



**AGRICULTURE AND FOOD DEVELOPMENT AUTHORITY**

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1 *Key index words:* Permeable reactive barrier; hydrogeological investigation; groundwater;  
2 nitrate; point source pollution.

3

4 **Introduction**

5

6 The Surface Water Directive (EEC, 1975), the Groundwater Directive (EEC, 1980),  
7 the Drinking Water Directive (EC, 1998) and the Nitrates Directive (EEC, 1991) has  
8 focused considerable attention on the disposal of agricultural wastewaters in Ireland.  
9 The Water Framework Directive (WFD) (EC, 2000) aims to achieve at least “good  
10 status” in all surface and groundwaters by 2015.

11

12 The nitrate-nitrogen (NO<sub>3</sub>-N) concentration in rivers and groundwater is a key water  
13 quality indicator in Ireland. From 2004 to 2006, 25% of groundwater had NO<sub>3</sub>-N  
14 concentrations greater than the drinking water guide concentration of 5.65 mg N L<sup>-1</sup>  
15 and 2% exceeded the maximum admissible concentration (MAC) of 11.3 mg N L<sup>-1</sup>  
16 (Lucey, 2006). Agricultural activities are probably the most significant anthropogenic  
17 sources of NO<sub>3</sub>-N contamination in groundwater (Oyarzun *et al.*, 2007). Current  
18 agricultural practices (application methods, dosages and storage) while achieving high  
19 nutrient efficiency and nutrient management cannot avoid incidental nutrient loss to  
20 surface and groundwater. In aquifers with low permeability pathways of nutrient loss  
21 both historically and in the future may pose a threat to receptors for long periods of  
22 time.

23 The control of phosphorus (particulate and soluble forms) before it enters a waterbody  
24 and remediation of nitrate in a waterbody should be integrated. The correct siting of  
25 an environmental technology (structure used to remediate or control a contaminant) to

1 intercept a pollution plume such as a permeable reactive barrier will be an important  
2 step in the remediation of point sources. Such technologies may be *ex - situ*  
3 (farmyard) and *in-situ* (in the field actually in the contaminant plume) (Fenton et al;  
4 2007).

5 Point source pollution from agricultural practices can include inappropriately  
6 managed agricultural soiled waters, such as dairy farmyard soiled water, leaking  
7 septic tanks or storage facilities (soiled water and slurry storage, lagoons,  
8 hydrocarbons) or drainage leaks from low points on the farmyard. Dairy farmyard  
9 soiled water may comprise farmyard runoff, parlour washings, silage and farmyard  
10 manure effluents, along with general farmyard washings. Under new legislation soiled  
11 water may not contain faecal matter leading to lower nutrient concentration (EC,  
12 2006). This soiled water is stored and then landspread or irrigated. Where hydraulic  
13 loads exceed the carrying capacity of the soil, irrigators may be point sources of  
14 pollution in the field. In poorly drained soils, surface runoff may also occur.

15  
16 When nitrogen (N)-rich fertilizer applications exceed plant demands and the  
17 denitrification capacity of a soil, leaching of N in the form of NO<sub>3</sub>-N to groundwater  
18 may occur. Due to its high mobility (Shamrukh *et al.*, 2001), significant amounts of  
19 excess N can be transported as NO<sub>3</sub>-N to a waterbody, potentially leading to  
20 eutrophication, and episodic and persistent hypoxia, where dissolved oxygen is less  
21 than 2 mg L<sup>-1</sup> (Abu – Ashour *et al*, 1994; Kung *et al*, 2000; NRC, 2000). NO<sub>3</sub>-N  
22 leaching is dependent on the hydraulic loading rate, soil water content, soil type and N  
23 loading rate.

24

1 Point source pollution has a clearly identifiable point of discharge and occurs at or  
2 near an agricultural waste facility and exhibits high levels of NO<sub>3</sub>-N or ammonium-  
3 nitrogen (NH<sub>4</sub>-N) in a limited area. The effects of point source pollution accumulate  
4 over time (Schilling and Wolter, 2001). Identifying the source, the potential nutrient  
5 pathway and a potential receptor (e.g. stream) is important, where remediation is  
6 considered. Both NO<sub>3</sub>-N and chloride (Cl) are negative ions and do not adsorb to the  
7 soil matrix. However, NO<sub>3</sub>-N concentrations are reduced by biochemical processes  
8 through denitrification. Using the NO<sub>3</sub>-N to Cl ratio, the source and groundwater flow  
9 pathway may be identified as Cl concentration is conservative and NO<sub>3</sub>-N  
10 concentration decreases relative to the distance from the source. The concentrations of  
11 both parameters are also affected by diffusion, dispersion and dilution (Obenhuber  
12 and Lowrance, 1991; Agriculture and Agri-Food Canada, 2002).

13

14 Conventional *in situ* methods for N removal include:

- 15 • monitored natural attenuation, wherein the source of pollution is initially  
16 found, stopped and then advection, dispersion and chemical-plus biological  
17 degradation of the contaminant is allowed to occur over a long period of time  
18 (USEPA, 1997a);
- 19 • pump-and-reuse, wherein the pumped water is recycled for a certain purpose  
20 (e.g. cooling equipment) and then treated;
- 21 • pump-and-treat, wherein treated water is used to irrigate crops;
- 22 • pump-and-waste (Bronstein, 2005), wherein contaminated water is evaporated  
23 or injected into a saline aquifer or geological unit;
- 24 • phytoremediation (Suresh and Ravishankar, 2004).

25

1 Monitored natural attenuation depends on the denitrification capacity of a soil and the  
2 distance from the receptor. Pump-and-treat may be expensive and pump-and-waste is  
3 not sustainable and may cause plume migration. For remediation of contaminated  
4 water generated on a farm, *ex situ* methods for N removal may be used. These include  
5 continuously moving biofilm reactors (Rodgers and Burke, 2002), sequencing batch  
6 biofilm reactors (Rodgers *et al.*, 2004), trickling filters (Kuai *et al.*, 1999), activated  
7 sludge systems (Gao *et al.*, 2004), and fluidised-bed biofilm reactors (Rabah and  
8 Dahab, 2004). These methods have shown good potential for biological N removal  
9 but need to be adapted for the control of farmyard point source pollution. Successful  
10 remediation prior to land application decreases the potential for groundwater  
11 contamination.

12

13 An *in situ* subsurface remediation barrier, comprising a treatment zone of reactive  
14 materials that degrades or immobilises contaminants as groundwater flows through it,  
15 referred to as a permeable reactive barrier (PRB), may be used to attenuate the  
16 movement of nutrients and other agricultural contaminants (Powell and Powell,  
17 1998). PRBs comprise low-cost, low-value permeable waste products, which provide  
18 a carbon (C)-rich substrate for NO<sub>3</sub>-N removal (USEPA, 1997b). They provide  
19 preferential conduits for contaminated groundwater flow, wherein wastewater flows  
20 through a C-rich mixture (e.g. woodchip) to reduce NO<sub>3</sub>-N concentration. A review of  
21 remediation and control systems for the treatment of agricultural wastewaters has  
22 identified PRBs as a feasible option for *in situ* NO<sub>3</sub>-N remediation from point sources  
23 on Irish farms (Fenton *et al.*, 2008). PRBs have been used extensively in the  
24 remediation of chlorinated solvents, metals and inorganics, fuel hydrocarbons,  
25 nutrients, radionuclides and other organic contaminants at full- and pilot-scales in

1 urban and industrial scenarios (USGS, 1999). Two traditional PRB designs are  
2 commonly used (Figure 1):

3 a) Funnel-and-gate system (Starr and Cherry, 1994) consisting of an impermeable  
4 funnel that directs groundwater to a reactive wall.

5 b) Shallow continuous trench (Pierzynski *et al.*, 2005), placed adjacent to  
6 groundwater flow and backfilled with reactive material and soil.

7 Two other adaptations are: (1) the injection well configuration (Pierzynski *et al.*,  
8 2005), where a well network is drilled perpendicular to the groundwater flow  
9 direction and the reactive material is injected directly into the plume, and (2)  
10 interception of the plume by a drainage system. Here, the contaminated water is  
11 transported off-site to a reactive cell (Pierzynski *et al.*, 2005).

12  
13 A review of existing worldwide PRB installations for inorganic and radionuclide  
14 contamination emphasises that PRBs may be successfully employed with a thorough  
15 site investigation, but the long-term performance of the reactive materials needs  
16 further investigation (Bronstein, 2005). PRBs installed for the interception and  
17 remediation of chlorinated hydrocarbon and chromium (VI) plumes in groundwater  
18 suggest various alterations to more traditional PRB types such as reactive wall type,  
19 excavate and fill, reaction vessel, funnel and multiple gate systems suggesting site  
20 specific conditions (USEPA, 1997). Temporary, continuous trenches have been  
21 installed in agricultural scenarios to investigate NO<sub>3</sub>-N removal rates from artificial  
22 recharge experiments (Robertson *et al.*, 2000; Schipper *et al.*, 2005). Fluctuations of  
23 watertable height may cause alternating anaerobic and aerobic conditions in  
24 continuous trenches leading to decreased denitrification rates (Schipper and Vojvodic-

1 Vukovic, 2001). The barrier porous media may be placed above the watertable only if  
2 it remains tension saturated allowing anaerobic conditions to exist (Robertson, 1995).

3  
4 The objective of this paper is to develop a methodology, based on site-specific  
5 conditions, to locate a PRB on unconsolidated material above bedrock to intercept  
6 NO<sub>3</sub>-N contamination from an agricultural point source. The methodology developed  
7 may be used to locate PRBs on other agricultural sites.

8

## 9 **Materials and Methods**

10

### 11 **Site identification**

12

13 The 4.2 ha study site was located at the Teagasc, Johnstown Castle Environmental  
14 Research Centre, Co. Wexford. Baseline data established a groundwater NO<sub>3</sub>-N plume  
15 arising from point source pollution from a soiled water irrigator system spreading  
16 effluent with a biochemical oxygen demand (BOD<sub>5</sub>) concentration believed to be  
17 greater than 1000 mg L<sup>-1</sup>. The irrigator moved over a 4000 m<sup>2</sup> area within the 4.2 ha  
18 site. However, due to the slope of the site, the irrigator was confined to a much  
19 smaller area, resulting in ponding with subsequent recharge. The source was identified  
20 by documenting historical management practices and locating irrigation infrastructure.  
21 This site was chosen to evaluate methodologies for the implementation of a PRB.

22

### 23 **Site description**

24



1 Identified potential receptors on site are: a) Tenches pit stream to the west which  
2 flows to a shallow lagoon; b) Tenches pit stream which connects to the Kildavin River  
3 to the south; and c) groundwater (Figure 2). In 2003, six hydrologically isolated study  
4 plots were established between the source and the receptor. Further isolation was  
5 achieved by excavating two shallow, unlined trapezoidal drains, excavated to a depth  
6 of 1 m, with bases ranging from 71.08 m AOD to 70.2 m AOD and 71.10 m AOD to  
7 70.30 m AOD, respectively, along the northern edge of the plots. Flow in these drains  
8 did not interact. Overland flow from each study plot was collected in a drain at the  
9 lowest topographical point. Subsurface drainage was collected with a herring bone  
10 subsurface drainage system (drain spacing, 1 m) located at a 1 m depth below the  
11 ground surface. Subsurface flow was measured using V-notch weirs. The study plots  
12 were instrumented with a total of 18 piezometers - 3 piezometers installed in each  
13 plot.

14

### 15 **Site characterisation**

16

17 A site characterisation was carried out to identify possible point sources and receptors.  
18 The contaminant  $\text{NO}_3\text{-N}$  from the point source was identified and all infrastructure  
19 (subsurface pipes and connectors for irrigator) located back to the surface storage  
20 area. The area was surveyed and the distance from source to receptors was measured.  
21 All existing data on the site, such as soil type, thickness and texture, soil profiles,  
22 drainage conditions, subsurface geology, and subsurface and surface drain location,  
23 was collated.

24

### 25 **Water balance**

1

2 A water balance of the site was used to calculate the travel time from the source to the  
3 watertable. Daily weather data, recorded at the Johnstown Castle Weather Station,  
4 were used to calculate daily soil moisture deficit (SMD) using a Hybrid model for  
5 Irish grasslands. The site had moderately drained soil. Potential evapotranspiration,  
6  $ET_0$  (mm day<sup>-1</sup>), was calculated using the FAO Penman-Montieth equation (Allen *et*  
7 *al.*, 1998):

8

$$9 \quad ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

10

11 where  $R_n$  is the net radiation at the crop surface (m<sup>-2</sup> d<sup>-1</sup>),  $T$  is the air temperature at a  
12 2 m height (°C),  $u_2$  is the wind speed at a 2 m height (m s<sup>-1</sup>),  $e_s$  and  $e_a$  are the  
13 saturation and the actual vapour pressure curves (kPa °C<sup>-1</sup>), and  $\gamma$  is the psychrometric  
14 constant (kPa °C<sup>-1</sup>).  $ET_0$  was then converted to actual evapotranspiration ( $Ae$ ) using an  
15 Aslyng scale recalibrated for Irish conditions (Schulte *et al.*, 2005). Effective rainfall  
16 was calculated by subtracting daily actual evapotranspiration from daily rainfall  
17 (assuming no overland flow losses due to the high infiltration capacity of the soil on  
18 this site). Soil moisture deficit (SMD) on day one (January 1<sup>st</sup>, 2006) was set to zero  
19 and effective drainage was estimated for each subsequent day. Modelling the effective  
20 drainage enables the infiltration depth of water to be calculated at specific hydraulic  
21 loads where the soil effective porosity is known. This infiltration depth may be  
22 compared to watertable data to investigate if recharge to groundwater in that  
23 particular year affects water quality.

24

1 **Groundwater characterisation**

2

3 A topographic base map with a contour interval of 2 m and a field boundary overlay  
4 was generated using ArcGIS™ for data obtained on 11 July, 2006. This allowed  
5 surface (topography) and subsurface features (watertable) to be compared spatially.  
6 Due to the sloped profile of the site, 18 multilevel piezometers were drilled (rotary  
7 drilling) prior to this study to represent specific geological units and not depths  
8 (Figure 2). Two stratigraphic units, from 63 m above ordnance datum (m AOD) to 67  
9 m AOD and from 67 m AOD to 70 m AOD, respectively, were drilled. Data will be  
10 described using m AOD to allow comparisons of plume position eliminating  
11 topographical differences. A further piezometer (FH7) was installed and surveyed on  
12 the Sandhill area in 2005 (Figure 2). All piezometers had a slotted screen length of 1  
13 m. Drilling logs and samples from the piezometers were used to develop a conceptual  
14 model of the subsurface. The piezometers were surveyed using TOPCON AT-G4  
15 equipment (TOPCON, Ireland) and the locations of the wells were recorded using  
16 digital mapping software (ArcGIS™ 9.1, ESRI, Ireland). The depth to water level in  
17 each monitoring well was measured using an electronic water-level indicator (Van  
18 Walt Ltd, Surrey, UK) and groundwater heads were determined in m AOD. Surface  
19 water features, such as streams, drains and lagoons, were also surveyed on 11<sup>th</sup> July,  
20 2006. Groundwater head data was contoured (block kriging) using GW-Contour 1.0  
21 software (Waterloo Hydrogeologic, Canada). The topographic base map was merged  
22 with well locations and groundwater head input files. These groundwater maps were  
23 used to track groundwater flow direction over time and NO<sub>3</sub>-N concentration using  
24 groundwater heads and water quality data in each well as inputs (Fenton and Hyde,  
25 2006). From March 2005 to March 2007, water levels were measured weekly in each

1 monitoring well and nitrite-nitrogen (NO<sub>2</sub>-N), total oxidized nitrogen (TON), NH<sub>4</sub>-N,  
2 ortho-phosphate (PO<sub>4</sub>), and Cl concentrations within each well were measured every 2  
3 weeks. Water samples were filtered through 0.45 µm filter paper and analysed using a  
4 Thermo Konelab 20 Analyser (Technical Laboratory Services, Ontario, Canada).

5

6 Prior to the study, soil cores (n = 46) at the piezometer locations and drains were taken  
7 at 1m depths and analysed for bulk density and particle density. Total porosity was  
8 calculated from (Brady and Weil, 1996):

9

$$10 \quad n = 100 \left( 1 - \frac{\rho_b}{\rho_d} \right) \quad (2)$$

11

12 where  $n$  is the total porosity (%),  $\rho_b$ , the bulk density (kg m<sup>-3</sup>), and  $\rho_d$  is the particle  
13 density (kg m<sup>-3</sup>).

14

15 Saturated hydraulic conductivity,  $K_{sat}$ , on site was determined using falling head slug  
16 tests (instantaneous injection of 1 L of water) (Horslev, 1951; Bouwer, 1976). To  
17 establish a hydraulic connection between the source and potential receptors, the  
18 hydraulic gradient was calculated using:

19

$$20 \quad \frac{h_A - h_B}{L} \quad (3)$$

21

22 where  $h_A$  and  $h_B$  are hydraulic heads calculated by electronically dipping a piezometer  
23 and converting depth to watertable to m AOD, and  $L$  (m) is the length between these  
24 two piezometers.

1

2 The quantity of water discharging from a known width of aquifer,  $Q$  ( $\text{m}^3 \text{ day}^{-1}$ ), was  
3 determined using (Darcy, 1856):

4

$$5 \quad Q = -K_{sat} A \frac{dh}{dx} \quad (4)$$

6

7 The average linear velocity,  $v$  ( $\text{m day}^{-1}$ ), was calculated from:

8

$$9 \quad v = -K_{sat} n \frac{dh}{dx} \quad (5)$$

10

11 where  $v$  is equal to  $Q/A$ ,  $K$  is the hydraulic conductivity ( $\text{m day}^{-1}$ ),  $A = bw$ , where  $b$  is  
12 the aquifer thickness (m),  $w$ , the width (m), and  $dh/dx$  is the hydraulic gradient.

13

14 The transmissivity,  $T$  ( $\text{m}^2 \text{ day}^{-1}$ ), is calculated using the aquifer thickness,  $b$ :

15

$$16 \quad T = K_{sat} b \quad (6)$$

17

18 To investigate the variation in the  $\text{NO}_3\text{-N:Cl}$  ratio on the site, groundwater and drain  
19 samples were analysed. Groundwater temperatures were recorded in two piezometers  
20 with similar piezometer total depths (2c and 5c, Figure 2) at 30 minute intervals using  
21 real time electronic divers (Van Walt Ltd, Surrey, U.K.).

22

23 **Trench thickness - bench scale testing**

24

1 The kinetics of denitrification will depend on C and NO<sub>3</sub>-N availability, pH,  
2 temperature, soil texture, soil management, tillage, rainfall events, rates of microbial  
3 respiration and nitrification, water filled porosity, soil mineral N content, soil type,  
4 and redox conditions. A reactive material should be chosen and tested to optimise  
5 contaminant residence times in the reactive barrier. On-site soil cores of fine loamy  
6 brown earth, fine loamy gley and sandy brown podzolic soils were tested for  
7 denitrification rate (µg N lost as NO<sub>3</sub>-N g<sup>-1</sup> dry soil day<sup>-1</sup>) using soil incubation tests.  
8 The denitrification rate of the gley soil amended with woodchips (5:2 g dry weight of  
9 woodchips to soil) was also examined. The retention time, *t* (days), needed to achieve  
10 denitrification was calculated using:

11

$$12 \quad t = \frac{C_{treated}}{C_{max}} / r \quad (7)$$

13

14 where  $C_{treated}$  is the desired concentration after remediation,  $C_{max}$  is the greatest  
15 concentration expected, and  $r$  is denitrification rate determined from batch  
16 experiments. The retention time was then multiplied by the groundwater flow velocity  
17 to calculate the thickness of the trench. Based on chemical stoichiometric relations,  
18 denitrification of one mole of NO<sub>3</sub>-N will require 1.25 moles of C. This equates to a  
19 mass balance of 1.07 kg of available C per 1 kg of NO<sub>3</sub>-N. With approximately 50 %  
20 of C availability in woodchip (based on bulk density) the treatment of 1 kg of NO<sub>3</sub>-N  
21 will require approximately 2 to 2.5 kg of woodchip (Fahner, 2002).

22

23

## Results

24

1 **Site characterisation**

2

3 The soil texture comprises a 15 to 40 cm-deep loam (soil group, brown earth in Plots  
4 1 and 2), overlying a loam-to-clay-loam (soil group, gley) subsurface soil and there  
5 was a quartzite outcrop along the western side of the site. The textural change across  
6 the site was responsible for differential drainage. The study area comprised two well-  
7 drained plots (Plots 1 and 2 - brown earth), two imperfectly-drained plots (Plots 3 and  
8 4 - gley) and two poorly-drained plots (Plots 5 and 6 - gley with higher clay content)  
9 (Figure 2).

10

11 **Water balance**

12

13 Over the study period, the site received mean precipitation of 1046 mm, of which the  
14 Hybrid model calculated 553 mm drainage through the root zone in a process known  
15 as effective drainage. Model output showed effective drainage occurred on 178 days,  
16 giving an average recharge rate of  $3.11 \text{ mm d}^{-1}$ . The mean soil total porosity was  
17  $32.2 \pm 4.9\%$ . The average pore velocity was estimated to be  $9.7 \text{ mm d}^{-1}$ , giving an  
18 approximate mean travel depth of 1.7 m in a moderately-drained soil over the study  
19 duration. The depth to the median watertable during this period was 1.01m, which  
20 equates with the base of the intersecting drains in Plots 3 and 4. Therefore, the  
21 watertable intersects these drains at certain times of the year and infiltrating water  
22 upslope from the drains recharges to groundwater within 1 year. The hydraulic load of  
23 the soiled water irrigator varied from 10 to  $50 \text{ mm year}^{-1}$ . This would increase the  
24 mean depth of travel on the irrigated site when the irrigator was in operation by 10

1 cm. Therefore, the main receptor was groundwater but with surface water receptors  
2 forming boundaries to the site.

3

#### 4 **Groundwater investigation**

5

6 Initial baseline sampling of the piezometers on-site showed NO<sub>3</sub>-N concentrations  
7 above the drinking water limit of 11.3 mg NO<sub>3</sub>-N L<sup>-1</sup>. Groundwater temperature on  
8 site during the study period ranged from 9.5°C to 10.5°C in piezometers 2c and 5c  
9 which is suitable for denitrification to occur at depths below 1 m.

10

11 The strike and dip of the quartzite outcrop combined with drilling log data gave an  
12 estimated unconfined aquifer thickness of approximately 10 m and a saturated  
13 thickness, based on mean watertable and depth to the impermeable zone, of  
14 approximately 7 m. Piezometer parameters,  $K_{sat}$ , and groundwater quality parameters  
15 are presented in Table 1. Hydraulic gradients, calculated using Equation (3) based on  
16 median and maximum watertable heights, showed a hydraulic gradient between the  
17 source and potential receptors.

18

19 A groundwater map was constructed using watertable data and surveyed surface water  
20 features on July 11<sup>th</sup>, 2006. As no significant seasonal deviation occurred, a median  
21 groundwater map was used to show groundwater flow direction. Groundwater  
22 contours (based on groundwater heads) deviated little from topography within the six  
23 isolated plots (Figure 3). Therefore, topography was used to infer the groundwater  
24 flow direction on the Sandhill area where a lower piezometer density exists.  
25 Groundwater flow direction was consistent throughout the study period and median



1 groundwater flow contours were used to locate a PRB parallel to watertable contours.  
2 Where groundwater flow direction changes, the orientation of the PRB should be  
3 based on mean conditions. Based on median and maximum hydraulic heads, a barrier  
4 containing a 2 m-deep reactive zone is needed (reactive media should fill subsurface  
5 from 68 m AOD to 70 m AOD). This would ensure the reactive material was covered  
6 at all times by the watertable. A cross sectional conceptual model of the plume  
7 positions the centroid (area with highest nutrient concentration) around 2c – 5c  
8 (Figure 4). Nutrient concentration decreases outwards from the centroid. The extent of  
9 the plume migration vertically is unknown. Lateral plume extent varies from 350 m  
10 from 1c to 6c and extends further to 400 m at piezometer 1b. As the lateral plume  
11 diameter near to the source decreases the trench needs to be less than 350 m (Figure  
12 3), to capture all groundwater flow migrating to Plots 2, 3, 4 and 5 (Figure 3).

13

14 Combining the hydrogeological characterisation data, plume distance and travel times  
15 were calculated (Table 2). A steep hydraulic gradient in Plot 4 resulted in  
16 groundwater flow to Plots 1 and 6. A significant hydraulic gradient existed between  
17 Plots 5 and 6. Average linear velocity was higher in Plots 4 and 5. Therefore, the  
18 centroid was able to migrate quickly in two directions. When aquifer thickness was  
19 considered, Plot 5 has highest  $T$  values indicating plume migration was quickest from  
20 Plots 4 and 5. Therefore, plume migration is greatest (in a given time interval) in Plot  
21 5, migrating to a potential receptor to the west. Migration from Plot 4 eastwards was  
22 slower. Travel times from the centroid outwards are also similar with plume migration  
23 faster in a westward direction. Therefore, two travel times must be considered in  
24 groundwater remediation of the site.

25

1 Due to subsurface characteristics, a plume originating from a point source may  
2 migrate to several receptors in different timescales. Remediation should concentrate  
3 on the most immediate of these pressures or be located close to the pollution source.

4

5 **Source tracking**

6

7 Source tracking was used to connect the source, pathway and receptor of the nutrient  
8 loss. The median NO<sub>3</sub>-N:Cl ratio in drains intersecting groundwater flow between the  
9 source and the plots were 0.46 (max 0.84) and 0.38 (max 0.72). Mean watertable  
10 depths in piezometers 3c and 2c during the same period are 0.52 m and 2.06 m,  
11 respectively. Therefore, the watertable from the up-gradient area intersected the drain  
12 adjacent to 3c and the flow in the drain was towards 2c. This means that contaminated  
13 groundwater passed into the plots and was then picked up in groundwater samples in  
14 the piezometers. To prevent contamination of surface water, the PRB should be  
15 located upslope from these drains and attenuate groundwater before any surface water  
16 groundwater interactions can take place (Figure 3).

17

18 **Trench thickness**

19

20 Using the denitrification rates in Table 3, Equation 7 was used to calculate the  
21 retention time needed to remediate the highest expected NO<sub>3</sub>-N concentration  
22 expected (24.24 NO<sub>3</sub>-N mg L<sup>-1</sup>) to allowable levels. The retention time was then  
23 multiplied by the groundwater flow velocity to give the barrier thickness. The site is  
24 primarily on gley soils (95%) and the proposed trench location was on this soil type.  
25 Natural attenuation on-site would take longer periods of time. Potential receptors on

1 site are approximately 200 m from the source. This would allow natural attenuation in  
2 gleys within 7.35 years. The travel time from Plots 3, 4, 5 and 6 would be less than  
3 this. However, natural attenuation to the east may be an option as travel times are  
4 much higher and the receptors are a greater distance away.

5

6 **Discussion**

7

8 The choice of PRB will depend on the scale of the project. In this investigation, a  
9 continuous trench was chosen over a funnel and gate system, as less geotechnical  
10 input was needed. Both options, however, would need hydrogeological professional  
11 input to locate a PRB. A site investigation of this scale may not be viable for  
12 individual farmers. Contamination may be from point or non-point sources needing  
13 varied amounts of site and hydrogeological characterisation. In this study, the site  
14 characteristics merited a PRB for groundwater remediation. Hydraulic conductivity,  
15 measured *in situ*, provides the retention times needed for denitrification to occur. This  
16 may be different on other sites where retention times or migration pathways may not  
17 make a PRB a viable option for remediation (unconsolidated material or bedrock).  
18 The watertable on other sites may not be shallow raising the costs of PRB  
19 construction. Once the pollution source has been stopped, contamination residence  
20 times in free draining fluviogravels may be short due to high permeability. Therefore  
21 construction of a PRB would be unjustified. Also where the groundwater body is an  
22 important receptor, remediation within this waterbody may not be justified. In such  
23 cases remediation of the pollution before it reaches the groundwater body is  
24 preferable.

25

1 Calculation of the contaminant flux at source or along a control plane away from the  
2 source may be expensive due to drilling costs. Therefore, this methodology is best  
3 suited to small point sources or plumes which have already reached shallow  
4 watertable interfaces at surface groundwater interaction sites. Further research into  
5 less permanent, low-cost monitoring systems is needed.

6  
7 For this case study the dimensions, orientation and reactive media chosen for the PRB  
8 on this site are presented in Table 3. The exact location of the proposed PRB is  
9 presented in Figure 3. The following methodology can be used to establish a PRB on  
10 this site for point source remediation:

- 11 1. Thorough site characterisation using all available data relating to the site is  
12 required. Data management and appropriate visual presentations such as  
13 maps, graphs and diagrams should be compiled. Distance from source to  
14 receptor should be calculated and topography defined.
- 15 2. Installation of a piezometer network between the source and potential  
16 receptors. Field visual tools (e.g. VS-Fast system) for soil field assessment  
17 may be a useful tool for preliminary studies, which enables *in situ* estimates  
18 of soil consistency, soil structure and texture (McGarry and Sharp, 2001).  
19 Other systems based on BS 5930:1999 are used in groundwater protection  
20 schemes to describe sub-soils (GSI, 1999).
- 21 3. Groundwater analysis and soil sampling should be carried out and a  
22 preliminary dataset should be compiled. Use calculated parameters to  
23 calculate groundwater travel times and distances in certain timeframes.  
24 Combine aquifer data with water quality data and form a three dimensional  
25 conceptual model of the subsurface and identify the plume centroid. This

1           conveys what is known or suspected about contamination sources, release  
2           mechanisms, and the transport and fate of the contaminant. Draw a sub-  
3           surface cross section. Construct groundwater flow maps. Compile watertable  
4           data (vertical position of reactive barrier).

5           4. The PRB trench thickness should be designed for specific water quality  
6           targets. Batch or column experiments should be carried out to calculate the  
7           reaction rate and equilibrium constant of the contaminant with the reactive  
8           media.

9           5. Identify travel times to potential receptors and locate the PRB up-gradient of  
10          the receptor. Compare PRB installation with monitored natural attenuation.

11

12          Before construction, the site should be evaluated to ensure design depth and width  
13          may be achieved. Trial holes should be considered. The ability of emplacing the  
14          reactive material without aquifer obstruction should be assessed to avoid clogging of  
15          media and smearing soil walls thus decreasing permeability. During and after  
16          installation, a monitoring network should be installed to investigate if denitrification  
17          is occurring in the trench and to investigate groundwater flow alteration due to the  
18          barrier construction. The ease of excavating the reactive media for replacement  
19          purposes after a period of time should be considered. Monitored natural attenuation on  
20          site should also be considered for areas further away from the source. A number of  
21          wells should be drilled in such locations. Pump-and-treat and pump-and-reuse would  
22          need considerable investment, drilling, discharge licences, and would need surface  
23          structures and maintenance which could interrupt farming practices. Recycling of  
24          water on farms is more likely to stem from soiled water remediation or rainwater  
25          harvesting and reuse. Pump-and-waste would also need a disposal licence and would

1 merely export the problem elsewhere. The funnel-and-gate option is cost-prohibitive  
2 and would need geotechnical and engineering input in the design phases. However, a  
3 more feasible option for gate construction, such as compressed clay or another low-  
4 permeability material, should be investigated. A PRB installed south of the  
5 investigative plots would not capture all contaminated groundwater and could not  
6 achieve surface water quality targets. The current configuration would intercept  
7 contaminated groundwater before entering the six plots and before hydraulic gradients  
8 at location 4c divide the plume.

9

10 **Conclusions**

11

12 A continuous, shallow PRB may be suitable for Irish conditions to remediate point  
13 sources. Each site will have site-specific conditions but the methodology developed  
14 for this study site, based on site and groundwater characterisation, can successfully  
15 site a PRB and calculate the dimensions and orientation of the barrier. Further  
16 research should be carried out on the denitrification rates of different reactive media  
17 when combined with different soil groups. Higher NO<sub>3</sub>-N removal rates will  
18 necessitate lower residence times and increased remediation. The longevity of the  
19 reactive media needs to be investigated and a cost-benefit analysis for the remediation  
20 of contaminated groundwater undertaken. A broader methodology should be  
21 investigated which takes into account other site characteristics, such as unconsolidated  
22 material, fractured bedrock and a deep watertable.

23

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4 **Captions for figures & tables**

5

6 **Figure 1:** Two types of subsurface PRBs a: funnel and gate, b: continuous trench;  
7 with source, NO<sub>3</sub>-N plume, reactive material, treated plume and receptor. Watertable  
8 (WT) positioned within treatment wall containing reactive material and barrier  
9 constructed adjacent to groundwater (GW) flow direction.

10 **Figure 2:** Field site layout showing plot location, irrigator source, potential receptors  
11 (Tenches pit stream, lagoon, Kildavin River and connection to artificial lake system),  
12 piezometer locations and drainage of the study site.

13 **Figure 3:** Groundwater contours (modelled using block kriging) based on  
14 groundwater heads and topography. Flow from high to low hydraulic head contours at  
15 right angles to contours. Plume centroid location (10 – 15 mg NO<sub>3</sub><sup>-</sup> N L<sup>-1</sup>) PRB  
16 orientation, location and dimensions.

17 **Figure 4:** Schematic diagram showing cross sectional (1c – 6c) conceptual model of  
18 the contamination plume with source on the sandhill. Highest median NO<sub>3</sub>- N  
19 concentration is within plume centroid. Watertable shows hydraulic gradient from plot  
20 4 towards plots 1 and 6. Centroid vertical and horizontal thickness and dilution fronts  
21 can also be seen.

22

23 **Table 1:** Piezometer parameters

24 **Table 2:** Plume distance and travel times using hydrogeological parameters

- 1 **Table 3:** Reactive media denitrification rate and PRB thickness to reduce  $\text{NO}_3^-$ - N
- 2 concentration from 24.24  $\text{NO}_3^-$ - N  $\text{mg L}^{-1}$  (highest concentration) to 11.3  $\text{mg NO}_3^-$ - N
- 3  $\text{L}^{-1}$  (allowable concentration)
- 4

**Table 1:** Piezometer and groundwater data over the study period.

| Plot | I.D | Elevation<br>m AOD | Total<br>depth<br>m | Multilevel | Watertable height |          |                                  | Groundwater NO <sub>3</sub> -N<br>concentration<br>mg L <sup>-1</sup> |                           | Groundwater NH <sub>4</sub> -N<br>concentration<br>mg L <sup>-1</sup> |                           |
|------|-----|--------------------|---------------------|------------|-------------------|----------|----------------------------------|---|---------------------------|---|---------------------------|
|      |     |                    |                     |            | Median<br>m       | Max<br>m | $K_{sat}$<br>m day <sup>-1</sup> | Median<br>mg l <sup>-1</sup>  | Max<br>mg l <sup>-1</sup> | Median<br>mg l <sup>-1</sup>  | Max<br>mg l <sup>-1</sup> |
| 1    | c   | 71.48              | 4.35                | 1          | 4.35              | 4.35     | 0.02                             | 4.8   | 11.85                     | 0.03  | 1.42                      |
|      | b   | 69.91              | 4.13                | 2          | 2.85              | 4.13     | 0.02                             | 12.71   | 22.56                     | 0.1   | 2.84                      |
|      | a   | 67.04              | 3.64                | 2          | 3.73              | 3.64     | 0.02                             | 6.37  | 9.54                      | 0.24  | 0.79                      |
| 2    | c   | 71.83              | 4.38                | 1          | 3.18              | 4.38     | 0.04                             | 12.8  | 24.24                     | 0.33  | 5.63                      |
|      | b   | 69.52              | 4.13                | 2          | 3                 | 4.02     | 0.18                             | 12.81   | 22.3                      | 0.38  | 5.72                      |
|      | a   | 67.22              | 3.14                | 2          | 1.01              | 3.14     | 0.08                             | 1.21  | 14.77                     | 0.05  | 2.05                      |
| 3    | c   | 70.87              | 3.24                | 1          | 0.74              | 2.29     | 0.02                             | 12.31   | 17.34                     | 0.07  | 1.38                      |
|      | b   | 69.47              | 2.67                | 1          | 1.09              | 2.59     | 0.18                             | 8.99  | 16.83                     | 0.02  | 0.31                      |
|      | a   | 67.6               | 3.55                | 2          | 0.8               | 2.15     | 0.07                             | 12.26   | 19.37                     | 0.07  | 2.18                      |
| 4    | c   | 70.96              | 2.49                | 1          | 1.04              | 2.24     | 0.02                             | 6.01  | 10.69                     | 0.05  | 0.14                      |
|      | b   | 68.92              | 2.94                | 2          | 0.69              | 1.41     | 0.13                             | 0   | 6.85                      | 0.08  | 0.41                      |
|      | a   | 67.34              | 2.7                 | 2          | 0.94              | 1.75     | 0.12                             | 0.02  | 6.57                      | 0.04  | 0.46                      |
| 5    | c   | 71.71              | 4.33                | 1          | 2.18              | 3.58     | 0.05                             | 14.29   | 19.94                     | 0.02  | 0.46                      |
|      | b   | 68.88              | 2.87                | 2          | 0.67              | 1.47     | 0.19                             | 9.08  | 18.92                     | 0.03  | 0.12                      |
|      | a   | 67.03              | 1.55                | 2          | 0.53              | 1.55     | 0.26                             | 9.06  | 11.35                     | 0.05  | 2.06                      |
| 6    | c   | 70.68              | 3.01                | 1          | 1.38              | 2.73     | 0.07                             | 9.61  | 11.09                     | 0.13  | 1.02                      |
|      | b   | 68.09              | 3.18                | 2          | 0.45              | 1.19     | 0.08                             | 4.19  | 8.44                      | 0.08  | 0.71                      |
| FH7  | a   | 67.24              | 2.95                | 2          | 0.96              | 1.55     | 0.07                             | 3.12  | 14.66                     | 0.04  | 2.23                      |
|      |     | 72.43              | 4.14                | 2          | 2.97              | 4.14     | 0.02                             | 6.44  | 12.66                     | 0.06  | 0.15                      |

\*  $K_{sat}$  measured *in situ* using falling head slug tests.

**Table 2:** Plume distance and travel times using hydrogeological parameters

| Parameters  | Plots  |        |        |        |        |        |
|---|--------|--------|--------|--------|--------|--------|
|   | 1      | 2      | 3      | 4      | 5      | 6      |
| area (ha)   | 0.78   | 0.75   | 1.01   | 0.94   | 0.41   | 0.41   |
| piezometers   | 3      | 3      | 3      | 3      | 3      | 3      |
| piezometer density (piezometer/ha)  | 0.26   | 0.25   | 0.34   | 0.31   | 0.14   | 0.14   |
| Total porosity (%)  | 0.32   | 0.32   | 0.32   | 0.32   | 0.32   | 0.32   |
| Depth to impermeable zone (m)   | 10.00  | 10.00  | 10.00  | 10.00  | 10.00  | 10.00  |
| Depth of saturated zone (m)   | 7.00   | 7.00   | 7.00   | 7.00   | 7.00   | 7.00   |
| Slope (%)   | 0.02   | 0.02   | 0.02   | 0.02   | 0.02   | 0.02   |
| width (m)   | 50.00  | 50.00  | 55.00  | 55.00  | 30.00  | 30.00  |
| $Q$ m <sup>3</sup> day <sup>-1</sup> (mean discharge)                           | 0.11   | 0.27   | 0.36   | 0.65   | 0.48   | 0.18   |
| $v$ m day <sup>-1</sup> (average linear velocity) (takes porosity into account) | 0.02   | 0.03   | 0.07   | 0.12   | 0.16   | 0.05   |
| $v$ m day <sup>-1</sup> (max)   | 0.02   | 0.06   | 0.07   | 0.13   | 0.18   | 0.07   |
| $K$ m day <sup>-1</sup> (mean hydraulic conductivity)                           | 0.02   | 0.08   | 0.07   | 0.12   | 0.19   | 0.07   |
| $T$ m <sup>2</sup> day <sup>-1</sup>  | 0.14   | 0.56   | 0.49   | 0.84   | 1.33   | 0.49   |
| Mean hydraulic head (piezometer c)  | 67.13  | 68.65  | 70.13  | 69.92  | 69.53  | 69.30  |
| Mean hydraulic head (piezometer a)  | 63.31  | 66.21  | 66.80  | 66.40  | 66.50  | 66.28  |
| Hydraulic head (piezometer c ) max  | 67.13  | 67.45  | 68.58  | 68.72  | 68.13  | 67.95  |
| Hydraulic head (piezometer a) min   | 63.40  | 66.21  | 65.45  | 65.59  | 65.48  | 65.69  |
| Mean distance (m) between source and piezometer (c)                             | 250.00 | 250.00 | 250.00 | 250.00 | 250.00 | 250.00 |
| Mean distance (m) between c and receptor (lower Tenches pit stream ) (LTPS)     | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 | 200.00 |
| Plume distance (m) in 1 year (mean)   | 8.51   | 11.32  | 24.99  | 42.84  | 57.43  | 18.04  |
| Plume distance (m) in 1 year (max)  | 8.71   | 22.27  | 26.59  | 48.18  | 65.67  | 24.11  |
| Travel time (year) from proposed PRB to piezometer (a) (120 m)                  | 14.10  | 10.61  | 4.80   | 2.80   | 2.09   | 6.65   |
| Travel time (year) from c to receptor (LTPS)(200 m)                             | 23.50  | 17.68  | 8.00   | 4.67   | 3.48   | 11.08  |

**Table 3:** Reactive media denitrification rate and PRB thickness to reduce  $\text{NO}_3^- \text{N}$  concentration from  $24.24 \text{ mg NO}_3^- \text{N L}^{-1}$  (highest concentration) to  $11.3 \text{ mg L}^{-1}$  (allowable concentration)

| Reactive media  | Denitrification rate*<br>( $\mu\text{g L g day}^{-1}$ ) | Retention time<br>(days) | PRB thickness<br>(m) |       |
|-----------------|---|--------------------------|----------------------|-------|
|                 |   |                          | mean                 | max   |
| Brown earth     | $2.09 \pm 0.01$   | 223.04                   | 16.61                | 19.91 |
| Gley            | $4.34 \pm 0.10$   | 107.41                   | 8.00                 | 8.00  |
| Gley + Woodchip | 21.70   | 21.48                    | 1.60                 | 1.91  |

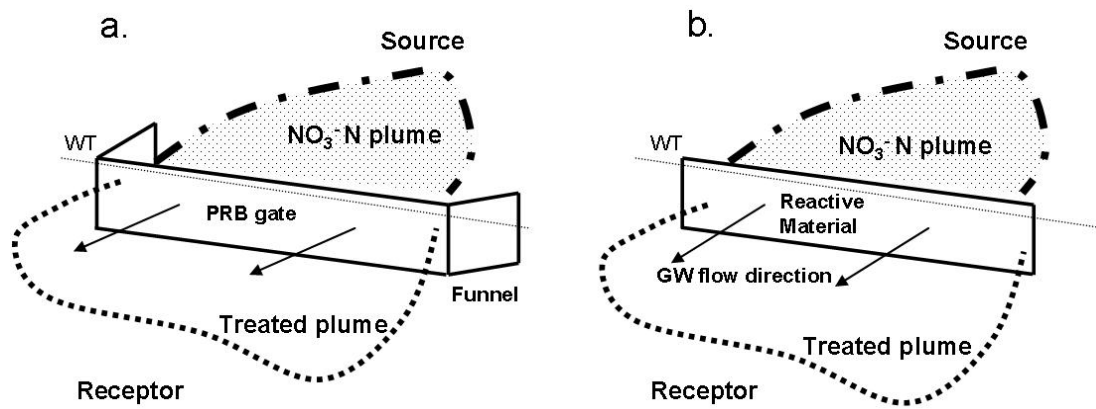
\*adapted from Sullivan and McDermott (2007)



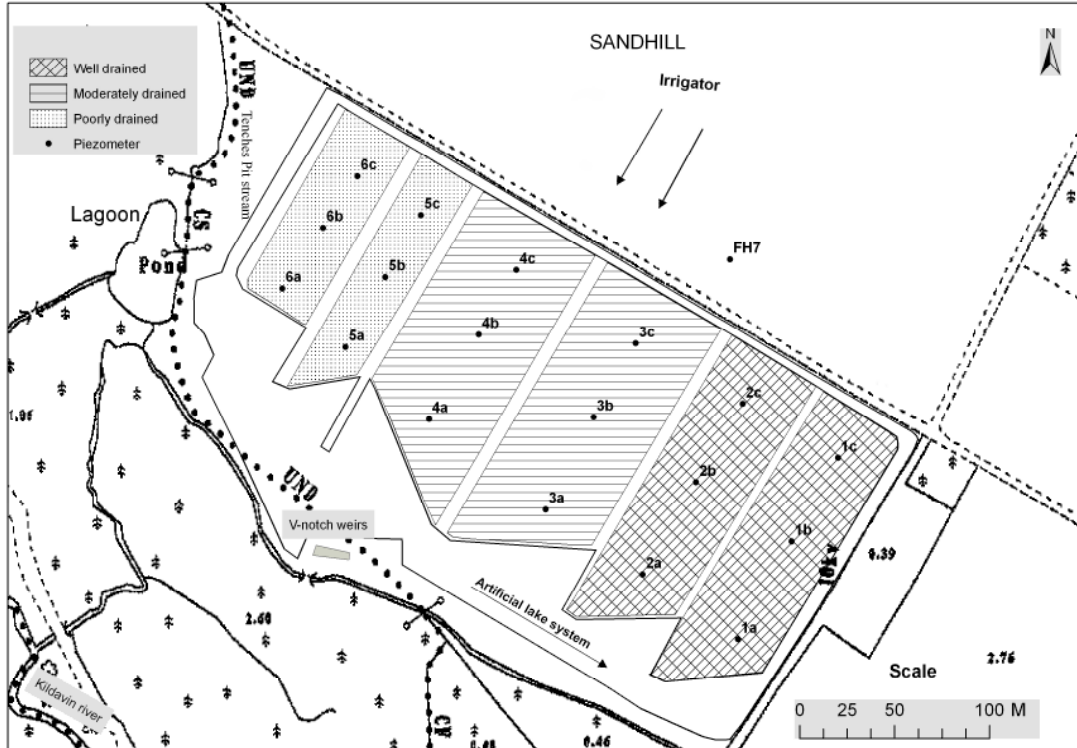
**Table 4:** PRB orientation, reactive media type and dimensions.

| PRB dimensions |  |               |
|----------------|--|---------------|
| Horizontal (x) | Vertical (y)                           | Thickness (z) |
| (m)            | (m)                                    | (m)           |
| 250            | 2                                      | 1.6 – 1.9     |
| Orientation    | Parallel to groundwater contours       |               |
| Reactive media | Woodchip and gley soil mix (ratio 5:2) |               |

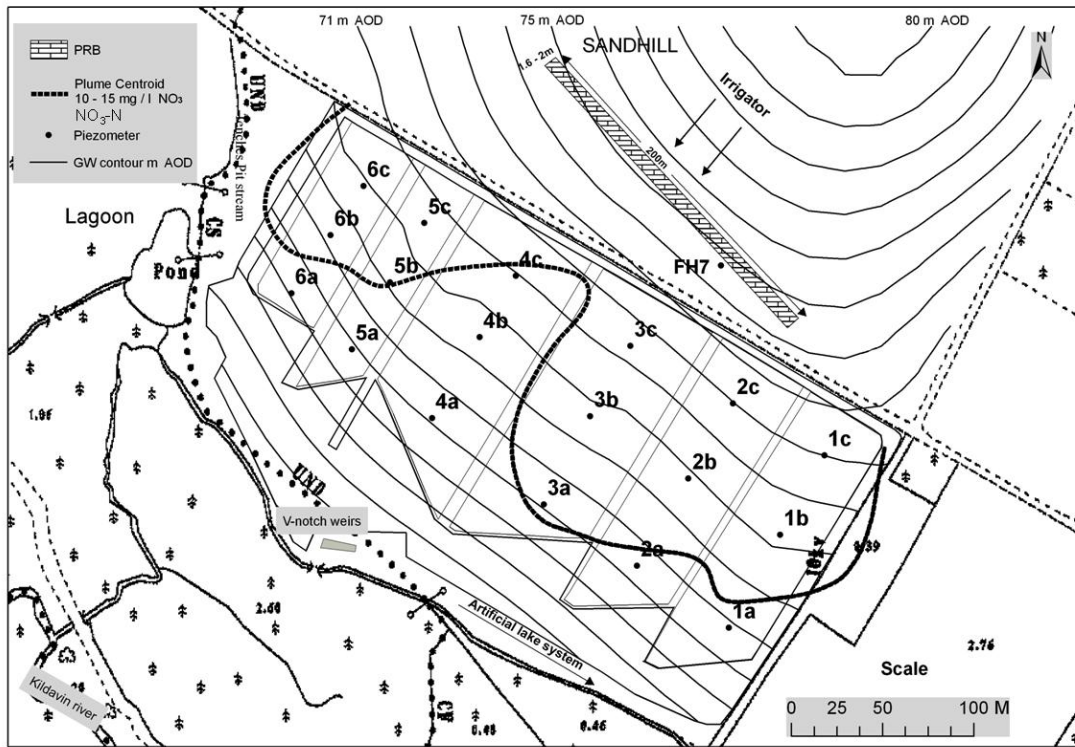
**Figure 1:** Two types of subsurface PRBs a: funnel and gate, b: continuous trench; with source, NO<sub>3</sub>-N plume, reactive material, treated plume and receptor. Watertable (WT) positioned within treatment wall containing reactive material and barrier constructed perpendicular to groundwater (GW) flow direction.



**Figure 2:** Field site layout showing plot location, irrigator source, potential receptors (Tenches pit stream, lagoon, Kildavin River and connection to artificial lake system), piezometer locations and drainage of the study site.



**Figure 3:** Groundwater contours (modelled using block kriging) based on groundwater heads and topography. Flow from high to low hydraulic head contours at right angles to contours. Plume centroid location (10 – 15 mg NO<sub>3</sub>-N L<sup>-1</sup>) PRB orientation, location and dimensions.



**Figure 4:** Schematic diagram showing cross sectional (1c – 6c) conceptual model of the contamination plume with source on the sandhill. Highest median  $\text{NO}_3\text{-N}$  concentration is within plume centroid. Watertable shows hydraulic gradient from plot 4 towards plots 1 and 6. Centroid vertical and horizontal thickness and dilution fronts can also be seen.

