CONSTRUCTED WETLANDS INCORPORATING SURFACE WATER HEAT PUMPS (SWHPS) FOR CONCENTRATED URBAN STORMWATER RUNOFF TREATMENT AND REUSE.

Kiran Tota-Maharaj[1,] Piotr Grabowiecki[2], Akintunde Babatunde[3] and Prasad Devi Tumula[1]

[1]University of Salford Manchester, Civil Engineering Research Centre, Newton Building,
Salford, Greater Manchester, United Kingdom Email: K.Tota-Maharaj@salford.ac.uk
[2]Institute of Geophysics, Polish Academy of Sciences, Warsaw, Poland
[3]Centre for Water Resources Research, School of Arch.,Landscape and Civil
Engineering, Newstead Building, University College Dublin, Ireland

ABSTRACT

The integration of constructed wetlands or natural wetlands and surface water heat pumps (SWHPs) leads towards the development of a novel sustainable technology treating urban stormwater and application of renewable energy technologies. SWHPs are a well-recognised source of renewable energy and provide high efficiencies for heating and cooling by employing the enormous renewable storage capacity of surface water systems such as wetlands. Engineered wetland systems are compact urban wastewater or stormwater treatment systems that encompass a plurality of treatment modules similar to processes occurring in natural wetlands. Wetlands are a preferred stormwater treatment system over conventional systems which are energy intensive and inadvertently contribute to greenhouse gas emissions. The incorporation of SWHPs within constructed wetlands has great potential for addressing global water and energy issues, providing significant and multiple benefits for energy and water usage, protecting and enhancing natural water systems within urban catchments and reducing the demand on potable water supplies by contributing to water recycling. Two experimental rigs simulating real-life scenarios of surface water heat pumps integrated with constructed wetlands were set up, and running in a green house (controlled environment) at The University of Salford Manchester. Temperatures and water quality analyses measured the treatment performance and water quality efficiency for the combined systems. The water quality analyses for treatment processes of the rigs showed no significant differences for the removal of biochemical oxygen demand, chemical oxygen demand, nutrients (phosphates, nitrates and ammonia) for the wetland system linked to water-sourced heating and cooling and the stand-alone constructed wetland.

Keywords: Constructed Wetland, Vertical Flow, Water Quality, Water-Source Heat Pump, Energy Efficiency

1. INTRODUCTION

1.1 Constructed Wetlands

Constructed wetlands are engineered systems designed to imitate the optimal treatment conditions found in natural wetlands, which filter out pollutants and act as sinks for nutrients by purifying water, wastewater and stormwater through physical (sedimentation and filtration), physical-chemical (adsorption on plants, soil and organic substrates) and biochemical (biochemical degradation, nitrification, denitrification, decomposition and plant uptake) processes [1]. Constructed wetlands for wastewater treatment have several advantages over conventional treatment methods such as enhanced biodiversity, greater sustainability and low cost of construction [2, 3]. Constructed wetlands also require low maintenance, limited energy requirements, consists of simple and natural technology systems and less susceptibility to variation in loading rate. Despite such advantages of constructed wetlands, however there are several limitations with regards to environmental conditions when treating high volumetric loads and heavily polluted wastewater. The treatment of wastewater by constructed wetlands is achieved by several chemical and biological processes including microbiological mediation. Table 1 presents some of the main processes affecting Biochemical Oxygen Demand (BOD_5), Nitrogen (as Ammonia and Nitrate) and Phosphorous within constructed wetlands. The mechanisms that improve water quality include [4] settling of suspended particulate matter; filtration and chemical precipitation through contact of the water with the substrate and litter; chemical transformation; adsorption and ion exchange on the surface of plants, substrate, sediment and litter; breakdown, transformation and uptake of pollutants and nutrients by microorganisms and plants; predation and natural die-off of pathogens. The most frequently used plant species worldwide is *Phragmites australis* or common reed [4]. Densely rooted *Phragmites australis* plants slow the water down and produce a more uniform flow, thus contributing to the stabilization of the sediments.

Table 1 - Processes occurring in constructed wetlands treatment of wastewater [1-3]

Water Quality Parameters	Wetland Location	Removal Processes
BOD_5 (Biochemical Oxygen Demand 5-day)	Stems and Leaves	Microbial respiration
	Roots	Microbial respiration
	Bed media (gravel/sand)	Microbial respiration
	Bed media (gravel/sand)	Settling

Nitrogen	Leaves	Volatilization (as N_2 and N_2O)
	Algae in water column	NO_3 and NH_4^+ -> Soluble Organic Nitrogen
	Roots	Ammonium -> Nitrate
	Soil	Nitrate -> N_2, N_2O, or NH^{4+}
	Bed media(gravel/sand)	Settling
Phosphorus	Stems and Leaves	Microbial Repiration
	Roots	Microbial Repiration
	Roots	Uptake
	Bed media (gravel/sand)	Sedimentation/Burial
	Bed media (gravel/sand)	Adsorption

1.2 Surface Water Heat Pumps (SWHPs)

Surface water heat pumps (SWHPs) are a viable and relatively low-cost renewable energy option. Heat sources for water energy production are naturally occurring, plentiful, and environmentally sustainable. These systems can replace the use of fossil fuels, which contribute to greenhouse gas production and global warming. SWHPs are considered a sustainable technology as it reclaims and recycles thermal energy from surface waters present in wet ponds, rivers or lakes. SWHPs are one of the most recognizable renewable energy applications around the globe today [5, 6]. Two types of surface water heat pumps exist: closed-loop and open-loop. A closed-loop surface water heat pump system (see Figure 1) transfers heat to or from a surface water body by circulating a heat transfer fluid in an enclosed pipe. A closed-loop system is immersed in a surface water body, such as a constructed pond. An open-loop heat pump system withdraws water from a surface water supply, passes it through a heat exchanger, and discharges the water to a surface body of water or a storm sewer. A series of coiled pipes are submerged below the surface of a lake or pond as the heat exchanger. This requires minimal piping and excavation; however, the pond or lake must be deep and large enough. The heat transfer fluid is pumped through the pipes in a closed loop avoiding adverse impacts on the aquatic ecosystem [7].

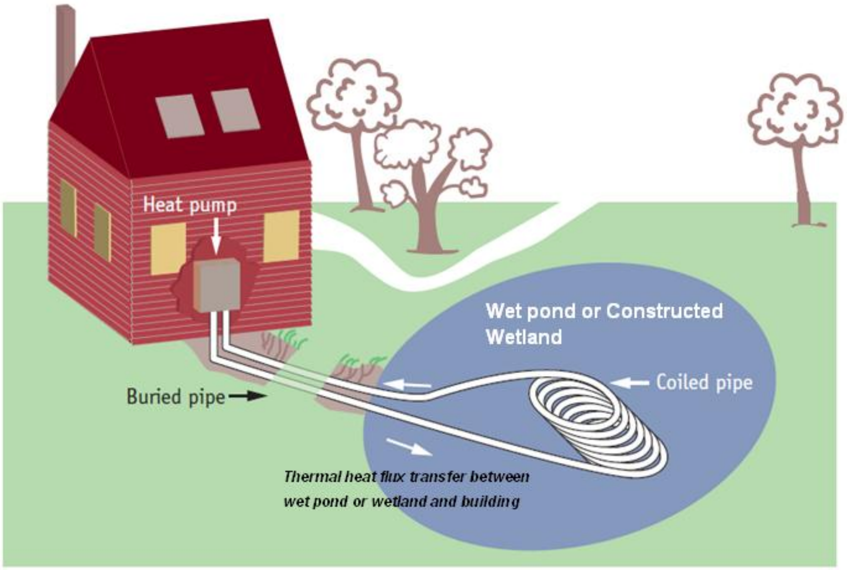

Figure 1: Surface Water Heat Pump (SWHP) in a closed-loop system utilising thermal energy transfer between either a wet pond or constructed wetland [8]

2. MATERIALS AND METHODS

2.1 System Design

The design and development of a novel constructed wetland system integrated with surface water heat pumps has been carried out. Two constructed wetland systems were set up within 1 meter tanked systems. The two constructed wetland system comprised of common reeds planted in pea gravel and supported by gravel. The engineered wetland system operates in a vertical flow (see Figure 2).The wetland design consisting of *Phragmites australis* (common reeds) was planted in a vertical flow, batch operating wetland, within a rectangular shape with a surface area of 0.35 $m^{2.}$ One month old *Phragmites australis* were initially planted. The support media consisted of (5-10 cm) pea gravel on the top layer, and 65-70 cm of gravel at the bottom layer. Both wetlands were identical in design being vertical flow and planted system with the first wetland being linked to a SWHP system.

Water sample pipes were placed at fixed intervals of 10 cm apart in assessing the vertical flow and hydraulic operation of the wetland systems. The wetland top surface area had a square cross-section of 55 cm in width by 70 cm in length. Each wetland systems was connected to an external cooling coil system, whereby cold water ranging from 6-8 °C was circulated around the sub-base of the wetlands via a coolant, water pump and water tubing. The surrounding cover of the tanked wetland systems were insulated with aluminium sheeting of 1 cm in thickness to prevent external heat transfer from entering the sub-base zone for the wetland. These conditions were set and kept temperatures of the sub-base at approximately 9-11 °C simulating real scenarios of ground and soil conditions within the UK.

Water source heating and cooling system included reinforced 5-mm polypropylene tubes placed in the lower sub-base of the first constructed wetland system. The tubing was looped approximately 10 times folded within the saturated water zone of the wetland structure with a total length of approximately 10 meters. Both ends of the tube were located in a plastic tank water vessel. One end was connected to a pump and the other end used as an orifice for discharges. The water pump directed either cooled water (<10 °C) in a cooling mode or hot water (between 20°C to 30°C) in a heating cycle via aquarium heaters (VISITHERM, Aquarium Systems NEWA, Loughborough, UK) used to achieve higher temperatures in the heating cycle (water heater) whilst In-line aquarium coolers (Titan 500, Aqua Medic, Bissendorf, Germany) were applied to decrease the temperatures within the coils for the cooling mode (water cooler).

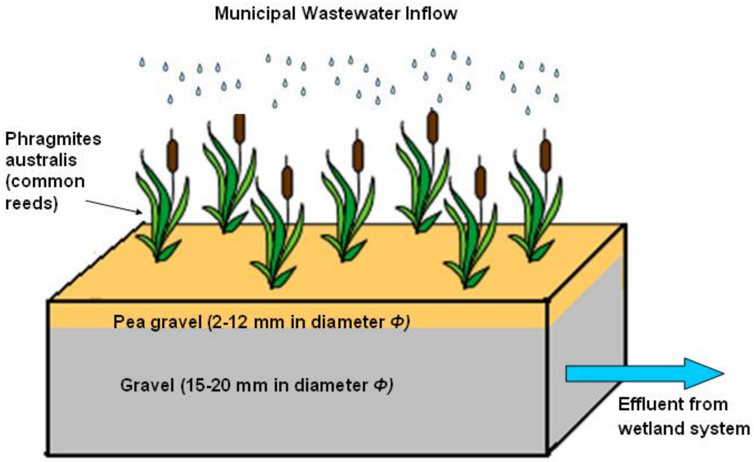

Figure 2: Experimental Layout of Vertical Flow Constructed Wetland System with Phragmites austalis (common reeds) planted within a pea gravel and gravel sub-base.

Figure 3: Photograph of combined constructed wetland and SWHP (I) and stand-alone constructed wetland system (II) taken October 2011, after four months into operation.

2.2 Experimental Analysis

Municipal wastewater from the inlets of the Davyhulme wastewater treatment plant, Greater Manchester, UK was fed into the surfaces of each wetland with a retention time of approximately 4 days on a weekly regime. Water pollutant removal efficiencies were assessed within the 2 different models of constructed wetlands. The concentrations of ammonia, nitrite, nitrate, orthophosphate, chemical oxygen demand, and suspended solids, were determined using Hach Lange DR 2800 spectrophotometer according to United Stated Environment Protections Agency [9] approved standards for wastewater analysis from the HACH manual [10] and as described by Tota-Maharaj *et al*. [11].

3. RESULTS

The first wetland system consisting of the water source heat pump followed a cooling cycle with temperatures ranging from 5 to 9 °C from June to October, and thereafter a heating mode whereby temperatures of the heater ranged from 19 to 25 °C (Figure 3). This simulated the performance of a water sourced heat pump with a cooling cycle throughout the warmer months of the year and a heating cycle for the colder periods. The mean weekly temperatures of the sub-base zone of wetland system 1 are presented in figure 3, with a cooling cycle followed by a heating cycle respectively.

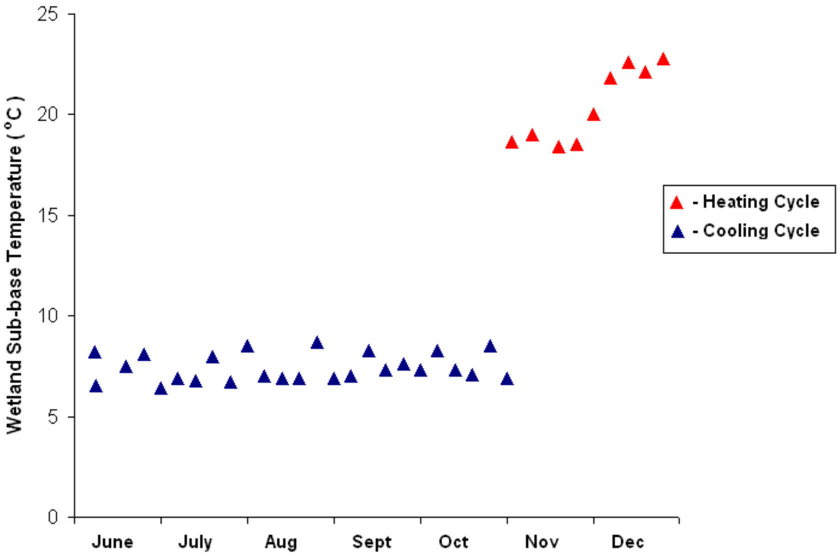

Figure 3: Mean Weekly Saturated Water Temperatures (°C) from June to December 2011 within sub-base zone of constructed wetland incorporating surface water heating and cooling system

Table 2: Statistical parameters for Inflow Wastewater (collected from the inlets of United Utilities Wastewater Treatment Plant, Greater Manchester UK)

Water Quality Parameters	Minimum	Maximum	Mean	Std. Error of Mean	Std. Deviation
Water Sample Temp (°C)	11.0	19.9	14.46	0.64	2.57
pH	7.20	7.98	7.58	0.08	0.31
Nitrite-Nitrogen (NO_2-N, mg/l)	0.02	0.12	0.06	0.01	0.03
Nitrate-Nitrogen (NO_3-N, mg/l)	0.21	1.7	0.56	0.10	0.39
Ortho-Phosphate-Phosphorous (PO_4-P, mg/l)	0.47	5.28	2.72	0.38	1.33
Phosphate (PO_4^{3-}, mg/l)	3.11	13.6	6.25	0.78	2.70
Ammonium-Nitrogen (NH_3-N, mg/l)	11.20	36.1	18.98	1.52	6.08
Chemical Oxygen Demand (COD, mg/l)	43.0	600.0	188.32	33.13	132.54
Suspended Solids (mg/l)	13.0	380.0	107.88	24.89	99.55

Table 3 presents the influent municipal wastewater variables collected from the United Utilities Wastewater Treatment Plant at Davyhulme, Manchester United Kingdom. Nitrogen-nutrient levels varied with diluting effects on ammonia, nitrate-nitrogen and nitrite-nitrogen, and organic matter reflecting the impact of stormwater runoff, sewer flows and wastewater mixing at the inlets of the treatment plant. Organic enrichment measured as a function of chemical oxygen demand (COD) and suspended solids had high influent variations ranging from 43-600 mg/l and 13 to 380 mg/l respectively (Table 3).

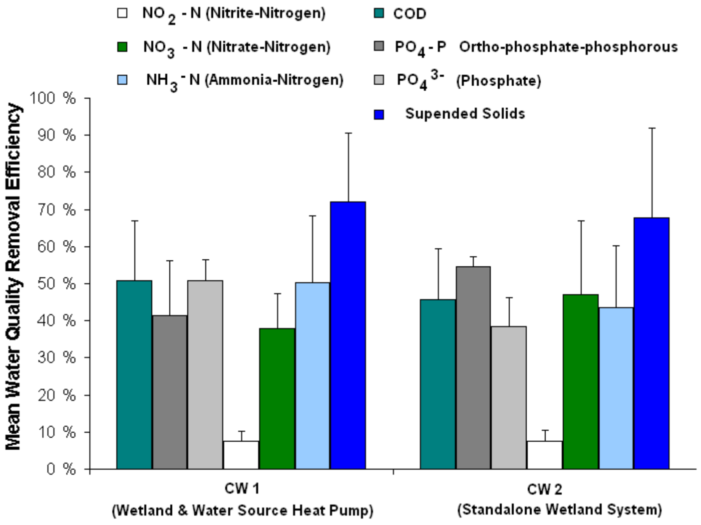

Figure 3: Average water quality removal efficiency and error bars (standard deviation) for chemical oxygen demand (COD), ortho-phosphate-phosphorous (PO_4-P); phosphates (PO_4^{3-}); nitrite-nitrogen (NO_2-N); nitrate-nitrogen (NO_3-N); ammonia-nitrogen (NH_3-N) and suspended Solids. Sample number n = 30, from June-December, 2011.

Results obtained so far presented in figure 3, indicate that the overall water treatment in both systems was high, with up to 75% suspended solid removal and 50 % chemical oxygen demand removal. Variable removal efficiencies have also been calculated for nutrients removal within the system. Air and water temperatures and water quality data variability within the system provide evidence of high level of biological processes. In constructed wastewater wetlands, the denitrification and ammonia adsorption process showed removal of 50-60% of the ammonia-nitrogen and nitrate-nitrogen and 5-10% of that is derived from plant uptake for nitrite removal. The two constructed wetland systems through chemical precipitation, substrate adsorption, bacterial action, plant uptake, and incorporation into organic matter and showed high water quality enhancement in degrading phosphates and ortho-phosphate-phosphourous and reducing the concentrations of the pollutants.

4. CONCLUSIONS AND FUTURE WORK

The experimental work on the constructed wetlands in a vertical flow pattern with integrated with surface water heat pumps and stand-alone vertical flow wetlands proved to be well suited for treating municipal wastewater. The both systems showed good water pollutant removal efficiencies. The main process for contaminant removal of filtration and sedimentation showed that varying temperatures of the sub-base for the wetland system which consisted of water-sourced heating or cooling still performed relatively well, with similar removal efficiencies for water purification. Initial one-way analysis of variance test (ANOVA) shows no statistical significance between the standalone wetland system and the wetland system linked to water-sourced heating and cooling ($p > 0.05$) for the effluent water quality parameter concentrations. This showed the SWHP system did not deter the wetland from its natural process of nutrient uptake, filtration, sedimentation and adsorption of the wastewater pollutants. However, further detailed analysis for a longer period will be carried out in assessing its water quality removal efficiency for long-term effects. In order to further assess the wastewater purifying efficiency it is necessary to conduct the experiment for a longer period, suited to a longer life plant cycle. Optimisation of the working conditions and improvement on the hydraulic system and retention time will also be addressed. Further results will be analysed to determine energy efficiency rates in order to provide evidence on the correctness in the design and setup of the water-sourced heat pump system. When fully researched and developed, the new system can be a strategic application in the domestic and industrial wastewater treatment and provide nearby heating and cooling for urban developments.

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