Nitrogen Removal and Sustainability of Vertical Flow Constructed Wetlands for Small-Scale Wastewater Treatment

Due to growing concerns about ammonium and nitrate discharges causing hypoxia, eutrophication, and contaminated drinking water, there is a need to develop sustainable technologies that also reliably remove nitrogen from wastewater. Research shows that wetlands with vertical flow regimes are effective at removing nitrogen species (ammonium and nitrate) from wastewater by nitrification-denitrification at the laboratory scale. This research focused on gaining a better understanding of the biochemical transformations occurring in the vertical flow regimes to allow designers to be more logical and economical about the use, design, and operation of constructed wetlands for wastewater treatment.

Specifically, the research focused on vertical flow constructed wetlands (VFCW) for removing ammonium and nitrate nitrogen from wastewater. Hydraulic regime and presence/absence of vegetation were the basis for a three-phase bench-scale experiment to determine oxygen transfer and nitrogen fate in VFCWs. Results showed that 90% NH_4^+-N removal was achieved in aerobic downflow columns, 60% NO_3^--N removal occurred in anaerobic upflow columns, and 60% removal of total nitrogen was achieved in downflow-upflow in-series. The oxygen transport and nitrogen fate mechanisms were explored further using a reactive transport model, HYDRUS-2D/CW-2D, which demonstrated the need to understand COD fractionation and design denitrification wetlands with that data. A life cycle assessment demonstrated the environmental improvement of VFCWs over horizontal flow constructed wetlands.

Bench-Scale Column Tests

Four vertical flow wetland columns (two vegetated, two non-vegetated) were constructed to test dissolved oxygen, ammonia, nitrate, COD, ORP, and pH of wastewater as it flowed through the soil profile in a three-phase test, 1) downflow, 2) upflow, 3) downflow-upflow in-series. Each phase lasted approximately one month, and effluent parameters reached a quasi-steady state within the first week. Influent was loaded at the rate of 3 L/m^2 for 30 seconds every 30 minutes. Flowrate, air temperature, and photosynthesis and transpiration of plants were also monitored. Downflow columns nitrified all ammonia up to 50 mg/L, maintained a nearly-saturated dissolved oxygen concentration, but removed only 40% of COD. Upflow columns were anoxic, nitrified 30-50% of ammonia, denitrified 50-60% of

Table 1. Diffusive Oxygen Transfer, Nitrification, and Denitrification Rates and Efficiency Obtained in this Study.

	Mean O_2 Transfer rate		Mean Nitrification Rate		Mean Denitrification Rate	
	g O_2/m^{2}d	*Eff.*	g NH_4^+-N/m^{2}d	*Eff.*	g NO_3^--N/m^{2}d	*Eff.*
Downflow planted	14.1	*84%*	2.9	*100%*	0.2	*5%*
Downflow unplanted	12.3	*76%*	2.8	*100%*	0.0	*1%*
Upflow planted	8.3	*45%*	1.9	*64%*	1.6	*44%*
Upflow unplanted	4.3	*25%*	1.2	*43%*	1.0	*28%*
Series planted	11.0	*57%*	2.1	*76%*	1.2	*29%*
Series unplanted	9.7	*53%*	1.8	*67%*	0.1	*2%*

BENEFITS

- Provides important information on removal technology to small-scale wastewater practitioners and constructed wetland researchers and designers on oxygen transfer and nitrogen fate mechanisms for treatment in vertical flow systems.
- Clarifies the effect of flow regime on nitrification and denitrification in vertical flow constructed wetlands.
- Shows a great potential for total nitrogen removal, and design modifications to improve nitrogen removal, in downflow and upflow wetlands in series.
- Demonstrates that vertical flow wetlands are superior to horizontal flow wetlands for reducing environmental impacts over the life cycle.

RELATED PRODUCTS

Residential and Commercial Source Control Programs to Meet Water Quality Goals (95IRM1)

Small-Scale Constructed Wetland Treatment Systems: Feasibility, Design Criteria, and O&M Requirements (01CTS5)

Improving the Efficacy of Wastewater-Polishing Reed Beds (DEC11U06)

Development of Design Criteria for Denitrifying Treatment Wetlands (DEC13U06)

AVAILABLE FORMAT

Soft cover and online PDF.

TO ORDER

Contact WERF at 571-384-2100 or visit www.werf.org and click on Search Research Publications & Tools.

WERF Subscribers: Download unlimited free PDFs at www.werf.org.

In addition to the WERF website, this report can also be downloaded from the National Decentralized Water Resources Capacity Development Project (NDWRCDP) website www.ndwrcdp.org.

Refer to: **STOCK NO. DEC12U06**

For more information, log on to **www.werf.org**.

nitrate, and produced up to 20% more COD. In-series columns removed 90% of ammonia, 50-60% of nitrate and 50-60% of total nitrogen, and removed 40% of CO, maintaining high oxygen in the downflow column and low oxygen in the upflow column. The presence of vegetation was correlated with 10% of the total nitrogen removal, although calculated nitrogen uptake based on measured photosynthetic rates did not show that uptake was the primary mechanism. The vegetation presence had a higher effect in upflow columns, possibly indicating that oxygen transfer by plant roots increased nitrification or organic matter from plant senescence contributed to available carbon for denitrification. Average removal for each phase was used to calculate diffusive oxygen transfer and nitrification and denitrification rates for columns with and without vegetation as listed in Table 1.

Variably Saturated Reactive Transport Modeling

The experimental results were studied further using a variably saturated flow and reactive transport model, HYDRUS-2D/CW-2D, which allowed a mechanistic explanation of the fate and transport of oxygen and nitrogen. Oxygen diffusion from the soil surface, due to the gradient created by carbon and nitrogen oxygen demand, was the primary oxygen transfer mechanism. Advection due to the pumping cycle contributed around 5% of oxygen in downflow columns. In upflow columns, saturation minimized oxygen diffusion, but where readily biodegradable organic matter was available, denitrification improved. All nitrification took place in the top 10 cm of the 65 cm downflow column, indicating that the downflow wetland depth could potentially be reduced. Upflow wetlands could be designed to take advantage of readily and slowly biodegradable carbon for denitrification (longer retention and/or recycle line to use influent COD).

Life Cycle Assessment Demonstrates Superiority of VFCW

A VFCW was then compared to a horizontal flow constructed wetland (HFCW) for life cycle environmental impacts, using Simapro 7.0 life cycle assessment software. High areal emissions of greenhouse gases from VFCWs compared to HFCWs are the driver for the study. The assessment showed that because a VFCW is only 25% of the volume of an HFCW designed for the same treatment quality, the VFCW has only 25-30% of HFCW impacts over 12 impact categories and three damage categories. Results showed that impacts could be reduced by design improvements.

Design Suggestions

Design suggestions are to use downflow wetlands for nitrification, upflow wetlands for denitrification, downflow-upflow series wetlands for total nitrogen removal, hydraulic load of 142 L/m^2d, 30 cm downflow wetland depth, 1.0 m upflow wetland depth, recycle, vegetation, and medium-grained sand. These improvements should optimize nitrogen removal, minimize gaseous emissions, and reduce wetland material requirements, thus reducing environmental impact without sacrificing wastewater treatment quality. The material and corresponding transportation and construction reductions will also save on capital expenses.

CONTRACTOR

John S. Gierke, Ph.D., P.E.
Michigan Technological University

RESEARCH TEAM

Valerie Fuchs, Ph.D.
Ashlee Vincent, M.S. Candidate
Noah Mirovsky, M.S. Candidate
Michigan Technological University

PROJECT SUBCOMMITTEE

A. Robert Rubin, Ed.D.
North Carolina State University, McKim and Creed

Ronald W. Crites, P.E.
Brown and Caldwell

The research on which this report is based was funded in part by the U.S. Environmental Protection Agency (U.S. EPA) through Cooperative Agreement No. X-830851-01 with the Water Environment Research Foundation (WERF). Unless an U.S. EPA logo appears on the cover, this report is a publication of WERF, not U.S. EPA. Funds awarded under the agreement cited above were not used for editorial services, reproduction, printing, or distribution.