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Waterloo Dentrification Barrier: Longer term  
performance of pilot scale field trials

By:

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Abstract: None

Management Perspective: Nitrate is usually the principal nutrient present in septic-system groundwater plumes. In aerobic aquifers, nitrate can migrate long distances from tile beds and can lead to degradation of drinking water supplies. The Waterloo denitrification barrier is an alternative treatment system for removing nitrate from flowing groundwater. An organic-carbon rich zone is installed in the path of the migrating groundwater to promote denitrification reactions and nitrate removal. Partial to nearly complete removal of nitrate from flowing groundwater is demonstrated at a number of field sites.

## **WATERLOO DENITRIFICATION BARRIER; LONGER TERM PERFORMANCE OF PILOT SCALE FIELD TRIALS**

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### **INTRODUCTION**

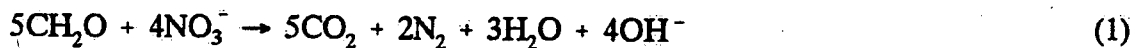
Nitrate generated by oxidation of septic-system effluent can occur in septic-system plumes at concentrations several times higher than the common drinking water limit of 10 mg/l as N (Walker et al., 1973; Robertson et al., 1991; Harman, 1992). In the groundwater zone,  $\text{NO}_3^-$  is mobile and can be unaffected by biodegradation reactions in plume zones that remain aerobic (Robertson et al., 1991). In addition, tracer tests have now demonstrated that hydrodynamic dispersion in most sand aquifers is much less than previously thought (Sudicky et al., 1983; Freyberg, 1986; Moltyaner and Killey, 1988a, b; Garabedian and LeBlanc, 1991). Thus, dilution models commonly used to attenuate  $\text{NO}_3^-$  from septic systems are probably physically unrealistic. This has been confirmed by several very detailed field studies in which above-the-drinking-water-limit  $\text{NO}_3^-$  plumes have been found to extend more than 100 m from even smaller septic systems (Robertson et al., 1991; Harman, 1992). As a result, in some jurisdictions such as the Province of Ontario,  $\text{NO}_3^-$  has become the septic-system contaminant of concern with regard to degradation of drinking water supplies.

To address the  $\text{NO}_3^-$  problem, several alternative septic system designs for enhanced N attenuation have been investigated in recent years. The "peat" system (Brooks et al., 1984) utilizes a layer of sphagnum peat moss placed below the weeping tile bed to provide an environment for N attenuation by assimilation into fungal biomass. The "Ruuk" system (Laak, 1981) utilizes dedicated household plumbing to selectively collect toilet effluent (black water) which is nitrified and then mixed with household gray water which provides an additional organic carbon source for denitrification. A somewhat similar system is the recirculating sand filter (e.g., Piluk and Hao, 1989) in which effluent is nitrified in a sand filter and then a portion is returned to the anaerobic septic tank where carbon is available for denitrification. The latter two systems provide only partial  $\text{NO}_3^-$  attenuation, however (generally 40 - 90%), unless an additional carbon source such as liquid methanol is continually dosed to the final treated effluent (e.g., Sikora and Keeney, 1976; Sikora et al., 1977; Andreoli et al., 1979). An overview of existing technologies for on-site nitrogen removal is provided by Whitmyer et al. (1985).

Although alternative systems such as these have been available for more than 10 years, none has achieved widespread usage in North America. Apparently this is because, until recently, the evidence for the occurrence of large-scale contaminant plumes from septic systems was not well-documented, with the result that regulators did not discourage the use of conventional septic systems. Thus, there has been little incentive to use the more expensive

alternative designs and to accumulate the field performance data necessary to allow accurate assessment of their effectiveness.

Although  $\text{NO}_3^-$  is mobile and persistent in aerobic groundwater environments, it has long been known that  $\text{NO}_3^-$  can be attenuated in anaerobic groundwater zones when a labile carbon source is available (Trudell et al., 1986; Starr and Gillham, 1989). Attenuation is presumed to occur by heterotrophic denitrification (i.e., Delwiche, 1981):



whereby  $\text{NO}_3^-$  is biodegraded to  $\text{N}_2$  gas. Attenuation of agriculturally derived  $\text{NO}_3^-$  in riparian groundwater zones has been attributed to denitrification resulting from increased availability of labile organic carbon in organic matter enriched sediments (Schipper et al., 1990). Likewise, Robertson et al. (1991) and Robertson and Cherry (1992) report abrupt and complete attenuation of septic-system  $\text{NO}_3^-$  in two aquifer zones where content of solid phase organic carbon in the sediments is enriched.

This abstract discusses the operating performance of a new alternative septic system design referred to as the Waterloo Denitrification Barrier, which attempts to mimic the environments of denitrification commonly observed in the field. This is done by using nitrate-reactive porous barriers augmented with solid organic carbon material capable of promoting denitrification. The barrier can be constructed as a layer installed in the subsurface below a conventional septic system or as a vertical wall intercepting a horizontally-flowing nitrate plume. Figure 1 shows examples of Waterloo Denitrification Barriers installed as a layer (Killarney site) and as a vertical wall positioned several meters downgradient from a septic system tile field (Long Point site). Advantages of the Waterloo Barrier for mitigating nitrate contamination are that attenuation occurs in-situ and the reaction is passive so that ideally no further maintenance or energy use is required after installation. However, the denitrification reaction (reaction 1) results in consumption of the carbon energy source thus replacement of the carbon material will eventually be required. For the in-situ application suggested here, replacement of the carbon material would require subsurface excavation and is thus likely to be costly, thus in many cases such barriers would be considered practical only if they are capable of operation for long periods without replenishment. The reactivity and longevity of the carbon material is thus crucial to this technology. To identify a suitable carbon source, one that is sufficiently labile to enable relatively rapid denitrification but is sufficiently insoluble to persist for many years in the subsurface, a number of laboratory and field trials have been undertaken utilizing materials such as cellulose, wheat straw, alfalfa, ryeseed, leaf compost and sawdust (Vogan, 1993; Carmichael, 1994; Robertson and Cherry, 1995). Although several of these materials appear promising, sawdust behavior was particularly of interest because it is readily available and is easily incorporated into porous media mixtures.

The following describes the performance of four Waterloo Denitrification Barriers that have been operating for periods of two to three years and which utilize sawdust. These include the Killarney and Long Point barriers shown in Figure 1, a second barrier layer installed below a conventional septic system (Borden site) and a barrier/reactor installed in a container

and treating nitrate from farm field runoff (North Campus Box). The latter installation is included for discussion here because the reaction chemistry is similar to that for septic systems and a relatively large number of pore volumes have currently passed through this reactor. Also, operation at low temperature has been documented in the latter case.

## SYSTEM DESCRIPTIONS

The Killarney and Borden barriers are 0.5 m thick layers placed in excavations below conventional septic system infiltration beds. They are separated from the infiltration pipes by an overlying 0.3 m thick layer of sand within which the effluent is oxidized prior to percolating downward into the denitrification barrier. Both are pilot scale field installations; the Killarney barrier is 2 m<sup>2</sup> in surface area and is dosed manually from an adjacent seasonal-use septic tank, while the Borden barrier is 20 m<sup>2</sup> in surface area and receives effluent from a seasonal use trailer camp wash-house. The Long Point barrier is a vertical wall that extends 0.8 m below the water table and intercepts part of a horizontally flowing nitrate plume emanating from the septic system infiltration bed at Long Point Provincial Park. All three barriers contain mixtures of sediment and sawdust and are described in more detail by Robertson and Cherry (1995).

The North Campus reactor is a 2 m<sup>3</sup> plywood container filled with wood chips and receives effluent from a farm field drainage tile. The effluent has moderate nitrate contamination (~4 mg/l NO<sub>3</sub> - N) as a result of fertilizer use on the field. A more detailed description of this type of reactor for treatment of redox-sensitive contaminants in farm field runoff is presented by Blowes et al. (1994).

## LONG TERM PERFORMANCE

Figures 2 and 3 show the degree of nitrogen removal in the four denitrification barriers during two to three years of operation. The amount of nitrate attenuation observed varies from about 3 mg/l as N (North Campus Box) to about 120 mg/l as N (Killarney layer) depending on factors such as temperature, carbon reactivity and porewater residence time within the barriers. The latter parameter appears particularly important with the greatest degree of nitrate removal observed in the location with greatest porewater residence time (Killarney site, 35 days) and the lowest removal observed at the site with shortest residence time (North Campus, 1 day; Figures 2 and 3). Figure 4 shows that even at temperatures as low as 3 °C the North Campus Box was successful at some nitrate removal (~ 1 mg/l as N) and that the removal rate improved substantially at temperatures above 5 °C.

In general, Figures 2 and 3 demonstrate that after an initial startup period of several months, the rate of denitrification has remained relatively constant at each of the sites even in the second and third years of operation. This suggests that a substantial amount of the solid carbon material in the sawdust is relatively insoluble, yet is sufficiently labile to promote denitrification. It is thus likely to be available as a long term source of carbon for denitrification, provided that the carbon mass is not entirely consumed.

## CARBON CONSUMPTION RATE

It is of interest to compare the estimated amount of carbon mass that has been consumed so far in these barriers to that of the initial carbon mass emplaced. Three reactions are likely to account for most of the carbon consumption in these barriers: 1) denitrification (reaction 1), 2) reduction of dissolved oxygen, and 3) leaching of soluble carbon compounds. The later reaction is reflected in the amount of dissolved organic carbon (DOC) present in the porewater exiting the barriers. Figure 5 shows that DOC levels were initially greatly elevated (100 - 325 mg/l) in porewater exiting each of the barriers during the first several months of operation, but that DOC leaching then declined to an equilibrium value (3 - 50 mg/l) closely correlated to the porewater residency within the barriers. The initial DOC spike is presumed to represent leaching of sugars and soluble hydrocarbon compounds that commonly comprise 10 - 30 % of plant matter (Vogan, 1993) while the longer term DOC is derived from the more slowly soluble wood compounds such as cellulose and semi-cellulose which commonly comprise more than 50% of the total wood mass (Vogan, 1993).

In the following section the amount of carbon mass lost from North Campus Box is estimated in detail. Although nitrate levels are relatively low at this site ( $\sim 4$  mg/l), flow rates have been measured precisely and a relatively large number of pore volumes have been passed through the reactor during its two years of operation. The  $2 \text{ m}^3$  reactor has been loaded intermittently at an average rate of about 1 l/min, providing a porewater residency of approximately one day in the reactor. A total of  $6.6 \times 10^5$  litres of farm field drainage water have passed through the reactor representing 688 pore volumes. The initial mass of wood chips contained in the reactor was estimated at be 475 kg (dry). This represents about 190 kg of carbon or  $1.6 \times 10^4$  moles of carbon. Assuming that water entering the reactor averages  $10^\circ \text{C}$  and is at saturation with dissolved  $\text{O}_2$  (11 mg/l) and that all dissolved oxygen is consumed in the reactor, dissolved oxygen attenuation will be 0.35 mmoles/l or a total of 225 moles. This reaction will consume 225 moles of carbon or 1.4% of the initial carbon mass. Nitrate attenuation averages about 3 mg/l as N in the reactor (Figure 3) or 0.21 mmoles/l. Total nitrate attenuation is thus  $14^\circ$  moles which represents carbon consumption of 175 moles (reaction 1) or 1.1% of the initial carbon mass. After the first several months of operation, DOC levels in porewater discharging from the reactor averaged about 4 mg/l compared to 3 mg/l in the influent water. This represents DOC leaching of only about 1 mg/l or 0.083 mmoles/l which equates to a total of 55 moles of carbon leached or 0.3% of the initial amount. This calculation suggests that during the first two years of operation less than 5 % of the initial carbon mass has been consumed. Thus the reactor has the potential to last for a decade or longer without replenishment of the carbon material.

## CONCLUSIONS

Several years of field operation of four pilot scale denitrification barriers has demonstrated that a degree of nitrate attenuation can be achieved proportional to the porewater residence time in the barriers. It is likely that for most in-situ applications in southern Canada, temperatures sufficient for adequate operation ( $>5^\circ \text{C}$ ) could be maintained even during winter operation. In each case, the development after several months operation, of near-

steady rates of denitrification, is suggestive of the potential for very long periods of operation without replenishment of the carbon source. Results suggest that such barriers may be useful in septic system design in areas where there is a desire to mitigate nitrate levels but, where resources are not available to allow construction, maintenance and monitoring of more mechanically complex treatment systems.

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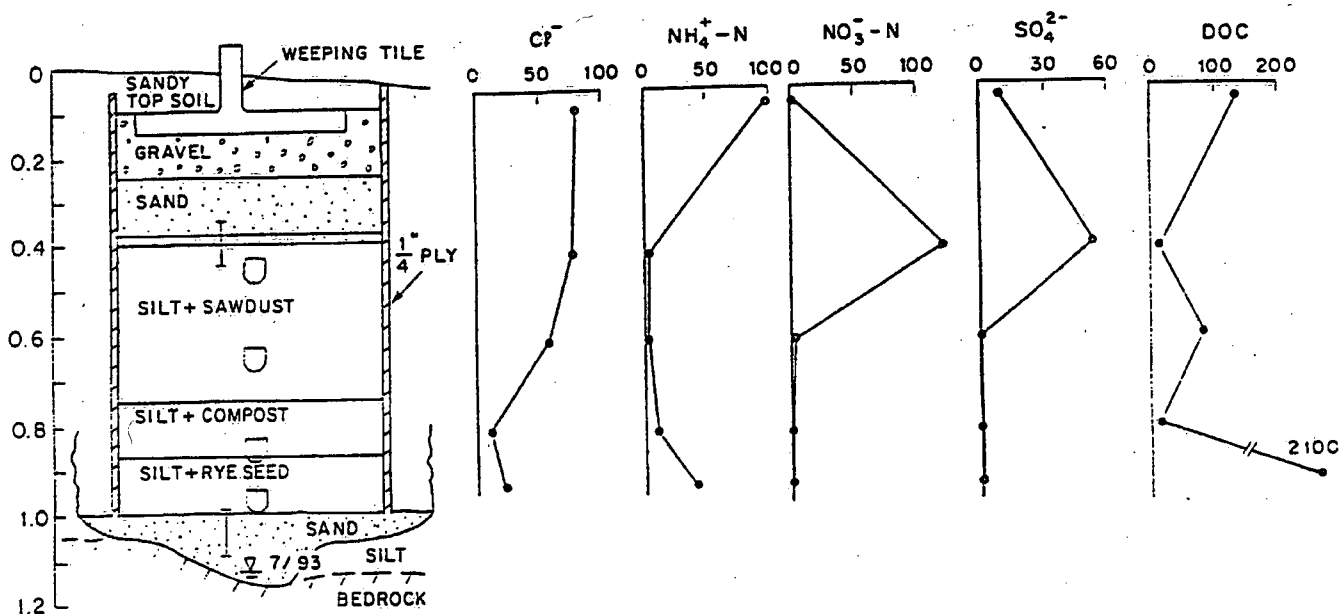
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## FIGURE LIST

- Figure 1: Waterloo Denitrification Barrier constructed as: a) a layer below a conventional septic system infiltration bed (Killarney site) and b) a vertical wall intercepting a horizontally flowing nitrate plume (Long Point site) (from Robertson and Cherry, 1995).
- Figure 2: Trends of barrier inflow and outflow nitrogen levels during two to three years of operation: a) Killarney layer, b) Borden layer and c) Long Point wall.
- Figure 3: Performance of North Campus barrier/reactor during two years of operation: a) cumulative pore volumes, b) flow rate, c) porewater temperature and d) nitrate levels.
- Figure 4: North campus reactor; temperature versus nitrate removal during second year of operation.
- Figure 5: Trend of DOC levels in effluent from the Killarney, Borden, Long Point, and North Campus barriers.

# KILLARNEY LAYER

DAY 420



## Long Point wall

370 days

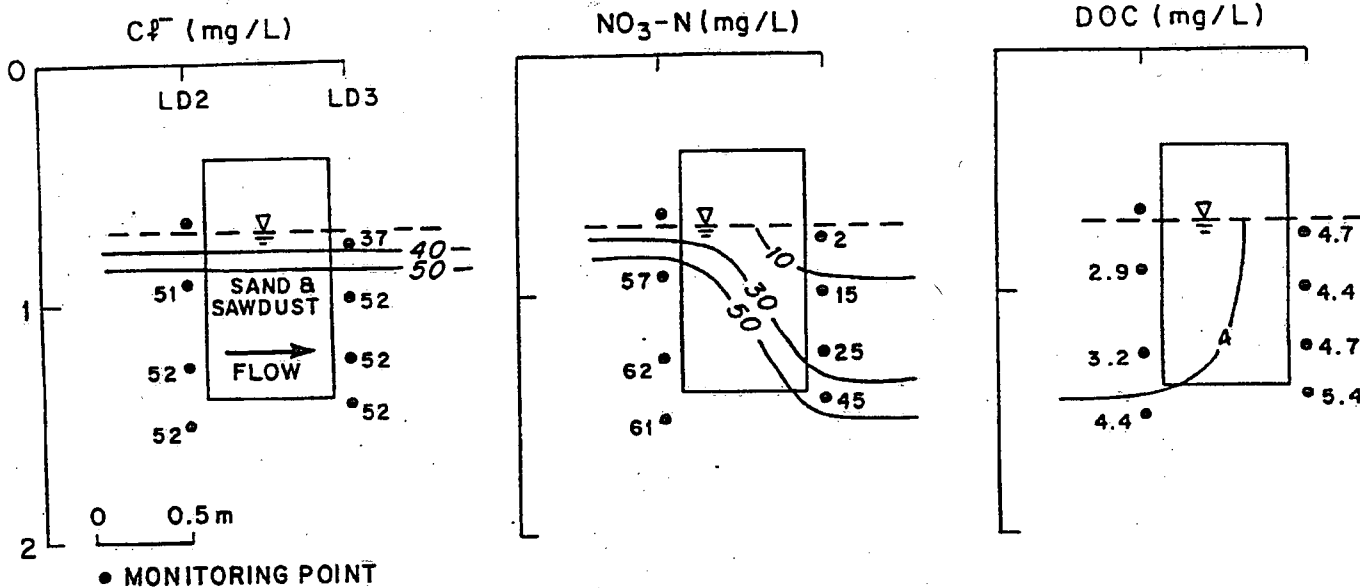


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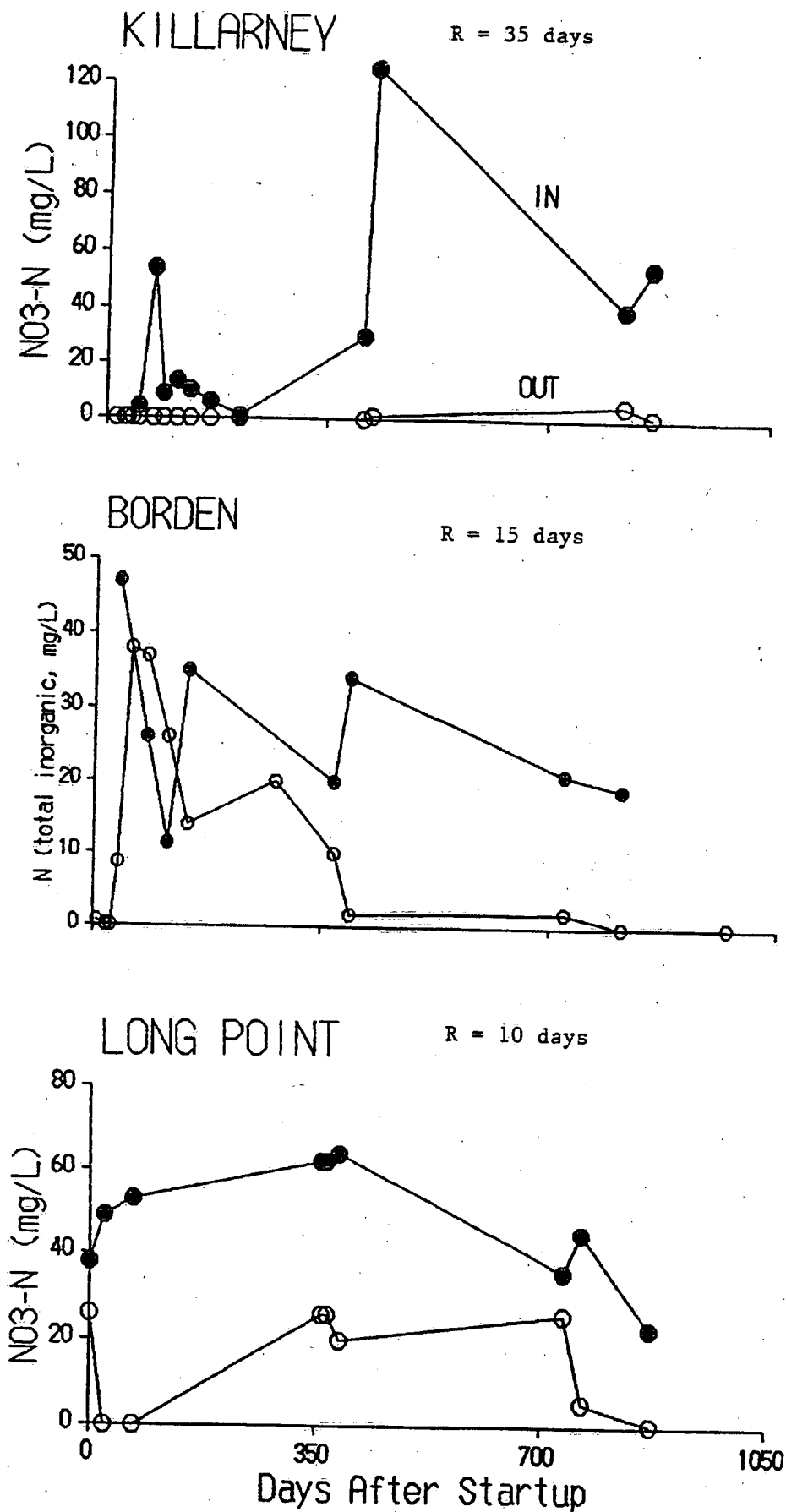


Figure 2: Trends of barrier inflow and outflow nitrogen levels during two to three years of operation: a) Killarney layer, b) Borden layer and c) Long Point wall.

$R$  = porewater residence time in barrier

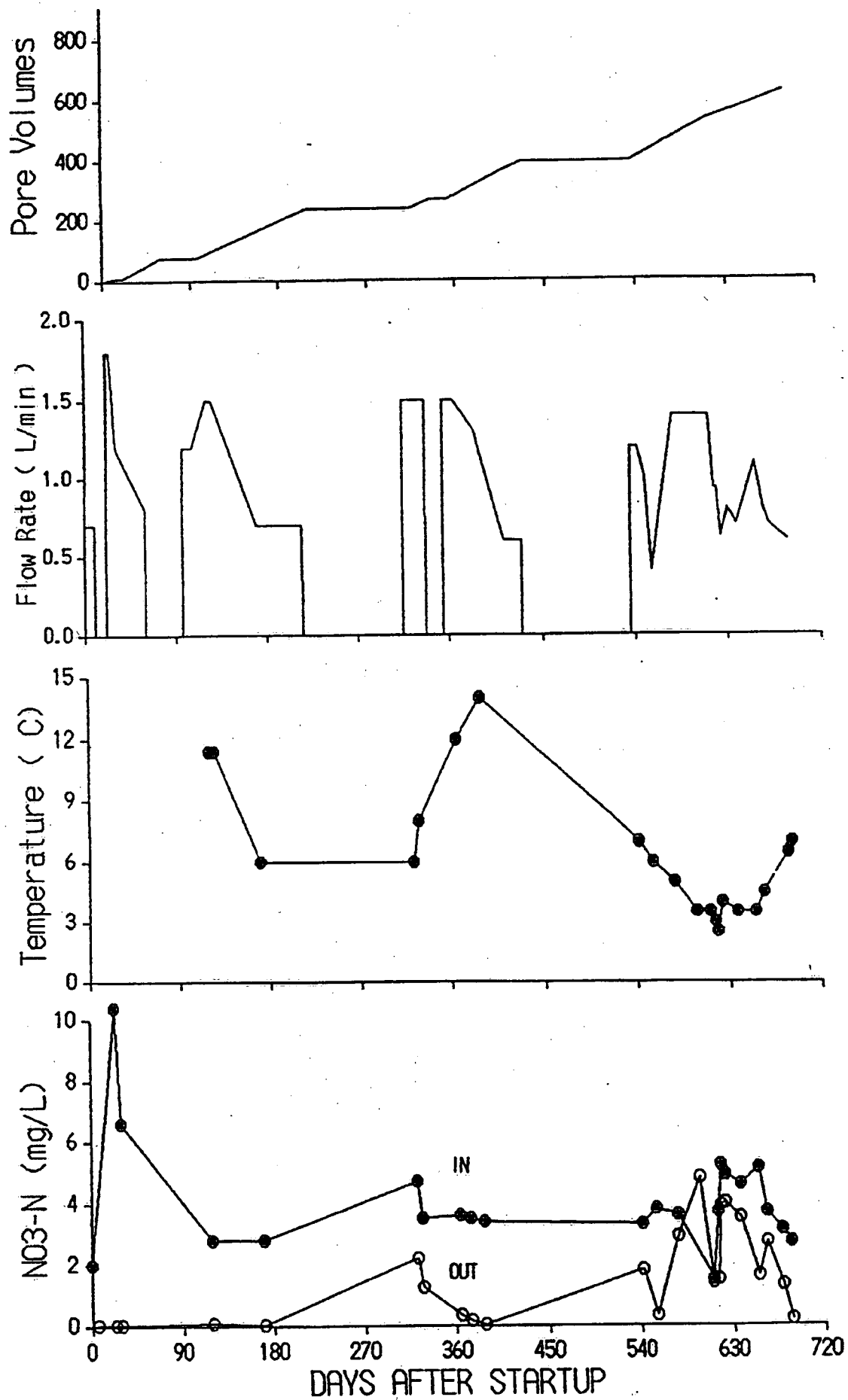


Figure 3: Performance of North Campus barrier/reactor during two years of operation:  
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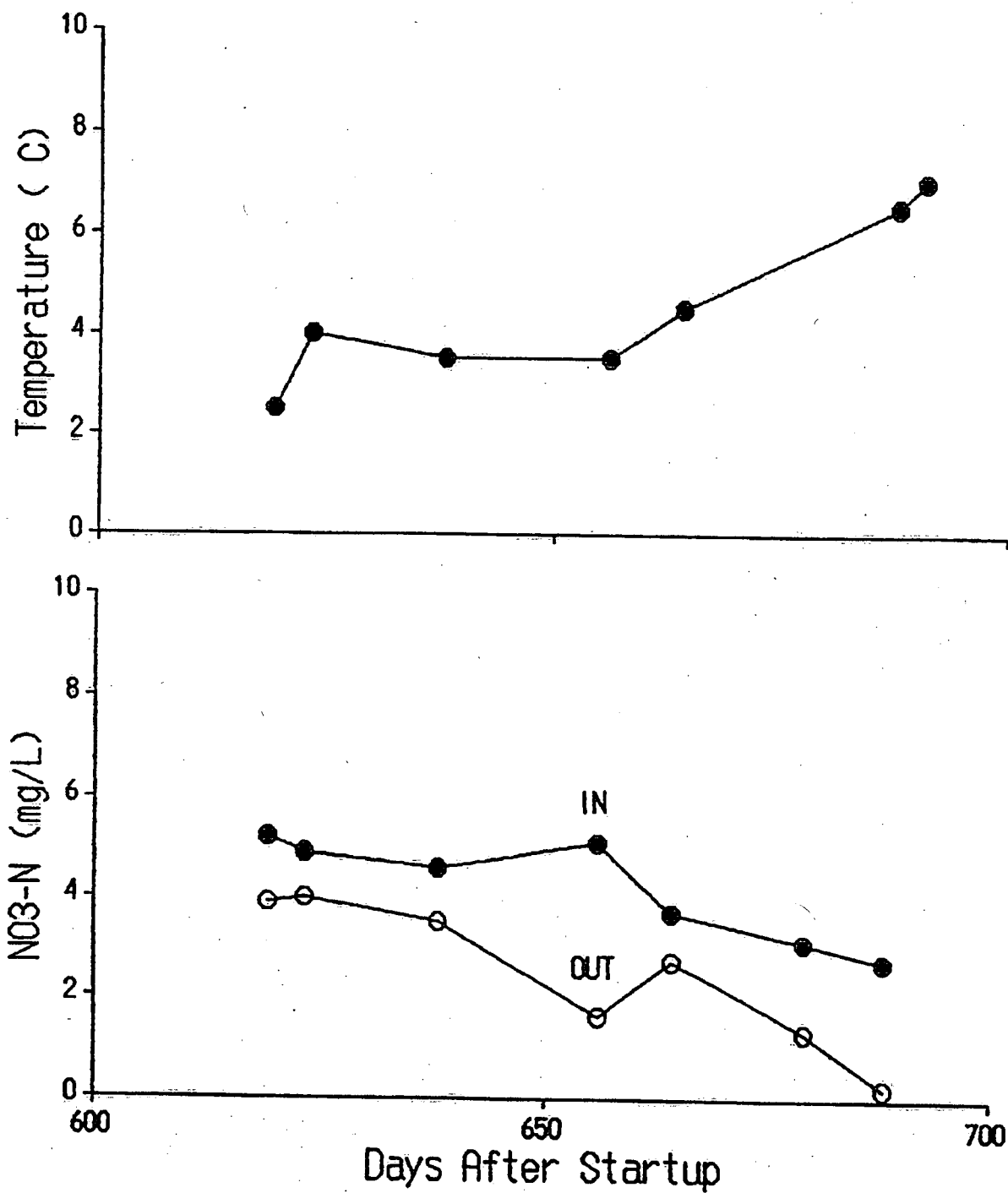


Figure 4: North campus reactor; temperature versus nitrate removal during second year of operation.

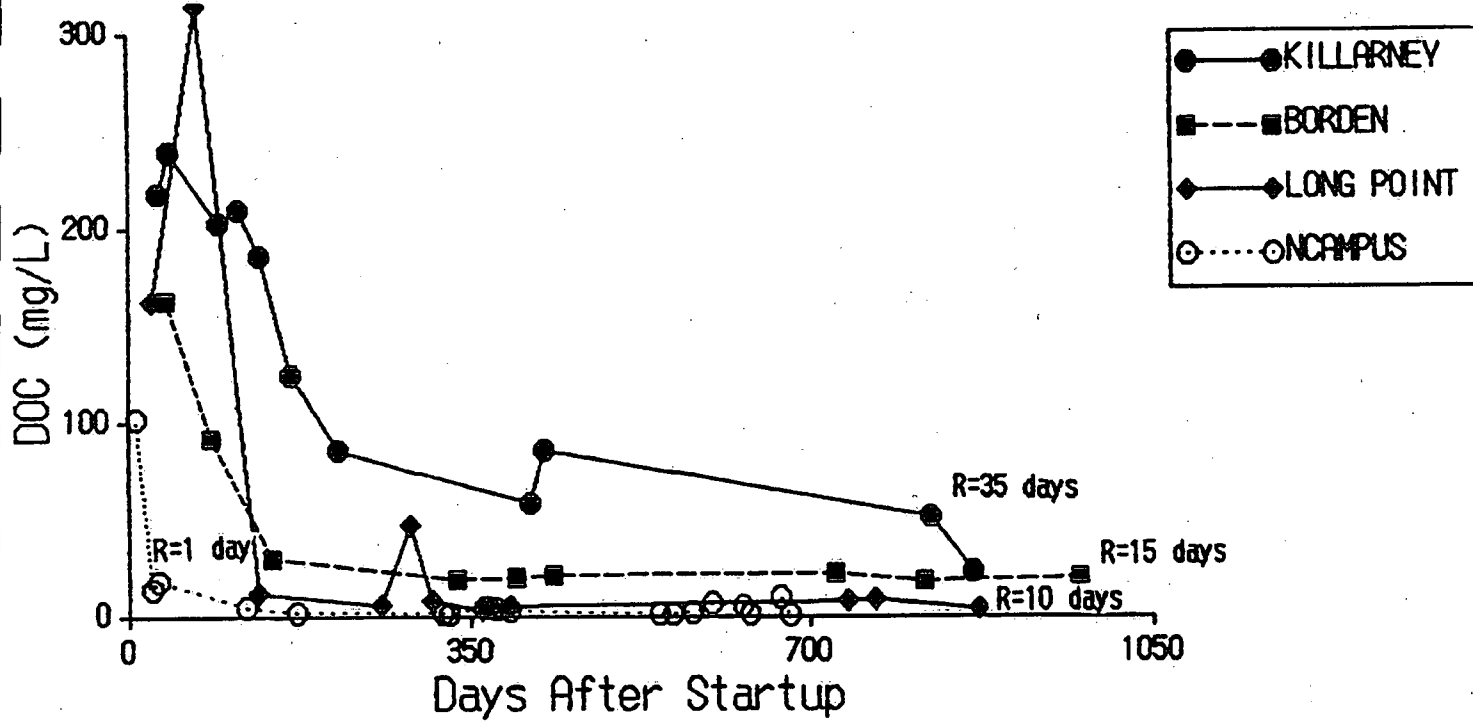


Figure 5: Trend of DOC levels in effluent from the Killarney, Borden, Long Point, and North Campus barriers.

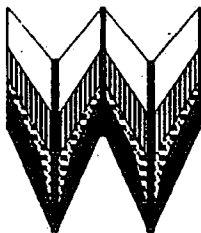
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