Low-Energy Nitrogen Removal in Intensified Wetlands

Jamie L. Hughes[1]*, Kenneth J. Williamson[1], David Austin[2]

[1] Clean Water Services, Hillsboro, Oregon.
[2] CH2M, Mendota Heights, Minnesota.
[*] Email: HughesJ@cleanwaterservices.org.

ABSTRACT

Clean Water Services is implementing a natural treatment system in Forest Grove, Oregon. The large wetland complex (~400,000 m^2) will provide tertiary treatment of effluent from the Hillsboro and Forest Grove wastewater treatment facilities and will include a vertical-flow wetland (VFW) for nitrogen removal. A pilot system was operated to determine the media selection and optimum design parameters for the VFW. The pilot system consisted of four columns, operated in two series; each column was filled with rock in gradations to provide drainage, treatment, and plant growth. Operating variables included two rock types, with adsorption capacities >40 g/m^3, two operational flow conditions, vertical-flow and flood-and-drain flow, and hydraulic loading rates (HLRs) ranging from 1 to 16 m/d. Results showed high rates of nitrification were achieved with >84% ammonia removal at HLRs ≤8 m/d under both operating conditions. Energy requirements and maintenance costs are to be reviewed.

KEYWORDS: Natural treatment system, vertical-flow wetlands, intensified wetlands, nitrification, nitrogen removal.

INTRODUCTION

Engineered wetlands are constructed treatment systems that are designed to remove pollutants from contaminated water and are often used for secondary or tertiary treatment. Conventional wetland treatment technologies are typically focused around passive horizontal flow designs divided into three types: surface flow, subsurface horizontal-flow, and subsurface vertical-flow. Surface flow wetlands are limited by low oxygen transfer rates resulting in large wetland footprints (i.e., ~27 d/m [25 ac/mgd] for nitrification) and subsurface flow wetlands are not suitable for aerobic biological treatment of either BOD or ammonia without additional aeration (US EPA, 2000). To increase oxygen transfer, intensified vertical-flow wetland (VFW) technologies have been developed that involve pulsed flow over rock beds.

The development of VFW technology has evolved in large part to promote wastewater nitrification (Austin and Nivala, 2009). VFWs can be designed with different hydraulic flow conditions including pulsed flow and pulsed flood-and-drain flow. The earliest known treatment wetland design envisioned both vertical flow and flood-and-drain hydraulics (Monjeau, 1901), clearly based on late 19th Century advances in contact bed and trickling filter wastewater treatment technology (Kinnicut et. al., 1919). Vertical-flow treatment wetlands may also include a reactive bed media that is designed to supply organic carbon (Kassenga et. al., 2003), absorb phosphorus (Johansson, 1997; Drizo et. al., 1997; Arias and Brix, 2004), or provide a specified cation exchange capacity (Johns et. al., 1998; Gisvold et. al., 2000). Flood-and-drain systems are termed tidal flow systems when several flood and drain cycles occur daily (Sun et. al., 1999). Tidal flow treatment wetlands are currently in use at the Village of Minoa, New York (US EPA, 2000), and at the Tennessee Valley Authority's reciprocating flow (Recip®) wetlands (Behrends, 1999). Presently, installed intensified wetlands for nitrification have successfully operated with footprints ranging from 17 to 170 d/m (16 to 160 ac/mgd) based on oxygen transfer rates of 0.5 to 5 g/m^2-d (Kadlec and Wallace, 2009).

Clean Water Services, a special service wastewater utility district in Washington County, Oregon, is implementing a natural treatment system (NTS) at Fernhill Wetlands adjacent to their Forest Grove Wastewater Treatment Facility (WWTF) in Forest Grove, Oregon. The wetlands complex, which is over 400,000 m^2 (100 acres), will provide tertiary treatment of secondary treated wastewater effluent from both the Hillsboro and Forest Grove WWTFs. The NTS will include waterfalls, a small lake, and several ponds for temperature reduction and habitat enhancement as well as emergent wetlands for nitrogen removal via nitrification and denitrification. An intensified VFW will be implemented in the NTS to promote nitrification with the potential for significantly lower energy and maintenance cost requirements.

A pilot system was built at the Forest Grove WWTF in order to optimize specific design parameters for the full-scale VFW design including media type and operational flow conditions. The proposed technology for the full-scale NTS will use a 2-m deep VFW filled with 0.63-cm to 1.27-cm (¼-inch to ½-inch) rock. Oxygen will be provided to the pilot system by dosing treated wastewater effluent over the rock bed at hydraulic loading rates (HLRs) ranging from 1 to 16 m/d (based on total bed volume). Effluent from the VFW pilot system will be denitrified in a subsequent subsurface horizontal flow wetland to remove any residual nitrate. The desired effluent inorganic nitrogen concentrations are less than 1 mg NH_3-N/L and 2 mg NO_3-N/L.

METHODOLOGY

The purpose of the pilot system research was to determine the optimal design parameters for a low-cost, low-maintenance intensified VFW for nitrification that can be implemented in the full-scale NTS design. The VFW pilot system was comprised of two sets of two columns operated in series. Each of the 0.8-m (32-inch) diameter columns contained 1 m of treatment rock (0.63 cm to 1.27 cm [¼ inch to ½ inch] diameter), 15.2 cm (6 inch) of cobble (3.81 cm to 10.1 cm [1.5 inch to 4 inch]) on the bottom of the column to provide rapid drainage, and 15.2 cm (6 inch) of fine rock (0.15 cm [1/16 inch] minus) on top of the treatment rock to facilitate plant growth and enhance flow distribution. Two types of treatment rock were tested: a smooth round river rock (Knife River, Corvallis, Oregon) and an angular crushed basalt (Eckman Creek Quarries, Waldport, Oregon), both with an ammonia adsorption capacity exceeding 40 g/m^3 (62 g/m^3 and 43 g/m^3, respectfully).

The pilot system was operated under two different operational conditions to determine the optimal oxygen transfer rates and variable redox conditions in the wetland: vertical-flow and flood-and-drain flow (Figure 1). With vertical-flow, the pilot system is intermittently dosed with a prescribed volume of water that then flows vertically as a sheet through the media, similar to a trickling filter. In this mode, the operational parameters include the dosage volume and the HLR which define the time between dosages. In flood-and-drain flow, the pilot system is also intermittently dosed, but fills incrementally from the bottom to the top and once full (the media completely submerged), the entire column is drained rapidly. In this mode, the flooded portion of the media acts as a batch reactor that increases in volume with each dose and has no oxygen replenishment until the entire column is drained at the end of each fill cycle.

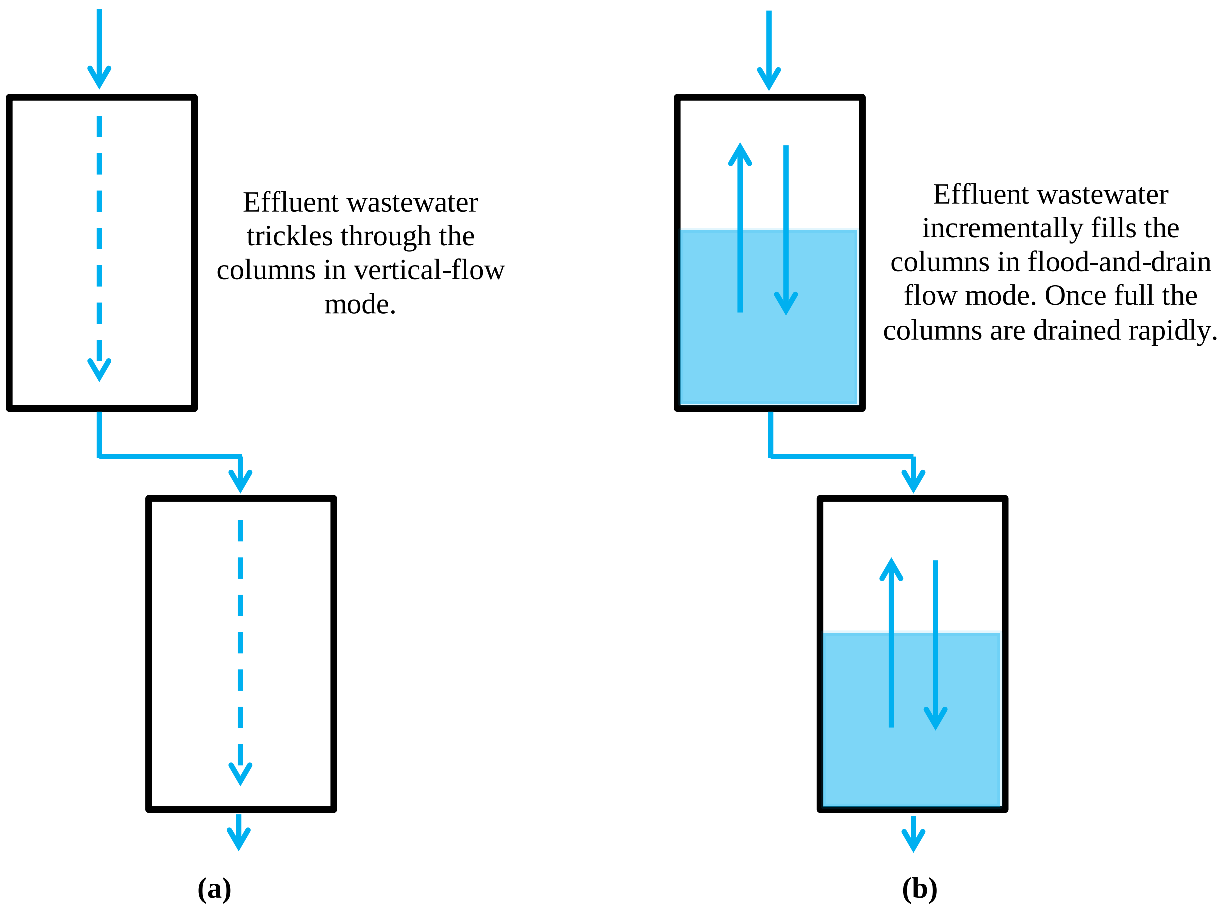

Figure 1. Operational modes (a) vertical-flow and (b) flood-and-drain flow used for the VFW pilot system.

The VFW pilot system is shown in Figures 2 and 3. Columns 1 and 3 contained the smooth round river rock and columns 2 and 4 contained the crushed angular basalt. Secondary wastewater effluent from the Forest Grove WWTF was discharged through a constant head tank into two dosing siphon boxes (Rissy Plastics, LLC, Torrington, Connecticut) at designated HLRs ranging from 1 to 16 m/d. In the dosing siphon boxes, the secondary wastewater effluent was supplemented with approximately 20 mg NH_3-N/L and 120 mg/L of alkalinity ($NaHCO_3$). The dosing siphons flooded approximately 10 L of water onto Columns 1 and 2 to provide a 5 cm deep dose at intervals dependent upon the HLR (interval was equal to 0.05/HLR in days).

When operated in vertical-flow, the wastewater effluent was intermittently dosed onto the columns and allowed to flow directly through the columns as a sheet into the reservoir totes. When operated in flood-and-drain flow, the bottom drain on each column was closed so that each dose filled the columns in 5 cm deep increments. Once the media was fully submerged, a pressure switch activated an airlift pump to rapidly drain the water from the columns into reservoir totes.

From the reservoir totes, the wastewater effluent flowed into another set of dosing siphon boxes where it was dosed at the same intervals onto columns 3 and 4. Columns 3 and 4 were operated in vertical-flow and flood-and-drain flow in the same manner as described previously. From Columns 3 and 4, the water drained into another set of reservoir totes, and from there was discharged to the drain.

To simulate the full-scale NTS wetland design, commonly used wetland plants including rushes, sedges and willows, were planted on top of each column to provide additional flow distribution and nutrient removal. Fluorescent grow lights installed above each column provided the plants with light for 14 hours every day.

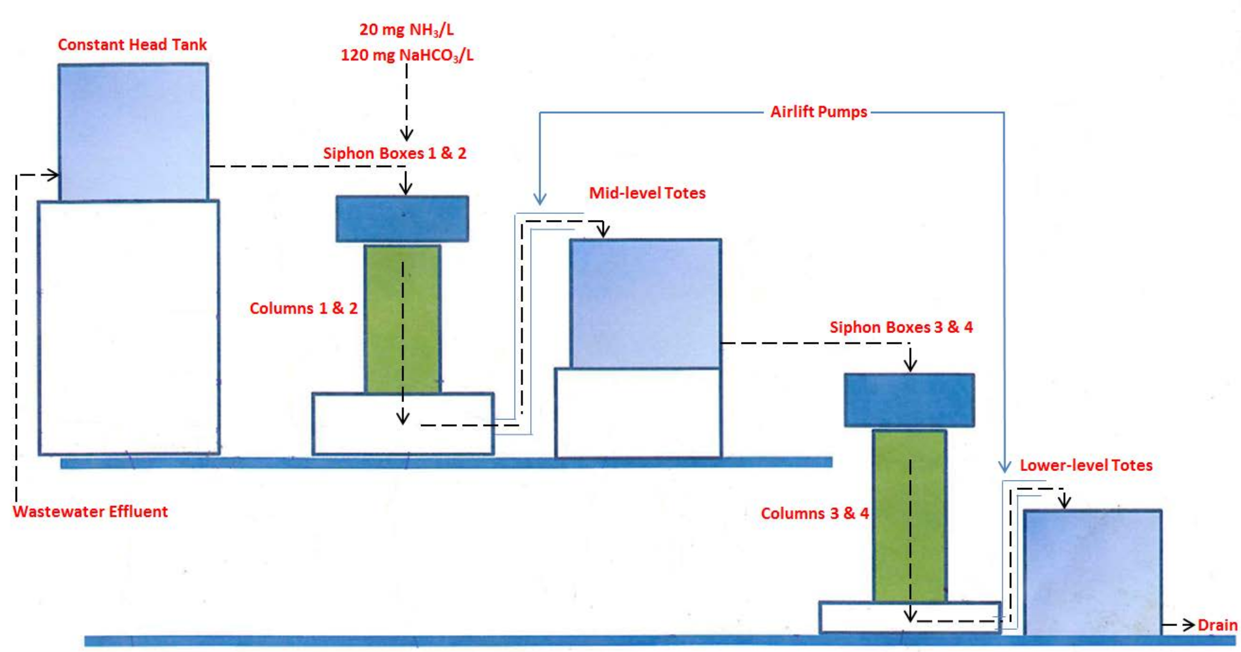

Figure 2. Profile view of the set-up for the VFW pilot system.

Figure 3. VFW pilot system set-up: (1) Constant head tank: supplies secondary wastewater effluent to the dosing siphon boxes 1 & 2, (2) Dosing siphon boxes 1 & 2: dose columns 1 & 2 with ~10 L of wastewater effluent, (3) Columns 1 & 2: the dosed wastewater effluent travels through the two columns that each contain different types of media in various layers, (4) Mid-level reservoir totes: collect and store water drained from columns 1 & 2, (5) Dosing siphon boxes 3 & 4: dose columns 3 & 4 with ~10 L of wastewater effluent, (6) Columns 3 & 4: the dosed wastewater effluent travels through the two columns that each contain different types of media in various layers, (7) Lower-level reservoir totes: collect and store water drained from columns 3 & 4, (8) Wetland plants: a variety of wetland plants grow in the columns providing additional flow distribution and nutrient removal, (9) Grow lights: fluorescent grow lights provide 14 hours of light for the wetland plants daily.

The pilot system was run in both vertical-flow and flood-and-drain flow condition under each HLR for a minimum of two weeks. All four columns were sampled a minimum of twice per week for ammonia, nitrite, and nitrate at the influent and effluent of each column. Ammonia samples were analyzed using an Astoria Analyzer® segmented flow auto analyzer equipped with an ammonia cartridge and following Standard Method 4500-NH3 G. Nitrate and nitrite samples were analyzed using a Dionex ICS-2100® ion chromatography system and following EPA Method 300.0. Target effluent concentrations of ammonia were less than 1 mg NH_3-N/L.

RESULTS

The VFW pilot system was operated to determine rates of nitrification using secondary wastewater effluent supplemented with ammonia at HLRs ranging from 1 to 16 m/d under both vertical-flow and flood-and-drain flow operating conditions. Samples were taken from the influent and effluent of each column. Average concentrations of ammonia in the influent to Columns 1 and 2 and in the effluent from Columns 3 and 4 as well as average percent removal were determined for HLRs of 1 to 16 m/d under both vertical-flow and flood-and-drain flow operational modes (Table 1). It is important to note that although the target influent ammonia concentration was 20 mg NH_3-N/L, inconsistencies in chemical measurement and dosing led to a somewhat variable influent concentration; however, average percent removal values were normalized to the influent ammonia concentration to provide comparable results.

Table 1. Average ammonia concentrations in the influent and effluent and average percent removal for the VFW pilot system when operated in vertical-flow and flood-and-drain flow modes at HRLs of 1 to 16 m/d.

		Flood-and-Drain Flow			Vertical-Flow		
		Average NH_3-N Concentration (mg/L)					
HLR (m/d)	**Media Type**	**Influent**	**Effluent**	**% Removal**	**Influent**	**Effluent**	**% Removal**
1	Crushed Basalt	16.9 ± 4.4	0.3 ± 0.3	98	16.2 ± 2.3	0.1 ± 0.0	99
	Smooth River Run	13.7 ± 1.2	0.8 ± 0.5	94	16.2 ± 0.9	1.1 ± 1.4	93
2	Crushed Basalt	23.7 ± 7.7	0.1 ± 0.0	100	24.7 ± 1.6	0.5 ± 0.7	98
	Smooth River Run	25.5 ± 8.0	0.2 ± 0.3	99	25.6 ± 6.9	3.5 ± 4.6	86
4	Crushed Basalt	23.1 ± 9.1	0.6 ± 0.8	97	18.8 ± 1.3	0.2 ± 0.1	99
	Smooth River Run	24.3 ± 5.8	3.0 ± 1.5	88	17.7 ± 0.5	0.2 ± 0.1	99
8	Crushed Basalt	20.2 ± 4.7	0.3 ± 0.2	98	18.4 ± 0.3	0.6 ± 0.7	97
	Smooth River Run	19.4 ± 0.6	0.5 ± 0.5	97	18.6 ± 0.1	3.0 ± 1.0	84
16	Crushed Basalt	19.4 ± 0.6	3.8 ± 0.3	80	21.1 ± 4.2	4.5 ± 1.9	79
	Smooth River Run	18.2 ± 0.1	4.7 ± 0.7	74	19.3 ± 0.8	4.8 ± 0.2	75

Pilot test results showed high nitrification rates for both rock types at all HLRs tested under both operational flow conditions ranging from 6 g/m^3-d to 125 g/m^3-d. At HLRs ≤ 8 m/d, pilot test results showed excellent operational characteristics with greater than 84% nitrification under both vertical-flow and flood-and-drain flow operational modes for both rock types. Several runs resulted in almost complete nitrification, with 97% or greater ammonia removal. At a HLR of 16 m/d, ammonia removal efficiencies under both operational flow conditions decreased slightly, with ammonia removal at ≤ 80% for both rock types. Effluent ammonia concentrations were often much less than the target value of 1 mg NH_3-N/L and several runs resulted in effluent concentrations ≤ 0.5 mg NH_3-N/L.

DISCUSSION

Minimal differences in ammonia removal efficiencies were observed when the pilot system was operated under vertical-flow and flood-and-drain flow conditions at the HLRs tested. This suggests that perhaps nitrification efficiency is not enhanced by the cyclic flooding and periodic oxygen replenishment that occurs during the flood-and-drain flow operating condition. Rather, the pulsed dosing of the wastewater effluent over the rock bed that occurs during both operational conditions may play an important role in the high ammonia removal rates observed. Further pilot testing is needed to more accurately compare the vertical-flow and flood-and-drain flow operating conditions.

Comparable ammonia removal efficiencies for the two rock types were also observed at the HLRs tested under both operational flow conditions. This suggests that bacterial growth and the resulting nitrification rates were not significantly affected by the different physical surface characteristics and ammonium exchange capacities of the smooth round river rock and the crushed angular basalt rock.

The uniqueness of this biofilm treatment process is the use of rock media with high ammonia adsorption capacity (> 40 g/m^3). The nitrification process is complex in a flood-and-drain VFW with a highly adsorptive rock bed. The dosing of the wastewater effluent onto the wetland results in a rapid flow of water through the wetland, where ammonia ions (NH_4^+) will diffuse from the water, through the biofilm and adsorb on to the rock surface. During the subsequent longer no-flow, drain period, air in the rock voids will be in contact with the biofilm. Ammonia will diffuse from the rock surface and oxygen will diffuse from the air-filled voids into the biofilm with subsequent nitrification. The frequent flood-and-drain cycling provides a continual supply of ammonia to the VFW as well as promotes the diffusion of oxygen into the biofilm (Austin et. al., 2003).

Overall, the pilot test results indicated that a HLR of 8 m/d or less should be used in the design of the full-scale VFW to achieve high ammonia removal. The results also showed that nearly complete nitrification can be achieved at loading rates ranging from 6.0 to 75 g N/m^3-d. The minimal differences in ammonia removal efficiencies observed between operating flow conditions and between rock types suggest that the use of either operational flow mode and the inclusion of either rock type would yield high rates of nitrification in the full-scale VFW design.

Using the resulting nitrification rates from the pilot research, a design flowrate of 6 mgd, and a media depth of 1.83 m (6 feet) for the NTS, design footprints for the full-scale VFW were determined to be less than 0.1 d/m (0.1 ac/mgd). This is smaller than presently installed intensified wetlands for nitrification which range from 17 to 170 d/m (16 to 160 ac/mgd) based on oxygen transfer rates of 0.5 to 5 g/m^2-d (Kadlec and Wallace, 2009).

The results of this research showed that VFWs that contain media with a high ammonium exchange capacity are highly effective for nitrification. However, energy and maintenance cost requirements must also be factored into the full-scale wetland design. The energy requirements for nitrification and biological nitrogen removal in a flood-and-drain or pulsed flow wetland system have been reported to be significantly lower than those of other engineered wetland systems. For flows of approximately 1000 m^3/d, a pulsed flow wetland and a flood-and-drain wetland system have energy requirements of 0.07 and 0.21 kW-hr per m^3/d of flow, respectively; compared to 0.88 kW-hr per m^3/d of flow for a Modified Ludzack-Ettinger activated sludge process. (Austin and Nivala, 2009) (Table 2).

Table 2. Austin D, Nivala J. 2009. Energy requirements for nitrification and biological nitrogen removal in engineered wetlands, comparisons are for 1000 m^3/d of domestic effluent. Ecol. Eng. 35(2):184-192.

Treatment Type	Energy Requirement (kW-hr per m^3/d of flow)
Activated Sludge	0.88
Aerated Wetland	0.49
Flood-and-Drain System	0.21
Pulsed Flow System	0.07

The substantial difference in energy requirements could have significant advantages for small- to medium-sized WWTFs. In addition, the operation and maintenance of a constructed wetland system is relatively simple, requires minimal maintenance, and typically comprises less than 10% of the total operations and maintenance costs of a conventional WWTF (US EPA, 2000). It is important to note that site conditions, design constraints, and effluent nitrogen concentration requirements will also substantially affect the overall energy requirements for a given treatment system and should be taken into account when determining the final wetland design (Austin and Nivala, 2009).

CONCLUSIONS

High rates of nitrification were achieved (6.0 to 125 g/m^3-d) with HLRs ranging from 1 to 16 m/d in a VFW pilot system when operated under both flood-and-drain flow and pulsed vertical-flow conditions. It is recommended that the full-scale VFW be designed at a HLR $\leq$ 8 m/d, as greater than 84% nitrification was achieved at these loading rates. Resulting design footprints for the full-scale VFW design were less than 0.1 d/m (0.1 ac/mgd), which is much less than presently installed intensified treatment wetlands for nitrification. Intensified VFWs should be both cost effective and energy efficient when compared to alternative wetland treatment technologies. This could have significant impacts for small- to medium-sized WWTFs.

Additional pilot testing is currently underway to determine the ability of a pulsed VFW system to perform anaerobic ammonia oxidation using a complete autotrophic nitrogen-removal over nitrite (CANON) process. The CANON process would have the advantage of being a single-stage, attached growth process that can operate at low temperatures and remove a significant portion of the ammonia as nitrogen gas without organic substrate addition (Third et. al., 2002). Under conditions of high ammonia loading (> 0.12 kg NH_4-N/m^3-d) and large oxygen gradients, Anammox bacteria can out-compete nitrite oxidizing bacteria in a CANON reactor. Due to varying dissolved oxygen concentrations in the VFW pilot system, the redox conditions will vary throughout the biofilm depth and throughout the depth of each column, potentially producing biofilm zones that will promote all three of the CANON processes of ammonia to nitrite, nitrite to nitrate, and ammonia/nitrite to nitrogen gas (Schmidt et. al., 2003). Depending on the HLR and the dosing/draining protocol of the full-scale NTS, the VFW will be used for either single-stage nitrification or single-stage CANON ammonia oxidation/nitrite reduction.

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