.0)	HSSF-1.8-L 2^o	~1	TWDB (2000)
		(23.3)	(7.3)	(68.6)	FWS-37.5-L 2^o	~15	TWDB (2000)
		(25.6)	(9.7)	(62.3)	FWS-3.7-2^o	<2	TWDB (2000)
		(19)	(4.97)	(73.8)	FWS-6.2-2^o	31 + 6½	TWDB (2000)
		36.8	9.4	74.5	FWS-130-2^o	14	Kadlec et al. (2010)
		(13.2)	(5.0)	(62.1)	FWS-130-2^o	14	
		(5.4)	(3.2)	(40.7)	FWS-15.3-L 2^o	½ + 10	Kadlec et al. (2012)
		38	8	78.9	FWS-0.4-L2^o	¾	Pride et al. (1990)
		104.5	20.1	80.8	FWS-0.18-2^o	½	Katsenovich et al. (2009)
		56.5	7.7	86.4	HSSF-2.33-^{p} L2^o	¾	Shi et al (2004)
COD	mg/L	60.7	40.9	32.6	FWS-130-2^o	14	Kadlec et al. (2010)
		209.1	72.8	65.2	FWS-0.18-2^o	½	Katsenovich et al. (2009)
		145.6	33.9	76.7	HSSF-2.33-^{p} L2^o	¾	Shi et al. (2004)

Table 3 Performance of full-Scale or large field Pilot (>405 m^2 or 0.1acres) constructed wetland for Tertiary (3^o) and Secondary (2^o) municipalwastewater (including facultative lagoons ($F2^o$)) treatment (to be continued)

	Unit	Influent conc.	Effluent conc.	Eff. (%)/Δ [diff] = Inf.-Eff.	CW type, size (acres) and influent quality	Years in Operation	References
TSS	mg/L	88.6	11.8	84.2	FWS-15-2^o	~3	USEPA (1993)
		51	11	78.4	FWS-15-L2^o	8	USEPA (1993)
		5.60	4.70	16.1	FWS-1400-2^o	~4	USEPA (1993)
		82.7	6.2	92.5	FWS-0.77-L 2^o	<1	Cameron et al. (2003)
		53.0	11.2	78.9	HSSF-15.2-L 2^o	~2	TWDB(2000)
		51.8	12.0	76.8	HSSF-1.8-L 2^o	~1	TWDB(2000)
		28.6	7.3	74.6	FWS-37.5-L 2^o	~15	TWDB(2000)
		57.4	10.7	81.4	FWS-3.7-2^o	<2	TWDB(2000)
		21.2	7.0	67.0	FWS-(?)-L2^o	16 + ¼	Anderson et al.(2013)
		16.6	14.7	11.4	FWS-130-2^o	14	Kadlec et al. (2010)
		13.2	7.2	45.5	FWS-15.3-L 2^o	½ + 10	Kadlec et al. (2012)
		135	19	85.9	FWS-0.4-L2^o	¾	Pride et al. (1990)
		59.9	7.9	86.8	HSSF-2.33-^{p}L2^o	¾	Shi et al. (2004)
TP (PO_4^{3-})	mg/L	9.05	4.22	53.4	FWS-1400-2^o	~4	USEPA (1993)
		0.33 (0.18)	0.03 (0.03)	89.9 (81.8)	FWS-0.77-L 2^o	<1	Cameron et al. (2003)
		0.05-0.12	<0.25	~0 or -ve	FWS-0.6-3^o	2	Beutel (2012)

Table 3 Performance of full-Scale or large field Pilot (>405 m^2 or 0.1acres) constructed wetland for Tertiary (3^o) and Secondary (2^o) municipalwastewater (including facultative lagoons ($F2^o$)) treatment (to be continued)

	Unit	Influent conc.	Effluent conc.	Eff. (%)/Δ [diff] = Inf.-Eff.	CW type, size (acres) and influent quality	Years in Operation	References
TP (PO_4^{3-})	mg/L	4.54	4.22	7	FWS-3.7-2^o	<2	TWDB (2000)
		1.42	< 0.02	>98.6	FWS-(?)-$L2^o$	16 + ¼	Anderson et al.(2013)
		1.95 (4.23)	0.95 (1.26)	51.3 (70.3)	FWS-0.12-2^o	5	Abe et al. (2014)
		2.54	2.41	5.1	FWS-130-2^o	14	Kadlec et al. (2010)
		0.38[j]	0.26	31.6	FWS-15.3-$L2^o$	½ + 10	Kadlec et al. (2012)
		5.55	1.86	66.5	FWS-0.18-2^o	½	Katsenovich et al.(2009)
		3.07	0.56	81.7	HSSF-2.33-[p]L 2^o	¾	Shi et al. (2004)
TN (TKN)	mg/L	15.5	-	-	FWS-15-2^o	~3	USEPA (1993)
		10.36	1.99	80.8	FWS-1400-2^o	~4	USEPA (1993)
		1.67	1.05	37.3	FWS-0.77-$L2^o$	<1	Cameron et al. (2003)
		14.1(13.8)	8.2(8.0)	42.0 (42.3)	HSSF-1.8-$L2^o$	~1	TWDB (2000)
		13.3(13.7)	9.8(10.3)	26.3 (25.0)	FWS-3.7-2^o	<2	TWDB(2000)
		20.2	2.17	89.1	FWS-6.2-2^o	31 + 6½	TWDB (2000)
		20.0	10.3	48.5	FWS-0.12-2^o	5	Abe et al. (2014)
		15.1(12.6)	11.7(10.2)	22.4(19.3)	FWS-130-2^o	14	Kadlec et al. (2010)
		(13.6)	(11.2)	(17.6)	FWS-15.3-$L2^o$	½ + 10	Kadlec et al. (2012)
		(15)	(4)	(73.3)	FWS-0.4-$L2^o$	¾	Pride et al. (1990)

Table 3 Performance of full-Scale or large field Pilot (>405 m^2 or 0.1acres) constructed wetland for Tertiary (3^o) and Secondary (2^o) municipal wastewater (including facultative lagoons ($F2^o$)) treatment (to be continued)

	Unit	**Influent conc.**	**Effluent conc.**	**Eff. (%)/Δ [diff] = Inf.-Eff.**	**CW type, size (acres) and influent quality**	**Years in Operation**	**References**
TN (TKN)	mg/L	14.8	6.1	58.6	FWS-0.18-2^o	½	Katsenovich et al. (2009)
		16.5	9.1	44.9	HSSF-2.33-^{p}L2 o	¾	Shi et al. (2004)
NH_3-N	mg/L	0.11	0.05	51.7	FWS-0.77-L2^o	< 1	Cameron et al. (2003)
		0.06-0.11	<0.11	~0 or -ve	FWS-0.6-3^o	2	Beutel (2012)
		6.11	2.35	61.5	HSSF-1.8-L2^o	~1	TWDB(2000)
		7.4	4.8	35.2	FWS-37.5-L2^o	15 + 1¼	TWDB (2000)
		5.0	7.0	-56.6	FWS-3.7-2^o	<2	TWDB(2000)
		4.2	1.3	68.3	FWS-6.2-2^o	31 + 6½	TWDB (2000)
		0.55	0.02	97.2	FWS-(?)-L2^o	16 + ¼	Anderson et al. (2013)
		0.69	0.52	25	FWS-3.0-3^o	<1	McLain and William (2008)
		7.6	3.8	50.0	FWS-0.12-2^o	5	Abe et al. (2014)
		9.93	8.61	13.3	FWS-130-2^o	14	Kadlec et al. (2010)
		13.31	9.42	29.2	FWS-15.3-L2^o	½ + 10	Kadlec et al. (2012)
		12.7	0.54	95.8	FWS-0.18-2^o	½	Katsenovich et al. (2009)
NO_3-N (NO_x-N)	mg/L	3.0-5.8	0.2-0.7	90	FWS-0.6-3^o	2	Beutel (2012)
		<0.1	<0.1	0	FWS-0.77-L2^o	<1	Cameron et al. (2003)
		0.29	0.29	0	FWS-37.5-L2^o	15 + 1¼	TWDB(2000)

Table 3 Performance of full-Scale or large field Pilot (>405 m^2 or 0.1acres) constructed wetland for Tertiary (3^o) and Secondary (2^o) municipal wastewater (including facultative lagoons ($F2^o$)) treatment (to be continued)

	Unit	**Influent conc.**	**Effluent conc.**	**Eff. (%)/Δ [diff] = Inf.-Eff.**	**CW type, size (acres) and influent quality**	**Years in Operation**	**References**
NO_3-N (NO_x-N)	mg/L	0.07	0.015	78.7	FWS-3.7-2^o	<2	TWDB (2000)
		1.23	0.07	94.8	FWS-6.2-2^o	31+ 6	TWDB(2000)
		10.3	4.8	53.4	FWS-0.12-2^o	5	Abe et al. (2014)
		(2.41)	(1.49)	(38.2)	FWS-130-2^o	14	Kadlec et al. (2010)
		0.53 (0.84)	0.34(0.46)	35.8 (45.2)	FWS-15.3-L2^o	½ + 10	Kadlec et al. (2012)
TC	cfu/100 mL	220	1.8×10^4	-ve	FWS-3.0-3^o	<1	McLain and William (2008)
FC or (E-Coli)	cfu/100 mL	82.8	39.4	52.4	FWS-0.77-L2^o	<1	Cameron et al. (2003)
		6.2×10^4	3.4×10^3	94.5	HSSF-15.2-L2^o	~2	TWDB(2000)
		1.2×10^4	3.5×10^3	69.8	FWS-3.7-2^o	<2	TWDB(2000)
		3.95×10^4	6.25×10^2	98	FWS-6.2-2^o	31 + 6½	TWDB(2000)
		(0)	(5.8×10^2)	-ve	FWS-3.0-3^o	<1	McLain and William (2008)
		(1.83×10^5)	(1.97×10^4)	(89.2)	FWS-130-2^o	14	Kadlec et al. (2010)
		(2.34×10^3)	(9.67×10^2)	58.7	FWS-15.3-L2^o	½ + 10	Kadlec et al. (2012)
pH	-	7.0	7.6	[-0.6]	FWS-3.0-3^o	<1	McLain and William (2008)
		9.6	7.5	[2.1]	FWS-(?)-L2^o	16 + ¼	Anderson et al. (2013)
		7.3	7.4	[-0.1]	FWS-0.12-2^o	5	Abe et al. (2014)
		7.45	7.58	[-0.13]	FWS-130-2^o	14	Kadlec et al. (2010)

Table 3 Performance of full-Scale or large field Pilot (>405 m^2 or 0.1acres) constructed wetland for Tertiary (3^o) and Secondary (2^o) municipalwastewater (including facultative lagoons ($F2^o$)) treatment

	Unit	Influent conc.	Effluent conc.	Eff. (%)/Δ [diff] = Inf.-Eff.	CW type, size (acres) and influent quality	Years in Operation	References
pH	-	8.10	7.18^o	[0.92]	FWS-~2-$L2^0$	6 + ½	Mwanyika et al. (2016)
Temp	^oC	28.1	23.8	[4.3]	FWS-3.0-3^o	<1	McLain and William (2008)
		19.4	18.7	[0.7]	FWS-(?)-$L2^o$	16 + ¼	Anderson et al. (2013)
		20	<15	[>5.0]	FWS-0.6-3^o	2	Beutel(2012)
		21.6	18.6	[3.0]	FWS-4.2-2^o	3 + 1½	Smesrud et al.(2014)
		17.7	14.8	[2.9]	FWS-130-2^o	14	Kadlec et al. (2010)
		18.6	17.3^o	[1.3]	FWS-~2-$L2^o$	6 + ½	Mwanyika et al. (2016)

Note: [n]See Table 2; [l]Alum dosing pre-treatment to remove PO_4^{3-}; [o]sample taken at the end of vegetation cover of the CW, after which increasing pH and temperature occurred traversing an open pond to its outlet; [p]raw wastewater also has industrial input.

Table 4 Performance of constructed wetlands (including small pilot scale (SP)) for treatment of raw ® or primary (1^o) municipal wastewater (to be continued)

	Unit	Influent conc.	Effluent conc.	Eff. (%)/Δ [diff] = Inf.-Eff.	CW type, size (acres) and influent quality	Years in Operation	References
BOD_5 (CBOD)	mg/L	113	20.6	81.8	-	-	Liu et al. (2009)
		165.8	49.7	70.0	FWS-0.025-1^o	<1	Gray (2008)
		17.4	7.0	52.0	[q]HYSF[s]-1.88-®	~1	Pan et al. (2012)
		220	32	85	VSSF-0.74	~8	Münich et al.(2009)
		63-189	14-72	71.4	HSSF-0.15	4	GöÇmez et al. (2010)
		121.7	9.7	91	HSSF-0.32-1^o	<2	Abou-Elila et al. (2014)

Table 4 Performance of constructed wetlands (including small pilot scale (SP)) for treatment of raw ® or primary (1^o) municipal wastewater (to be continued)

	Unit	Influent conc.	Effluent conc.	Eff. (%)/Δ [diff] = Inf.-Eff.	CW type, size (acres) and influent quality	Years in Operation	References
BOD_5	mg/L	768	33	95.7	^{v}HYSF-2.3-1^o	2 + ¼	Rivas et al. (2011)
(CBOD)		420	30	92.9	^{q}HYSF-0.08-1^o	<1	Kouki et al. (2009)
		(56)	(9)	(83.9)	HSSF-0.64-1^o	2	TWDB (2000)
		164	13	92.1	^{t}HY-(SP)-1^o	2 + 1	Ávila et al. (2013)
		107.7	15.7	85.0	^{u}HY-0.22	12	Arroyo et al. (2013)
		132.1	74.2	43.8	HSSF-0.003-1^o	2	Hench et al. (2003)
		(293.7)	(2.8)	(99.0)	VSSF^r-0.001-1^o	2 +1	Boog et al. (2014)
		(293.7)	(3.3)	(98.9)	VSSF^s-0.001-1^o	2 +1	
		318	47	85.2	HSSF-0.87-1^o	2¼	Kröpfelová et al.
		190	19	90.0	HSSF-0.12-1^o	2¼	(2009)
		78	13.2	83.1	HSSF-0.24-1^o	2¼	
		138	14	89.9	^{n}HY-0.04-1^o	3 + 2¼	de la Varga (2013)
COD	mg/L	234.7	62.5	73.4			Liu et al. (2009)
		53.6	33.2	34.1	^{q}HYSF^s-1.88- ®	~1	Pan et al. (2012)
		446	70	84	VSSF-0.74	~8	Münich et al. (2009)
		179-389	51-135	63.1	HSSF-0.15	4	GöÇmez et al. (2010)
		246.2	49.2	80	HSSF-0.32-1^o	<2	Abou-Elila et al. (2014)
		911	100	89	^{v}HYSF-2.3-1^o	2 + ¼	Rivas et al. (2011)
		1339	134	90.0	^{q}HYSF-0.08-1^o	<1	Kouki et al. (2009)
		205	49	76.1	^{t}HY-(SP)-1^o	2 + 1	Ávila et al. (2013)
		20.9.6	61.2	70.0	^{u}HY-0.22	12	Arroyo et al. (2013)
		716	134	81.3	HSSF-0.87-1^o	2¼	Kröpfelová et al.
		480	117	75.6	HSSF-0.12-1^o	2¼	(2009)
		200	66	67.0	HSSF-0.24-1^o	2¼	
		258	34.7	86.6	^{n}HY-0.04-1^o	3 + 2¼	de la Varga (2013)
TSS	mg/L	51.6	13.3	67.5	FWS-0.025-1^o	<1	Gray (2008)
		13.1	9.9	38.9	^{q}HYSF^s-1.88- ®	~1	Pan et al. (2012)
		179-389	51-135	63.1	HSSF-0.15	4	GöÇmez et al. (2010)

Table 4 Performance of constructed wetlands (including small pilot scale (SP)) for treatment of raw ® or primary (1^{o}) municipal wastewater (to be continued)

	Unit	Influent conc.	Effluent conc.	Eff. (%)/Δ [diff] = Inf.-Eff.	CW type, size (acres) and influent quality	Years in Operation	References
TSS	mg/L	246.2	49.2	80	HSSF-0.32-1^{o}	2	Abou-Elila et al. (2014)
		911	100	89	^{v}HYSF-2.3-1^{o}	2 + ¼	Rivas et al. (2011)
		1339	134	90.0	^{q}HYSF-0.08-1^{o}	<1	Kouki et al. (2009)
		83	3	96.4	HSSF-0.64-1^{o}	2	TWDB (2000)
		161	4	97.5	^{t}HY-(SP)-1^{o}	2 + 1	Ávila et al. (2013)
		119.3	23.5	75.3	^{u}HY-0.22	12	Arroyo et al. (2013)
		156.0	14.6	90.6	HSSF-0.003-1^{o}	2	Hench et al. (2003)
		398	10.5	97.4	HSSF-0.87-1^{o}	2¼	Kröpfelová et al.
		176	20	88.6	HSSF-0.12-1^{o}	2¼	(2009)
		54	18	66.7	HSSF-0.24-1^{o}	2¼	
		167.3	5.3	96.8	^{n}HY-0.04-1^{o}	3 + 2¼	de la Varga (2013)
TP	mg/L	2.9	1.1	62.1	-	-	Liu et al. (2009)
(PO_4^{3-})		4.1	1.9	53.9	FWS-0.025-1^{o}	<1	Gray (2008)
		0.64	0.37	41.61	^{q}HYSF^{s}-1.88- ®	~1	Pan et al. (2012)
		(59.2)	(18.7)	68	VSSF-0.74	~8	Münich et al. (2009)
		12	9	25	FWS- (P)-1^{o}	~2?	Greenway (2005)
		7-11	3-6	46.4	HSSF-0.15	4	GöÇmez et al. (2010)
		3.2	1.2	63.5	HSSF-0.32-1^{o}	<2	Abou-Elila et al. (2014)
		25	15	40	^{v}HYSF-2.3-1^{o}	2 + ¼	Rivas et al. (2011)
		3.56	0.29	91.8	HSSF-0.001-1^{o}	0.5	Wu et al.(2008)
		30.7	7.17	76.6	^{q}HYSF-0.08-1^{o}	<1	Kouki et al. (2009)
		3.4	2.1	41.9	HSSF-0.64-1^{o}	2	TWDB (2000)
		4.6	4.1	10.9	^{t}HY-(SP)-1^{o}	2 + 1	Ávila et al. (2013)
		6.7	3.9	38.4	^{u}HY-0.22	12	Arroyo et al. (2013)
TN	mg/L	24.1	13.4	44.3	-	-	Liu et al. (2009)
(TKN)		43.1	23.1	46.4	FWS-0.025-1^{o}	< 1	Gray (2008)
		9.50	6.55	31.05	^{q}HYSF^{s}-1.88-®	~1	Pan et al. (2012)
		50	<5	>90	FWS (SP)-1^{o}	~2?	Greenway (2005)

Table 4 Performance of constructed wetlands (including small pilot scale (SP)) for treatment of raw ® or primary (1^o) municipal wastewater (to be continued)

	Unit	Influent conc.	Effluent conc.	Eff. (%)/Δ [diff] = Inf.-Eff.	CW type, size (acres) and influent quality	Years in Operation	References
TN (TKN)	mg/L	40-57	21-39	37.6	HSSF-0.15	4	GöÇmez et al. (2010)
		30.7	17.8	42	HSSF-0.32-1^o	<2	Abou-Elila et al. (2014)
		85	31	63.5	^{v}HYSF-2.3-1^o	2 + ¼	Rivas et al. (2011)
		53.4	11.2	79.1	HSSF-0.001-1^o	0.5	Wu et al. (2008)
		205	117	42.9	^{q}HYSF-0.08-1^o	<1	Kouki et al. (2009)
		34.0	3.1	90.9	^{t}HY-(SP)-1^o	2 +1	Ávila et al. (2013)
		(43.8)	(22.7)	(47.3)	^{u}HY-0.22	12	Arroyo et al. (2013)
		(11.0)	(5.0)	(54.5)	HSSF-0.003-1^o	2	Hench et al. (2003)
		(91.2)	(39.1)	(57.1)	VSSF^r-0.001-1^o	2 +1	Boog et al. (2014)
		(91.2)	(20.0)	(78.1)	VSSF^s-0.001-1^o	2 +1	
NH_3-N	mg/L	14.6	5.9	59.8	-	-	Liu et al. (2009)
		13.1	7.6	42.1	FWS-0.025-1^o	<1	Gray (2008)
		5.14	2.14	58.41	^{q}HYSF^s-1.88- ®	~1	Pan et al. (2012)
		17.2	9.5	45	HSSF-0.32-1^o	<2	Abou-Elila et al. (2014)
		69	20	71	^{v}HYSF-2.3-1^o	2 + ¼	Rivas et al. (2011)
		20.9	1.7	91.9	HSSF-0.001-1^o	0.5	Wu et al. (2008)
		22	16	27.3	HSSF-0.64-1^0	2	TWDB (2000)
		24.4	0.9	96.3	^{t}HY-(SP)-1^o	2 +1	Ávila et al. (2013)
		31.0	13.7	53.3	^{u}HY-0.22	12	Arroyo et al. (2013)
		71.2	0.8	98.9	VSSF^r-0.001-1^o	2 +1	Boog et al. (2014)
		71.2	4.9	93.1	VSSF^s-0.001-1^o	2 +1	
NO_3-N	mg/L	2.1	1.8	14.1	-	-	Liu et al. (2009)
(NO_x-N)		0.14	≤0.10	24.4	FWS-0.025-1^o	<1	Gray (2008)
		0.130	0.22	-69.2	^{q}HYSF^s-1.88-®	~1	Pan et al. (2012)
		1	45	-97.8	VSSF-0.74	~8	Münich et al. (2009)
		0.11	0.17	-54.5	HSSF-0.32-1^o	<2	Abou-Elila et al. (2014)
		0.25	0.01	97.3	HSSF-0.64-1^o	2	TWDB (2000)
		0.3	13.6	-44.3	^{t}HY-(SP)-1^o	2 + 1	Ávila et al. (2013)

Table 4 Performance of constructed wetlands (including small pilot scale (SP)) for treatment of raw ® or primary (1^o) municipal wastewater

	Unit	Inf. conc.	Eff. conc.	Eff. (%)/Δ [diff] = Inf.-Eff.	CW type, size (acres) and influent quality	Years in Operation	References
NO_3-N	mg/L	(0.1)	(23.3)	-232	VSSF[r]-0.001-1^o	2 +1	Boog et al. (2014)
(NO_x-N)		(0.1)	(6.8)	-67	VSSF[s]-0.001-1^o	2 +1	
DOC	mg/L	72.8	17.2	76.4	HSSF-0.001-1^o	0.5	Wu et al. (2008)
(TOC)		(163.6)	(17.2)	(89.5)	VSSF[r]-0.001-1^o	2 +1	Boog et al. (2014)
		(163.6)	(12.0)	(92.7)	VSSF[s]-0.001-1^o	2 +1	
SO_4^{2-}	mg/L	157	141	10.2	[t]HY-(SP)-1^o	2 + 1	Ávila et al. (2013)
		141	56	60.3	HSSF-0.87-1^o	2¼	Kröpfelová et al. (2009)
		37	21	43.2	HSSF-0.12-1^o	2¼	
		41	14	65.9	HSSF-0.24-1^o	2¼	
		226	161	28.8	HSSF-0.87-1^o	2 + 1	Vymazal (2005a)
TC	cfu/ 100mL	≥7.5 × 10^6	≥1.01 × 10^5	98.7	FWS-0.025-1^o	<1	Gray (2008)
		~2.9 × 10^7	~2.9× 10^3	99.99 (4-log)	HSSF-0.32-1^o	<2	Abou-Elila et al. (2014)
FC or (E-coli)	cfu/ 100mL	≥4.8 × 10^6	≥8.8 × 10^4	98.2	FWS-0.025-1^o	<1	Gray (2008)
		~2.5 × 10^6	~2.5× 10^2	99.99 (4 log)	HSSF-0.32-1^o	<2	Abou-Elila et al. (2014)
		~2.9 × 10^7	~7.0×10^2	99.998(4-5 log)	[v]HYSF-2.3-1^o	2 + ¼	Rivas et al. (2011)
		~2.7× 10^7	~1.9×10^3	99.99 (4 log)	[q]HYSF-0.08-1^o	<1	Kouki et al. (2009)
pH	-	8.03	7.51	[0.52]	[q]HYSF-0.08-1^o	<1	Kouki et al. (2009)
		7.05	6.58	[0.47]	HSSF-0.003-1^o	2	Hench et al. (2003)
		7.32	6.88	[0.44]	[w]HY-0.22-1^o	8 + 3	Arroyo et al. (2010)
Temp	^{o}C	20.0	19.1	[0.9]	[t]HY-(SP)-1^o	3 + 1	Ávila et al. (2013)
		16.1	14.0	[2.1]	[n]HY-0.04-1^o	3 + 2¼	de la Varga (2013)
		13.3	12.0	[1.3]	[w]HY-0.22-1^o	8 + 3	Arroyo et al.(2010)

Note: [n]See Table 2; [q]VSSF-HSSF CW; [r]Planted wetland with continuous aeration; [s]Unplanted wetland with intermittent aeration; [t]VSSF-HSSF-FWS CW; [u]lagoon (with microphyte)-FWS-HSSF CW; [v]HSSF-Maturation lagoon-VSSF CW

3.4.2 Removal of nitrogen compounds

The results shown in Tables 2 and 3 do indicate, generally, that CWs are capable to effectively remove ammonia and nitrate from secondary and tertiary MWW. Although removal of ammonia by CWs is demonstrated also for primary and raw MWW treatment (Table 4), net release of nitrate is generally realized when such quality of MWW is treated. Unlike organic contents, removal efficiency of nitrogen compounds is not consistent amongst the types of CWs and varies substantially depending on the quality of and/or the inflow concentration in the wastewater being treated or perhaps the specific site conditions.

TN removal from secondary and tertiary MWW averages 52 ± 28% and 45± 27% from small scale and large scale demonstrations, respectively; whilst removal from primary and raw MWW is modestly higher at 58 ± 20%. Similarly, NH_3-N removal from secondary and tertiary MWW averages 61± 32% and 39±43% from small scale and large scale demonstrations, respectively; whilst removal from primary and raw MWW is modestly higher at 67 ± 25%. In contrast, NO_3^--N removal from secondary and tertiary MWW averages 48± 64% and 49± 37% from small scale and large scale demonstrations, respectively; whilst net releases (-48 ± 92%) are observed when primary and raw MWW are treated.

The high standard deviations in the data above simply reflect variations in removal efficiencies with respect to the type of CW and/or the level (quality) of the treated MWW. For NO_3^--N, it is noted (Tables 2-4) that net accumulation or least removal is commonly observed for CW treatment of MWW of quality equal or less than that of facultative lagoon effluent (i.e. L2^o, 1^o or ® from the tables) and/or treatment by VSSF CW singly and/or in a hybrid configuration. NO_3^- removal seems to be more efficient when FWS CW is used in treating secondary MWW. Ammonia removal from MWW is common but quite variable and site specific and does not seem to be dictated necessarily by the quality of wastewater treated or the type of CWs. However, VSSF (based on the limited data) seems to be consistently more effective in ammonia removal.

3.4.3 Removal of phosphorous compounds

P removal, although appears somehow consistent for raw/primary MWW treatment (~51 ± 22%) (Table 4), is less consistent for secondary and tertiary MWW treatment (~45 ± 35%) (Tables 2 and 3). The removal efficiency also appears to be very dependent on site specificity and/or operation of the CW.

P removal from MWW and other high P effluents is usually limited, because seasonal plant uptake is relatively small compared to loading, whilst release does occur with senescence. Besides, soil-binding sites become saturated relatively rapidly (Horner, 2015). It is noteworthy that most of the studies reported here (Tables 2-4) are for only short periods of operation from the wetlands' commission dates and some of the data are scanty to provide better representation of the CW performance over extended period of time. Nonetheless, the data generally shows more effective TP removal for CWs that have been in operation for only ≤2 years (~56 ± 28%) than for those that have operated longer (~39± 26%). The observed more effective P removal by young treatment wetlands is typical; it is when the soil sorption capacity is high and vegetation is maturing (Kadlec and Wallace, 2009). With time, as soil sorption sites get exhausted and vegetation well established, P removal can be expected to attain equilibrium via sustainable processes such as detritus sorption, precipitation, and burial/soil storage (Frank et al., 2011).

In Table 3 for instance, apart from some three FWS CW outliers (*vide infra*), an average TP removal of 64% is estimated for CW which have been in operation for less or equal to 2 years and only 34% for longer operations.

Beyond the type of CW, specific site conditions which may include the quality level of MWW effluent being treated, soil material and the CW vegetation, harvesting practices, climatic conditions, etc. may account for the deviations in P-removal efficiencies that cannot be attributed solely to the juvenility of the CW. For instance, a FWS CW which has been in operation for over 16 years reportedly removed over 98% of TP, whilst two others in operation for only ≤2 years removed 7% or less (See Table 3).

3.4.4 Bacteria removal

The results shown in the Tables 2 to 4 do indicate that CWs are generally effective in improving the bacteria quality in MWW. In some cases, especially when raw/primary municipal effluents were involved, even 4 to 5 log removal is achievable (Table 4). The conclusion here is consistent with that from another review (Ghermanhi et al., 2007) on faecal coliform removal by FWS CW treating secondary effluent, where an average removal of 89% was noted. However, depending on site specific activities coupled with seasonal influence, some exceptional behaviour where the bacteria quality is worsened across a CW may occur on polishing higher level of treated MWW (e.g. tertiary or advanced secondary) effluent (see Table 3). For instance, at Tres Rios, AZ, where the CW operational concepts extend beyond just water quality improvements, habitation of variety of waterfowl and migrating birds, mammals and amphibians are encouraged as part of public outreach and education (Elkins, 2011). Consequently, these animals contribute through defecation to higher bacteria content (coliform and e-coli) in the wetland effluent as compared to the tertiary treated influent into the wetland (McLain and William, 2008).

3.4.5 Effect on auxiliary water quality parameters

As shown in Tables 2-4, auxiliary water quality parameters such as water pH and temperature may also be affected by the various CW processes. Although decline in pH is a more common occurrence across CWs (likely due to the following processes: nitrification, ammonia volatilization, biodegradation of organics to carboxylic acids and CO_2, etc.), pH increases can also occur in some other cases.

As revealed in the Tables 2 to 4, the outlet water temperatures from CWs are generally lower than the inlet temperatures; with temperature reductions ranging from ~1^{o}C to >5^{o}C across CWs. It is noteworthy, that temperature reduction even within same CW is quite variable depending on several climatic and other external influences and hence appears to be season-dependent. Temperature reduction measured 9 m apart from inlet to outlet in the vegetated bed of a HSSF CW in spring, summer, and fall were 1.1 ± 0.6˚C, 0.4 ± 0.4˚C, and 0.7 ± 0.7˚C, respectively (Šíma et al., 2016). Substantial decrease of industrial and MWW water temperature (up to 10˚C) in a CW/filter basin treatment system was reported from an 18-months investigation (Lazareva, 2010; Lazareva and Pichler, 2010).

Kadlec (2006) refers to CWs as solar powered ecosystems; where the energy balance is dominated by radiation to and from the wetland, heat transfer from air, and evaporative losses. Plants transpiration causes energy dissipation from the canopy, while water evaporation causes energy loss and subsequent cooling of the surface water. Therefore, through radiant and convective heat transfer, as well as through evaporation, water in the wetlands cools as it passes from inlet to outlet (Kadlec, 2006; Polson, 2009). In contrast to an open pond, the vegetation that flourishes in wetlands provides shade for all or part of the water surface, avoiding the counteracting solar gain that can otherwise occur with an open lagoon. This is important in ensuring cooling through the warmer months and avoids temperature rises through the wetlands (Polson, 2009). Consistent with this idea, Mwanyika et al. (2016) observed temperature reduction of up to 1.3˚C from the inlet to the end of the vegetated zone of a FWS CW, which is attributed to the cooling effect from the vegetation cover; whilst temperature rise up to 0.75˚C was observed thereafter through an open pond with little vegetation down to its outlet.

3.4.6 Heavy metal (and other trace element) removal from municipal wastewater

As discussed earlier, the contaminants focus for MWW treatments by CWs have traditionally been centered on BOD and TSS, which usually have regulatory limits for discharge or reuse in various jurisdictions around the world. Bacteria content, organic fraction (as TOC or DOC) and nutrients (nitrogen as ammonia, nitrate, nitrite, in organic form or as total nitrogen, and phosphorus as phosphate or total phosphate) are also commonly monitored. These are monitored either because of regulatory requirements (in some jurisdictions) or simply as they symbolize the biological instability of the wastewater, especially for reuse applications. Metal removal from MWW by CWs has however traditionally not been of focal research or commercial interest.

Most studies of heavy metal removal by CWs are related to their contamination in mine drainage and industrial wastewaters (Abe et al., 2014; Dunbabin and Bowmer, 1992). The next Section provides examples of such studies as they apply to treatment of power plant wastewaters (CT blow-down, FGD wastewaters, ash lagoon effluent or leachate etc.). Processes of metal removal and mobilization by CWs include sedimentation, cation exchange, precipitation, adsorption, complexation, plant uptake, and microbially-mediated reactions including oxidation and reduction (Dunbabin and Bowmer, 1992). In a review article by Odinga et al. (2013), it is remarked that removal mechanism of heavy metals within the CWs is mainly through wetland vegetation, wetland hydrology and the soil substrate. Phytoremediation was implied as the main means for the removal, which includes the following specific processes (Prasad and Freitas, 2003): (a) Phytoextraction/phytoaccumulation, which involves the use of plants to remove heavy metals from soil matrix to accumulate in plant tissues and/or adsorb on root zone of emergent and free-floating macrophytes or from water column through leaves in the case for both floating and submerged leaves; (b) Phytovolatilization, which employs plants to absorb elemental and organic forms of the metals (e.g. Hg and Se) from the soil and convert them biologically to gaseous species, which are released to the atmosphere; (c) Phytostabilization, where the metal's movement is hydraulically suppressed and restricted to the soil matrix only, thus preventing migration of the metal into the groundwater below or into the above ground water column or biomass. The metal immobilization in CWs is achieved physically by root sorption and chemically by fixation with various soil amendments such as phosphates, organic matter, Fe and Mn which accumulate over time as integral part of the overall CW treatment process. The plant species *Agrostis tenuis* Sibth of the poaceae family-a poor translocator of metal contaminants, for example, may be used for phytostabilization of Zn, Cu and Pb within the soil matrix (Prasad and Freitas, 2003).

Heavy metal concentration ranges do vary depending on the origin of the wastewaters (Galletti et al., 2010). MWWs often do not contain high concentrations of heavy metals (Galletti et al., 2010; Kröpfelová et al., 2009). Consequently, heavy metals or generally trace elements are usually not target of MWW treatments, and as such, reports on CW capability in removing trace metals from MWW effluents have likewise been more limited and sporadic. Nonetheless, heavy metals concentrations in MWW may not always be at trace levels, especially in urban settlements with mixed waste collection system where inputs from laboratories, industries, and agricultural drainage may not be completely prohibited. Various household activities may also contribute significant amount of metals into the MWW collection system.

As discussed earlier, for some reuse applications particularly cooling systems, heavy metals even at trace levels may concentrate and cause operational difficulties and hence the need to ensure they are removed to acceptable levels. Table 5 provides a summary of some of the few up-to-date reports on trace metal removal efficiency from different grades of MWW by, mostly HSSF and hybrid types of CW.

HSSF CW is shown as effective and more consistent p in removing Al and U from primary and/or secondary municipal effluent at an average efficiency of 89.6 ± 6.5% and 72.4± 3.2%. Other metals are also removed by HSSF CW but to a lesser extent and with less consistent removal efficiencies. These include (and in decreasing order of removal) the following: Zn (64±28%) >Pb (57±26%) >Cu (56± 27%) >Ba (54±25%) >Cr (50±28%) >Sn (47±43%) >Cd (40±28%). Although Hg and Se, on the average, are removed to a lesser extent than the above metals, their removal rates were more consistent than most; i.e. Hg = 34 ± 17% and Se = 34 ±10%. Other metals (not in Table 5) such as Co, Rb, Sr and Li are also reportedly removed by HSSF CWs. Šíma et al. (2016) report removal efficiency of 20.9%, 21.5%, 27.7% and 43.9%, respectively; whilst Kröpfelová et al. (2009) report removal efficiencies ranging 7.4-33.2%, 0.0-13.6%, and12.6-26.0% for Rb, Sr andLi, respectively. Insoluble sulfide precipitations in the anaerobic zones of HSSF (where reduction of sulfate to sulfides occur) have been shown to contribute significantly to the removal of heavy metals such as Cu and Zn (Šíma et al., 2016).

Some hybrid forms of CWs have also demonstrated ability to remove trace metals, but the removal rates are quite inconsistent between studies. Average removals however follow the following order for the trace metals: Sn (94%) >Cu (57 ± 25%) >Pb (56 ± 19%) >Cr (51±36%) >Zn (43±30%) >Cd (34±24 %) >Hg (22±18%).

Reports on heavy metal removal from municipal or domestic wastewaters exclusively by FWS CWs appear limited in the literature. Ghermanhi et al. (2007) however provided a summary of average removal of heavy metals and other inorganic contaminants by FWS CW treating secondary effluent, where moderately good removal of some metals such as Cu (39%), Hg (47%), Ag (36%), and Zn (37%) occurs, while other metals are poorly removed or not removed at all. The averages for the various elements were obtained from different number of site sample data (N, which ranged from 3 for Tl; 6 for B, Co and Ag; 7 for Al, Ba, Be and Li, and up to 15 CWs for only Zn and Cu) in a compiled database of both full-and pilot-scale systems, which were unfortunately not identified in the report. Abe et al. (2014), Arroyo et al. (2010) and Chagué-Goff (2005) have reported on studies of MWW effluent treatment by FWS CW at full-scale levels. These CWs have demonstrated consistent but significantly variable removal of Zn (51.5-83.3%) and Cu (33.8-82.4%), and to a lesser extent Pb (9.5-28.9%). Removed Cu was mostly associated with the organic/sulfide fractions in the wetland sediments, whereas Zn and Pb showed strong affinity for hydroxides and organic/sulfides (Chagué-Goff, 2005).

From Table 5, CWs are poor in removing arsenic from MWW, as they are generally released into the water column and discharged with the CW effluent. Nonetheless, a FWS CW treating a cooling pond fed by a blend of tertiary MWW, industrial wastewater, storm and surface water was reported to remove arsenic at an efficiency of ~33-74% (Lazareva, 2010; Lazareva and Pichler, 2010). CWs performance with respect to iron and manganese removal is rather erratic; in most cases it resulted in significant leaching of soil materials from the CW into the effluent water. The variability of Fe removal is demonstrated by changes in seasons even for same CW. Treating an aerated pond treated domestic wastewater by an FWS CW; Fe removal (though minimal) was realized during summer, whilst releases occurred in winter (Chagué-Goff, 2005).

Table 5 Performance of constructed wetlands for trace elements and hardness (Ca and Mg)removal from various treated municipal wastewaters (raw ®; primary (1^o); secondary (2^o), tertiary (3^o) and tertiary with blend of industrial, storm and surface sources (3^{o*})) (to be continued)

	Influent (g/L)	**Effluent (g/L)**	**Eff. (%)**	**CW type, size(acres) and influent quality**	**Years in operation**	**References**
Al	866	83	90.4	HSSF-0.32-2^o	3 + 1¾	Lesage et al. (2007)
	5658	84	98.5	HSSF-0.87-1^o	2¼	Kröpfelová et al. (2009)
	3748	328	91.2	HSSF-0.12-1^o	2¼	
	938	186	80.2	HSSF-0.24-1^o	2¼	
	567	<40	>92.9	HSSF-0.87-1^o	2 + 1	Vymazal (2005a)
	77.0	12.0	84.4	HSSF-0.012-®	1	Singh and Srivastava (2016)
As	2.64	4.50	-70.5	^{u}HY-0.22-®	6 + 4	Arroyo et al. (2013)
	1.15	1.56	-35.7	HSSF-0.87-1^o	2¼	Kröpfelová et al. (2009)
	2.45	3.80	-55.1	HSSF-0.12-1^o	2¼	
	1.39	2.49	-79.1	HSSF-0.24-1^o	2¼	
	1.9	2.0	-6.7	^{n}HY-0.04-1^o	3 + 2¼	de la Varga (2013)
	2.8	4.0	-45.2	^{w}HY-0.22-1^o	8 + 3	Arroyo et al. (2010)
	2.7	0.7/1.8	53.7	FWS-3.0-3^{o*}	7 + 1½	Lazareva and Pichler (2010)
	2.63	2.60	1.1	FWS-20-2^o	1¾	Crites et al. (1997)
B	118.25	110.40	6.6	^{u}HY-0.22-®	6 + 4	Arroyo et al. (2013)
	210	157	25.1	HSSF-0.87-1^o	2¼	Kröpfelová et al. (2009)
	110	86	21.8	HSSF-0.12-1^o	2¼	
	76	77.4	-1.8	HSSF-0.24-1^o	2¼	
	131.6	114.7	12.8	^{w}HY-0.22-1^o	8 + 3	Arroyo et al. (2010)
Ba	68.5	26.2	61.8	HSSF-0.87-1^o	2¼	Kröpfelová et al. (2009)
	479	124	74.1	HSSF-0.12-1^o	2¼	
	72.2	53.2	26.3	HSSF-0.24-1^o	2¼	
Cd	2.62	2.18	16.8	^{u}HY-0.22-®	6 + 4	Arroyo et al. (2013)
	0.55	0.30	45.5	HSSF-0.32-2^o	3 + 1¾	Lesage et al. (2007)

Table 5 Performance of constructed wetlands for trace elements and hardness (Ca and Mg)removal from various treated municipal wastewaters (raw ®; primary (1^o); secondary (2^o), tertiary (3^o) and tertiary with blend of industrial, storm and surface sources (3^{o*})) (to be continued)

	Influent (g/L)	Effluent (g/L)	Eff. (%)	CW type, size(acres) and influent quality	Years in operation	References
Cd	1.63	0.6	61.3	HY-0.04$^+$-2^o	3 + 3	Obarska-Pempkowiak and Klimkowska(1999)
	0.32	0.07	78.1	HSSF-0.87-1^o	2¼	Kröpfelová et al. (2009)
	0.33	0.10	69.7	HSSF-0.12-1^o	2¼	
	0.10	0.10	0	HSSF-0.24-1^o	2¼	
	0.81	0.73	9.9	FWS-0.59-1^o	2	Březinová and Vymazal(2015)
	2.74	2.13	22.3	^{w}HY-0.22-1^o	8 + 3	Arroyo et al. (2010)
	0.11	0.05	54.5	FWS-20-2^o	1¾	Crites et al. (1997)
Cr	2.83	1.35	52.3	^{u}HY-0.22-®	6 + 4	Arroyo et al. (2013)
	2.5	1.5	40.0	HSSF-0.32-2^o	3 + 1¾	Lesage et al. (2007)
	3.13	3.10	4.2	HY-0.04$^+$-2^o	3 + 3	Obarska-Pempkowiak and Klimkowska (1999)
	6.75	1.99	70.5	HSSF-0.87-1^o	2¼	Kröpfelová et al. (2009)
	11.3	3.66	67.6	HSSF-0.12-1^o	2¼	
	2.88	2.10	27.1	HSSF-0.24-1^o	2¼	
	53.0	3.7	93.0	^{n}HY-0.04-1^o	3 + 2¼	de la Varga (2013)
	0.91	0.75	17.6	FWS-0.59-1^o	2	Březinová and Vymazal (2015)
	5.64	2.53	55.0	^{w}HY-0.22-1^o	8 + 3	Arroyo et al. (2010)
	3.75	1.10	70.7	FWS-20-2^o	1¾	Crites et al. (1997)
Cu	6.84	4.82	29.5	^{u}HY-0.22-®	6 + 4	Arroyo et al. (2013)
	20.5	2.5	87.8	HSSF-0.32-2^o	3 + 1¾	Lesage et al. (2007)
	6.8	3.0	55.9	HY-0.04$^+$-2^o	3 + 3	Obarska-Pempkowiak and Klimkowska (1999)
	2.3	2.2	3.4	HSSF-0.0069-2^o	1 + ¾	Galletti et al. (2010)
	2.3	2.1	9.0	HSSF-0.0074-2^o	1 + ¾	
	25.2	6.6	73.8	HSSF-0.87-1^o	2¼	Kröpfelová et al. (2009)
	40.7	6.5	84.0	HSSF-0.12-1^o	2¼	
	25.2	14.7	41.7	HSSF-0.24-1^o	2¼	
	118	11.8	90.0	^{n}HY-0.04-1^o	3 + 2¼	de la Varga (2013)
	4.4	<2.0	>54.5	HSSF-0.87-1^o	2 + 1	Vymazal (2005a)
	5.7	3.8	33.3	FWS-0.59-1^o	2	Březinová and Vymazal (2015)
	10.3	5.0	51.6	^{w}HY-0.22-1^o	8 + 3	Arroyo et al. (2010)

Table 5 Performance of constructed wetlands for trace elements and hardness (Ca and Mg) removal from various treated municipal wastewaters (raw ®; primary (1^o); secondary (2^o), tertiary (3^o) and tertiary with blend of industrial, storm and surface sources (3^{o*})) (to be continued)

	Influent (g/L)	**Effluent (g/L)**	**Eff. (%)**	**CW type, size(acres) and influent quality**	**Years in operation**	**References**
Cu	17.0	3.0	82.4	FWS-84-L2^o	^{x}4 + ½	Chagué-Goff (2005)
	6.0	1.3	78.3	FWS-84-L2^o	^{y}4½ + ½	
	7.12	3.2	55.1	FWS-20-2^o	1¾	Crites et al. (1997)
	1087.8	324.7	70.2	FWS-~2-L2^0	6 + ½	Mwanyika et al. (2016)
	27.6	5.1	81.5	HSSF-0.19-1^o	12½ + ¾	Šíma et al. (2016)
	102.5	68.5	33.2	HSSF-0.012-®	1	Singh and Srivastava (2016)
Fe	106.1	112.6	-6.1	^{u}HY-0.22-®	6 + 4	Arroyo et al. (2013)
	583	1724	-195.7	HSSF-0.32-2^o	3 + 1¾	Lesage et al. (2007)
	930	460	50.5	HSSF-0.87-1^o	2¼	Kröpfelová et al. (2009)
	2417	1072	55.6	HSSF-0.12-1^o	2¼	
	980	4077^z	-358	HSSF-0.24-1^o	2¼	
	853.3	315.7	63.0	^{n} HY-0.04-1^o	3 + 2¼	de la Varga (2013)
	301	348	-15.6	HSSF-0.87-1^o	2 + 1	Vymazal (2005a)
	110.9	124.1	-12.0	^{w}HY-0.22-1^o	8 + 3	Arroyo et al. (2010)
	260	500	-92.3	FWS-84-L2^o	^{x}4 + ½	Chagué-Goff (2005)
	340	270	20.6	FWS-84-L2^o	^{y}4½ + ½	
	860	4300	-400	HSSF-0.19-1^o	12½ + ¾	Šíma et al. (2016)
	913.0	150.5	83.5	HSSF-0.012-®	1	Singh and Srivastava (2016)
Hg	0.93	0.87	6.5	^{u}HY-0.22-®	6 + 4	Arroyo et al. (2013)
	0.17	0.12	29.4	HSSF-0.87-1^o	2¼	Kröpfelová et al. (2009)
	0.18	0.11	38.9	HSSF-0.12-1^o	2¼	
	0.19	0.10	47.4	HSSF-0.24-1^o	2¼	
	0.20	<DL	>42.0	^{n}HY-0.04-1^o	3 + 2¼	de la Varga (2013)
	1.4	1.1	18.8	^{w}HY-0.22-1^o	8 + 3	Arroyo et al. (2010)
	10.61^{aa}	4.71^{aa}	55.6	FWS-20-2^o	1¾	Crites et al. (1997)
Mn	100.11	177.64	-77.4	^{u}HY-0.22-®	6 + 4	Arroyo et al. (2013)
	57.5	186	-223.5	HSSF-0.32-2^o	3 + 1¾	Lesage et al. (2007)
	7.9	2.1	73.4	HY-0.04^+-2^o	3 + 3	Obarska-Pempkowiak and Klimkowska (1999)
	85	101	-18.8	HSSF-0.87-1^o	2¼	Kröpfelová et al. (2009)
	202	245	-21.9	HSSF-0.12-1^o	2¼	
	192	241	-25.5	HSSF-0.24-1^o	2¼	
	96.0	106.6	-11.0	^{n}HY-0.04-1^o	3 + 2¼	de la Varga (2013)

Table 5 Performance of constructed wetlands for trace elements and hardness (Ca and Mg) removal from various treated municipal wastewaters (raw ®; primary (1^o); secondary (2^o), tertiary (3^o) and tertiary with blend of industrial, storm and surface sources (3^{o*})) (to be continued)

	Influent (g/L)	Effluent (g/L)	Eff. (%)	CW type, size(acres) and influent quality	Years in operation	References
Mn	107	400	-274	HSSF-0.87-1^o	2 + 1	Vymazal (2005a)
	98.8	171.7	-72.8	^{w}HY-0.22-1^o	8 + 3	Arroyo et al. (2010)
	310	280	9.7	HSSF-0.19-1^o	12½ + ¾	Šíma et al. (2016)
Ni	2.97	3.18	-7.1	^{u}HY-0.22-®	6 + 4	Arroyo et al. (2013)
	7.0	4.5	35.7	HSSF-0.32-2^o	3 + 1¾	Lesage et al. (2007)
	8.9	6.0	35	HSSF-0.0069-2^o	1+ ¾	Galletti et al. (2010)
	8.9	6.7	25	HSSF-0.0074-2^o	1+ ¾	
	17.5	8.9	49.1	HSSF-0.87-1^o	2¼	Kröpfelová et al. (2009)
	22.4	12.1	46.0	HSSF-0.12-1^o	2¼	
	5.84	6.54	-12.0	HSSF-0.24-1^o	2¼	
	6.7	3.4	48.9	^{n}HY-0.04-1^o	3 + 2¼	de la Varga (2013)
	1.36	4.61	-239	HSSF-0.87-1^o	2 + 1	Vymazal (2005a)
	2.8	2.1	25.0	FWS-0.59-1^o	2	Březinová and Vymazal (2015)
	3.7	4.6	-24.5	^{w}HY-0.22-1^o	8 + 3	Arroyo et al. (2010)
	6.91	5.9	14.6	FWS-20-2^o	1¾	Crites et al. (1997)
	2.84	1.71	39.8	HSSF-0.19-1^o	12½ + ¾	Šíma et al. (2016)
	37.0	29.0	21.6	HSSF-0.012-®	1	Singh and Srivastava (2016)
Pb	0.50	0.29	42.0	^{u}HY-0.22-®	6 + 4	Arroyo et al. (2013)
	11.0	3.5	68.2	HSSF-0.32-2^o	3 + 1¾	Lesage et al. (2007)
	2.5	1.25	50.0	HY-0.04^+-2^o	3 + 3	Obarska-Pempkowiak and Klimkowska (1999)
	15.6	2.46	84.2	HSSF-0.87-1^o	2¼	Kröpfelová et al. (2009)
	13.2	2.9	78.0	HSSF-0.12-1^o	2¼	
	3.66	2.72	25.7	HSSF-0.24-1^o	2¼	
	9.5	1.6	83.0	^{n}HY-0.04-1^o	3 + 2¼	de la Varga (2013)
	5.9	<2.0	>65.8	HSSF-0.87-1^o	2 + 1	Vymazal (2005a)
	4.5	3.2	28.9	FWS-0.59-1^o	2	Březinová and Vymazal (2015)
	0.55	0.29	47.8	^{w}HY-0.22-1^o	8 + 3	Arroyo et al. (2010)
	2.1	1.9	9.5	FWS-84-L2^o	^{x}4 + ½	Chagué-Goff (2005)
	1.5	1.1	26.7	FWS-84-L2^o	^{y}4½ + ½	
	1.57	0.2	87.3	FWS-20-2^o	1¾	Crites et al. (1997)

Table 5 Performance of constructed wetlands for trace elements and hardness (Ca and Mg) removal from various treated municipal wastewaters (raw ®; primary (1^o); secondary (2^o), tertiary (3^o) and tertiary with blend of industrial, storm and surface sources (3^{o*})) (to be continued)

	Influent (g/L)	Effluent (g/L)	Eff. (%)	CW type, size(acres) and influent quality	Yearsin operation	References
Pb	1252.5	69.6	94.4	FWS-~2-L2^0	6 + ½	Mwanyika et al. (2016)
	62.5	26.0	58.4	HSSF-0.012-®	1	Singh and Srivastava (2016)
Se	0.96	0.63	34.4	HSSF-0.87-1^o	2¼	Kröpfelová et al. (2009)
	1.25	0.71	43.2	HSSF-0.12-1^o	2¼	
	0.65	0.50	23.1	HSSF-0.24-1^o	2¼	
Sn	5.55	0.25	95.5	HSSF-0.87-1^o	2¼	Kröpfelová et al. (2009)
	1.59	1.14	28.3	HSSF-0.12-1^o	2¼	
	0.50	0.42	16.0	HSSF-0.24-1^o	2¼	
	28.0	1.7	94.0	^{n}HY-0.04-1^o	3 + 2¼	de la Varga (2013)
U	1.93	0.47	75.6	HSSF-0.87-1^o	2¼	Kröpfelová et al. (2009)
	4.69	1.44	69.3	HSSF-0.12-1^o	2¼	
	2.94	0.81	72.4	HSSF-0.24-1^o	2¼	
Zn	37.68	28.90	23.3	^{u}HY-0.22-®	6 + 4	Arroyo et al. (2013)
	34.0	10.1	70.3	FWS-0.12-2^o	5	Abe et al. (2014)
	121.5	16.5	86.4	HSSF-0.32-2^o	3 + 1¾	Lesage et al. (2007)
	12.1	6.3	47.9	HY-0.04^+-2^o	3 + 3	Obarska-Pempkowiak and Klimkowska (1999)
	59.0	43.0	27	HSSF-0.0069-2^o	1 + ¾	Galletti et al. (2010)
	59.0	44	26	HSSF-0.0074-2^o	1 + ¾	
	232	22	90.5	HSSF-0.87-1^o	2¼	Kröpfelová et al. (2009)
	186	26	86.0	HSSF-0.12-1^o	2¼	
	72	30	58.3	HSSF-0.24-1^o	2¼	
	260.0	44.2	83.0	^{n}HY-0.04-1^o	3 + 2¼	de la Varga (2013)
	75.0	6.4	91.5	HSSF-0.87-1^o	2 + 1	Vymazal (2005a)
	26.4	12.8	51.5	FWS-0.59-1^o	2	Březinová and Vymazal (2015)
	57.7	47.5	17.8	^{w}HY-0.22-1^o	8 + 3	Arroyo et al. (2010)
	21.0	3.5	83.3	FWS-84-L2^o	^{x}4 + ½	Chagué-Goff (2005)
	14.3	5.5	61.5	FWS-84-L2^o	^{y}4½ + ½	
	39.14	7.4	81.1	FWS-20-2^o	1¾	Crites et al. (1997)
	151.7	ND	100	FWS-~2-L2^0	6 + ½	Mwanyika et al. (2016)
	65.9	6.7	89.8	HSSF-0.19-1^o	12½ + ¾	Šíma et al. (2016)
	65.5	45.5	30.5	HSSF-0.012-®	1	Singh and Srivastava (2016)

Table 5 Performance of constructed wetlands for trace elements and hardness (Ca and Mg) removal from various treated municipal wastewaters (raw ®; primary (1^o); secondary (2^o), tertiary (3^o) and tertiary with blend of industrial, storm and surface sources (3^{o*}))

	Influent (g/L)	**Effluent (g/L)**	**Eff. (%)**	**CW type, size(acres) and influent quality**	**Years in operation**	**References**
Ca	69100	72300	-4.6	FWS-0.27-2^o	1 + 5	Mulling et al. (2013)
	~280000	~350000	-25	VSSF^{ab}-(SP)-1^o	1½	Morari and Giardini (2009)
	~220000	~300000	-36.4	VSSF^{ac}-(SP)-1^o	1½	
	53900	44100	18.2	FWS-3.0-3^{o*}	7 + 1½	Lazareva and Pichler (2010)
Mg	15900	18400	-15.7	FWS-0.27-2^o	1 + 5	Mulling et al. (2013)
	~60000	~105000	-75	VSSF^{ab}-(SP)-1^o	1½	Morari and Giardini (2009)
	58000	~85000	-46.6	VSSF^{ac}-(SP)-1^o	1½	
	33600	25300	24.7	FWS-3.0-3^{o*}	7 + 1½	Lazareva and Pichler (2010)

Notes: ^{n}See Table 2; ^{u}See Table 4; ^{w}Stabilization pond-FWS-HSSF CW; ^{x}data exclusively in winter; ^{y}data exclusively in summer; ^{z}Filtration beds sealed with clay high in Fe content; ^{aa}ng/L; ^{ab}*Phagmites australis* vegetated CW; ^{ac}*Typha latifolia* vegetated CW

3.4.7 Removal of hardness (Ca and Mg)

There is ample evidence in the literature of calcium (Ca) and magnesium (Mg) removal by CWs by various mechanisms including plant uptake and soil microbial activities (Morari and Giardini, 2009). Various plant species including floating plants such as duckweed and hyacinth (Fazal et al., 2015; Krishma and Polprasert, 2008; Sharma and Gaur, 1995) and emergent macrophytes such as *Typha latifolia* (cattails) and *Phragmites australis* (Morari and Giardini, 2009) in CWs have been reported to remove Ca and Mg from wastewaters, with Ca removal usually being more prevalent (Morari and Giardini, 2009; Tanner and Headley, 2011). For both *Typha latifolia* (cattails) and *Phragmites australis*, Ca and Mg accumulated initially in the leaves, but changed over a 2 year period to predominate in the roots; with the latter more prevailing.

Despite uptakes of both Ca and Mg by various plants, because their concentrations in the MWW exceed the plant requirements, they are not significantly affected by the plant uptake with passage through CWs (Richardson, 1989). Furthermore, high water losses through evapotranspiration (ET) concentrate these metal ions in the CW; therefore the effluent concentrations are commonly higher than in the influent. This is exemplified by the higher effluent Ca and Mg concentrations shown in Table 5. From a laboratory-scale experiment, Ca removal of 14.7% and 13.5% and Mg of 2.45% and 37.2%, each respectively across water hyacinth CW and sludge-based CW treating a combined industrial wastewater was reported (Fazal et al., 2015). This anomalous result can be explained by the batch (not continuous flow) nature of the test, which is reported to limit effects of evaporation (Jesus et al., 2016). Furthermore, the sludge-based CW test unit was covered by aluminium foil (Fazal et al., 2015), which would further limit the effect of evaporation. Also, and as shown in Table 5, promising treatment of Ca and Mg was reported for a FWS-CW treating a blend of industrial wastewater (cooling water), tertiary treated MWW effluent, storm and surface sources. This result is also unique for CWs and is attributable to dilution effects from precipitation and groundwater inflow-as the CW is not lined (Lazereva and Pichler, 2010). This is supported by the fact that the concentrations of these metal ions (and other cations) in the inflow (cooling pond) was close to that in the CW during dry season; whilst during the rainy season the concentration of these cations in the CW was around 1.5 times less than in the inflow.

As discussed earlier, the water quality discharged from CWs is strongly influenced by ET. Novel treatment methods to integrate with conventional CW systems are thus needed to obtain high removal efficiencies that reduce the effect of ET on water quality. Floating emergent macrophytes, where common emergent macrophytes used in FWS-CWs and SSF-CWs are grown on mats floating on the surface of the water rather than rooted in the sediments is one such novelty; and it has been reported to remove Ca and Mg in a substantial manner (Tanner and Headley, 2011). Because they are not rooted in soils at the base of the CWs, floating emergent macrophytes are particularly forced to acquire their nutrition directly from the water column including mineral and element uptakes into biomass. Of note is that accumulations of Ca or Mg in either the above-mat biomass or below-mat biomass of floating emergent macrophytes were observed to depend on the plant species as well as the metal ions (Tanner and Headley, 2011). Thus, for a floating mat planted with *Cyperus ustulatus*, Ca was found to accumulate more in the below-mat biomass than the above-mat biomass; whilst it accumulated more in the above-mat biomass than the below-mat biomass for other plant species including *Carex virgate*, *Juncus edgariae* and *Schoenoplectus tabernaemontani*. For Mg, irrespective of the plant species, it accumulated more in the below-mat biomass than the above-mat biomass.

4. CW TREATMENT APPLICATIONS IN POWER PLANT OPERATIONS

The feed to Lakeland CW (566 hectares in size) in Florida (USA), which is mainly effluent from a WWTP, has since 1989 been augmented with the inclusion of CT blow-down wastewater and periodic discharges from ash ponds of the McIntosh Power Plant (USEPA, 1993). The effluent from this CW is discharged to a receiving lake. Since 1993, Valmont Power Plant (Colorado, USA) has had two separate SSF CW treatment systems (~¾ acres) located adjacent to the power plant that treat on-site domestic wastewater from office buildings (Valmont Power Plant, 2004). The wetlands were designed to polish septic overflow to reduce particularly BOD and TSS and allow discharge into a receiving water body.

The Electric Power Research Institute (EPRI) has since 1990’s been involved in developing CW treatment systems as cost-effective technology for the treatment of metal-bearing electric utility wastewaters prior to discharges (Goodrich-Mahoney, 1996). More recently, the U.S. Department of Energy (DOE), through the National Energy Technology Laboratory (NETL), has also been engaged in evaluating the benefits, costs and limitations of using constructed or restored wetlands for power plant water use and as tertiary treatment of wastewater treatment plant effluent prior to use in a power plant (NETL, 2015). It is noteworthy that most of the existing power plant applications or pilot demonstrations of CW is usually restricted to treatment of domestic, process or industrial wastewater for discharge into receiving water bodies; only few examples use CW effluent directly for cooling. The next two subsections discusses published information on the use of CW in treating various power plant process and/or wastewater for discharge (Section 4.1) and in treating various source waters for power plant cooling (Section 4.2).

4.1 CW treatment of power plant process and/or wastewaters

From the EPRI initiative, feasibility studies and pilot or full scale demonstrations of using CW for treating power plant wastewaters have been reported for CT blowdown (Bayley et al., 2009; Lazareva and Pichlet, 2010; USEPA, 1993), flue gas desulfurization (FGD) wastewater (Eggert et al., 2008; Iannacone et al., 2009; Lazareva and Pichlet, 2010;Mooney and Murray-Gulde, 2008; Rodgers et al., 2005;Snider et al., 2012; Wylie et al., 2008), coal combustion by-product (CCB)-ash leachate (EPRI, 1998), and periodic discharges from ash ponds (USEPA, 1993).

EPRI and Allegheny Power have been in collaboration to test both the efficiency and economic feasibility of CW for use in remediating CCB leachate from Springdale Power Station, Pennsylvania (USA) (EPRI, 1998). The Springdale system consists of oxidation/precipitation basin, vegetated wetlands, manganese-oxidizing rock drains, organic reduction environments and phytoremediation. Some success reports from this project include substantial reduction of TSS, sulfate, and metals such as Fe, Mn, Al, As and Zn (EPRI, 1998; Goodrich-Mahoney, 1996). EPRI has also been in collaboration with Tennessee Valley Authority (TVA), Tennessee in establishing a CW research facility to provide removal rates data for various parameters in power plant related wastewaters (EPRI, 1999; Goodrich-Mahoney, 1996). Manganese and trace metal removal rates through successive anaerobic and aerobic CW system for the treatment of acidic aerobic discharges from such sources as coal mine, coal pile rejects and coal piles were demonstrated (Goodrich-Mahoney, 1996). TVA had also constructed CW system (of three cells) in 1986 at Widows Creek Electric plant to treat run-off and leachate coal and coal combustion by-product storage piles. A 15-month study, sponsored by EPRI, on the role of plants in trace element removal with two cells (3,250 m^2 or 0.8 Acres) dominated by cattail and soft rush also showed success in removing 25-50% of most of the elements, and up to 90% for Fe, Cd, V and Cr (EPRI, 1999).

In collaboration with NETL, a pilot-scale CW treatment system for treatment of targeted constituents (Hg, Se, As) in coal-fired power plant FGD wastewater has been demonstrated at Clemson University with initial removal rates of Hg of~64-97%; Selenium of 84-90% and As of about 70% (Rodgers et al., 2005). Jeffrey Energy Centre of Wester Energy, Inc. (a coal fired plant with 3-800 MW units) also undertook a pilot CW project to treat FGD wastewater for 1½ years (in 2011/12) with promising results and thus contemplated on full scale design for treatment (Snider et al., 2012). A full scale 24 acres CW was recently completed in July 2014 and now treats 100% of the sites scrubber wastewater discharge (Reitenbach, 2014). Progress/Duke Energy use CW to treat FGD wastewater at their Ashville Plants in North Carolina (Duke Energy, 2012; Wylie et al., 2008). For the above examples, the goal for utilizing CWs has essentially been to treat the wastewater to chemical/microbiological quality acceptable for permits to discharge. Of increasing importance to power plants however is also temperature regulation on discharge to waterways to protect cold water fish such as salmon, trout, and steelhead (Smesrud et al., 2014), of which wetland technology provides another benefit by its cooling effect as discussed in Section 3.4.5. Further discussions on the cooling benefits of CW are deferred to a later article in the publication series.

4.2 CW treatment of wastewaters for power plant cooling

Although there are now many drivers compelling the use of wastewaters, particularly those of municipal sources for industrial cooling purposes, only few power plants in the world seem to take advantage of the treatment capability of CW in polishing wastewaters for cooling purposes. The Shand Power Station (SaskPower), which is the focus of this present manuscript, seems to have led in this area, at least within North America; having been using CW since 1994 to further treat secondary treated municipal wastewater for condenser cooling. Further details of its design, planning and operation are deferred to a separate section (Section 5).

Between April 2006 to October 2007, the performance of a FWS CW (3 acres)/filter basin (1.5 acres) treatment system originally constructed in 1999 was evaluated for its treatment of a cooling pond water from a power generating station (Hines Energy Complex in Florida, USA) (Lazareva and Pichler, 2010). The CW showed promising treatment efficiency for the remediation of the wastewater. It showed significant change in pH from ~9 to 6.5-7; substantial reduction of inorganic ions such as SO_4^{2-}, Ca^{2+}, Mg^{2+}, F^-, Cl^-, NO_3^-, NO_2^-, Br^- and Na^+; and reduction in faecal and total coliform. Further, the chemical/microbiological composition of the treated water remained relatively constant irrespective of the season.

Still in the United States, a Regional Reclaimed Water Project in Florida was recently commissioned to supply a CW (i.e. Lakeland Wetland) treated effluent to a power station (i.e. Tampa Electric Company's-TECO's Polk Power Station) for reuse as cooling water (TECO, 2015). The feed to the Lakeland CW is primarily a blend of a secondary treated MWW and a CT blow-down from another power plant (McIntosh) that also receives the municipal effluent as part of its cooling water make-up (USEPA, 1993). To address inconsistent water quality and to meet Polk's quality requirement for cooling, effluent from the Lakeland CW is subjected to further treatment by the power station; i.e. 3-stages of treatment including: high rate settling and clarification, gravity-flow filtration, and reverse osmosis. It is noteworthy, that high concentrated wastewater from the Polk power station (which includes RO rejects and CT blow-down) are pumped into deep-injection wells 8,000 feet underground.

In Europe, effluent from the Fusina Treated Wetlands sited near Venice, Italy (said to be the largest of its kind in Europe) is reused by nearby industrial complex (potential to include power plants) for cooling water or discharged to the Adriatic Sea (Albano et al., 2014; Frank et al., 2011;Zaffaroni et al., 2016; Zanovello et al., 2003). This 100 hectare CW was completed in 2011 as polishing unit to remove trace levels of nutrients, metals and other contaminates from combined storm water and municipal/industrial wastewater mix prior to reuse. In its early years of operation both nitrogen (TN) and phosphate-P were reduced by 70-75%, with outlet NO_3^--N below detection limits. BOD and COD were typically below detection levels entering and exiting the wetland (Albano et al., 2014).

5. CW EFFLUENT FOR CONDENSER COOLING: SHAND POWER STATION

5.1 Background

As interest in using CW effluents for power plant cooling is gathering new momentum, so should the knowledge of the associated benefits and limitations. Commercial scale applications are however lacking and so is the data required to inform choices and design strategies for this technological process. SaskPower is one of the unique power utilities in the world, which since 1994 has been using CW as a tertiary polishing technology for reuse of municipal secondary treated effluent in condenser cooling at its Shand Power Station sited in Estevan, Saskatchewan (Canada). This section provides highlights on the rationale behind this choice of technology over 20 years ago. What were the drivers then, and how would current knowledge and pressures have influenced the choice?

To meet its future base load requirements, SaskPower in the 1980's considered amongst other options additional two-300 MW thermal generating units to its generation pool. Condenser cooling became one of the critical factors in evaluating the site location and various cooling options plus associated costs had to be considered. The decision seems to have been fairly influenced by water source availability and quality; and the Shand station, which offered more water supply options, became the eventual site of choice. Cooling alternatives assessed for the Shand site included dry cooling, wet cooling from a groundwater source (Estevan Valley Aquifer), and a wet cooling from a surface water reservoir. Cost wise, the groundwater wet cooling was considered as significantly more expensive; and even accounting for a significant financial contribution to the construction of a new dam reservoir (the Rafferty Reservoir), surface water wet cooling was comparable to the dry cooling. Dry cooling is sparingly used in larger power plants because of its inherent less efficiency in electricity generation and the consequential high air pollution and environmental impacts.

The higher cost for the groundwater usage was associated with high cost of water treatment. Furthermore, the Boundary Reservoir which supplied once-through cooling water to the existing SaskPower's 6-unit Power Plant (Boundary Dam Station), also in Estevan, had reached low levels of concern and therefore required supplementary allocation from groundwater sources. There was however concerns about the medium to long-term sustainability of the groundwater sources to cope with the cooling water needs of the thermal generating stations in Estevan and pumping limitations were imposed accordingly to protect this source water. The surface water reservoir was therefore to be the major source for cooling the two units at Shand (~72.5% of the supply), with the remaining from other sources including coal mine dewatering which could only supply about 4% of the water need.

To meet the extra cooling water needs, an agreement was made between the City of Estevan and SaskPower, which involved the availability/utilization of the entire annual municipal effluent from the city (whose population in 1981 was only 9,523 but was anticipated to increase to 13,400 by the year 2016) as cooling water for the Shand Power Station. The agreement was to last the longer of 30 years or the life of the power station. As part of the agreement, a CW was built to operate during normal plant growing season of each year (from spring to fall) to upgrade the effluent quality from a facultative municipal treatment facility consisting of primary and secondary waste stabilization lagoons and storage cells. 180 days storage of actual production by the city's municipal effluent was to be maintained from November to April (i.e. during the non-operational period of the CW). The BOD and TSS limit at the point of delivery to the CW was to be of a quality of municipal effluent consistent with that expected from a facultative secondary treatment type system and each to be less than 100 mg/L 99% of the time. However, there was the intent of upgrading the municipal treatment facility to a conventional secondary treatment capable of producing effluent in the 20-35 mg/L range for both parameters. The concentrations of animals and mineral based oil and greases, trace metals and toxic substances in the municipal effluent were to be minimized to avoid negative impacts to the CW or the operation at the power station.

Table 6 Wetland Design Parameters (Lakshman, 1994)

Parameter	Value
Designed Wastewater flow through the wetland	7,500 m^3/d (86.8 L/s)
Mean sewage production rate at time of design	3,750 m^3/d (43.4 L/s)
Typical Operating Period	150-180 days
Constructed Wetland Area	23.5 ha (58.1 ac; 235,000 m^2)
Wetland Configuration	2 major cells of 700 m long and 180 m wide. Each cell is divided into 3 sub-cells of 60 m wide. Each cell has two open water sections
Substrate	Compacted clay liner & top soil
Planting Scheme	Cattail transplanted into all cells at an approximate density of 9 plants/m^2. Cattail and bulrush hydroseeded in all cells. Cattail seeding: less than 7 kg/ha
Operating Depth of Water	0.2 to 0.3 m
Hydraulic Retention Time	5 to 9 days

5.2 Constructed wetland design

Construction of the wetlands began in spring of 1993 and completed in 1994. The CW design parameters are summarized in Table 6. The wetlands vegetation currently still consists mainly of bulrushes and cattails and as well as a variety of voluntary sedges. The cattails and bulrushes were selected because of their resistance to bacterial and parasitic damage and resilience in various climatic conditions.

Though not necessarily part of the CW treatment system, a shallow pond (~1-2 m deep and with surface area of 289 acres (~1.2 million m^2)) -appropriately called “Duck Pond”, was developed adjacent to the wetland as an integral part of the project. The duck pond provides a marsh habitat for various wildlife and migrating waterfowl to nest each spring. It also serves as an alternative area for effluent discharge when required.

5.3 Cooling water make-up blends to the shand power station for the past 2-decades

In 1994 when the CW became operable, the municipal effluent from the City’s MWW treatment facility which was feed into the wetland was of facultative lagoon treated quality. See column 8 of Table 1 for the average concentrations of various parameters in the municipal effluent. The city’s WWTP was upgraded later to a Biological Nutrient Removal (BNR)/Activated Sludge Process and was put in operation in January 1996. The treated effluent is kept in holding ponds operating in series; the last from which the effluent is pumped to the CW for polishing before use at the power station. The average concentrations of various parameters in the conventional secondary treated effluent at the point of delivery (in 1996) are shown in column 9 of Table 1.The designed effluent quality from the CW based on the influent quality (effluent from the facultative lagoon) is as follows: BOD = 5mg/L; TSS = 5 mg/L; NH_3 = 1 mg/L; TKN = 5 mg/L; TP = 1 mg/L.This was to achieve reduction of 92-97%, 79%, 96%, 86% and 90%, respectively. However, and as the main purpose of the CW was to provide make-up water for condenser cooling at a power station, the ultimate designed objective was to meet the following water quality criteria (maximum annual average) at the discharge point from the CW (Lakshman, 1994): BOD = 1 mg/L; TSS = 5 mg/L; NH3-N = 1 mg/L; TKN = 5 mg/L; TP = 1 mg/L; TOC = 20 mg/L. Some further improvement of BOD in the CW effluent was therefore anticipated to meet the cooling water objective; i.e. from improvement in the influent quality after the anticipated upgrade of the city's WWTP. As can be inferred from Table 1, this water quality to be delivered by the CW is significantly an improvement over the facultative lagoon treated sewage effluent as well as the later upgraded conventional secondary treatment effluent from the city of Estevan. Furthermore, apart from TOC, the water quality criterion (though limited in specified parameters) is comparable, if not better to other recommended reclaimed water criteria for cooling water make-up reuse (see Table 1). As well, this quality as a whole seems generally better than most reclaimed water quality being used or deemed qualified for reuse in power plant cooling around the world (e.g. Bayley et al., 2009;EPRI and CEC, 2003; Hansen and Harder, 2006;Lotts, 2014;NPDES, 2010;Selby et al., 1996; Victoria University, 2010; Vidic et al., 2009; Xu et al., 2012). Information from 8 facilities in the United States using reclaimed water for power plant cooling indicates a starting level of treatment that ranges from secondary to tertiary and additional treatments are provided which includes chemical addition, clarification, disinfection, pH adjustment and biological treatment (USEPA, 2004; Veil, 2007). The actual performance of the SaskPower CW to meet the designed quality criterion and/or the cooling water quality needs is however reserved for subsequent articles in these series of publication.

Though initially intended for two units, only one unit was actually, till date, constructed at the Shand site. This has been in operation since commission in 1992. The plant is a "Zero Liquid Discharge-ZLD" facility with cooling towers expected to operate typically between 6 to 8 cycles of concentration with the blowdown from the towers directed to a pond which feeds two Vapor Compressor Evaporators (VCEs) to process this wastewater. The product from the VCEs is further treated through a demineralizer bed to provide boiler make-up water. At the onset (1992/93), the main cooling water source was groundwater; since 1994 when construction of both the surface dam reservoir and the constructed wetland were completed, variable blend of these water sources have been the main supply (Table 7).

The CW effluent is piped into a 23 km pipeline from the Rafferty Reservoir and at about 18 km to the power plant. On annual basis, the CW polished municipal effluent constituted only ~3% of the cooling make-up water at the start of operation in 1994, increasing to ~9% during the plant developmental stages in 1995, and between 30 to 40% in 1996 to 2001. The usage however dwindled since until 2013; ranging typically from ~20 to 30%. Flooding that occurred in the area in 2011 however made the CW not to be operable in 2011 and 2012 and only partially in 2013 to contribute only 12.5% of the cooling water at Shand. The proportion of CW effluent used as cooling water make-up, however, reached its historic high in 2014. It has to be noted that the original anticipated annual percentage of the CW effluent contribution to the total CT make-up was only ~23.5% for each of the two proposed units.The CW effluent is piped into a 23 km pipeline from the Rafferty Reservoir and at about 18 km to the power plant. On annual basis, the CW effluent constituted only ~3% of the cooling make-up water at the start of operation in 1994, increasing to ~9% during the plant developmental stages in 1995, and from 30 to 40% in 1996 to 2001. The usage however dwindled since until 2013; ranging typically from ~20 to 30%. Flooding that occurred in the area in 2011 however made the CW not to be operable in 2011 and 2012 and only partially in 2013 to contribute only 12.5% of the cooling water at Shand. The proportion of CW effluent used as cooling water make-up, however, reached its historic high in 2014. It has to be noted that the original anticipated annual percentage of the CW effluent contribution to the total CT make-up was only about 23.5% for each of the two proposed units.

The CW treated municipal effluent source contribution to the CT make-up is however significantly higher during its operational period from May to November, when up to 100% may be from this source anytime within that period. There are several reasons that may account for the significant variability of the CW effluent portion of the cooling water (both on monthly and annual basis). They include: Plant scheduled overhauls (when and how long); maintenance limitations (pumps & other equipment downtimes from both the supply and receiving end); operational limitations at the power station (i.e. water quality and/or chemical treatment limitations); weather and climatic conditions (may influence CT cycles of concentrations and subsequently demand higher requirements to treat/manage CT blow-down); and lastly, though seldom, limitations imposed by the CW operation itself (to include moments of plant growth delay, harvesting, or replanting).

Table 7 Annual& monthly (May to October)% of CT make-up from CW effluent

Year	May	June	July	August	September	October	Annual
1994	0	0	0	0	4.4	28.3	3.1
1995	16.4	0	9.1	0	35.1	26.1	9.1
1996	95.0	100	82.3	58.6	38.4	86.9	40.9
1997	46.5	70.7	72.0	46.5	72.8	45.3	34.2
1998	78.4	52.7	65.1	45.2	17.9	37.5	30.4
1999	42.7	90.1	77.1	59.4	51.5	74.1	38.3
2000	0	88.0	55.5	64.8	70.3	73.6	35.1
2001	59.4	81.2	57.3	77.2	53.7	53.0	34.9
2002	52.8	46.7	41.4	41.0	87.4	17.8	23.4
2003	48.7	74.6	41.7	46.4	61.0	13.1	24.4
2004	51.9	72.7	38.2	40.3	54.3	73.3	28.8
2005	69.3	0	45.8	57.1	68.0	89.6	31.0
2006	51.3	31.4	48.6	63.8	33.4	0.0	20.9
2007	32.1	52.5	42.2	53.3	19.3	68.0	23.2
2008	8.8	55.1	49.6	30.8	29.0	22.0	16.7
2009	46.5	21.7	45.0	49.4	47.7	50.3	25.0
2010	22.0	35.4	51.5	46.0	42.9	43.8	22.6
2011	Constructed Wetland Flooded						
2012	Constructed Wetland Restoration						
2013	30.9	38.1	3.7	17.8	25.8	36.8	12.5
2014	65.3	91.1	97.5	56.7	62.8	62.6	45.4

The above limitations and the requirement for the power station to receive the entire annual treated sewage effluent sometimes demanded operating the CW in April and/or November (i.e. outside its designed periods of operation). These periods (e.g. Apr’14, Nov’14, Apr’09, Nov’07, Nov’05, Nov’04, Apr’01, Nov’01and Nov’00, with respective CT make-up percentages of approximately 38, 58, 5, 3, 25, 13, 16, 25and 22) are however excluded from Table 7. With the availability of the duck pond, a buffer is created where the effluent from the CW or direct city’s MWW may be pumped under any or all of the above limiting conditions that would prevent the ability of the power station to receive the CW effluent for cooling. In 2014, the duck pond was full to its capacity throughout the CW operating season; this therefore compelled a disproportionate amount of the CW effluent as CT make-up for the power station.

Water pumped to the duck pond is usually left to evaporate, but under critical situations it may be pumped directly to the power station or returned to the CW effluent storage pond and recirculated through the CW for further polishing before delivery to the Power Station.

5.4 Benefits

With the use of the SaskPower CW to polish the secondary treated MWW effluent, the following benefits were derived-directly or indirectly:

- Elimination of semi-annual discharge of effluent to the Souris River by the City and its associated public concerns;
- Assurance of supplementary source of cooling water for the Shand Power Station;
- Water conservation and protection of potable water (groundwater and surface water) sources within the locality;
- Operational benefits in comparison to direct reuse of the city’s treated MWW effluent (this is discussed in more details in subsequent publications in the series);
- Other benefits include (Apfelbaum et al., 2013; Reitenbach, 2014):
  - ➢ Provision of habitat for aquatic species of plants and animals, although when uncontrolled defeats the purpose of the CW in improving the treated water quality.
  - ➢ Land conservation. Wetlands impact is usually a consideration for permit approval in the construction of new power generating plants. CW or wetland restorations do therefore serve as compensatory mitigation approach (Schumacher et al., 2007).
  - ➢ Public acceptance for associated power generation project(s). CWs, because they use naturally occurring soil, plant materials, and soil microbes for treatment, and do exhibit CO_2 removal from the atmosphere through photosynthesis is generally regarded as a “green” solution (Zhao et al., 2013) and promotes public approval for projects they are integrated in. Its emission of $CO_2$is less concerning as it is usually from aerobic decomposition of carbon (organic matter) previously sequestered from the atmosphere and hence of actual near zero net carbon emission.

There are other benefits derivable from CW technology for power plant cooling, which may not have been perceived at the designing stages of the SaskPower project or if considered, may have been found probably to be logistically infeasible in that particular case. These, including extra cooling, storm water harvesting, and enhanced treatments and reduced greenhouse gas emissions by integrating CW with other technologies such as microbial fuel cells are discussed in details in a later paper of the publication series.

CONCLUSIONS

With world population increase, climatic changes, rapid urbanization, etc. wastewater reuse has been a topic of recent intense interest. MWW treatment, in particular, has been a focus in meeting requirements for discharge into water bodies and/or for agricultural and industrial reuse, including power plant cooling. For these purposes, a minimum of secondary effluent standard(s) is usually required; and depending on the reuse application, additional treatment to tertiary standard is necessary.

CW is currently more commonly used for tertiary treatment of MWW to meet discharge permit requirements set in more industrialized areas. In developing countries and other areas with less stringent discharge requirements, CWs are used as secondary treatment process. The review shows that more efficient treatment is typically realized by CWs in treating primary or raw effluent than secondary and/or tertiary effluents, but the outflow quality of the former is not consistently good enough to meet stringent discharge requirements. For power plant cooling purposes, MWW of secondary effluent standard is commonly required as a minimum, although needs in preventing scaling, corrosion, and bio-fouling of process equipment and concerns for human health usually would dictate additional treatments at the MWW treatment plant or the power station. Despite the treatment efficacy of CWs in the light of their low capital and operational cost, power plants have not well utilized this technology for tertiary treatment to its advantage for cooling purposes. SaskPower's Shand Power Plant appears to have been a pace-setter in this endeavor; having utilized this process for over 2-decades. There is currently a rejuvenated strive by the power industry to exploit CWs for water harvesting and cooling purposes, having already demonstrated its importance in treating power plant process and/or wastewaters such FGD, ash ponds, CT blow-down, etc. It is anticipated that the sharing of experience already gained in this field at commercial level of reuse application will be helpful for the long-term evaluation of such new endeavors.

This review presents the benefits of CWs as rationale for consideration in designing new power plant cooling systems. It outlines realized benefits of CW for the Shand Power Plant project, whilst laying the foundation for a later discussion and on other derivable benefits (in the light of current advancement in the CW technology) that may not have been perceived at the designing stages of the SaskPower project, two decades ago.

ACKNOWLEDGEMENTS

The author would like to thank Mr. Bruce Duncan, under whom the Shand CW was operated since the early stages until later in 2013 when he relinquished that role to the author. Acknowledgment also goes to predecessor chemists-Mr. Doug Kenzil, Dr. David Jobe, and Dr. Rod Nashiem who were pioneers in facing the challenges associated in using CW effluent as cooling water source.

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