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Comparative assessment of managed aquifer recharge versus constructed wetlands in managing chemical and microbial risks during wastewater reuse: a review

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ABSTRACT

Constructed wetlands (CWs) and managed aquifer recharge (MAR) represent commonly used natural treatment systems for reclamation and reuse of wastewater. However, each of these technologies have some limitations with respect to removal of different contaminants. Combining these two technologies into a hybrid CW-MAR system will lead to synergy in terms of both water quality and costs. This promising technology will help in the reduction of bacteria and viruses, trace and heavy metals, organic micropollutants, and nutrients. Use of subsurface flow CWs as pre-treatment for MAR has multiple benefits: (i) it creates a barrier for different microbial and chemical pollutants, (ii) it reduces the residence time for water recovery, and (iii) it avoids clogging during MAR as CWs can remove suspended solids and enhance the reclaimed water quality. This paper analyzes the removal of different contaminants by CW and MAR systems based on a literature review. It is expected that a combination of these natural treatment systems (CWs and MAR) could become an attractive, efficient and cost-effective technology for water reclamation and reuse.

Key words | aquifer recharge, bank filtration, constructed wetlands, pathogen removal, pharmaceutically active compounds, soil aquifer treatment, water reuse

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INTRODUCTION

There is a growing pressure on water resources worldwide, resulting from high population growth and thus increasing water demands. Nowadays, treated wastewater effluent is well accepted as one of the important water resources in many parts of the world. Treated wastewater has the potential to become an important water source for different purposes, but the quality of the treated wastewater is often a potential constraint, depending on the specific (re)use.

Natural wastewater treatment systems, namely, constructed wetlands (CWs) and managed aquifer recharge (MAR) which comprises aquifer recharge and recovery (ARR), soil aquifer treatment (SAT), and river bank filtration (RBF), are simple, cost-effective, robust, chemical-free, and efficient methods to further polish wastewater effluents. Their extreme simplicity in construction, operation and maintenance makes these natural systems competitive with conventional wastewater treatment methods (Sharma & Amy 2010).

Bank filtration (BF) can be considered to be a robust treatment system able to maintain its active processes through extreme scenarios such as temperature changes, high contaminant concentration peaks, and shorter residence times due to flood events (Schmidt *et al.* 2007).

CWs are engineered systems that have been designed and constructed to utilize the natural processes involving wetland vegetation, soils, and associated microbial assemblages to assist in treating wastewaters. They are designed to take advantage of many treatment mechanisms that occur in natural wetlands, but do so within a more controlled environment. CWs for wastewater treatment may be classified according to the wetland hydrology (free water surface (FWS) and subsurface flow (SSF) systems).

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SSF CWs can be further classified according to the flow direction (horizontal (HF) and vertical (VF)) (Vymazal 2010).

The treatment mechanisms that occur in CWs and MAR systems include settling, microbial oxidation, anaerobic decomposition, nitrification, denitrification, adsorption, desorption, and precipitation. CWs systems use many plants such as cattails and bulrushes, and their associated bacterial populations, to break down contaminants into relatively innocuous byproducts. Thus, CWs can effectively treat domestic wastewater, industrial wastewater, animal wastewater, contaminated groundwater, mine waste, urban runoff, and other contaminated waters (Kadlec & Wallace 2008).

Natural wastewater treatment systems are used throughout the world for wastewater treatment to enhance reclaimed water quality to be reused for different purposes such as groundwater recharge. CWs and SAT can be applied to primary or secondary effluents, allowing the removal of most bacteria and other microorganisms and the degradation of bulk organic matter. SAT can also remove part of the nutrients and a wide range of organic micropollutants (OMPs), while CWs are efficient in removing bulk organics and suspended solids, but are less effective than SAT in removing nitrogen and phosphorus compounds. Hybrids that integrate different natural treatment systems are expected to be more effective for water reclamation and provide multiple barriers for different contaminants.

RESEARCH METHODOLOGY

Several research studies have been conducted throughout the world to study the efficiency and capability of MAR and CWs to remove wastewater-derived contaminants (bulk organic matter, OMPs, nitrogen, phosphorus and pathogenic microorganisms) from primary and secondary effluents through the natural, chemical and biological processes associated with soils and plants.

This study is based on an extensive literature review, the performance data of more than 30 CWs and 20 MAR systems all over the world; pilot and field scale systems were included. The collected data were used for the analysis of the removal efficiencies of OMPs (such as pharmaceutically active compounds (PhACs) and personal care products (PCPs)), nutrients (nitrogen and phosphorus), organic matter and pathogenic microorganisms from MAR and CWs. Moreover, the potential integration of applying CWs and MAR either in hybrid or integrated processes under different environmental conditions, different water qualities and different types of CWs has also been investigated.

Synergies between CWs and MAR are expected to enhance the removal capabilities of micropollutants, nutrients, bacteria, and viruses from different types of wastewater in a sustainable way, which cannot be achieved by MAR or CWs alone. The following sections summarize the performance of MAR, CWs and the potential combinations thereof for removal of different contaminants.

ORGANIC MATTER AND SUSPENDED SOLIDS REMOVALS

CWs and MAR are very effective in total suspended solids (TSS) removal (Table 1). In both systems, most of the removal occurs within the first few meters of travel distance from the inlet zone. Adsorption and biodegradation are considered to be the dominant removal processes in these systems (Maeng *et al.* 2012). TSS in wastewater effluent is usually relatively fine and in organic form (sewage sludge, bacteria, floes, algal cells, etc.). The main constituent that must be removed from the effluent before it is applied to a SAT system is TSS due to infiltration basin clogging. However, a higher biochemical oxygen demand (BOD) content would also result in somewhat lower hydraulic loading rates (HLR) for the SAT system and would require more frequent basin cleaning. Thus, using CWs as a pre-treatment for ARR and SAT systems will

Table 1 | BOD_5 and TSS removals through MAR and different types of CWs

System	BOD_5 % removal	TSS % removal	Reference
FWS CWs	73	73	Vymazal (2010)
HF CWs	75	75	Vymazal (2010)
VF CWs	90	89	Vymazal (2010)
MAR	90	90	Oron (2001)

not only reduce TSS from the influents but also avoid potential clogging and maintain the HLR.

Dissolved organic carbon (DOC) removal through BF, for Lake Tegel in Berlin (Germany), was 44% over 135 days of residence time as shown in Figure 1. This removal could be enhanced up to 80% for a longer distance as shown in Table 2. Chung *et al*. (2008) found that a 72% removal of DOC could be achieved within 5 days of hydraulic residence time (HRT) through a subsurface flow horizontal CW.

Hybridization between these two systems will enhance the DOC removal and also reduce the residence time, as shown in Figure 2.

NITROGEN AND PHOSPHORUS REMOVAL

Nitrogen species present in wastewater usually include various forms of organic and inorganic nitrogen (ammonium, nitrite and nitrate). Significant nitrification and subsequent denitrification normally occur and remove nitrogen through the treatment systems.

Nitrogen removal has been observed through CWs and MAR systems. Table 3 shows the removal efficiencies for different nitrogen species in a BF system.

It was found that 40–70% removal could be achieved for different nitrogen species in different types of CWs, as shown in Table 3. VF CWs are more efficient in

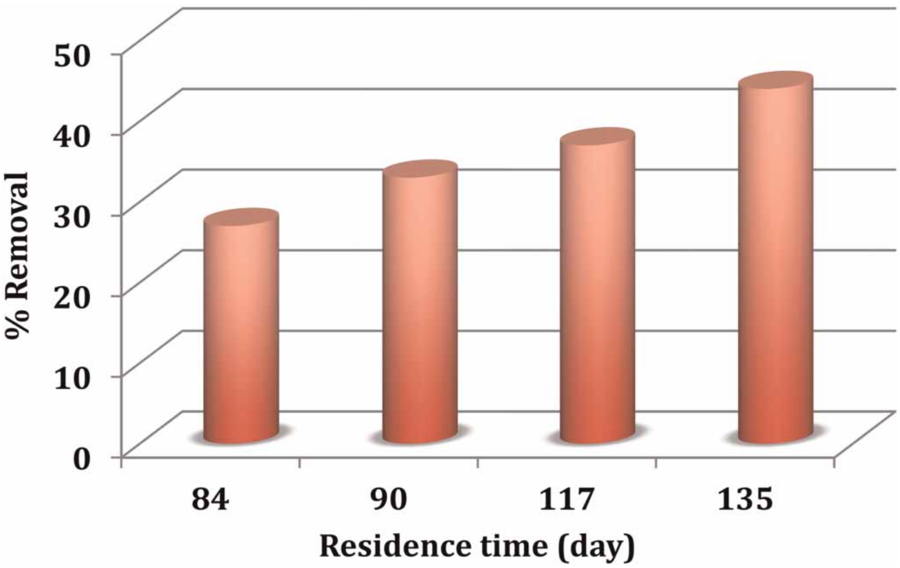

Figure 1 | DOC removal through bank filtration for Lake Tegel in Berlin (*Source*: Grunheid *et al*. 2005).

Table 2 | DOC removal efficiency by bank filtration technology

RBF site location	Distance well from river (m)	Residence time (day)	Influent conc. (mg/l)	Effluent conc. (mg/l)	Removal efficiency (%)	Reference
Lake Tegel Berlin (Germany)	30	84	7.5	5.5	27	Grunheid *et al.* (2005)
	25	90		5.6	25	
	55	90		5	33	
	77	117		4.7	37	
	90	135		4.2	44	
Lake Tegel Berlin (Germany)	100	135	7.5	1.5	80	Jekel & Gruenheid (2005)

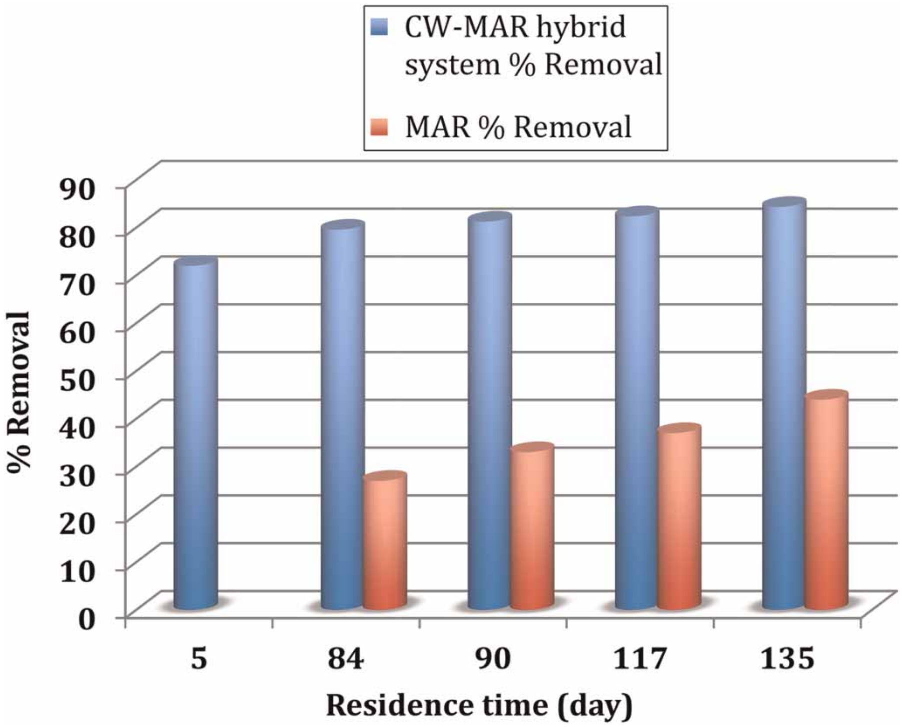

Figure 2 | DOC accumulative removal through CW-MAR hybrid system.

Table 3 | TN, NH_4^+-N and NO_3^--N removals through MAR and different types of CWs (*Sources*: Idelovitch *et al*. 2003; Vymazal 2005, 2010)

Treatment technique	NO_3^--N % removal efficiency	NH_4^+-N % removal efficiency	TN % removal efficiency
FWS CWs	61	47	51
HF CWs	39	35	38
VF CWs	(–97)	73	43
MAR	62	60	70

ammonia removal because they normally operate under oxic conditions which promote nitrification. The phosphorus is removed during SAT by adsorption to soil during reclaimed wastewater percolation through the soils and sediments and/or a chemical precipitation reaction with the calcium and magnesium ions present in the soil (Idelovitch *et al.* 2003). Plant uptake, in the case of CWs, tends to have a relatively small effect on removal (Vymazal 2010).

The synergy between these two systems will be useful to enhance nitrogen removal, as shown in Figure 3.

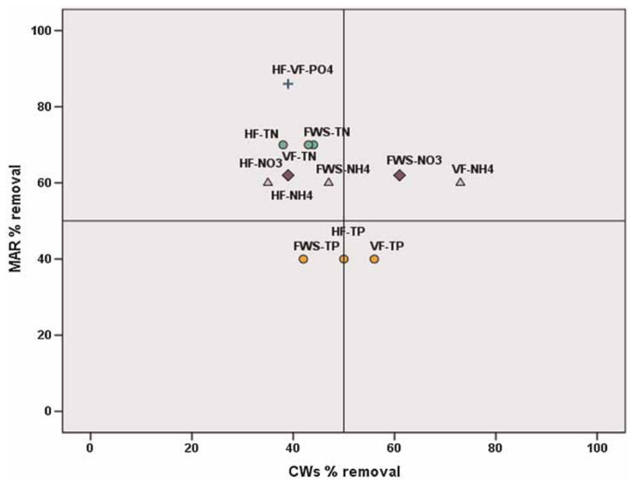

Figure 3 | TN, NH_4^+-N, NO_3^--N, P, and TP removals through CWs and MAR systems.

High ammonia removal can be achieved if VF CWs are used before MAR and generate nitrate. However, using HF CWs before MAR and after VF CWs will enhance the removal of all nitrogen and phosphorus species.

OMP REMOVAL

Municipal wastewater represents the main disposal pathway for PhACs and PCPs consumed in households, hospitals and industry. After passing through a wastewater treatment plant, the treated wastewater is often discharged into rivers and streams, which may percolate or infiltrate into groundwater or pass through river banks. Several OMPs, such as bezafibrate, ketoprofen, iopromide, gemfibrozil, erythromycin, trimethoprim and fluextine, appear to be removed effectively during MAR and/or CWs. However, OMP removal will be enhanced through the CW-MAR combined system, especially for some OMPs which show resistance such as diclofenac, clofibric acid, carbamazepine and dilantin, as shown in Figure 4.

METALS REMOVAL

During water percolation through soil, trace elements such as iron, manganese, and various heavy metals are eliminated by filtration and sorption processes. In an aerobic environment, ion exchange processes at negatively charged surfaces can achieve removal, while in an anoxic environment, the removal of metal ions is dominated by precipitation reactions with sulfide. Plant uptake was also found to be an influential removal process in CWs (Cheng *et al*. 2002).

Several metals show very high removals through BF, such as iron and chromium, while others show high removals through both systems, such as zinc. However, metals removals can be clearly enhanced through the combined system (e.g. Cd, Pb, Cr and Fe), as shown in Figure 5, although some metals show some persistence for the CW-MAR hybrid system such as selenium, tin and silver.

PATHOGEN REMOVAL

Pathogenic bacteria, viruses and *Cryptosporidium* can be effectively reduced or eliminated during soil passage but for reasons that are not entirely understood (Hiscock & Grischek 2002). During soil passage, microorganisms may be removed from the aqueous phase primarily by straining, inactivation, and attachment to the aquifer grains (in combination with inactivation). CWs have been found to reduce microbial pathogens with varying but significant degrees of effectiveness. As water passes through a CW system, pathogens are removed through a combination of physical mechanisms (filtration and sedimentation) and chemical mechanisms such as oxidation and adsorption to organic matter. CWs are highly efficient and remove 2logs of *Giardia* and around 1log of *Cryptosporidium*. At the same time, MAR shows lesser removal for both organisms, as shown in Table 4. However, the hybrid system is expected

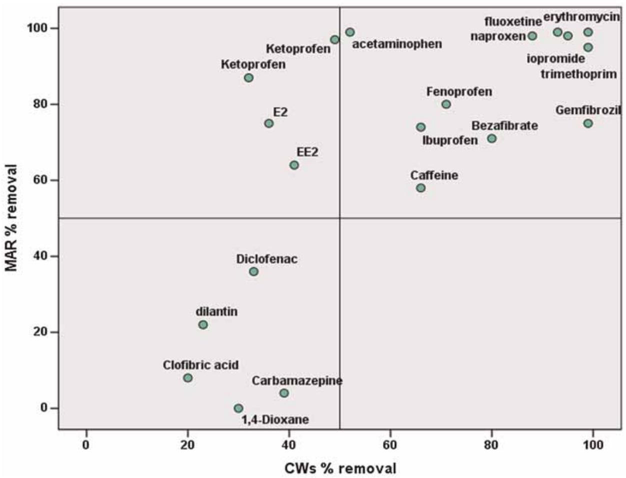

Figure 4 | OMP removal through CWs and MAR systems (*Sources*: Conkle *et al.* 2008; Matamoros & Bayona 2008; Snyder *et al.* 2008; Onesios *et al.* 2009; Valsero *et al.* 2010; Sharma *et al.* 2011; Hamadeh *et al.* 2012).

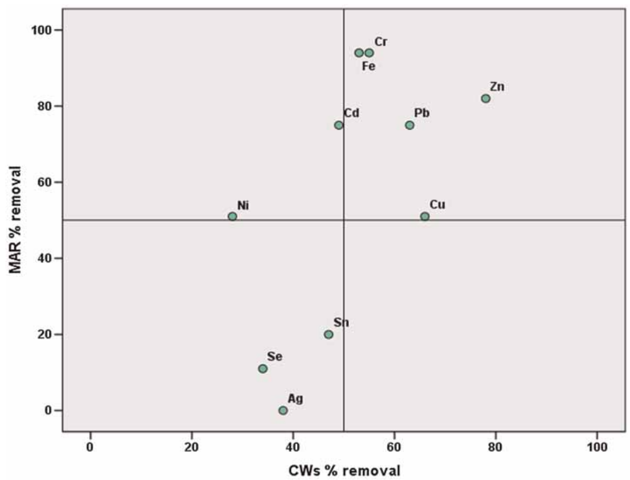

Figure 5 | Metals removal through CWs and MAR systems (*Sources*: Laszlo & Literathy 2002; Kropfelova *et al*. 2009).

Table 4 | Removal of *Giardia* and *Cryptosporidium* through CWs and MAR (*Sources*: Bosuben 2007; Kadlec & Wallace 2008)

Bacteria	CWs removal (log)	MAR removal (log)
Giardia	2	1.6
Giardia	2	1.9
Cryptosporidium	1	0.5
Cryptosporidium	1	1

to guarantee high reduction of both *Giardia* and *Cryptosporidium* as shown in Figure 6.

MAR and CW systems are very efficient in microorganism removal, as shown in Table 5. The combination will substantially reduce their risk. Generally, MAR shows better removal for all types of viruses than CWs as shown in Table 6.

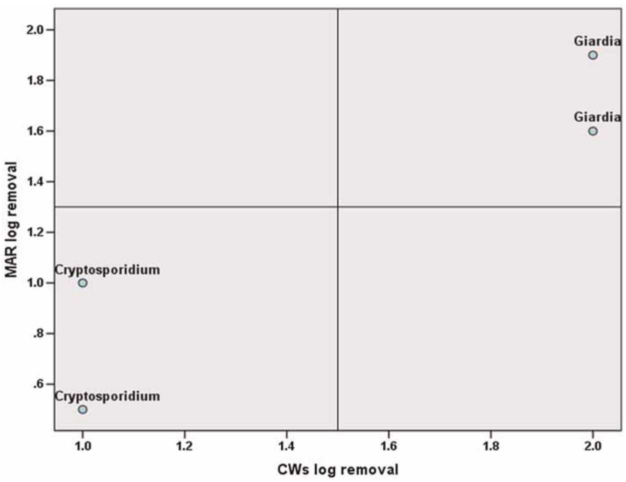

Figure 6 | *Giardia and Cryptosporidium* removal through CWs and MAR systems.

Table 5 | Bacteria removal through CWs and MAR (*Sources*: Gilbert *et al.* 1976; Laszlo & Literathy 2002; Akber *et al.* 2003; Cameron *et al.* 2003; Garcia *et al.* 2008; Kadlec & Wallace 2008; Abidi *et al.* 2009)

Bacteria	FWS CWs removal (log)	SSF CWs removal (log)	MAR removal (%)
Fecal coliform	2.5	2.6	100
Total coliform	2.74	2.48	100
Fecal streptococci	3.17	2.45	99.93
E. coli	0.20	1.45	100
Salmonellae	NA	3.84	100

Table 6 | Reduction of viruses through gravel HF CWs and MAR (*Sources*: Bosuben 2007; Harun 2008; Kadlec & Wallace 2008)

Organism	HF CWs (log)	MAR (log)
FRNA cacteriophage	3.07	6.2
Fecal streptococci	2.1	3.3
Enteroviruses	0.69	2.3
Somatic coliphages	1.3	5.3
Clostridium	2.8	4.7
Poliovirus	4.1	4.6

Synergetic effect between the two processes will enhance virus removal and reduce risks.

CWs and MAR are contrasted, as shown in Figure 7, indicating high removal for FRNA bacteriophages; however this virus can be used as an indicator of the fate of human enteroviruses as they are very similar in physical size and structure and capable of surviving in many sewage treatment processes.

FUTURE RESEARCH AND PRACTICAL APPLICATION FOR THE CW-MAR HYBRID SYSTEM

This review indicates that the hybrid CW-MAR system could be an effective multi-barrier technology and the removal efficiencies for different contaminants can be maximized in such hybrid systems. Such a hybrid can enhance the

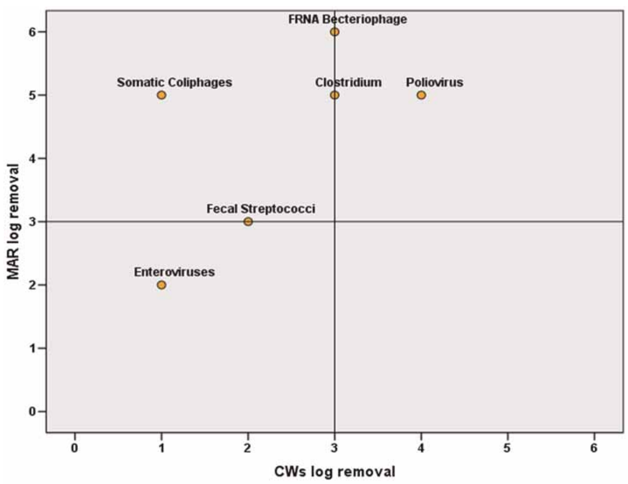

Figure 7 | Virus log removals through CWs and MAR systems.

removal efficiencies for DOC, different nutrients and guarantee high removals for bacteria and viruses. A number of metals and OMPs can be virtually completely removed while removal of some others can be improved, especially for those that are persistent.

Practical studies are required to prove the benefits of this promising technology, involving laboratory scale studies followed by field studies to analyze the mechanism of removal of different contaminants in the hybrid system under different water quality and process conditions. Specifically, the ability of such a system to remove suspended solids, bulk organic carbon, trace organic compounds, as well as bacteria and viruses, should be investigated. Besides that, economic feasibility studies should be conducted in parallel to analyze capital, operation and maintenance costs of this technology in comparison with other mechanized wastewater reclamation reuse technologies.

CONCLUSIONS

A CW-MAR hybrid system provides an effective treatment technology of reclaimed water for replenishing aquifers and subsequent reuse. This hybrid system embodies the performance advantages of both processes and exhibits very good potential for the removal of bulk organics, suspended solids, OMPs, nutrients (nitrogen and phosphorus) as well as pathogens, bacteria and viruses. Furthermore, a CW-MAR hybrid system is a cost-effective, sustainable and efficient treatment technology which can promote water reuse for different applications. It is expected that this technology can produce water of high quality, meeting the direct potable reuse requirements, help to store and increase water in the aquifer and create a reliable water resource from wastewater effluent, overcoming the psychological barrier of water reuse.

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