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RADNOR HILLS

# Radnor Hills Effluent Discharge

## Evaluation of Risks to the Water Environment – Addendum A

Client:

Radnor Hills Mineral Water

Report Reference (Project/Document/Issue)

00058/RP210/Issue 2

Report Status:

For NRW Review

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18 October 2016

Prepared by:

RUKHYDRO Limited

RUKHYDRO Limited
Groundwater Protection & Leachate Management Consultancy
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## Report for

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## Reviewed by:

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## Notices and Disclaimer

### Scope of Work

This report has been prepared to provide supplementary information against an original proposed scope of work set out in Rukhydro Limited's proposal (Ref 00058/Cp004i1) dated 08 October 2015. The report contents reflect the scope, information provision by the client and third parties, time and costs and other assumptions agreed in that proposal or documented in writing as amendments to that proposal.

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# Summary

## Purpose and Layout of this Document

This report provides supplementary information to a Rukhydro (2015) report entitled "*Radnor Hills Effluent Discharge - Evaluation of Risks to the Water Environment*" dated 20 November 2015. This addendum provides additional information on:

- Shallow piezometers completed in the vicinity of the discharge and details of groundwater levels and groundwater quality obtained from them (Section 2).
- New source protection zone modelling which has investigated the risk of the current soakaway to Radnor Hills' abstractions (Section 3).
- An evaluation of information related to flows on the River Teme including information on which reaches dry up at times of low flows and an estimate of mean and low (95%ile) flows for use in surface water discharge calculations (Section 4).
- An update on what the additional information means in terms of the risks to groundwater from the proposed treated effluent discharge scenarios (Section 5).

This addendum report has been prepared by Rukhydro Limited for Radnor Hills Mineral Water Company Limited ("Radnor Hills") of Heartsease, near Knighton, Powys. It is prepared to support discussions with Cyfoeth Naturiol Cymru / Natural Resources Wales ("NRW") regarding an environmental permit for the discharge.

## Piezometers, Groundwater Levels and Gradients

Twelve shallow piezometers were installed in the vicinity of the lagoon / soakaway discharge in January and February 2016 and one replacement and three more were added in July 2016. A number of these continue to provide groundwater level data.

Groundwater level data described in Section 2 show the direction of groundwater flow in the gravels which underlies the lagoon is, as expected, down the valley in an approximate west to east direction. The average hydraulic gradient between piezometer PZ#6(2), through PZ#8b to the River Teme is ~0.008, whereas between PZ#8b and the River Teme is 0.015. These gradients are for groundwater levels recorded in February 2016.

Groundwater levels are typically no more than 2 m below ground level and in places at less than 1 m depth. Levels vary seasonally and have declined by ~0.5 m since February 2016.

## Water Quality Sampling

Six of the piezometers have been sampled for groundwater quality. A small abstraction at the nearby chicken farm has been used to provide background groundwater quality samples.

Lagoon and stream samples have also been taken.

Apart from a single manganese concentration exceeding its environmental quality standard (EQS) in the downstream stream sample, there were no other EQS exceedances for the stream samples. There is only minor / negligible evidence of the local stream being impacted by the lagoon discharge.

The groundwater downgradient of the lagoon discharge is, as expected, impacted by the discharge. There are elevated concentrations of some trace metals and ammoniacal nitrogen above drinking water standards and above the EQS for the River Teme. It is likely that these elevated concentrations are due to reactions in the groundwater system as the current high organic loading is degraded rather than being in the lagoon discharge itself.

Excluding manganese and zinc, the most that the most stringent EQS is exceeded by is an anomalous reading for nonylphenol (17x), then iron (8x) followed by cobalt (3.9x), then ammoniacal nitrogen (3.4x). PZ#8b generally has the highest concentrations. Zinc and manganese exceedances are up to 150 times their EQS.

The water quality data has been used:

- To calculate the proportion of lagoon water in groundwater (and stream) samples. The average proportion of lagoon water in the most affected piezometer (PZ#8b) is 16%. With an average current effluent discharge of 160 $m^3$/day, this implies the effluent is diluted downgradient by an average of 840 $m^3$/day to give total average flows of 1000 $m^3$/day;
- To provide evidence for natural attenuation of the current effluent loading. This suggests degradation of the high organic loading is occurring as a result of oxygen, nitrate and sulphate consumption in groundwater and the reduction of manganese and iron oxides in the aquifer materials. There is also evidence for significant organic matter degradation by methanogenesis with loss of methane and carbon dioxide to air above the lagoon.
- To provide evidence that, at the current discharge rate of 160 $m^3$/day, an effluent filtered BOD of ~50 mg/l $O_2$ could be accommodated by aerobic oxidation using background groundwater dissolved oxygen. If beneficial nitrate reduction was also considered then an effluent filtered BOD of ~100 mg/l $O_2$ could be accommodated without releasing dissolved metals from the aquifer materials or generating methane gas.

## Source Protection Zones

A detailed MODFLOW model (with 5 m grid) has been set up of the Radnor Hills area by Groundwater Science and calibrated against groundwater levels. This has been used with FlowSource to define new source protection zones for Radnor Hills' operational use. It has also been used to examine the potential for the soakaway's plumes to impact upon Radnor Hills' abstracted water.

Modelled plumes are consistent with groundwater sampling data in terms of width and extent of the plume and suggest negligible risk to the Radnor Hills abstraction under current and future abstraction and discharge scenarios.

Groundwater flows calculated using the SPZ model calibrated hydraulic properties and plume widths suggest a diluting groundwater flow of 500 $m^3$/day for the current 160 $m^3$/day discharge. This is less than the 1000 $m^3$/day estimated using water quality data, although in hydrogeological terms is a broadly similar number.

Hydraulic gradients may be steeper (between the lagoon and piezometer PZ#8b in summer when the river dries up and thus stops constraining groundwater levels near the river. Alternatively, the hydraulic conductivity of the gravels may be higher closer to the river.

## River Teme Flows and Dry Reaches

Flow data for the River Teme near Heartsease are limited and some sections of the river are prone to drying out. Through careful evaluation of available information, the reaches prone to drying out have been mapped out and flow statistics for the River Teme at Lingen Bridge have been estimated. Flow estimates have been provided for use in evaluating a discharge to river near Lingen Bridge.

The flow estimates have been checked against dates on which fish results took place and suggest fish rescues occur under plausible low ($92^{nd}$ to $99.5^{th}$) river level conditions.

The assessment has shown there is good evidence for a consistent net loss from the river to groundwater between Milebrook Bridge and Lingen Bridge of between 8,640 $m^3$/day at high river flows and 15,552 $m^3$/day during dry (low river flow) periods. These losses have been estimated to give a flow per metre width of gravels near the river of between 21.6 $m^3$/day/m and 38.9 $m^3$/day/m. This is more than that derived using water quality data and plume modelling which suggests ~10 $m^3$/day/m width of background groundwater flow and so suggests the dilution assumed for the discharge is not only plausible but conservative. It also suggests the hydraulic conductivity of the gravels may be greater close to the river.

## Risks from the Proposed Discharges

Discharge rates and quality have been defined for the future discharge scenarios including Klargester ("septic tank") only (8 $m^3$/day), normal operations (100 $m^3$/day) and maximum (298 $m^3$/day). In terms of infiltration rates, discharge of the Klargester only to "the Wet" and final lagoon would meet Environment Agency and Building Regulations guidance, but the other scenarios would exceed this capacity.

Under normal operating conditions (100 $m^3$/day), "the Wet" and the final lagoon have a proven current capacity to accept this (and up to ~160 $m^3$/day), but this capacity will be insufficient to accept the maximum discharge scenario (298 $m^3$/day). It is likely that the infiltration capacity of "the Wet" and final lagoon have reduced as a result of sediment deposition, but in theory the gravels have the capacity to accept this higher discharge rate. Desludging is therefore likely to be required before this higher rate could be accepted.

Attenuation of contaminants in the unsaturated zone may be significant for the Klargester only scenario, but would be minimal for the other scenarios.

Dilution of all the discharges would be significant leading to a large reduction in Klargester concentrations (x1.9%) and ~x16.5% concentrations for both of the other scenarios. The worst case is diluted concentration increases in downgradient groundwater of 1.7 mg/l $O_2$ $BOD_{5ATU}$, 0.71 mg/l N ammoniacal nitrogen and 0.1 mg/l P phosphorus / phosphate.

The $BOD_{5ATU}$ and ammoniacal nitrogen are likely to be oxidised by dissolved oxygen from the upgradient groundwater and leave a downgradient dissolved oxygen concentration of >7 mg/l $O_2$. This means conditions in groundwater will remain aerobic and there is unlikely to be release of dissolved metals associated with iron and manganese reduction.

Phosphate attenuation is likely to be significant in the groundwater environment.

Unretarded travel times between the final lagoon and the River Teme are likely to be of the order of 1 year. This is also the likely timescale for flushing of currently impacted groundwater from the system, although there may be some delay if reduced metals need to be oxidised and re-precipitated in the alluvium / gravels.

## Recommendations

Recommendations have been made for on-going and future monitoring and with regard to desludging and bund maintenance of "the Wet" and final lagoon. This includes a period of testing the "the Wet" and final lagoon at increasing discharge rates during a period when discharge to river is a back-up option.

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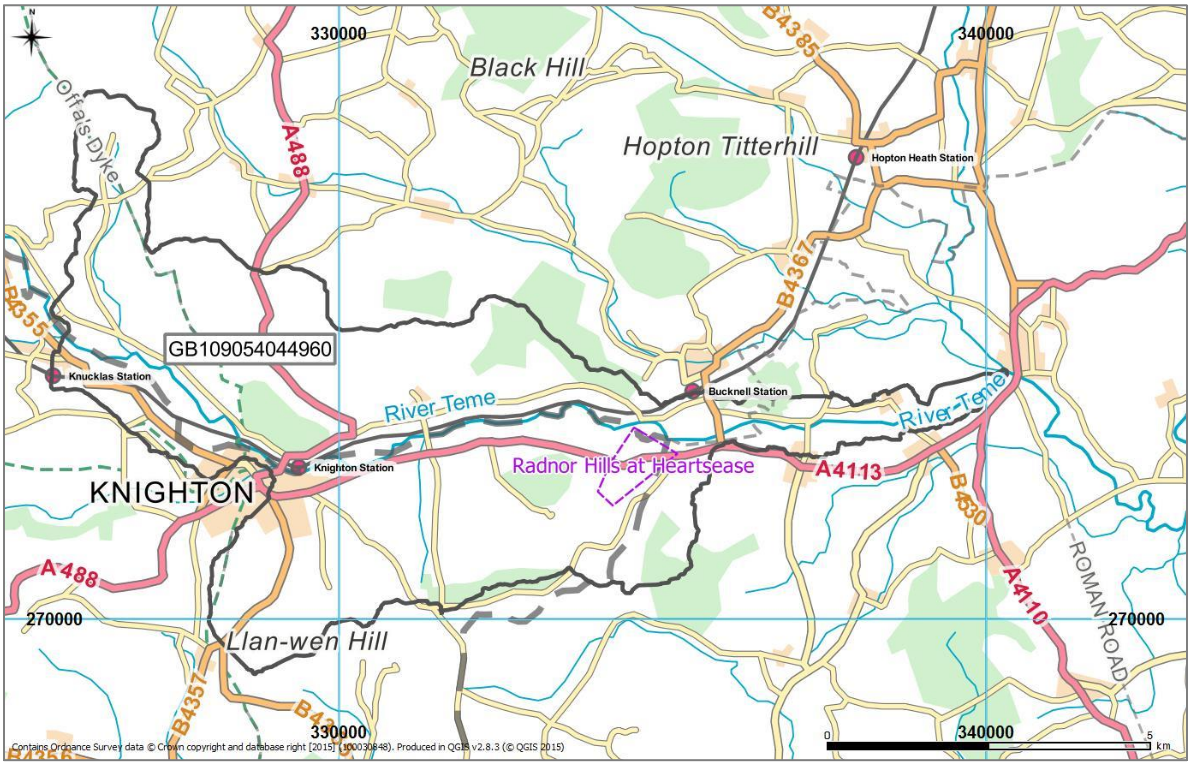
# 1. Introduction

## 1.1 Purpose of this Report

The purpose and scope of this report is set out in detail on the Summary page (i). It provides supplementary information to a Rukhydro (2015) report entitled "*Radnor Hills Effluent Discharge - Evaluation of Risks to the Water Environment*" dated 20 November 2015.

It has been prepared by Rukhydro Limited for Radnor Hills Mineral Water Company Limited ("Radnor Hills") of Heartsease, near Knighton, Powys (see Figure 1.1). It is prepared to support discussions with Cyfoeth Naturiol Cymru / Natural Resources Wales ("NRW") regarding an environmental permit for the discharge.

**Figure 1.1 – Location of Radnor Hills Premises**




**Note**: Contains Ordnance Survey data © Crown Copyright and database right [2016]. Produced in QGIS v2.8.3 © 2016.

The **black outlined area** is the catchment (Cycle 2, draft) of Water Framework Directive (WFD) River Water Body GB109054044960 – the River Teme from "*source to conf Ffwdwen Bk to conf R Clun*" at Leintwardine at the eastern end of the catchment. The boundary was downloaded from the Environment Agency's Geostore website on 03 November 2015. The Teme catchment extends further west and northwest.

## 1.2 Background Information

Details of the Radnor Hills abstractions and treated effluent discharge to soakaway, the site setting and an initial evaluation of the potential impacts to groundwater and the River Teme are provided in the Rukhydro (2015) report.

This addendum is prepared assuming the reader has access to, and is familiar with, the Rukhydro (2015) report and does not repeat that report's detail.

## 1.3 Work by SDL

Radnor Hills is being supported by Sustainable Direction Ltd (SDL) to help obtain regulatory permission to discharge treated effluent to groundwater or surface water, specify a treatment plant design to complement the discharge, and to optimise efficiency and reduce resource use and waste generation.

This Rukhydro report addendum work has been undertaken in discussion with SDL.

## 1.4 Layout of this Report

Following this introduction, Section 2 describes new piezometers and associated groundwater level and quality data and Section 3 summarises the findings of Source Protection Zone modelling. Section 4 summarises an evaluation of flows and drying up reaches for the River Teme and Section 5 provides an updated evaluation of the potential impact to groundwater of the soakaway discharge. Each report section has a final summary section. Recommendations are provided in Section 6.

Figures and tables are provided within the sections and Appendices provide supporting information.

# 2. Piezometers, Levels and Quality

## 2.1 Purpose of this Section

This section presents the details of piezometers installed in and around the soakaway discharge primarily to constrain groundwater levels, but also to allow reconnaissance sampling.

## 2.2 Location and Construction

### 2.2.1 Location

Figure 2.1 shows the location of the piezometers installed on 12 January 2016, 01 February 2016 and 21 June 2016. The second date was used to drive-in slightly deeper piezometers where shallower ones had subsequently dried out or had insufficient water for sampling. On the third date, additional piezometers were installed intending to be immediately downgradient of the discharge to ground.

### 2.2.2 Details

Table 2.1 provides details of the piezometer depths, screen length, height above ground level and geology where excavated. Elevations were initially estimated using LiDAR data, but the locations and elevations of some were subsequently surveyed in on 10 August 2016 by Invar Mapping Surveys Ltd.

### 2.2.3 Construction

The piezometers were designed primarily for a quick and cost effective reconnaissance of groundwater levels, but with an option for water quality sampling. Therefore instead of contracting, mobilisation and supervision of a drilling rig, the piezometers were installed by either augering or as drive-in.

Two types of piezometers were installed:

- 42 mm internal diameter PVC piezometers were installed using a hole advanced initially by fence post whacker, deepened further using a hand auger, and then completed with PVC screen (with geotextile sock) and casing.
- 19 mm internal diameter, drive-in galvanised steel piezometers were also installed with a 0.3 m long screen and internal geotextile sleeve.

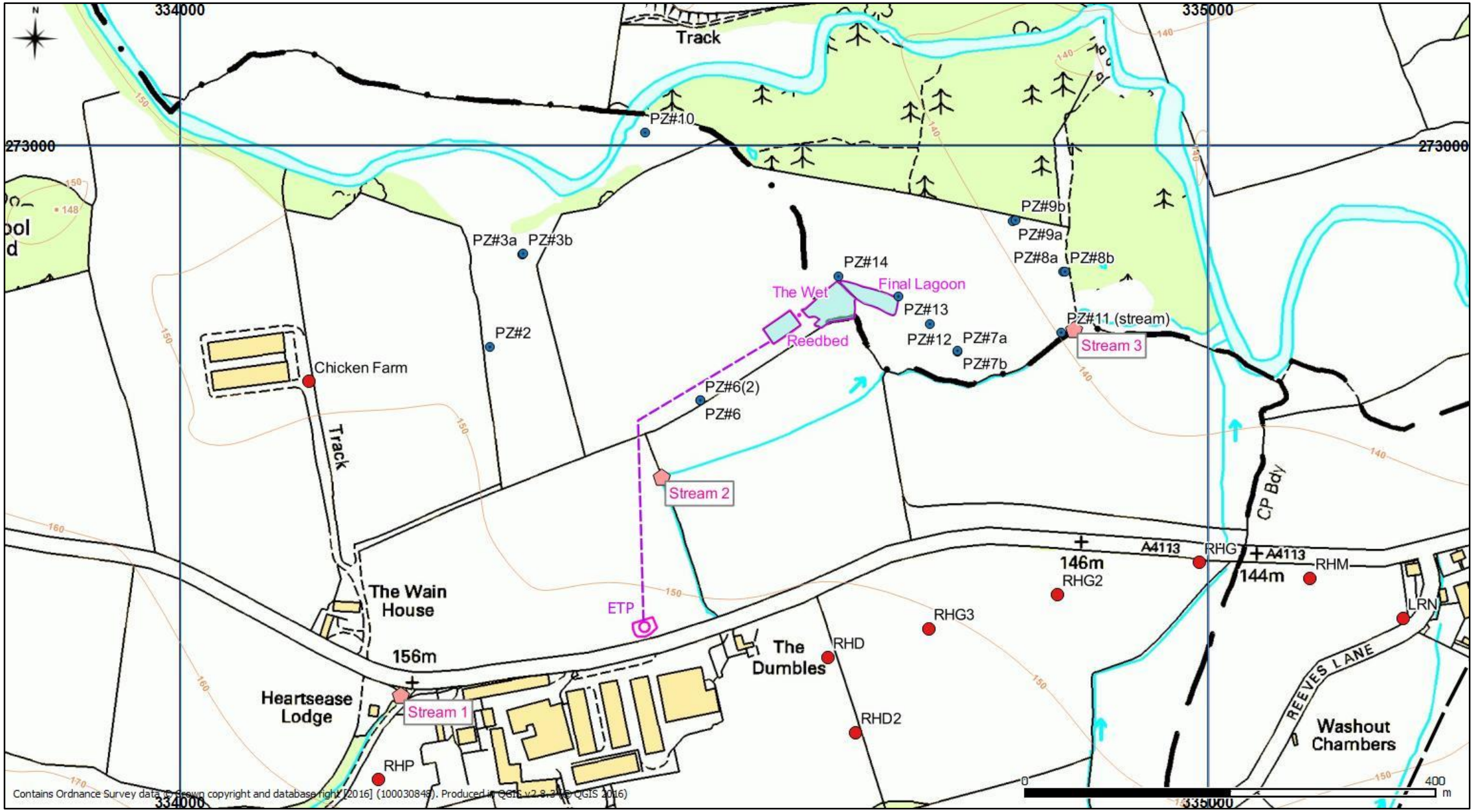
The 42 mm piezometers could not be advanced very deeply (<2 m bgl) as the holes rapidly collapsed as the auger encountered gravels. The drive-in 19 mm metal piezometers achieved a slightly greater depth (up to 3.3 m bgl).

The tops of the piezometers were sealed in the upper 20-30 cm using locally sourced clayey material to prevent surface water ingress.

### 2.2.4 Strata Encountered

Table 2.1 presents information on the geology encountered in the 42 mm id piezometer holes. Typically, clay with fine gravel was present in the top metre and below this “fine gravels in a sand/clay mix” were encountered. Close to the river, at PZ#10, pebble sized clasts were present. The strata encountered is consistent with that recorded in a borehole (see Appendix A for borehole log) at the chicken farm operated by Dumbles Poultry Limited.

**Figure 2.1 – Location of Piezometers and Stream Sample Locations**




**Note:** Contains Ordnance Survey data © Crown Copyright and database right [2016] (100030848). Produced in QGIS v2.8.3 © 2016. ETP = effluent treatment plant. RH = Radnor Hills production borehole. 'Chicken Farm' is a small abstraction at Dumbles Poultry Limited. PZ = piezometer. Stream = surface water sample location.

**Table 2.1 Piezometer and Chicken Farm Borehole Details**

| Piezometer | Easting | Northing | Ground Level[1] m AOD | Height of Pipe m agl | Top of Screen m bgl | Base of Screen m bgl | Construction[2] | Geology where excavated | Date Installed | Water Strike Comments[3] |
|---|---|---|---|---|---|---|---|---|---|---|
| PZ#1, 4 & 5 | | | | | | | | | Cancelled[4] | |
| PZ#2 | 334301.5 | 272804.8 | 144.903 | 0.59 | 2.11 | 2.41 | 19 mm i.d. metal | | 01/02/2016 | |
| PZ#3a | 334333 | 272895 | *144.07* | 0.69 | 0.88 | 1.88 | 42 mm i.d. PVC | Sandy clay to approx. 0.8mbgl, then pale yellow-white clayey sand and fine gravel to base. | 12/01/2016 | Rising through day |
| PZ#3b | 334333.6 | 272895.2 | 144.07 | 0.86 | 2.84 | 3.14 | 19 mm i.d. metal | | 01/02/2016 | |
| PZ#6 (lost) | *334505* | *272752* | *143.388* | 0.64 | 2.06 | 2.36 | 19 mm i.d. metal | | 01/02/2016 | |
| PZ#6(2) | 334505.5 | 272752.4 | 143.388 | 0.581 | 1.52 | 1.82 | 19 mm i.d. metal | | 21/07/2016 | |
| PZ#7a | *334756* | *272800* | *140.917* | 0.94 | 0.92 | 1.92 | 42 mm i.d. PVC | Clay to 0.4mbgl then fine gravels in sand/clay. | 12/01/2016 | <0.1 m bgl |
| PZ#7b | 334756.2 | 272801.4 | 140.917 | 0.114 | 2.03 | 2.33 | 19 mm i.d. metal | | 12/01/2016 | Slowly filling |
| PZ#8a | *334859* | *272878* | *140.39* | 0.44 | 0.40 | 1.40 | 42 mm i.d. PVC | Clay with fine gravel dominates top metre then fine gravels in sand/clay. | 12/01/2016 | < a few cm bgl |
| PZ#8b | 334860.3 | 272877.8 | 140.497 | 0.543 | 3.03 | 3.33 | 19 mm i.d. metal | | 12/01/2016 | |
| PZ#9a | *334810* | *272927* | *140.901* | 0.405 | 0.46 | 1.46 | 42 mm i.d. PVC | Clay with fine gravel dominates top metre then fine gravels in sand/clay | 12/01/2016 | 0.6 m after 1 hour |
| PZ#9b | 334812.9 | 272928 | 140.901 | 0.877 | 2.80 | 3.10 | 19 mm i.d. metal | | 01/02/2016 | |
| PZ#10 | 334452 | 273013 | 142.25 | 0.84 | 0.96 | 1.96 | 42 mm i.d. PVC | Clay with fine gravel dominates top metre then pebble sized clasts brought up by auger below. | 12/01/2016 | Filling to ~river level |
| PZ#11 (stream) | 334857.3 | 272818.9 | 140.141 | 0.752 | 3.01 | 3.31 | 19 mm i.d. metal | | 01/02/2016 | |
| PZ#12 | 334728.8 | 272827 | 140.986 | 0.895 | 2.205 | 2.505 | 19 mm i.d. metal | | 21/07/2016 | |
| Pz#13 | 334698.9 | 272854.2 | 141.078 | 1.074 | 2.026 | 2.326 | 19 mm i.d. metal | | 21/07/2016 | |
| Pz#14 | 334640.5 | 272873.7 | 141.649 | 0.471 | 2.629 | 2.929 | 19 mm i.d. metal | | 21/07/2016 | |
| Chicken Farm | 334125.5 | 272771.1 | 147.977 | 0.519 | 6.78 | 11.28 | 100 mm i.d. HDPE | Made ground to1.22 m (4ft), sandy gravel to 4.57 m (15ft) then gravel to 11.28 m (37ft). | 02/03/2009 | (24ft) 7.315 m bgl |

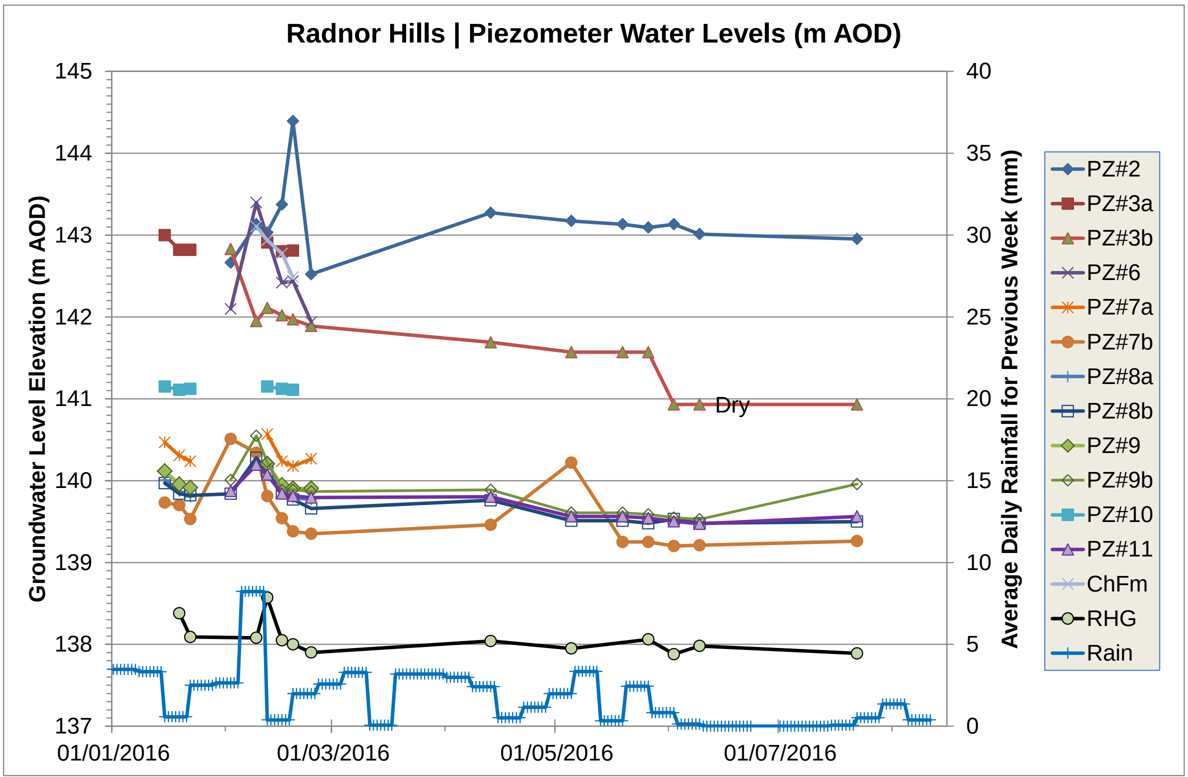
1) Notes: Surveyed in by Invar Mapping Surveys Ltd on 10 August 2016 (if underlined or assumed to be the same as surveyed in if in italics) or estimated using approximate location and LiDAR data for that location.
2) The 42 mm internal diameter (i.d.) were installed using a hole advanced initially by fence post whacker, deepened further using a hand auger, and then completed with PVC screen (with geotextile sock) and casing. The 19 mm i.d. galvanised steel piezometers were driven-in. They have a 0.3 m long screen and internal geotextile sleeve.
3) See Table 2.2 for monitored groundwater levels data.
4) PZ#1 was to be close to the location of the Chicken Farm borehole, but cancelled when the presence of that borehole was identified. PZ#4 and #5 were not installed due to lack of time.

## 2.3 Groundwater Levels

### 2.3.1 Data and Time Series Chart

Table 2.2 provides groundwater levels recorded between 15 January 2016 and 22 July 2016 and those to 24 February 2016 are illustrated on a time series chart on Figure 2.2.

**Figure 2.2 – Time Series Chart for Piezometer Water Levels**




**Notes**: See Figure 2.1 for locations of piezometers and Table 2.1 for piezometer construction details.

### 2.3.2 Interpretation of Groundwater Level Data

Table 2.2 shows that groundwater levels are shallow; being less than 2 m below ground level (bgl) in a number of the piezometers. Groundwater levels are deeper (~5 m bgl) in the chicken farm borehole.

Figure 2.2 shows:

- A general pattern of gradual decline since late January 2016 consistent with variations in rainfall and mirrored by water level variation in abstraction borehole RHG. Some piezometers have dried out since June 2016.
- The water level fluctuation appears largest at PZ#7b near the soakaway.
- Higher water level elevations in the shallower ("a", PVC) piezometers than the adjacent drive-in ("b", metal) piezometers at locations PZ#3 and PZ#7 implying a downward gradient consistent with rainfall recharge to the surface and greater flow at depth in more permeable horizons.
- Anomalously high water levels in PZ#2 on 16 and 19 February 2016.

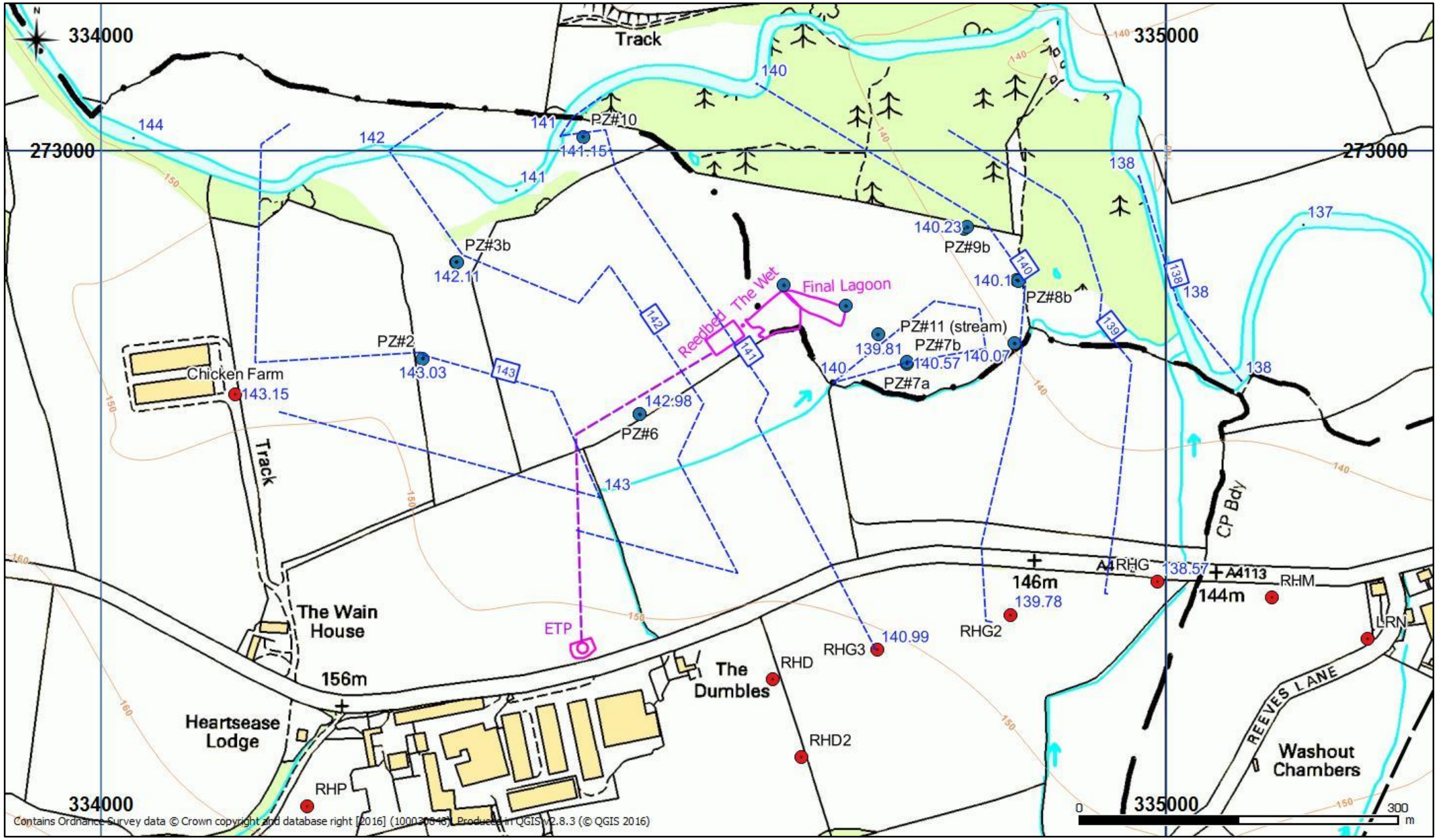
Overall, the piezometers appear to be providing plausible water level data. Figure 2.3 maps water level elevations on 11th or 12th February 2016 including water levels from the Radnor Hills abstractions from the drift. The chicken farm borehole was abstracting on this date. River stage elevations are also shown as used in the Rukhydro (2015) report.

**Table 2.2 Monitored Groundwater Levels in the Piezometers and Chicken Farm Borehole**

| Piezo-meter[1] | Ground Level[2] m AOD | Height of Pipe m agl | Depth to Water Level (m bgl) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 15/01/2016 | 19/01/2016 | 22/01/2016 | 02/02/2016 | 09/02/2016 | 12/02/2016 | 16/02/2016 | 19/02/2016 | 24/02/2016 | 13/04/2016 | 05/05/2016 | 19/05/2016 | 26/05/2016 | 02/06/2016 | 09/06/2016 | 22/07/2016 |
| PZ#2 | 144.903 | 0.59 | | | | 2.24 | 1.77 | 1.87 | 1.53 | 0.51 | 2.38 | 1.63 | 1.73 | 1.77 | 1.81 | 1.77 | 1.89 | 1.95 |
| PZ#3a | 143.5 | 0.69 | 1.07 | 1.25 | 1.25 | | | 1.16 | 1.27 | 1.26 | | | | | | | | |
| PZ#3b | 144.07 | 0.86 | | | | 1.24 | 2.12 | 1.96 | 2.05 | 2.1 | 2.18 | 2.38 | 2.5 | 2.5 | 2.5 | >3.14 | >3.14 | >3.14 |
| PZ#6(lost) | 143.388 | 0.64 | | | | 1.29 | -0.01 | 0.41 | 0.97 | 0.95 | 1.45 | | | | | | | |
| Pz#6(2) | 143.388 | 0.581 | | | | | | | | | | | | | | | | |
| PZ#7a | *140.917* | 0.94 | 0.45 | 0.61 | 0.68 | | | 0.35 | 0.68 | 0.74 | 0.65 | | | | | | | |
| PZ#7b | 140.917 | 0.114 | 1.19 | 1.22 | 1.39 | 0.41 | 0.58 | 1.11 | 1.38 | 1.54 | 1.57 | 1.46 | 0.70 | 1.67 | 1.67 | 1.72 | 1.71 | 1.66 |
| PZ#8a | 140.39 | 0.44 | 0.38 | 0.52 | 0.59 | | | 0.30 | 0.52 | 0.60 | 0.62 | | | | | | | |
| PZ#8b | 140.497 | 0.543 | 0.53 | 0.66 | 0.68 | 0.66 | 0.22 | 0.39 | 0.65 | 0.73 | 0.84 | 0.74 | 0.99 | 0.99 | 1.02 | 0.97 | 1.02 | 1.00 |
| PZ#9a | *140.901* | 0.405 | 0.78 | 0.94 | 0.98 | | | 0.69 | 0.95 | 0.99 | 0.99 | | | | | | | |
| PZ#9b | 140.901 | 0.877 | | | | 0.89 | 0.35 | 0.67 | 1.01 | 1.01 | 1.03 | 1.01 | 1.29 | 1.29 | 1.31 | 1.35 | 1.37 | 0.94 |
| PZ#10 | 142.25 | 0.84 | 1.10 | 1.14 | 1.13 | | | 1.10 | 1.13 | 1.14 | | | | | | | | |
| PZ#11 ('stream') | 140.141 | 0.752 | | | | 0.27 | -0.05 | 0.07 | 0.30 | 0.33 | 0.35 | 0.34 | 0.58 | 0.58 | 0.60 | 0.64 | 0.67 | 0.58 |
| Pz#12 | 140.986 | 0.895 | | | | | | | | | | | | | | | | 1.80 |
| PZ#13 | 141.078 | 1.074 | | | | | | | | | | | | | | | | 2.09 |
| Pz#14 | 141.649 | 0.471 | | | | | | | | | | | | | | | | 1.61 |
| Chicken Farm | 147.977 | 0.519 | | | | | 4.87 | 5.04 | 5.20 | 5.49 | | | | | | | | |

Notes:
1) See Table 2.1 for construction details and location.
2) Surveyed in by Invar Mapping Surveys Ltd on 10 August 2016 (if underlined or assumed to be the same as surveyed in if in italics) or estimated using approximate location and LiDAR data for that location.

**Figure 2.3 – Comparison of Rukhydro (2015) Estimated and Piezometer Measured Groundwater Levels on 11 to 12/02/2016**




**Note:** Contains Ordnance Survey data © Crown Copyright and database right [2016] (100030848). Produced in QGIS v2.8.3 © 2016. ETP = effluent treatment plant. RH = Radnor Hills production borehole. 'Chicken Farm' is a small abstraction at Dumbles Poultry Limited. Where there are two piezometers at one location, the deeper drive-in piezometer is labelled with its name and water level, except for PZ#7a/7b where there is a difference in levels.

The water level elevations have been contoured simplistically in QGIS and suggest a general west to east, down valley, hydraulic gradient. The chicken farm borehole water level is a pumped water level. Water levels at the deeper piezometer PZ#7b are anomalously low compared to PZ#7a and the contoured groundwater levels. Ground levels, casing dipping point and dips for PZ#7b have been checked. The August 2016 survey noted a lagoon water level of 141.469 m AOD, placing this 0.5 to 1.0 m above contoured groundwater levels in that area.

For the February 2016 dates, the average hydraulic gradient between near PZ#6(2), through PZ#8b to the river Teme is ~0.008, whereas between PZ#8b and the River Teme it is 0.015.

## 2.4 Lagoon and Stream Water Quality

### 2.4.1 Samples collected

Samples were collected from the lagoon / soakaway and the stream which drains eastwards to the River Teme and runs from upstream of the Radnor Hills site. Locations of sample points are shown on Figure 2.1. Stream samples were collected on 26 January 2016 (Stream 1, 2 & 3) and 23 February 2016 (lagoon and Stream 2 & 3).

The samples were stored in a cool box and despatched on the day of sampling to Alcontrol Laboratories for analysis.

### 2.4.2 Results

Analytical data are reported in Table 2.3 and 2.4. Determinands were chosen to be consistent with samples of groundwater; the rationale for which is discussed in Section 2.5.2.

### 2.4.3 Exceedances of Environmental Quality Standards

Environmental quality standards (EQSs) are for protection of surface waters. For those parameters analysed, and for which have EQSs, then there were two possible exceedances in the stream samples (one upstream and one downstream):

- Dissolved manganese (annual average = bioavailable = 123 µg/l):
  - Stream 3 (downstream of the soakaway) (178 µg/l dissolved).
- Dissolved zinc (maximum = 300 µg/l; annual average = 50 µg/l):
  - Stream 2 (up-stream of the soakaway) (82.4 µg/l).

### 2.4.4 Evaluation of Impact from the Lagoon Discharge

With the Stream 3 sample downstream of the area of the lagoon and the Stream 2 sample upstream of the lagoon, then a downstream increase in concentration of a substance that was present in high concentrations in the lagoon could imply some impact by the lagoon. Changes could also be to do with field runoff.

Chloride concentrations are consistently high (average 73.9 mg/l) in the lagoon relative to those in the upstream samples (43.2 and 19.2 mg/l) and chloride is a conservative parameter (only affected by dilution and dispersion). For the sample on 26 January 2016, the increase in chloride from Stream 2 to 3 is 4.7 mg/l which could translate[1] into the Stream 3 sample containing 9% lagoon water. It may also be related to runoff from fields. There is no change in chloride concentration on 23 February 2016, when lower electrical conductivities suggest more diluting runoff was present.

[1] Using the following formula to work =out the proportion of Stream 3 water that is lagoon water:

$$\text{Lagoon volume} \div \text{Stream 3 volume} = ([\text{Stream } 3_{conc} - \text{Stream } 2_{conc}]/[\text{Mean Lagoon}_{conc} - \text{Stream } 2_{conc}])$$

Where 'conc' means concentration.

### Table 2.3 Sampled Lagoon Quality (Page 1 of 2)

| Determinand | Units | LOD[1] | AA-EQS[1] | MAC-EQS[1] | Lagoon[2] 07/07/15 | Lagoon[2] 02/09/15 | Lagoon[2] 23/02/16 | Lagoon[2] 19/05/16 | Lagoon[2] 29/06/16 | Lagoon[2] 31/08/16 | Lagoon Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | | <1 | | 6.0-9.0 | **5.9** | **4.49** | **5.52** | **5.10** | **5.60** | **5.31** | 5.32 |
| EC@20°C | mS/cm | <0.005 | | | | | 1.01 | 0.862 | 0.956 | 0.731 | 0.89 |
| Suspended Solids | mg/l | <2 | | | 118 | | 96 | 74 | 110 | 213 | 122.20 |
| Total Dissolved Solids | mg/l | <5 | | | 982 | | 779 | 613 | 749 | 595 | 743.60 |
| Calcium (total) | mg/l | <0.057 | | | 51.5 | | 58.6 | 52.1 | 46.8 | 60.2 | 53.84 |
| Magnesium (total) | mg/l | <0.05 | | | 7.18 | | 8.19 | 7.54 | 6.96 | 8.49 | 7.67 |
| Sodium (total) | mg/l | <0.047 | | | 265 | | 267 | 153 | 163 | 125 | 194.60 |
| Potassium (total) | mg/l | <2 | | | 16.9 | | 24.8 | 24 | 24.3 | 26 | 23.20 |
| Chloride | mg/l | <2 | 250 | | 157 | 57.8 | 91.5 | 45.5 | 39.9 | 51.7 | 73.90 |
| Bromide | mg/l | <0.06 | | | 0.415 | 2.06 | <0.06 | <0.30 | 0.352 | 0.281 | 0.58 |
| Fluoride | mg/l | <0.5 | 5 | 15 | 0.956 | | <0.5 | 0.581 | 0.843 | 0.908 | 0.82 |
| Sulphate | mg/l | <2 | 400 | | <2 | <2 | 12.1 | <2 | <2 | <2 | 3.68 |
| Sulphide | mg/l | <0.01 | | | 0.596 | 0.515 | 0.275 | 0.813 | 1.110 | 0.233 | 0.59 |
| Alkalinity (as $CaCO_3$) | mg/l | <2 | | | | | 315 | 187 | 350 | 235 | 271.75 |
| Nitrate as N | mg/l | <0.0677 | | | <0.1 | | 0.0896 | <0.0677 | <0.0677 | 0.165 | 0.10 |
| Nitrite as N | mg/l | <0.0152 | | | | | <0.0152 | <0.0152 | <0.0152 | <0.0152 | 0.02 |
| Ammoniacal N | mg/l | <0.2 | | 0.3 | **7.28** | <0.2 | 0.232 | 0.3 | <0.2 | 0.811 | 1.76 |
| Dissolved Oxygen | mg/l | <0.3 | | | <0.3 | | <0.3 | <0.3 | <0.3 | <0.3 | 0.30 |
| BOD, unfiltered | mg/l $O_2$ | <1 | | | 838 | | 1110 | 1370 | 1160 | 930 | 1081.60 |
| BOD, filtered | mg/l $O_2$ | <1 | | | 840 | | 1070 | 970 | 990 | 834 | 940.80 |
| COD, unfiltered | mg/l $O_2$ | <7 | | | 1240 | | 1680 | 1610 | 1990 | 1460 | 1596.00 |
| COD, filtered | mg/l $O_2$ | <10 | | | 1250 | | 1650 | 1590 | 1760 | 1260 | 1502.00 |
| Total Organic Carbon | mg/l | <3 | | | 434 | | 536 | 601 | 580 | 466 | 523.40 |
| TPH / Oil & Greases | mg/l | <1 | | | 9.31 | | 6.55 | (-) | 12.4 | 6.74 | 8.75 |
| Nonylphenols | µg/l | <0.02 | 0.3 | 2.0 | <0.02 | **0.53** | **1.7** | **0.7** | **1.06** | | 1.00 |
| Toluene | µg/l | | 74 | 380 | **548** | **147** | | **269** | **225** | **123** | **262.40** |

Notes:

1) LOD = limit of detection, AA-EQS = annual average environmental equality standard, and MAC-EQS = maximum admissible concentration EQS. for inland waters from (Environment Agency, 2011b). It is noted that the guidance has been updated as Environment Agency (2014), but no longer includes these collated EQS values. Where limits are hardness dependent a hardness of >50 mg/l CaCO3 has been assumed. Likewise the altitude at Heartsease is >80 m AOD.
2) Lagoon = soakaway, also referred to as sample point P4.

**Table 2.3 Sampled Lagoon Quality (Page 2 of 2)**

| Determinand | Units | LOD[1] | AA-EQS[1] | MAC-EQS[1] | Lagoon[2] 07/07/15 | Lagoon[2] 02/09/15 | Lagoon[2] 23/02/16 | Lagoon[2] 19/05/16 | Lagoon[2] 29/06/16 | Lagoon[2] 31/08/16 | Lagoon Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Dissolved Methane | µg/l | <1 | | | | | | 9770 | 6520 | 6110 | 7466.67 |
| Phosphorus (total) | µg/l | <20 | | | | 1240 | 49 | 140 | 1480 | 853 | 752.40 |
| Phosphate (ortho) as P | µg/l | <0.02 | | | | | <20 | <20 | <20 | <20 | 20.00 |
| Iron (diss.filt) | mg/l | <0.019 | 1 | | **2.1** | **2.8** | **1.38** | **1.71** | 1.73 | 2.27 | 2.00 |
| Manganese (diss.filt) | mg/l | <0.04 | (bioav.)123 | | 154 | | 83.1 | 87.3 | 124 | 96.4 | 108.96 |
| Arsenic (diss.filt) | µg/l | <0.12 | 50 | | 0.974 | 1.28 | 0.752 | 1.04 | 1.37 | 1.25 | 1.11 |
| Boron (diss.filt) | µg/l | <9.4 | 2000 | | 51.4 | 63.6 | 63.8 | 79.9 | 81.4 | 63.1 | 67.20 |
| Cadmium (diss.filt) | µg/l | <0.1 | 0.09 | 0.06 | <0.1 | <0.1 | <0.1 | <0.1 | **0.374** | **0.24** | **0.17** |
| Chromium (diss.filt) | µg/l | <0.22 | 4.7 | 32 | 2.6 | **4.77** | | **4.85** | **7.12** | 3.13 | 4.49 |
| Chromium (tot.unfilt) | µg/l | <3 | | | 2.74 | | <3 | | | | 2.87 |
| Cobalt (diss.filt) | µg/l | <0.06 | 3.0 | 100 | 0.753 | 0.685 | 0.322 | 0.236 | 0.544 | 0.386 | 0.49 |
| Copper (diss.filt) | µg/l | <0.85 | 6.0 | | 2.09 | 2.33 | 2.13 | 1.68 | 4.18 | 5.57 | 3.00 |
| Lead (diss.filt) | µg/l | <0.02 | 7.2 | | 1.07 | 0.867 | 0.724 | 0.441 | 3.26 | 0.399 | 1.13 |
| Nickel (diss.filt) | µg/l | <0.15 | 20 | | 2.58 | 3.12 | 2.62 | 2.85 | 3.01 | 3.15 | 2.89 |
| Selenium (diss.filt) | µg/l | <0.39 | | | | | 1.34 | 2.04 | 1.92 | <0.81 | 1.77 |
| Tin (diss.filt) | µg/l | <0.36 | 25 | | <0.36 | 0.737 | 1.42 | <0.36 | <0.36 | 1.24 | 0.75 |
| Vanadium (diss.filt.) | µg/l | <0.24 | 20 | | 2.51 | 4.18 | 2.97 | 3.27 | 4.16 | 3.09 | 3.36 |
| Zinc (diss.filt.) | µg/l | <0.41 | 50 | 300 | 48.7 | **60.3** | 32.1 | 36.1 | 35.1 | **113** | **54.22** |

Notes:

1) LOD = limit of detection, AA-EQS = annual average environmental equality standard, and MAC-EQS = maximum admissible concentration EQS. for inland waters from (Environment Agency, 2011b). It is noted that the guidance has been updated as Environment Agency (2014), but no longer includes these collated EQS values. Where limits are hardness dependent a hardness of >50 mg/l CaCO3 has been assumed. Likewise the altitude at Heartsease is >80 m AOD.
2) Lagoon = soakaway, also referred to as sample point P4.

**Table 2.4 Sampled Surface Water Quality (Page 1 of 2)**

| Determinand | Units | LOD[1] | AA-EQS[1] | MAC-EQS[1] | Stream 1<br>26/01/16 | Stream 2<br>26/01/16 | Stream 3<br>26/01/16 | Stream 2<br>23/02/16 | Stream 3<br>23/02/16 |
|---|---|---|---|---|---|---|---|---|---|
| pH | | <1 | | 6.0-9.0 | 7.73 | 7.67 | 7.31 | 7.78 | 7.58 |
| EC@20°C | mS/cm | <0.005 | | | 0.174 | 0.298 | 0.303 | 0.189 | 0.197 |
| Suspended Solids | mg/l | <2 | | | 24 | 250 | 500 | 5 | 15.5 |
| Total Dissolved Solids | mg/l | <5 | | | | | | 149 | 153 |
| Calcium (total) | mg/l | <0.057 | | | 21.9 | 30 | 34.2 | 21.6 | 22.2 |
| Magnesium (total) | mg/l | <0.05 | | | 4.98 | 7.22 | 10.1 | 4.73 | 4.77 |
| Sodium (total) | mg/l | <0.047 | | | 9.57 | 28.4 | 33.5 | 13.4 | 13.6 |
| Potassium (total) | mg/l | <2 | | | <2 | 3 | 3.9 | <2 | <2 |
| Chloride | mg/l | <2 | 250 | | 14.8 | 43.2 | 47.9 | 19.3 | 19.3 |
| Bromide | mg/l | <0.06 | | | <0.06 | <0.06 | <0.06 | <0.06 | <0.06 |
| Fluoride | mg/l | <0.5 | 5 | 15 | <0.5 | <0.5 | <0.5 | <0.5 | <0.5 |
| Sulphate | mg/l | <2 | 400 | | 7.5 | 8.1 | 7.3 | 13.6 | 10.2 |
| Sulphide | mg/l | <0.01 | | | <0.01 | 0.0646 | <0.01 | <0.01 | <0.01 |
| Alkalinity (as $CaCO_3$) | mg/l | <2 | | | 50 | 80 | 90 | 60 | 65 |
| Nitrate as N | mg/l | <0.0677 | | | 2.88 | 1.66 | 0.644 | 2.65 | 2.65 |
| Nitrite as N | mg/l | <0.0152 | | | <0.0152 | 0.0192 | 0.0259 | <0.0152 | <0.0152 |
| Ammoniacal N | mg/l | <0.2 | | 0.3 | 0.222 | <0.2 | <0.2 | <0.2 | <0.2 |
| Dissolved Oxygen | mg/l | <0.3 | | | | | | 9.46[3] | 10.5[3] |
| BOD, unfiltered | mg/l $O_2$ | <1 | | | 18 | <1 | 27.5 | <1 | <1 |
| BOD, filtered | mg/l $O_2$ | <1 | | | | | | <1 | <1 |
| COD, unfiltered | mg/l $O_2$ | <7 | | | 33 | 11.9 | 49 | 20.3 | 12.7 |
| COD, filtered | mg/l $O_2$ | <10 | | | | | | 12.3 | 13.7 |
| Total Organic Carbon | mg/l | <3 | | | 4.41 | 4.89 | 5.25 | 3.62 | 3.8 |
| TPH / Oil & Greases | mg/l | <1 | | | <1 | 1.57 | 3.88 | <1 | <1 |
| Nonylphenols | µg/l | <0.02 | 0.3 | 2.0 | 0.09 | 0.25 | 0.19 | <0.02 | <0.02 |
| Toluene | µg/l | | 74 | 380 | | | | | |

Notes:

1) LOD = limit of detection, AA-EQS = annual average environmental equality standard, and MAC-EQS = maximum admissible concentration EQS. for inland waters from (Environment Agency, 2011b). It is noted that the guidance has been updated as Environment Agency (2014), but no longer includes these collated EQS values. Where limits are hardness dependent a hardness of >50 mg/l $CaCO_3$ has been assumed. Likewise the altitude at Heartsease is >80 m AOD.
2) Lagoon = soakaway, also referred to as sample point P4.
3) These samples were not preserved in the field and were analysed by oxygen meter rather than Winkler titration and so are less reliable.

**Table 2.4 Sampled Surface Water Quality (Page 2 of 2)**

| Determinand | Units | LOD[1] | AA-EQS[1] | MAC-EQS[1] | Stream 1<br>26/01/16 | Stream 2<br>26/01/16 | Stream 3<br>26/01/16 | Stream 2<br>23/02/16 | Stream 3<br>23/02/16 |
|---|---|---|---|---|---|---|---|---|---|
| Dissolved Methane | µg/l | <1 | | | | | | | |
| Phosphorus (total) | µg/l | <20 | | | 76.9 | 322 | 549 | 56.3 | 65.2 |
| Phosphate (ortho) as P | µg/l | <0.02 | | | 0.0222 | <0.02 | <0.02 | <0.02 | <0.02 |
| Iron (diss.filt) | mg/l | <0.019 | 1 | | 0.0367 | 0.0301 | 0.0386 | 0.0309 | 0.0232 |
| Manganese (diss.filt) | mg/l | <0.04 | (bioav.)123 | | 5.44 | 11.4 | 178 | 7.28 | 13.1 |
| Arsenic (diss.filt) | µg/l | <0.12 | 50 | | 0.369 | 0.658 | 0.809 | 0.439 | 0.264 |
| Boron (diss.filt) | µg/l | <9.4 | 2000 | | 23.7 | 24.1 | 16.6 | 16.7 | 16.8 |
| Cadmium (diss.filt) | µg/l | <0.1 | 0.09 | 0.06 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 |
| Chromium (diss.filt) | µg/l | <0.22 | 4.7 | 32 | 1.91 | 1.23 | 1.23 | | |
| Chromium (tot.unfilt) | µg/l | <3 | | | <3 | 12.4 | 24.3 | <3 | <3 |
| Cobalt (diss.filt) | µg/l | <0.06 | 3.0 | 100 | 0.089 | 0.142 | 0.899 | 0.094 | 0.074 |
| Copper (diss.filt) | µg/l | <0.85 | 6.0 | | 1.42 | 3.15 | 3.16 | 1.54 | 1.82 |
| Lead (diss.filt) | µg/l | <0.02 | 7.2 | | 0.157 | 0.226 | 0.239 | 0.124 | 0.109 |
| Nickel (diss.filt) | µg/l | <0.15 | 20 | | 0.897 | 1.04 | 1.16 | 0.964 | 1.11 |
| Selenium (diss.filt) | µg/l | <0.39 | | | <0.39 | <0.39 | <0.39 | <0.39 | <0.39 |
| Tin (diss.filt) | µg/l | <0.36 | 25 | | 1.79 | 2.21 | 1.34 | 1.12 | <0.36 |
| Vanadium (diss.filt.) | µg/l | <0.24 | 20 | | 0.599 | 0.726 | 0.674 | 0.503 | 1.02 |
| Zinc (diss.filt.) | µg/l | <0.41 | 50 | 300 | 3.15 | 19.9 | 21.5 | **82.4** | 45 |

Notes:

1) LOD = limit of detection, AA-EQS = annual average environmental equality standard, and MAC-EQS = maximum admissible concentration EQS. for inland waters from (Environment Agency, 2011b). It is noted that the guidance has been updated as Environment Agency (2014), but no longer includes these collated EQS values. Where limits are hardness dependent a hardness of >50 mg/l $CaCO_3$ has been assumed. Likewise the altitude at Heartsease is >80 m AOD.
2) Lagoon = soakaway, also referred to as sample point P4.

Repeating this calculation using sodium and potassium, which are not as conservative as chloride, would suggest the Stream 3 sample on 26 January 2016 contained 3.1% or 4.5% of lagoon water. Again however, these changes may be related to field runoff as implied by an increase in total phosphorus and suspended solids. Unfiltered BOD and COD would suggest Stream 3 contains 2.5% and 2.3% lagoon water respectively on 26 January 2016 and a below detection contribution on 23 February 2016.

Overall, there is a possible up to 9% contribution from the lagoon in the downstream stream sample at lower background stream flows. And regardless of the contribution, there is no exceedance of environmental quality standards, perhaps apart from for manganese.

## 2.5 Ground Water Quality

### 2.5.1 Samples collected

Samples of groundwater were collected on:

- 26 January 2016 (PZ#7b and PZ#8b);
- 23 February 2016 (PZ#7b, PZ#8b, PZ#9b, PZ#11 and the chicken farm borehole);
- 19 May 2016 (PZ#8b);
- 29 June 2016 (PZ#8a, PZ#14, chicken farm borehole);
- 31 August 2016 (PZ#14, the other piezometers being dry).

On 26 January 2016, the shallower (PZ#_a) PVC piezometers had insufficient water to allow sampling on that date and this is why additional drive-in piezometers were installed on 01 February 2016 to provide deeper sampling points. All but piezometer PZ#14 were also found to be dry on 31 August 2016 as groundwater levels had declined (see Figure 2.2).

Each sampled piezometer was purged of approximately three wells volumes using a dedicated HDPE 18 mm diameter bailer. The chicken farm borehole samples were from abstracted water. The samples were stored in a cool box and despatched on the day of sampling to Alcontrol Laboratories for analysis.

### 2.5.2 Results

The analytical suite was initially designed to evaluate evidence for gross contamination of groundwater (and surface water) by the lagoon discharge rather than be a comprehensive suite of e.g. all trace organics. The priority substance nonylphenol was specifically determined as this had previously been detected in the lagoon at concentrations of 0.53 µg/l and 0.95 µg/l. Toluene had also been measured in the lagoon water, but was not analysed initially, as it tends to be degradable, but subsequent discussions with NRW led to the addition of determination of volatile organics (including toluene) by headspace / GC-MS in samples collected in May, June and August 2016.

Analytical data (except the full list of volatile organics) are provided in Table 2.4 together with the drinking water standard and environmental quality standard (EQS) as reported in the Rukhydro (2015) report. The table also provides background groundwater quality for a pumped borehole at the chicken farm, upgradient and to the west of the lagoon.

Total inorganic carbon concentrations have been calculated using measured alkalinity and pH and assumed dissociation constants and are also shown in Table 2.4.

**Table 2.4 Sampled Groundwater Quality (Page 1 of 4)**

| Determinand | Units | LOD[1] | DWS[1] | AA-EQS[1] | MAC-EQS[1] | CH Farm[2] 03/05/13 | CH Farm[2] 23/02/16 | CH Farm[2] 29/06/16 | CH Farm[2] Average | PZ8b 26/01/16 | PZ8b 23/02/16 | PZ8b 19/05/16 | PZ8a 29/06/16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | | <1 | | | 6.0-9.0 | | 8.05 | 8.00 | 8.025 | 7.32 | 7.48 | 7.38 | 7.37 |
| EC@20°C | mS/cm | <0.005 | | | | 0.333 | 0.341 | 0.335 | 0.338 | 0.585 | 0.621 | 0.531 | 0.490 |
| Suspended Solids | mg/l | <2 | | | | | - | 6 | 6 | 2020 | 269 | 227 | 425 |
| Total Dissolved Solids | mg/l | <5 | | | | 206 | 256 | 262 | 259 | | 473 | 360 | 383 |
| Calcium (total) | mg/l | <0.057 | | | | 63 | 57.9 | 51.7 | 54.8 | 77.9 | 67.4 | 59.2 | 57.8 |
| Magnesium (total) | mg/l | <0.05 | | | | 7.2 | 7.62 | 6.59 | 7.105 | 16.4 | 6.32 | 6.98 | 3.78 |
| Sodium (total) | mg/l | <0.047 | 200 | | | 9.6 | 10.3 | 8.23 | 9.265 | 58.0 | 53.9 | 42.6 | 42.1 |
| Potassium (total) | mg/l | <2 | | | | 1.5 | <2 | 1.43 | <1.715 | 4.67 | 2.84 | 2.56 | 2.97 |
| Chloride | mg/l | <2 | 250 | 250 | | 15.18 | 15.4 | 14.5 | 14.95 | 20.1 | 25.3 | 22.7 | 21.3 |
| Bromide | mg/l | <0.06 | | | | 0.04 | <0.06 | <0.06 | <0.06 | 0.146 | 0.137 | 0.096 | 0.103 |
| Fluoride | mg/l | <0.5 | 5 | 15 | | 0.0434 | <0.5 | <0.5 | <0.5 | <0.5 | 0.549 | <0.5 | 0.564 |
| Sulphate | mg/l | <2 | 250 | 400 | | 14 | 14.9 | 12.7 | 13.8 | <2.0 | 8.4 | 8.9 | 7.0 |
| Sulphide | mg/l | <0.01 | | | | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | 0.448 | 0.0797 | 0.065 |
| Alkalinity (as $CaCO_3$) | mg/l | <2 | | | | 146.4 | 150 | 150 | 150 | 335 | 355 | 248 | 265 |
| Nitrate as N | mg/l | <0.0677 | 11.3 | | | 4.24 | 4.69 | 3.74 | 4.215 | <0.0677 | <0.0677 | 1.4 | <0.0677 |
| Nitrite as N | mg/l | <0.0152 | | | | <0.0012 | <0.0152 | <0.0152 | <0.0152 | <0.0152 | <0.0152 | <0.0152 | <0.0152 |
| Ammoniacal N | mg/l | <0.2 | 0.39 | | 0.3 | <0.01 | <0.2 | <0.2 | <0.2 | 0.353 | 0.353 | <0.2 | <0.2 |
| Dissolved Oxygen | mg/l $O_2$ | <0.3 | | | | | 9.77[3] | 11.5[3] | 10.65 | | 8.35[3] | 2.34 | 3.08 |
| BOD, unfiltered | mg/l $O_2$ | <1 | | | | | <1 | <1 | <1 | <1 | <1 | <1 | <1 |
| BOD, filtered | mg/l $O_2$ | <1 | | | | | <1 | <1 | <1 | | <1 | <1 | <1 |
| COD, unfiltered | mg/l $O_2$ | <7 | | | | | <7 | <7 | <7 | 35.2 | 55.3 | 65.9 | 90.9 |
| COD, filtered | mg/l $O_2$ | <10 | | | | | <10 | <10 | 10 | | 46 | 28 | 25.9 |
| Total Organic Carbon | mg/l | <3 | | | | | <3 | <3 | <3 | 6.16 | 6.17 | 3.98 | 4.00 |
| TPH / Oils & Greases | mg/l | <1 | | | | | <1 | <1 | 1 | 1.63 | 1.58 | 1.06 | 1.01 |
| Nonylphenols | µg/l | <0.02 | No std | 0.3 | 2.0 | | <0.02 | 0.05 | <0.035 | 0.18 | 0.18 | <0.02 | **0.55** |

Notes:

1) LOD = limit of detection, DWS = drinking water standard (2010, see references - standard are not available for some determinands), AA-EQS = annual average environmental equality standard, and MAC-EQS = maximum admissible concentration EQS. for inland waters from (Environment Agency, 2011b). It is noted that the guidance has been updated as Environment Agency (2014), but no longer includes these collated EQS values. Where limits are hardness dependent a hardness of >50 mg/l CaCO3 has been assumed. Likewise the altitude at Heartsease is >80 m AOD. Concentrations in excess of any of the standards are shown in **bold** text.
2) This is a small abstraction borehole at Dumbles Poultry Limited to the west of the fields containing the soakaway. The average uses 2016 data for consistency in detection limits.
3) These samples were not preserved in the field and were analysed by oxygen meter rather than Winkler titration and so are less reliability.

**Table 2.4 Sampled Groundwater Quality (Page 2 of 4)**

| Determinand | Units | LOD[1] | DWS[1] | AA-EQS[1] | MAC-EQS[1] | CH Farm[2] 03/05/13 | CH Farm[2] 23/02/16 | CH Farm[2] 29/06/16 | CH Farm[2] Average | PZ#8b 26/01/16 | PZ#8b 23/02/16 | PZ#8b 19/05/16 | PZ#8a 29/06/16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Toluene | µg/l | <1 | | | | | | <1 | <1 | | | <1 | <1 |
| Dissolved Methane | µg/l | <1 | | | | | | 2.77 | 2.77 | | | 4860 | 4440 |
| Phosphorus (total) | µg/l | <20 | | | | | <20 | <20 | 20 | 1090 | 428 | 177 | 336 |
| Phosphate (ortho) as P | mg/l | <0.02 | | | | | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 |
| Iron (diss.filt) | mg/l | <0.019 | 0.2 | 1 | | | <0.019 | <0.019 | <0.019 | **8.03** | <0.019 | 0.325 | 0.257 |
| Manganese (diss.filt) | µg/l | <0.04 | 50 | (bioav)123 | | | 0.432 | 23.9 | 12.166 | **18400** | **18200** | **10300** | **9480** |
| Arsenic (diss.filt) | µg/l | <0.12 | 10 | 50 | | | <0.12 | <0.12 | <0.12 | 8.23 | 5.29 | 2.45 | 2.31 |
| Boron (diss.filt) | µg/l | <9.4 | 1000 | 2000 | | | 14.7 | 11 | 12.85 | 33.6 | 31.1 | 31.6 | 28.9 |
| Cadmium (diss.filt) | µg/l | <0.1 | 5.0 | 0.09 | 0.06 | | <0.1 | <0.1 | 0.1 | 0.117 | <0.1 | <0.1 | <0.1 |
| Chromium (diss.filt) | µg/l | <0.22 | 50 | 4.7 | 32 | | | 2.28 | 2.28 | 4.54 | | 3.19 | 0.815 |
| Chromium (tot.unfilt) | µg/l | <3 | | | | | <3 | | <3 | 58.6 | 18.6 | | |
| Cobalt (diss.filt) | µg/l | <0.06 | | 3.0 | 100 | | <0.06 | 0.097 | <0.097 | **11.7** | **9.79** | **4.45** | **5.51** |
| Copper (diss.filt) | µg/l | <0.85 | 2000 | 6.0 | | | <0.85 | <0.85 | <0.85 | **9.04** | <0.85 | 2.58 | 0.951 |
| Lead (diss.filt) | µg/l | <0.02 | 10 | 7.2 | | | 0.062 | 0.196 | 0.129 | **20.3** | 0.273 | 1.61 | 1.38 |
| Nickel (diss.filt) | µg/l | <0.15 | 20 | 20 | | | 0.45 | 1.05 | 0.75 | **36.8** | **37.2** | **27.0** | **34.7** |
| Selenium (diss.filt) | µg/l | <0.39 | | | | | 0.698 | <0.39 | <0.54 | 0.954 | <0.39 | 0.667 | 0.641 |
| Tin (diss.filt) | µg/l | <0.36 | | 25 | | | 1.07 | 0.384 | 0.727 | 5.88 | 0.589 | <0.36 | 2.06 |
| Vanadium (diss.filt.) | µg/l | <0.24 | | 20 | | | 1.23 | 0.679 | 0.9545 | 6.78 | 3.48 | 1.32 | 1.06 |
| Zinc (diss.filt.) | µg/l | <0.41 | | 50 | 300 | | 0.978 | 8.19 | 4.584 | **1680** | **3230** | **2350** | **1590** |
| **Calculated Inorganic Carbon[3]** | | | | | | | | | | | | | |
| $H_2CO_3$ (as CaCO3) | mg/l | | | | | | 3.88 | 4.35 | 4.11 | 46.64 | 34.18 | 30.07 | 32.88 |
| $HCO_3^-$ (as CaCO3) | mg/l | | | | | | 149.42 | 149.48 | 149.45 | 334.76 | 354.64 | 247.80 | 264.79 |
| $CO_3^{2-}$ (as CaCO3) | mg/l | | | | | | 0.54 | 0.48 | 0.51 | 0.23 | 0.35 | 0.19 | 0.20 |
| Total Inorganic Carbon (as CaCO3) | mg/l | | | | | | 153.84 | 154.32 | 154.07 | 381.63 | 389.17 | 278.06 | 297.87 |

Notes:

1) LOD = limit of detection, DWS = drinking water standard (2010, see references - standard are not available for some determinands), AA-EQS = annual average environmental equality standard, and MAC-EQS = maximum admissible concentration EQS. for inland waters from (Environment Agency, 2011b). It is noted that the guidance has been updated as Environment Agency (2014), but no longer includes these collated EQS values. Where limits are hardness dependent a hardness of >50 mg/l $CaCO_3$ has been assumed. Likewise the altitude at Heartsease is >80 m AOD. Concentrations in excess of any of the standards are shown in **bold** text.
2) This is a small abstraction borehole at Dumbles Poultry Limited to the west of the fields containing the soakaway. The average uses 2016 data for consistency in detection limits
3) Calculated from pH and alkalinity and using the following dissociation constants (for 10°C) (after Hem, 1989): $K1 = ([HCO_3^-].[H^+])/[H_2CO_3] = 3.436E-07$ mol/l and $K2 = ([CO_3^{2-}].[H^+])/[HCO_3^-] = 3.236E-11$ mol/l. Alkalinity from hydroxide and borate are negligible meaning total alkalinity = carbonate alkalinity.

**Table 2.4 Sampled Groundwater Quality (Page 3 of 4)**

| Determinand | Units | LOD[1] | DWS[1] | AA-EQS[1] | MAC-EQS[1] | CH Farm[2] Average | PZ#7b 26/01/16 | PZ#7b 23/02/16 | PZ#9b 23/02/16 | PZ#11b 23/02/16 | PZ#14 29/06/16 | PZ#14 31/08/16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | | <1 | | | 6.0-9.0 | 8.025 | 7.2 | 7.37 | 7.21 | 7.35 | 7.37 | 6.03 |
| EC@20°C | mS/cm | <0.005 | | | | 0.338 | 0.4 | 0.35 | 0.276 | 0.465 | 0.289 | 0.295 |
| Suspended Solids | mg/l | <2 | | | | 6 | 2330 | 7380 | 4060 | - | 846 | <9 |
| Total Dissolved Solids | mg/l | <5 | | | | 259 | | 273 | 216 | 364 | 227 | 220 |
| Calcium (total) | mg/l | <0.057 | | | | 54.8 | 66.8 | 55.9 | 44.7 | 76 | 33.9 | 37.9 |
| Magnesium (total) | mg/l | <0.05 | | | | 7.105 | 19.3 | 30.7 | 25.8 | 14 | 2.16 | 3.6 |
| Sodium (total) | mg/l | <0.047 | 200 | | | 9.265 | 22 | 19.3 | 11.2 | 33.7 | 11.9 | 13.6 |
| Potassium (total) | mg/l | <2 | | | | <1.715 | 4.87 | 5.68 | 4.83 | 3.86 | 2.74 | 2.88 |
| Chloride | mg/l | <2 | 250 | 250 | | 14.95 | 18.9 | 17.3 | 14 | 18.8 | 12.7 | 14.6 |
| Bromide | mg/l | <0.06 | | | | <0.06 | 0.079 | 0.082 | 0.062 | 0.073 | 0.0877 | 0.077 |
| Fluoride | mg/l | <0.5 | 5 | 15 | | <0.5 | <0.5 | <0.5 | 0.89 | 1.51 | 0.796 | 0.56 |
| Sulphate | mg/l | <2 | 250 | 400 | | 13.8 | 9.9 | 15.5 | 17.7 | 10.9 | 15.3 | 13.3 |
| Sulphide | mg/l | <0.01 | | | | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | 0.0221 | 1.24 |
| Alkalinity (as $CaCO_3$) | mg/l | <2 | | | | 150 | 200 | 175 | 145 | 265 | 180 | 145 |
| Nitrate as N | mg/l | <0.0677 | 11.3 | | | 4.215 | 0.709 | 1.62 | 0.505 | 0.213 | <0.0677 | <0.0677 |
| Nitrite as N | mg/l | <0.0152 | | | | <0.0152 | 0.0158 | <0.0152 | <0.0152 | <0.0152 | <0.0152 | <0.0152 |
| Ammoniacal N | mg/l | <0.2 | 0.39 | | 0.3 | <0.2 | <0.2 | <0.2 | **1.03** | <0.2 | **0.733** | **0.548** |
| Dissolved Oxygen | mg/l $O_2$ | <0.3 | | | | 10.65 | | 7.72[3] | 7.02[3] | 6.58[3] | 2.46 | 6.03[3] |
| BOD, unfiltered | mg/l $O_2$ | <1 | | | | <1 | 5.68 | 2.22 | 3.04 | 2.2 | <1.5 | 4.12 |
| BOD, filtered | mg/l $O_2$ | <1 | | | | <1 | | <1 | <1 | <1 | <1 | 3.25 |
| COD, unfiltered | mg/l $O_2$ | <7 | | | | <7 | 21.5 | 206 | 260 | 110 | 98.2 | 320 |
| COD, filtered | mg/l $O_2$ | <10 | | | | 10 | | 12.9 | 39 | 16.4 | 20.5 | 21.5 |
| Total Organic Carbon | mg/l | <3 | | | | <3 | 3.75 | <3 | <3 | <3 | <3 | <3 |
| TPH / Oils & Greases | mg/l | <1 | | | | 1 | 1.82 | 1.51 | 4.68 | 2.83 | 2.6 | <1 |
| Nonylphenols | µg/l | <0.02 | No std | 0.3 | 2.0 | <0.035 | 0.13 | 0.08 | **0.36** | 0.14 | **5.1** | |

Notes:

1) LOD = limit of detection, DWS = drinking water standard (2010, see references - standard are not available for some determinands), AA-EQS = annual average environmental equality standard, and MAC-EQS = maximum admissible concentration EQS. for inland waters from (Environment Agency, 2011b). It is noted that the guidance has been updated as Environment Agency (2014), but no longer includes these collated EQS values. Where limits are hardness dependent a hardness of >50 mg/l CaCO3 has been assumed. Likewise the altitude at Heartsease is >80 m AOD. Concentrations in excess of any of the standards are shown in **bold** text.
2) This is a small abstraction borehole at Dumbles Poultry Limited to the west of the fields containing the soakaway.
3) These samples were not preserved in the field and were analysed by oxygen meter rather than Winkler titration and so are less reliability.

## Table 2.4 Sampled Groundwater Quality (Page 4 of 4)

| Determinand | Units | LOD[1] | DWS[1] | AA-EQS[1] | MAC-EQS[1] | CH Farm[2] Average | PZ#7b 26/01/16 | PZ#7b 23/02/16 | PZ#9b 23/02/16 | PZ#11b 23/02/16 | PZ#14 29/06/16 | PZ#14 31/08/16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Toluene | µg/l | <1 | | | | <1 | | | | | <1 | <1 |
| Dissolved Methane | µg/l | <1 | | | | 2.77 | | | | | 302 | 108 |
| Phosphorus (total) | µg/l | <20 | | | | 20 | 1040 | 2070 | 1850 | 980 | 1040 | 21.8 |
| Phosphate (ortho) as P | mg/l | <0.02 | | | | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 | <0.02 |
| Iron (diss.filt) | mg/l | <0.019 | 0.2 | 1 | | <0.019 | <0.019 | <0.019 | <0.019 | <0.019 | 1.41 | <0.019 |
| Manganese (diss.filt) | µg/l | <0.04 | 50 | (bioav)123 | | 12.166 | **1830** | **645** | **5730** | **3270** | **8130** | **6700** |
| Arsenic (diss.filt) | µg/l | <0.12 | 10 | 50 | | <0.12 | 2.19 | 0.5 | 0.189 | 0.271 | 3.65 | 3.98 |
| Boron (diss.filt) | µg/l | <9.4 | 1000 | 2000 | | 12.85 | 54.9 | 21 | 15.6 | 22.8 | 18.2 | 24.4 |
| Cadmium (diss.filt) | µg/l | <0.1 | 5.0 | 0.09 | 0.06 | 0.1 | <0.1 | <0.1 | **0.124** | **0.237** | <0.1 | <0.08 |
| Chromium (diss.filt) | µg/l | <0.22 | 50 | 4.7 | 32 | 2.28 | 1.43 | | | | 2.1 | <1.2 |
| Chromium (tot.unfilt) | µg/l | <3 | | | | <3 | 53.9 | 108 | 93 | 31.7 | | |
| Cobalt (diss.filt) | µg/l | <0.06 | | 3.0 | 100 | <0.097 | 2.62 | 2.03 | 2.19 | **4.81** | 1.28 | 0.92 |
| Copper (diss.filt) | µg/l | <0.85 | 2000 | 6.0 | | <0.85 | 2.63 | 1.18 | 0.852 | 2.8 | <0.85 | <0.85 |
| Lead (diss.filt) | µg/l | <0.02 | 10 | 7.2 | | 0.129 | 0.285 | 0.304 | 0.117 | 0.259 | 0.446 | 0.813 |
| Nickel (diss.filt) | µg/l | <0.15 | 20 | 20 | | 0.75 | 10.3 | 13 | 6.55 | 17 | 10.5 | 9.51 |
| Selenium (diss.filt) | µg/l | <0.39 | | | | <0.54 | <0.39 | <0.39 | <0.39 | <0.39 | 0.39 | <0.81 |
| Tin (diss.filt) | µg/l | <0.36 | | 25 | | 0.727 | 5.95 | 0.896 | 2.19 | 3.85 | 1.31 | 1.17 |
| Vanadium (diss.filt.) | µg/l | <0.24 | | 20 | | 0.9545 | 0.832 | 2.12 | 1.08 | 0.543 | 1.15 | <1.3 |
| Zinc (diss.filt.) | µg/l | <0.41 | | 50 | 300 | 4.584 | 681 | **2400** | **6620** | **6820** | **1390** | **4240** |
| **Calculated Inorganic Carbon[3]** | | | | | | | | | | | | |
| $H_2CO_3$ (as CaCO3) | mg/l | | | | | 4.11 | 36.71 | 21.71 | 26.01 | 34.43 | 22.33 | 15.31 |
| $HCO_3^-$ (as CaCO3) | mg/l | | | | | 149.45 | 199.89 | 174.86 | 144.92 | 264.80 | 179.86 | 144.86 |
| $CO_3^{2-}$ (as CaCO3) | mg/l | | | | | 0.51 | 0.10 | 0.13 | 0.08 | 0.19 | 0.14 | 0.13 |
| Total Inorganic Carbon (as CaCO3) | mg/l | | | | | 154.07 | 236.70 | 196.70 | 171.00 | 299.42 | 202.32 | 160.30 |

Notes:

1) LOD = limit of detection, DWS = drinking water standard (2010, see references - standard are not available for some determinands), AA-EQS = annual average environmental equality standard, and MAC-EQS = maximum admissible concentration EQS. for inland waters from (Environment Agency, 2011b). It is noted that the guidance has been updated as Environment Agency (2014), but no longer includes these collated EQS values. Where limits are hardness dependent a hardness of >50 mg/l $CaCO_3$ has been assumed. Likewise the altitude at Heartsease is >80 m AOD. Concentrations in excess of any of the standards are shown in **bold** text.
2) This is a small abstraction borehole at Dumbles Poultry Limited to the west of the fields containing the soakaway.
3) Calculated from pH and alkalinity and using the following dissociation constants (for 10°C) (after Hem, 1989): $K1 = ([HCO_3^-].[H^+])/[H_2CO_3]$ = 3.436E-07 mol/l and $K2 = ([CO_3^{2-}].[H^+])/[HCO_3^-]$ = 3.236E-11 mol/l. Alkalinity from hydroxide and borate are negligible meaning total alkalinity = carbonate alkalinity.

### 2.5.3 Exceedances of Water Quality Standards

***Exceedance of the Drinking Water Standard***

The following groundwater samples had exceedances of the drinking water standard:

- Ammoniacal nitrogen (standard = 0.39 mg/l N):
  - PZ#9b (1.03 mg/l N);
  - PZ#14 (0.733 and 0.548 mg/l N);
- Dissolved manganese (standard = 50 µg/l):
  - All piezometers (645 to 18,400 µg/l)*;
- Dissolved lead (standard = 10 µg/l):
  - PZ#8b (20.3 µg/l – anomalous reading)
- Dissolved nickel (standard = 20 µg/l):
  - PZ#8a (34.7 µg/l);
  - PZ#8b (27.0 and 37.2 µg/l).

**Note**: (*) There are also elevated concentrations of zinc, for which there is no current drinking water standard. It was thought that the elevated zinc and manganese might come from the zinc galvanised drive-in piezometers, but then a sample was collected from the plastic PZ#8a (slightly upgradient of the metal PZ#8b) and that also detected manganese, nickel and zinc. Total chromium concentrations are elevated, but the available dissolved concentrations are below the drinking water standard.

Overall, with the exception of the elevated manganese concentrations, the sampled groundwaters generally meet the drinking water standard. The manganese, zinc and nickel concentrations are higher than in the soakaway (see Table 2.3) indicating they are derived from the aquifer materials.

***Exceedances of Environmental Quality Standards***

Environmental quality standards (EQSs) are for protection of surface waters rather than groundwaters. Their use here therefore is to see if there are substances in groundwater that when discharged to surface water would require further dilution or attenuation to meet their EQS.

The following samples had exceedances of the environmental quality standards and so would require further evaluation to check if they could impact the River Teme:

- Ammoniacal nitrogen (maximum = 0.3 mg/l N):
  - PZ#9b (1.03 mg/l N);
  - PZ#8b (0.353 mg/l N)
  - PZ#14 (0.733 and 0.548 mg/l N);
- Nonylphenol (maximum = 2.0 µg/l; annual average = 0.3 µg/l):
  - PZ#8a (0.55 µg/l);
  - PZ#9b (0.36 µg/l);
  - PZ#14 (5.1 µg/l – anomalous reading);
- Dissolved iron (annual average = 1 mg/l):
  - PZ#8b (8.03 mg/l – anomalous reading);
  - PZ#14 (1.41 mg/l);
- Dissolved manganese (annual average = 123 µg/l (bioavailable):
  - PZ#7b to 11b (645 to 18400 µg/l)*;

- Dissolved cobalt (maximum = 100 µg/l; annual average = 3 µg/l):
  - PZ#8a (5.51 µg/l);
  - PZ#8b (4.45 to 11.7 µg/l);
  - PZ#11b (4.81 µg/l)
- Dissolved copper (annual average = 6 µg/l):
  - PZ#8b (9.04 µg/l – anomalous reading);
- Dissolved lead (annual average = 7.2 µg/l):
  - PZ#8b (20.3 µg/l – anomalous reading)
- Dissolved nickel (annual average = 20 µg/l):
  - PZ#8a (34.7 µg/l);
  - PZ#8b (36.8 and 37.2 µg/l);
- Dissolved zinc (maximum = 300 µg/l; annual average = 50 µg/l):
  - All piezometers (681 to 6820 µg/l)*.

Excluding manganese and zinc, the most that the most stringent EQS is exceeded by is an anomalous reading for nonylphenol (17x), then iron (8x) followed by cobalt (3.9x), then ammoniacal nitrogen (3.4x). PZ#8b generally has the highest concentrations. Zinc and manganese exceedances are up to 150 times their EQS.

### 2.5.4 Proportion of Lagoon Discharge in Groundwater

As for the evaluation of evidence for possible impact on stream water quality from the lagoon / soakaway discharge, changes in groundwater quality have been used to estimate the proportion of lagoon / soakaway water in groundwater. Abstracted water from the chicken farm borehole has been assumed to be representative of upgradient groundwater quality.

Table 2.5 makes estimates of the proportion of lagoon / soakaway water in the groundwater samples using the most conservative determinands (i.e. those most likely to be affected by dilution and dispersion only rather than sorption, degradation or release from aquifer materials due to other reactions. Figure 2.4 shows the estimated proportions on a chart for the three most likely conservative parameters (chloride, bromide and sodium) and for EC and total inorganic carbon.

Chloride and bromide are the two most conservative determinands, but the signal (lagoon) to background (chicken farm) ratio is better from bromide ([0.58/0.04 =] x14.5) than chloride ([73.9/14.95 =] x4.9). Using bromide, Table 2.5 and Figure 2.4 suggest PZ#8b/a has 10-20% lagoon water present, piezometers PZ#7b and PZ#14 have ~7-9% lagoon water present and PZ#9b and PZ#11b have ~4 to 6% lagoon water present.

Sodium, electrical conductivity and total dissolved solids (TDS) suggest the same relative order of most to least impacted, but in some samples imply higher proportions of lagoon water present. Each of these three determinands are however likely to be affected by reactions between the lagoon water and the gravels.

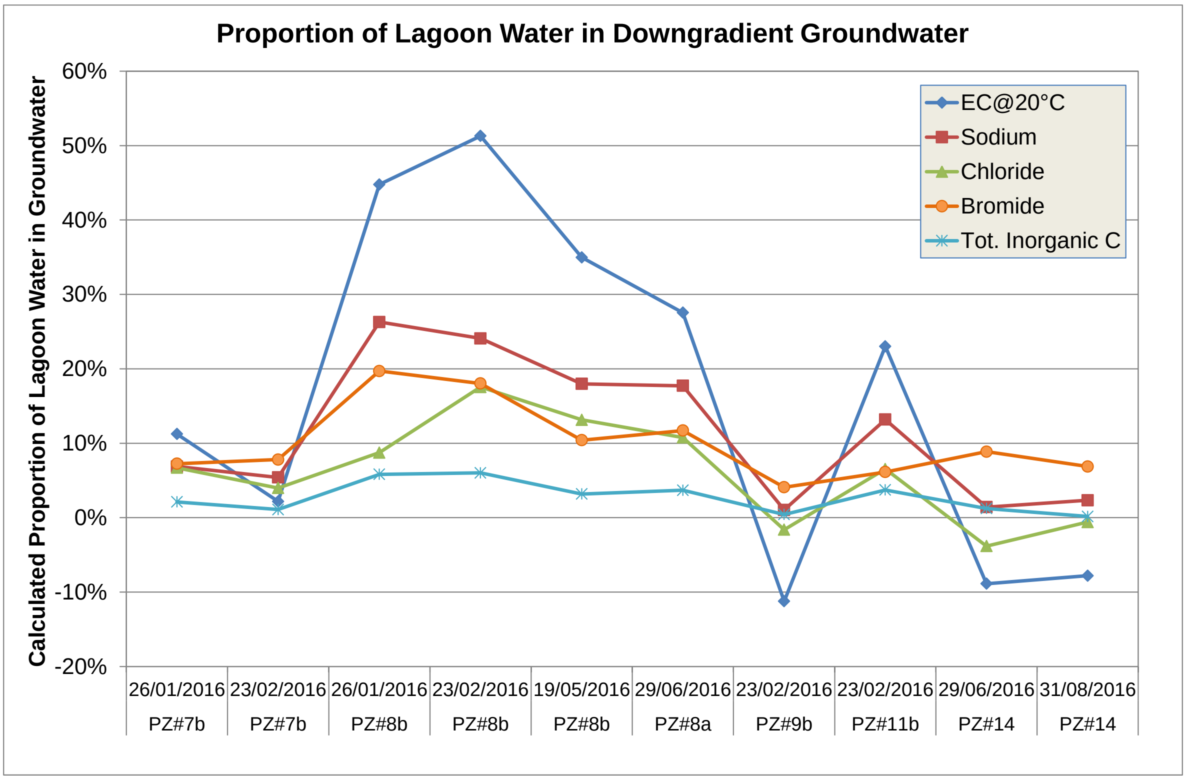
Using calculated total inorganic carbon shows lower proportions of lagoon water to those derived using bromide and chloride. This suggests loss of dissolved inorganic carbon.

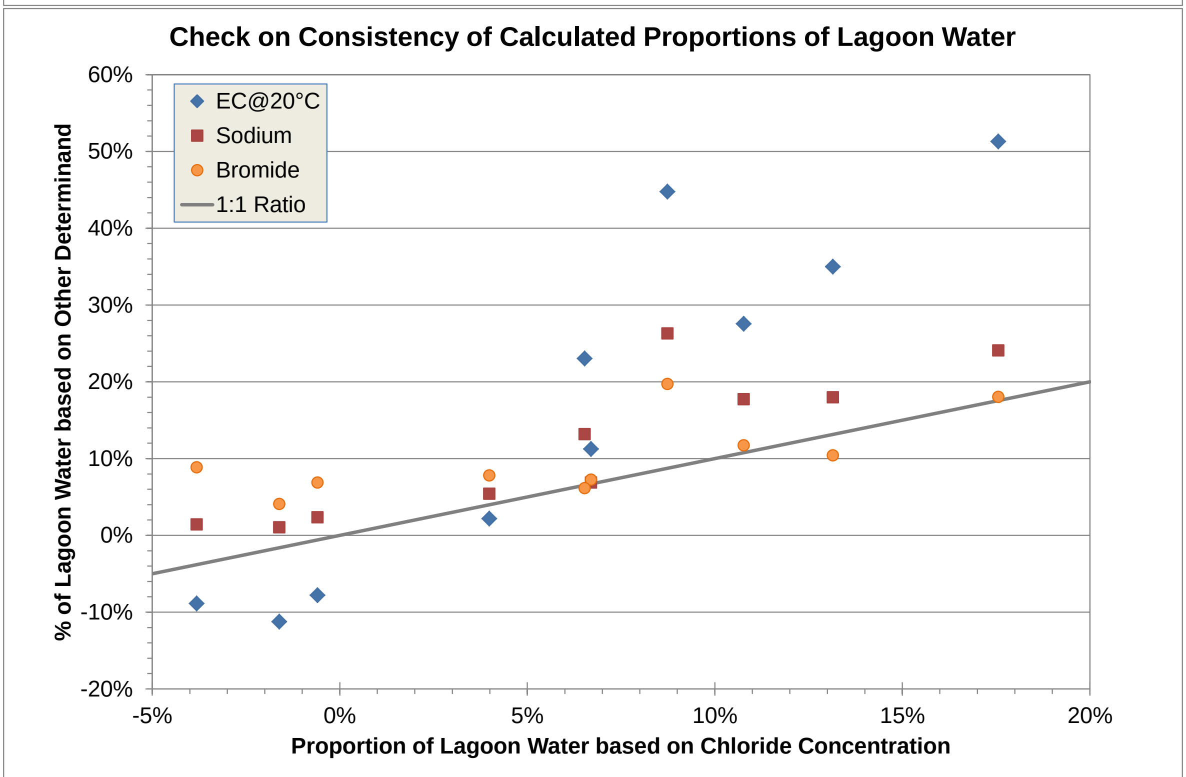
### Table 2.5 Estimates of Lagoon / Soakaway Water in Groundwater Samples

| Determinand[1] | Units | LOD[2] | Lagoon Average | CH Farm[3] Average | PZ#7b 26/01/16 | PZ#7b 23/02/16 | PZ#8b 26/01/16 | PZ#8b 23/02/16 | PZ#8b 19/05/16 | PZ#8a 29/06/16 | PZ#9b 23/02/16 | PZ#11b 23/02/16 | PZ#14 29/06/16 | PZ#14 31/08/16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EC@20°C | mS/cm | <0.005 | 0.89 | 0.338 | 0.4 | 0.35 | 0.585 | 0.621 | 0.531 | 0.49 | 0.276 | 0.465 | 0.289 | 0.295 |
| Total Dissolved Solids | mg/l | <5 | 743.6 | 259 | | 273 | | 473 | 360 | 383 | 216 | 364 | 227 | 220 |
| Sodium (total) | mg/l | <0.047 | 194.60 | 9.27 | 22 | 19.3 | 58 | 53.9 | 42.6 | 42.1 | 11.2 | 33.7 | 11.9 | 13.6 |
| Potassium (total) | mg/l | <2 | 23.20 | <1.72 | 4.87 | 5.68 | 4.67 | 2.84 | 2.56 | 2.97 | 4.83 | 3.86 | 2.74 | 2.88 |
| Chloride | mg/l | <2 | 73.90 | 14.95 | 18.9 | 17.3 | 20.1 | 25.3 | 22.7 | 21.3 | 14 | 18.8 | 12.7 | 14.6 |
| Bromide | mg/l | <0.06 | 0.58 | <0.06 (0.04) | 0.079 | 0.082 | 0.146 | 0.137 | 0.096 | 0.103 | 0.062 | 0.073 | 0.0877 | 0.077 |
| Nonylphenols | µg/l | <0.02 | 0.80 | <0.035 | 0.13 | 0.08 | 0.18 | 0.18 | <0.02 | 0.55 | 0.36 | 0.14 | 5.1 | |
| Total Inorganic Carbon (as $CaCO_3$) | mg/l | | 4057.63 | 154.07 | 236.70 | 196.52 | 381.42 | 388.92 | | | 170.85 | 299.23 | | |
| EC@20°C | | | 100% | 0.0% | 11.2% | 2.2% | 44.8% | 51.3% | 35.0% | 27.5% | -11.2% | 23.0% | -8.9% | -7.8% |
| Total Dissolved Solids | | | 100% | 0.0% | #N/A | 2.9% | #N/A | 44.2% | 20.8% | 25.6% | -8.9% | 21.7% | -6.6% | -8.0% |
| Sodium (total) | | | 100% | 0.0% | 6.9% | 5.4% | 26.3% | 24.1% | 18.0% | 17.7% | 1.0% | 13.2% | 1.4% | 2.3% |
| Potassium (total) | | | 100% | 0.0% | 14.7% | 18.5% | 13.8% | 5.2% | 3.9% | 5.8% | 14.5% | 10.0% | 4.8% | 5.4% |
| Chloride | | | 100% | 0.0% | 6.7% | 4.0% | 8.7% | 17.6% | 13.1% | 10.8% | -1.6% | 6.5% | -3.8% | -0.6% |
| Bromide[5] | | | 100% | 0.0% | **7.2%** | **7.8%** | **19.7%** | **18.0%** | **10.4%** | **11.7%** | **4.1%** | **6.1%** | **8.9%** | **6.9%** |
| Nonylphenols | | | 100% | 0.0% | 12.4% | 5.9% | 18.9% | 18.9% | -2.0% | 67.1% | 42.4% | 13.7% | 660.4% | #N/A |
| Total Inorganic Carbon | | | 100% | 0.0% | 2.1% | 1.1% | 5.8% | 6.0% | 3.2% | 3.7% | 0.4% | 3.7% | 1.2% | 0.2% |

1) Determinand selected as likely to be relatively conservative with the most conservative to least conservative likely to be in the order bromide, chloride, sodium, potassium, EC@20°C, total dissolved solids, and nonylphenols. Nonylphenols may be degraded and adsorbed.
2) LOD = limit of detection.
3) This is a small abstraction borehole at Dumbles Poultry Limited to the west of the fields containing the soakaway and is used to represent upgradient groundwater quality.
4) Calculated using the following formula: The proportion of groundwater that is lagoon water: Lagoon volume ÷ Downgradient groundwater volume = ([PZ#_conc – Chicken Farm_conc]/ ([Average Lagoon_conc – Chicken Farm_conc]). Where 'conc' means concentration. Calculated negative percentages arise where downgradient groundwater has lower values / concentrations than up-gradient groundwater.
5) Estimates based on bromide are likely to be the most reliable as bromide is conservative and there is a higher signal (lagoon) to background (chicken farm) ratio than for chloride.

**Figure 2.4 – Calculated Proportions of Lagoon Water in Groundwater**




**Notes**: See text for method of calculating proportions of lagoon water in downgradient groundwater. Bromide is likely to be the most sensitive measure due to it being conservative and having a high signal (lagoon concentration) to background groundwater ratio.

### 2.5.5 Lines of Evidence for Attenuation

***Microbial degradation processes to consider***

Data in Tables 2.3 and 2.4 show that the sampled groundwaters have very low filtered BOD (<3.5 mg/l $O_2$) and TOC (<~6 mg/l) compared to lagoon averages (941 mg/l $O_2$ and 523 mg/l respectively). Dilution (and dispersion) would need to be greater than ~100:1 and there is no evidence for this from the chloride and bromide data discussed above. This therefore suggests attenuation processes.

The high (filtered) BOD in the lagoon water shows that the organic matter is highly degradable. Using the generic equation for oxidation ($CH_2O + O_2 \rightarrow H_2O + CO_{2(g)}$) in Table 2.6, an average BOD of 941 mg/l $O_2$ translates back into (941x [12/32] =) 352.9 mg/l organic carbon which is 67% of the average 523 mg/l organic carbon recorded. Degradation of this organic matter (and meeting of the biochemical oxygen demand) is plausibly coming from:

- aerobic degradation (oxidation) in any unsaturated zone beneath the lagoon;
- aerobic degradation (oxidation) through use of dissolved oxygen in up-gradient groundwater mixing with the infiltrating lagoon water;
- anaerobic degradation through nitrate reduction and sulphate reduction; using dissolved nitrate and sulphate in upgradient groundwater mixing with the infiltrating lagoon water;
- anaerobic degradation through manganese reduction and iron reduction; using biochemically available manganese and iron oxides/ hydroxide coatings on the drift strata through which groundwater flows.
- Anaerobic degradation through methanogenesis (leading to the production of methane gas; some of which will be lost to air or the unsaturated zone and some will remain dissolved).

Studies (EA, 2000) have shown that microbial degradation of organic matter occurs preferably in the order: aerobic degradation using dissolved oxygen (oxidation), then nitrate reduction, manganese reduction, iron reduction and sulphate reduction. When all of these are consumed, methanogenesis can occur. In reality there is an overlap of the successive processes. Each of these processes has a by-product of carbon dioxide, and nitrate, manganese, and iron reduction each consume hydrogen ions and so can increase the pH of the water if it is not buffered. Together these reactions tend to increase the alkalinity (mainly as dissolved bicarbonate) of the groundwater.

Table 2.6 presents details of the different microbial degradation processes, their dissolved inorganic carbon by-products and whether they can increase alkalinity. Using the processes equations, the relative amounts of organic matter to oxidant or reduced species are also shown. Table 2.7 uses these relative amounts of oxidant or reduced species with changes between upgradient groundwater (at the chicken farm) and downgradient groundwater (at PZ#8b) to check for evidence of the amounts of organic matter degradation between the lagoon and PZ#8b.

## Table 2.6 Organic Matter Microbial Degradation Processes (Generic)

| Process for Microbial Degradation of Organic Matter (expressed[1,2] as $CH_2O$) | | | Oxidant | Reduced Species | Dissolved Inorganic Carbon By-products | Excess Hydroxide ($OH^-$) | Increases Total Alkalinity[3] | Mass (mg) of $CH_2O$ degraded per unit mass of oxidant | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Oxidant[4] | Reduced Species[5] |
| Oxidation | $CH_2O + O_2 \rightarrow$ | $H_2O + CO_{2(g)}$ | Oxygen ($O_2$) | | $H_2CO_3$ | None | No | 0.938 | |
| Denitrification | $5CH_2O + 4NO_3^- \rightarrow$ | $2N_2(g) + 5HCO_3^- + 2H_2O + H^+$ | Nitrate ($NO_3^-$) | Nitrogen gas ($N_2$) | $H_2CO_3 + 4HCO_3^-$ | None | Yes | 0.605 | |
| Manganese reduction | $CH_2O+2MnO_{2(s)} + H_2O\rightarrow$ | $2Mn^{2+} + HCO_3^- + 3OH^-$ | Manganese Oxides ($MnO_2$) | Dissolved manganese ($Mn^{2+}$) | $2HCO_3^-$ | $2OH^-$ | Yes | 0.173 | 0.273 |
| Iron reduction | $CH_2O+4Fe(OH)_{3(s)} \rightarrow$ | $4Fe^{2+} + HCO_3^- + 3H_2O + 7OH^-$ | Iron Hydroxides ($Fe(OH)_3$) | Dissolved iron ($Fe^{2+}$) | $HCO_3^-$ | $7OH^-$ | Yes | 0.070 | 0.134 |
| Sulphate reduction | $2CH_2O + SO_4^{2-} \rightarrow$ | $S^{2-} + 2CO_2 + 2H_2O$ | Sulphate ($SO_4^{2-}$) | Sulphide ($S^{2-}$) | $2H_2CO_3$ | None | No | 0.625 | |
| Methanogenesis | $2CH_2O \rightarrow$ | $CH_{4(g)} + CO_{2(g)}$ | | Methane gas ($CH_4$) | $H_2CO_3$ | None | No | | 3.750 |

1) This notation is used in a wide range of texts to represent generic organic matter.
2) Equations deduced by Rukhydro, but guided by other sources (e.g. EA, 2000, Table A5.1);
3) Total alkalinity is mainly a measure of bicarbonate ($HCO_3^-$), but as pH increases to greater than pH 8.0 can include carbonate ($CO_3^{2-}$) and hydroxide ($OH^-$).
4) Uses the process equation regarding relative proportions of $CH_2O$ and oxidant and molecular weights (mwt). (e.g. for manganese reduction: 1 part $CH_2O$ of mwt = 30 mg/mmol is oxidised by 2 parts $MnO_2$ of mwt 86.94 mg/mmol, so 30 mg of $CH_2O$ is oxidised by (86.94x2=173.88) mg $MnO_2$ and 30/173.88 = 0.173.
5) Uses the process equation regarding relative proportions of $CH_2O$ and reduced species and molecular weights (mwt). (e.g. for manganese reduction: oxidation of 1 part $CH_2O$ of mwt = 30 mg/mmol produces 2 parts dissolved $Mn^{2+}$ of mwt 54.94 mg/mmol, so oxidation of 30 mg of $CH_2O$ produces (54.94x2=109.88) mg $Mn^{2+}$ and 30/109.88 = 0.273.

**Table 2.7 Evidence for Organic Matter Degradation in Groundwater downgradient of the Lagoon / Soakaway**

| Process for Microbial Degradation of Organic Matter (expressed[1] as $CH_2O$) | Measure of Process[1] | Mass (mg) of $CH_2O$ degraded per mg of measure[2] mg/mg | Average Conc'n in Upgradient Groundwater (Chicken Fm) mg/l | Up-gradient Load assuming Upgradient Groundwater Flow of 840 $m^3$/day[3] g/day | Conc'n in Downgradient Groundwater (PZ#8b average) mg/l | Downgradient Load assuming Downgradient Groundwater Flow of 1000 $m^3$/day[4] g/day | Down-gradient Change in Load g/day | Load of $CH_2O$ degraded or left[5] g/day | Load of TOC degraded or left gC/day | Calculated Increase in Total Inorganic Carbon (T.I.C.)[6] mg/l $CaCO_3$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Oxidation | Decrease in dissolved oxygen ($O_2$) | 0.938 | 10.65 | 8946 | 0.500[7] | 500 | -8446 | 7918 | 3167 | 26.4 |
| Denitrification | Decrease in dissolved nitrate ($NO_3^-$) as mg/l $NO_3$ | 0.605 | 18.67 | 15680 | <2.27 | 2267 | -13413 | 8113 | 3245 | 27.0 |
| Manganese reduction | Increase in dissolved manganese ($Mn^{2+}$) | 0.273 | <0.012 | 10 | 15.633 | 15633 | 15623 | 4265 | 1706 | 14.2 |
| Iron reduction | Increase in dissolved iron ($Fe^{2+}$) | 0.134 | <0.019 | 16 | 2.79 | 2790 | 2774 | 373 | 149 | 1.2 |
| Sulphate reduction | Decrease in dissolved sulphate ($SO_4^{2-}$) | 0.625 | 13.8 | 11592 | <6.43 | 6430 | -5162 | 3226 | 1291 | 10.8 |
| Methanogenesis | Increase in dissolved methane ($CH_4$) | 3.750 | 0.0028 | 2 | 4.86 | 4860 | 4858 | 18216 | 7287 | 60.7 |
| No degradation | Increase in TOC | (2.500) | 1.00[8] | 840 | 5.44 | 5437 | 4597 | 11492 | 4597 | |
| Totals | | | | | | | | 53603 | **21441** | 140.4 |
| Checks | TOC Load to Soakaway | | | | | | | | 83680 | |
| | Degradable and soluble TOC load from Soakaway[9] | | | | | | | | **56460** | |
| Checks | T.I.C input from Soakaway (as $CaCO_3$) | | | | | | 492096 | | | 649.2 |
| Checks | Increase in T.I.C (as $CaCO_3$) | | 154.1 | 129419 | 385.17 | 385170 | 255751 | | | 255.8 |

Notes: See overleaf.

Notes for Table 2.7:

1) See Table 2.6 for notes on $CH_2O$ notation and biochemical processes.
2) This is e.g. the mass (mg) of $CH_2O$ degraded per mg of dissolved oxygen consumed or mg of dissolved manganese released. See Table 2.6 for further information.
3) Concentration x flow. Flow based on downgradient groundwater contains average of 16% lagoon water (from bromide dilution) and the lagoon discharge rate is ~160 $m^3$/day (Rukhydro, 2015), so downgradient flow is (160/16%=) 1000 $m^3$/day and upgradient flow is therefore (1000-160=) 840 $m^3$/day.
4) Uses the process equation regarding relative proportions of $CH_2O$ and reduced species and molecular weights (mwt). (e.g. for manganese reduction: oxidation of 1 part $CH_2O$ of mwt = 30 mg/mmol produces 2 parts dissolved $Mn^{2+}$ of mwt 54.94 mg/mmol, so oxidation of 30 mg of $CH_2O$ produces (54.94x2=109.88) mg $Mn^{2+}$ and 30/109.88 = 0.273.
5) Downgradient change in load of e.g. dissolved oxygen multiplied by "mass of $CH_2O$ degraded per mg of measure".
6) From the equations in Table 2.6, except for methanogenesis, each gram of degraded organic carbon produces one gram of inorganic carbon. This excludes reactions with carbonate minerals (e.g. $CO_2 + CaCO_3 + H_2O = Ca^{2+} + 2HCO_3^-$). 1 g inorganic carbon = 100/12 inorganic carbon expressed as $CaCO_3$. Concentration after diluting in 840 $m^3$/day.
7) Assumed as 0.5 mg/l $O_2$ (measured average using Winkler titration is 2.71 mg/l $O_2$) as anaerobic degradation is unlikely to occur at DO concentrations greater than 0.5 mg/l, and does not occur at concentrations greater than 1mg/l. (EA, 2000, Table 3.4). Anaerobic concentrations evident from low nitrate, sulphate and high manganese concentrations.
8) Measured = <3 mg/l, but "clean" groundwaters typically have no more than ~1 mg/l TOC.
9) This is derived from a mean filtered BOD value of 941 mg/l $O_2$ expressed as mg/l organic carbon (353 mg/l C) assuming $CH_2O + O_2 \rightarrow H_2O + CO_{2(g)}$ multiplied by 160 $m^3$/day.

### *Evidence for microbial degradation in groundwater*

The main findings from the evaluation in Table 2.7 are:

- aerobic degradation (oxidation) and anaerobic degradation (utilising nitrate, manganese, iron and sulphate and producing dissolved methane) in groundwater can account for:
  - 21441 g/day (38%) of the 56460 g/day degradable organic carbon discharged to the lagoon each day;
  - An increase in total inorganic carbon of 140 mg/l $CaCO_3$ compared to a calculated increase in groundwater of 256 mg/l $CaCO_3$ and a measured input to the lagoon which should have increased groundwater concentrations by 649 mg/l $CaCO_3$.
- More total inorganic carbon is being discharged to the lagoon than is being found in groundwater.

### *Taking into account mineral dissolution*

The inorganic carbon calculations do not take into account reactions with aquifer materials, e.g.:

$$CO_2 + CaCO_3 + H_2O = Ca^{2+} + 2HCO_3^- \text{ (reaction with calcite)}$$

$$2CO_2 + CaMg(CO_3)_2 + 2H_2O = Ca^{2+} + Mg^{2+} + 4HCO_3^- \text{ (reaction with dolomite)}$$

Where 1 mole of dissolved $CO_2$ leads to 2 moles of bicarbonate ($HCO_3^-$).

Average calcium and magnesium concentrations are higher in PZ#8b (68.2 mg/l; 9.9 mg/l) than in the upgradient chicken farm borehole (54.8 mg/l; 7.1 mg/l) by 13.4 mg/l and 2.8 mg/l respectively. Assuming their increase was due to some dolomite and calcite dissolution, then this would produce an additional 44.9[2] mg/l $CaCO_3$ of dissolved inorganic carbon. The dissolution likely comes from the $CO_2$ produced from aerobic degradation and sulphate reduction (see reactions in Table 2.6). Including this extra inorganic carbon increases the total calculated from degradation processes to (140.4 + 44.9=) 185.3 mg/l $CaCO_3$. This leaves a shortfall of (256-185.3=) 70.7 mg/l $CaCO_3$ in the measured increase in dissolved inorganic carbon in groundwater and a shortfall of (649-185.3=) 463.7 mg/l $CaCO_3$ of the input to the lagoon.

### *Attenuation in the unsaturated zone*

It is possible that some degradation of organic matter and production of dissolved inorganic carbon occurs as the lagoon water infiltrates through the unsaturated zone. This process is significant beneath septic tank discharges which typically have infiltration rates beneath correctly sized drainage fields of 0.036 $m^3$/day/$m^2$ (Environment Agency, 2011, its Box 2.3).

The lagoon is anoxic (dissolved oxygen = <0.3 mg/l $O_2$, see Table 2.3) so there would be no oxygen entrainment into the unsaturated zone from above. Assuming discharge rates of 160 $m^3$/day infiltrate through “the Wet” (1267 $m^2$) and lagoon (779 $m^2$) of combined basal area of 2046 $m^2$, then infiltration rates equate to 0.078 $m^3$/day/$m^2$. This is (0.078/0.036=) 2.16 times faster than beneath a septic tank drainage field and so gives less time for oxygen entrainment.

[2] This assumes all of the 3.74 mg/l magnesium (Mg) is from dolomite dissolution. 2.8 mg/l Mg = (2.8/24.3=) 0.115 mmol/l Mg, and so 0.115 mmol of dolomite would have dissolved to produce 4x0.115 mmol of $HCO_3^-$, but a net gain of 2x0.115 mmol of dissolved inorganic carbon. This equates to (2x0.115x100 =) 23 mg/l $CaCO_3$ of dissolved inorganic carbon.

Similarly, assuming the increase in calcium (Ca) less that from dolomite dissolution is from calcite dissolution. 13.4 mg/l Ca = (13.4/40.08=) 0.334 mmol/l Ca, less 0.115 mmol from dolomite dissolution leaves 0.219 mmol/l Ca from calcite dissolution which provides an extra 0.219 mmol/l of dissolved inorganic carbon equating to 21.9 mg/l $CaCO_3$. So (23+21.9=) 44.9 mg/l $CaCO_3$ in total.

Finally, the unsaturated zone beneath the lagoon is relatively thin (likely <1 m when taking into account local mounding evident at PZ#7a and 7b, see Table 2.1) and so further suggests aerobic degradation in the unsaturated zone may be limited.

***Evidence for methanogenesis***

The calculations in Table 2.7 assume the only methanogenesis occurring is that measured by the increase in dissolved methane in downgradient groundwater. Methane has a limited solubility in groundwater however, and will be preferentially released to air above the lagoon or into the soil air above the water table. If the remaining (100%-35.6%=) 64.4% (36,360 gC/day) of the 56,460 gC/day degradable organic carbon discharged to the lagoon each day was being oxidised as a result of methanogenesis then it could also lead to an increase in dissolved carbon dioxide and so total inorganic carbon in groundwater.

From Table 2.6, 2 moles of degraded organic carbon produce 1 mole of methane and 1 mole of carbon dioxide. If it is assumed the (36,360/2= 18,180 mg/l C equivalent) methane from this is lost to air, but the carbon dioxide from this is dissolved in groundwater, then 36 360 gC/day of organic carbon is predicted to produce an additional (([36 360/2] x [100/12])/1000=) 151.5 mg/l $CaCO_3$ inorganic carbon when diluted in 1000 $m^3$/day of downgradient groundwater.

This 151.5 mg/l $CaCO_3$ is higher than the calculated shortfall of 70.7 mg/l $CaCO_3$ between the measured increase in dissolved inorganic carbon and the calculated increase including only measured dissolved methane in groundwater. This suggests loss of methane to air but also loss of ([151.5-70.7]/151.5=) ~53% of the associated carbon dioxide to air. Carbon dioxide is least soluble at lower pH and the pH is much lower in the lagoon (average 5.32) than in groundwater (average PZ#8b = 7.39). Together with the greater exposure to air, this suggests loss of the carbon dioxide (and probably methane) from the lagoon rather than groundwater. On inspection of the lagoon on 12 May 2016, bubbles were seen rising through the water column.

***Summary of evaluation of attenuation***

The above subsections suggest the attenuation of the current lagoon discharge as summarised in Table 2.8.

Table 2.8 suggests that to limit anaerobic conditions occurring from the current lagoon discharge layout to consumption of mainly dissolved oxygen in groundwater would require the BOD to be reduced to 53 mg/l $O_2$ for 160 $m^3$/day. If nitrate reduction was also considered (a positive environmental effect), providing an additional attenuation of 54 mg/l $O_2$ equivalent BOD, then the BOD in the discharge would need to be reduced to (53+54=) 107 mg/l total BOD for 160 $m^3$/day.

By doing that, there would be a low likelihood of manganese, iron reduction and sulphate reduction. Methanogenesis would be very unlikely. By avoiding manganese and iron reduction, there would be a reduced likelihood of releasing other trace metals absorbed on the iron and manganese oxides in the strata. There could be a lowering of pH if the hydroxide generating manganese and iron reduction reactions cease, but there is evidence of buffering of pH by dissolution of calcite and dolomite.

For the current discharge, a changed discharge layout could provide slower travel times and infiltration rate through a larger drainage field, and there would likely be more attenuation in the unsaturated zone and potentially greater dilution in groundwater (if the drainage field had a larger width perpendicular to the direction of groundwater flow). Conversely, as planned, the effluent quality should be improved.

**Table 2.8 Summary of Lagoon Effluent Attenuation Assessment**

| Process | Measure of Process | Load of TOC degraded or left | | Equivalent BOD in the lagoon 160 $m^3$/day discharge |
|---|---|---|---|---|
| | | gC/day | % of total degradable | mg/l $O_2$ |
| **In Groundwater** | | | | |
| Oxidation | Decrease in dissolved oxygen ($O_2$) | 3167 | 5.6% | 52.8 |
| Denitrification | Decrease in dissolved nitrate ($NO_3^-$) as mg/l $NO_3$ | 3245 | 5.7% | 54.1 |
| Manganese reduction | Increase in dissolved manganese ($Mn^{2+}$) | 1706 | 3.0% | 28.4 |
| Iron reduction | Increase in dissolved iron ($Fe^{2+}$) | 149 | 0.3% | 2.5 |
| Sulphate reduction | Decrease in dissolved sulphate ($SO_4^{2-}$) | 1291 | 2.3% | 21.5 |
| Methanogenesis | Increase in dissolved methane ($CH_4$) | 7287 | 12.9% | 121.4 |
| " | Loss of methane to air | 19392 | 34.3% | 323.2 |
| " | Loss of carbon dioxide to air | 9696 | 17.2% | 161.6 |
| " | Added dissolved carbon dioxide to groundwater | 8484 | 15.0% | 141.4 |
| No degradation | Increase in TOC in groundwater. | 4597 | 8.1% | 76.6 |
| Totals | Degradable and soluble TOC load from Soakway[1] | 56460 | 100.0% | 941.0 |
| **In the Soakaways** | | | | |
| Settlement?[3] | By difference | 27220 | | |
| Overall Total | Total TOC Load to Soakaway[2] | 77600 | | |

Notes:

1) This is derived from a mean filtered BOD value of 941 mg/l $O_2$ expressed as mg/l organic carbon assuming $CH_2O + O_2 \rightarrow H_2O + CO_{2(g)}$ multiplied by 160 $m^3$/day.
2) This is the mean total organic carbon of 485 mg/l C in the lagoon discharge multiplied by the lagoon discharge of 160 $m^3$/day.
3) This is 83680 – 56460 g/day of organic carbon being discharged to the lagoon which does not have an equivalent filtered BOD.

## 2.6 Summary

Twelve shallow piezometers were installed in the vicinity of the lagoon / soakaway discharge in January and February 2016 and one replacement and three more were added in July 2016. A number of these continue to provide groundwater level data and six have been sampled for groundwater quality. A small abstraction at the chicken farm has been used to provide background groundwater quality samples.

Lagoon and stream samples have also been taken.

Apart from a single manganese concentration exceeding its environmental quality standard (EQS) in the downstream stream sample, there were no other EQS exceedances for the stream samples. There is only minor / negligible evidence of the local stream being impacted by the lagoon discharge.

The groundwater downgradient of the lagoon discharge is, as expected, impacted by the discharge. There are elevated concentrations of some trace metals and ammoniacal nitrogen above drinking water standards and above the EQS for the River Teme. It is likely that these elevated concentrations are due to reactions in the groundwater system as the high organic loading is degraded rather than being in the lagoon discharge itself.

Excluding manganese and zinc, the most that the most stringent EQS is exceeded by is an anomalous reading for nonylphenol (17x), then iron (8x) followed by cobalt (3.9x), then ammoniacal nitrogen (3.4x). PZ#8b generally has the highest concentrations. Zinc and manganese exceedances are up to 150 times their EQS.

Using conservative determinands (chloride and bromide) it is estimated that worst impacted groundwater (PZ#8b) contains ~10-20% lagoon water.

A detailed evaluation of the attenuation processes in groundwater has been undertaken. This suggests degradation of the high organic loading is occurring as a result of oxygen, nitrate and sulphate consumption in groundwater and the reduction of manganese and iron oxides in the aquifer materials. There is also evidence for significant organic matter degradation by methanogenesis with loss of methane and carbon dioxide to air above the lagoon.

To limit anaerobic conditions occurring from the current lagoon discharge layout to consumption of mainly dissolved oxygen and nitrate in groundwater would require the BOD to be reduced to less than ~100 mg/l $O_2$.

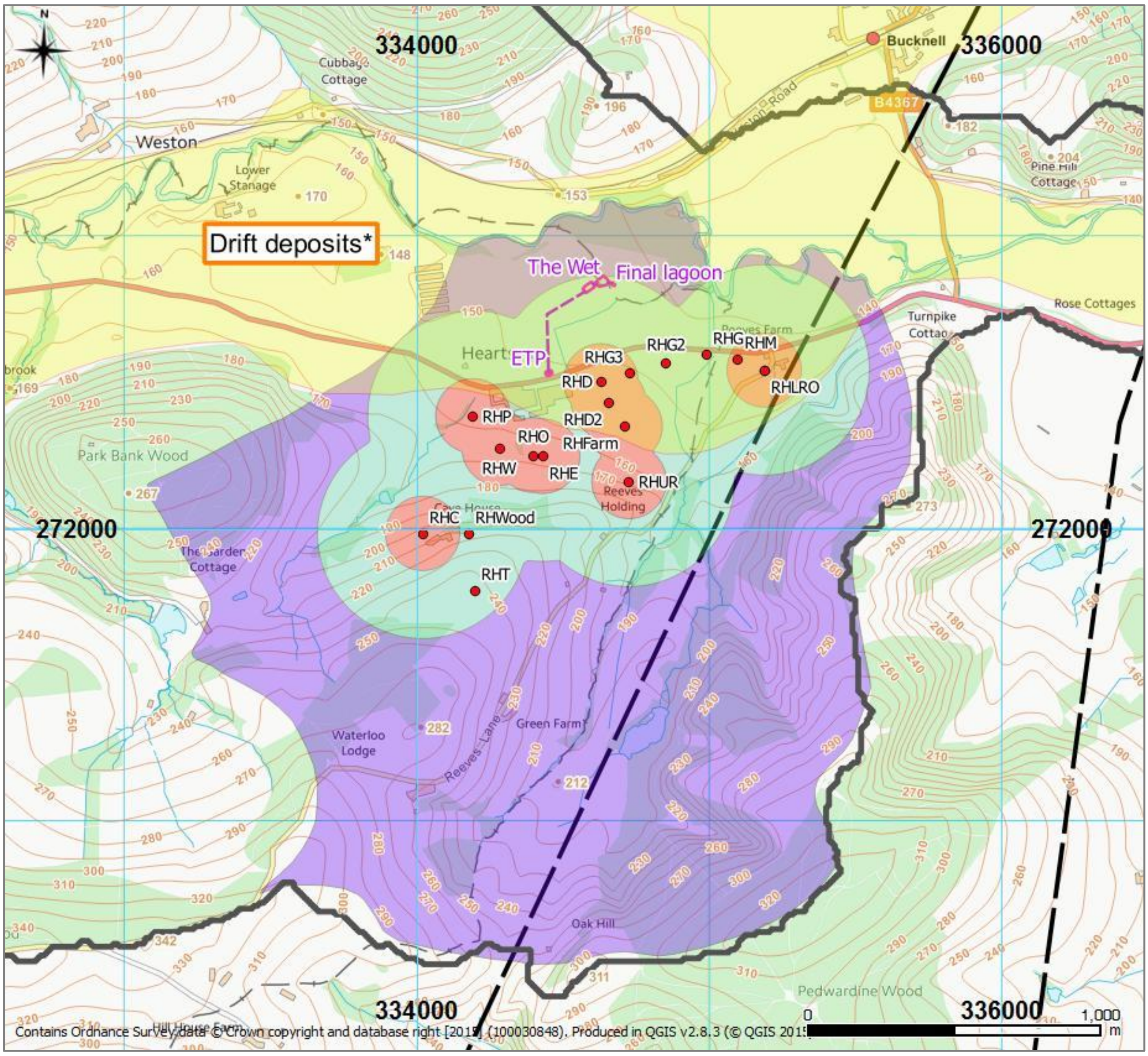
Section 5 provides further discussion on the impact of the proposed treated effluent discharge.

# 3. Source Protection Zone Modelling

## 3.1 Existing Regulatory Source Protection Zones

Source protection zones (SPZs), based on a report by Rigare (2011), are shown on the Environment Agency's website and were reproduced in the Rukhydro (2015) report as shown below on Figure 3.1.

**Figure 3.1 – Existing Source Protection Zones**




**Source**: Contains Ordnance Survey data © Crown Copyright and database right [2016] (100030848) including 1:50k scale topographic contours. Also contains Environment Agency source protection zone data (licensed), Environment Agency extent of Minor Aquifer Intermediate groundwater vulnerability (used here to show the extent of drift deposits) and BGS mapped faults from DiGMapGB-625, with the permission of the British Geological Survey.

**Legend**: **Purple** (Total Catchment, Zone 3), **Green** (Outer Zone, Zone 2), **Red** (Inner Zone, Zone 1). These are overlain by the yellow mapped drift deposits. RH*** are Radnor Hills abstraction boreholes.

**Note**: Source protection zone not defined for new boreholes RHM, RHG, RHG2 and RHG3.

The source protection zones are based on protected yields (a total of 2028 $m^3$/day), but are not defined for more recent boreholes (RHM, RHG, RHG2 and RHG3).

Rigare (2011) noted that due to the apparent complexity of the hydrogeology and the lack of detailed hydrogeological information, it was decided to delineate the SPZs using professional judgement alone. A number of metrics for the different protections zones are provided in Table 3.1.

**Table 3.1 Existing Environment Agency Source Protection Zone Metrics**

| Zone | Zone Name | Travel Time[1] (days) | Default Minimum Radius (m) | Radius (m) Assumed by Rigare (2011) | Total Area of Zones[2] (ha) | Daily Volume of Water provided by Zone Area[3] ($m^3$/day) | |
|---|---|---|---|---|---|---|---|
| | | | | | | Min | Max |
| 1 | Inner | 50 | 50 | 127 | 12.1973 | 38 | 75 |
| 2 | Outer | 400 | 250 | 360 | 132.9340 | 419 | 819 |
| 3 | Total Catchment | | | | 473.3178 | 1490 | 2916 |

Notes:
1) Travel time for a conservative, un-retarded contaminant (e.g. chloride or bromide).
2) Calculated in QGIS using Environment Agency shapefiles of the different zones. The area of the inner forms part of the area of the outer which in turn is part of the total catchment, i.e. the areas are not additive.
3) This is the area multiplied by a recharge rate of 115 mm/year (minimum) or 225 mm/year (maximum) expressed in units of $m^3$/day. The volumes are not additive because the areas are not additive.

## 3.2 Model set up to develop New Operational SPZs

### 3.2.1 Reasons for Reviewing the SPZs

As noted, the existing source protection zones are not defined for more recent boreholes (RHM, RHG, RHG2 and RHG3). Rukhydro (2015) also noted that the SPZs are very conservative – designed to protect a total yield of 2028 $m^3$/day with total catchment areas protecting between 1490 and 2916 $m^3$/day (see Table 3.1).

Figure 3.1 suggests that the current lagoon / soakaway discharge sits on the Zone 2 – Outer catchment boundary for drift borehole RHD. Rukhydro (2015) showed that, conservatively, the lagoon discharge was unlikely to be in the catchment area of the drift boreholes under the current abstraction regime, but could fall within that catchment under predicted increased abstraction plans. Against this background, Radnor Hills requested a review of the SPZs:

- To provide greater confidence on any risk from the current lagoon discharge;
- To understand the extent of the SPZs under anticipated future increased abstraction (and increased discharge rates).

### 3.2.2 Support by Groundwater Science

Groundwater Science was subcontracted to undertake the detailed modelling in support of new SPZs. Rukhydro and Groundwater Science worked closely to ensure the understanding of the area, its hydrogeology and available data was efficiently taken into account. A stand-alone Groundwater Science report was prepared and reviewed by Rukhydro. That Groundwater Science (March 2016) report forms a more detailed stand-alone accompaniment to this report regarding SPZ delineation.

### 3.2.3 Summary of Key Assumptions

Tables 3.2 and 3.3 replicate Groundwater Science's (2016) summary of model input parameters and assumed abstraction and soakaway discharge rates.

**Table 3.2 SPZ Model Input Parameters (after Groundwater Science, 2016)**

| Parameter | Units | Assumed by Rigare (2011) in Previous SPZs | | Assumed in the GW Science Model for New SPZs | |
|---|---|---|---|---|---|
| | | Assumed Value | Basis | Simulated Value(s) | Basis |
| **Recharge** | | | | | |
| to Bedrock | mm/yr. | 225 | Based on estimated mean annual recharge to the River Teme catchment at Tenbury | 225 | Catchment scale water balance assessment |
| to Gravel / Alluvial Aquifer | mm/yr. | 225 | “ | | |
| **Hydraulic Conductivity** | | | | | |
| of Bedrock | m/day | 0.067 | Overview of pumping test data | 0.067 | Pumping test data |
| of Gravel / Alluvial Aquifer | m/day | 10.0 | Overview of pumping test data | 11.22 (mean) | Calibration to recent groundwater level monitoring (properties variable over space) |
| **Effective Porosity** | | | | | |
| of Bedrock | (-) | 0.05 | Recommended value for Devonian Sandstones from Environment Agency (2009) | 0.01 | Experience from studies where tracer test data breakthroughs imply a faster travel time than literature porosities. 0.01 selected as a conservative estimate. |
| of Gravel / Alluvial Aquifer | (-) | 0.2 | Not stated. | 0.05 | Travel times implied by initial concentration monitoring rounds and past experience of fate and transport simulation in gravels.<br>5% relative to 20% allows for localised fast pathways within the 25m$^2$ cell size of the model grid is therefore conservative. |

**Table 3.3 Assumed Borehole Abstraction and Soakaway Discharge Rates for SPZ Delineation Model (after Groundwater Science, 2016)**

| Borehole | Protected Maximum Yield[1] m³/day | Strata | Scenario 1 (Situation in 2015) m³/day | Scenario 2 (Possible Future) m³/day |
|---|---|---|---|---|
| RHC | 48.0 | Bedrock | #N/A | #N/A |
| RHD | 480.0 | Drift | 83.2 | 83.2 |
| RHD2 | 480.0 | Bedrock | 81.2 | 81.2 |
| RHE | 120.0 | Bedrock | 24.4 | 24.4 |
| RHFarm | 336.0 | Bedrock | 21.6 | 21.6 |
| RHG | | Drift | 47.7 | 47.7 |
| RHG2 | | Drift | #N/A | 280.0 |
| RHG3 | | Drift | #N/A | 180.0 |
| RHM | | Drift | 52.8 | 52.8 |
| LRN | 168.0 | Drift | 20.6 | 20.6 |
| LRO | 72.0 | Drift | 5.0 | 5.0 |
| RHO | 48.0 | Bedrock | #N/A | #N/A |
| RHP | 84.0 | Bedrock | 19.2 | 19.2 |
| RHT | | Bedrock | #N/A | #N/A |
| RHUR | 96.0 | Bedrock | 5.0 | 5.0 |
| RHW | 96.0 | Bedrock | 33.9 | 33.9 |
| Total[2] | | Drift | 209.3 | 669.3 |
| Total[2] | | Bedrock | 185.3 | 185.3 |
| Total[2] | | Combined | 394.6 | 854.6 |
| Chicken Farm | | Drift | 60.0 | 60.0 |
| Soakaway Discharge | | | 160 | 240[3] |

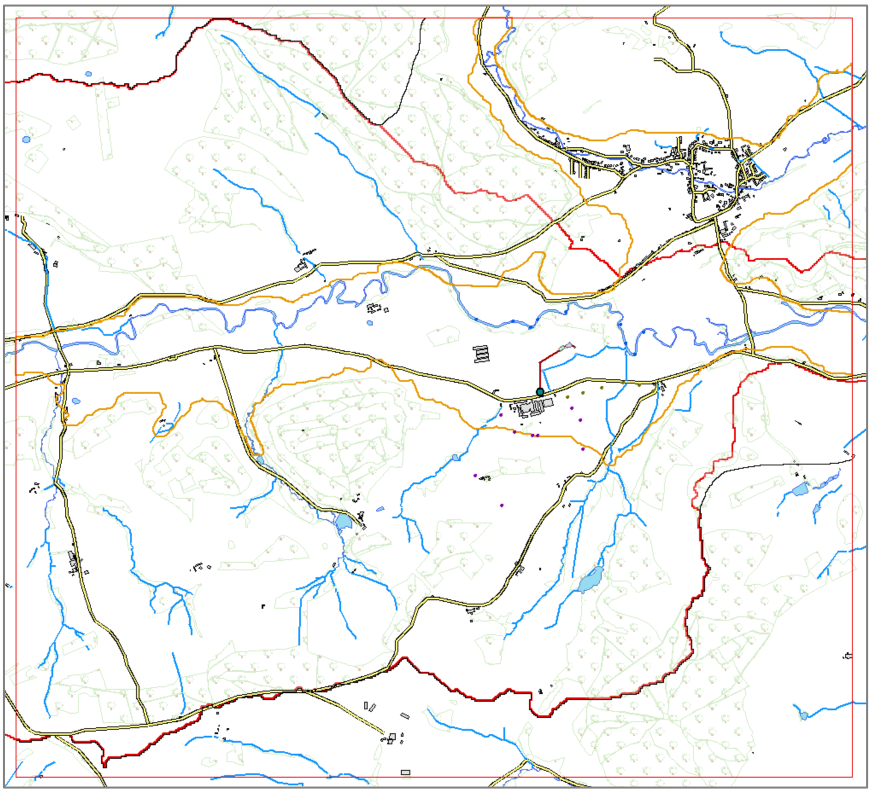
Notes:

1) Derived by Rigare (2011) based on based the higher estimates of the quantities that can be obtained from each borehole, but not taking into account where these high rates are sustainable in the long term.
2) These totals added by Rukhydro for this report.
3) The discharge rate of 240 $m^3$/day was the value assumed at the time (January to March 2016) when the SPZ modelling work was undertaken.

### 3.2.4 SPZ Model Features

The areal extent and key features of the Groundwater Science (2016) SPZ model for the Radnor Hills resource area are shown in Figure 3.2 and Box 3.1 respectively.

**Figure 3.2. Extent of the SPZ Model Area (after Groundwater Science, 2016)**



**Notes**: Contains Ordnance Survey data © Crown Copyright and database right [2016]. Red polygon is the Teme surface water catchment boundary, Orange polygon is the extent of the Glacial-Alluvial deposits as inferred from Environment Agency groundwater vulnerability mapping. The short red line from the bottling plant represents the pipeline carrying treated effluent to the reedbed, "the Wet" and a final soakaway / lagoon. (Adapted from Groundwater Science (2016) Figure 1).

**Box 3.1 – Key Features of the SPZ Model (after Groundwater Science, 2016)**

The underlying model uses the industry standard **MODFLOW 96** and **Groundwater Vistas v6** codes.

The modelled area is 5.5 km (E-W) by 5.0 km (N-S) and extends from Milebrook (E33100) in the west to the B4367 crossing of the River Teme (E336500) in the east. It encompasses the surface water catchment boundaries to the north and south of the River Teme (see Figure 3.2).

The model has **two layers** (drift and underlying fractured bedrock) and uses a **5 m grid**, which is far more detailed than the Environment Agency standard of 200 m. It has 1.1 million model cells per layer.

**MODPATH** and **FlowSource** software used to delineate the SPZs.

The base of the glacial deposits has been defined by interpolating the hill topography down beneath the river valley and controlling the interpolation with the Radnor Hills borehole log data. A borehole at Knighton provides a sense check of glacial deposit thickness. The Groundwater Science (2016) report provides cross sections through the model area.

Surface drainage network modelled using MODFLOW River package (RIV).

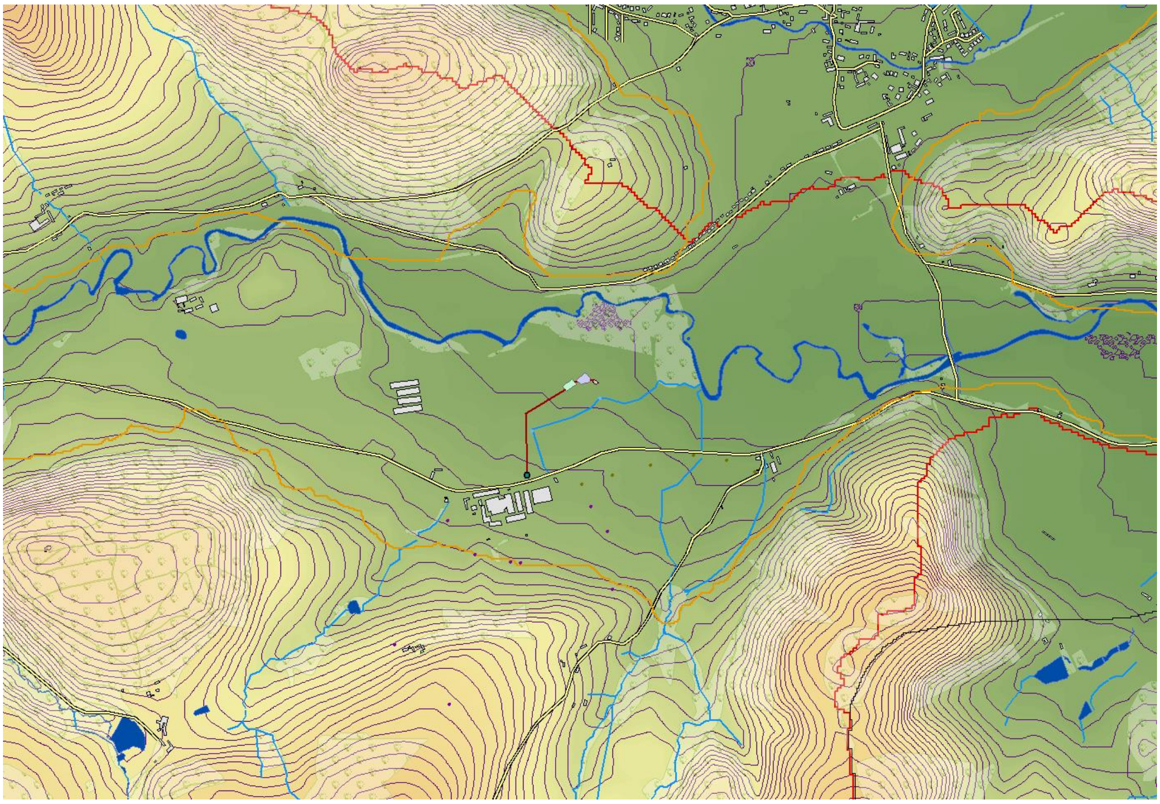
The river package in the Radnor Hills model is setup to 'gain' via the described linear and unlimited relationship, 'loss' from the river however is capped. When the simulated groundwater head drops lower than 1m below the river stage the river is conceptualised to be hydrogeologically isolated from the groundwater system and leaks a uniform (limited) rate. This represents a small driving head and typically only occurs when low recharge in summer months result in lowered local piezometry. (The SPZ model was set up before the work in this reports Section 4 noted evidence of river losses).

The stage of the river is set equal to the topography along the course of the river. Where Lidar data are available this has been applied in preference to the less precise Ordnance Survey PANORAMA dataset.

**Source**: Adapted from Groundwater Science (2016)

The topographic detail of the SPZ model area is shown in Figure 3.3. Further details of the model's set up are provided in the Groundwater Science (2016) report.

**Figure 3.3. Topography of the SPZ Model Area (after Groundwater Science, 2016)**



**Notes**: Contains Ordnance Survey data © Crown Copyright and database right [2016]. Colour scale changes in 1m elevation increments and contours at 5m increments. Red polygon is the Teme surface water catchment boundary, Orange polygon is the extent of the Glacial-Alluvial deposits as inferred from Environment Agency groundwater vulnerability mapping The short red line from the bottling plant represents the pipeline carrying treated effluent to the reedbed, "the Wet" area and the final soakaway / lagoon. (Adapted from Groundwater Science (2016) Figure 2).

## 3.2.5 Model Calibration and Validation (by Groundwater Science)

Box 3.2 reproduces text from the Groundwater Science (2016) report regarding the SPZ model calibration and validation. The model has been calibrated to measured groundwater levels using plausible inputs of recharge, hydraulic conductivity and connection to the river.

**Box 3.2 – SPZ Model Calibration and Validation (after Groundwater Science, 2016)**

Initial model calibration focussed on reproducing a river reach scale water balance assessment and constrained the overall bulk hydraulic conductivity of the valley and regional recharge. The river reach scale water balance assessment was based on the observed groundwater gradients between the west and eastern extent of the model area and areal effective rainfall volume captured within the area. With these data and estimates of alluvial valley cross sectional areas catchment scale average horizontal conductivities can be backed out. These properties were consistent with past studies and approximately 10m/d was inferred.

In addition to the water balance assessment the initial model was constructed to permit the conceptualised upwards flow from the bedrock to the glacial deposits and river. Furthermore at the early stages of calibration proven abstractions were confirmed to be sustainable without 'going dry'.

Finally pump test data assisted in constraining the bedrock hydraulic conductivity as approximately 0.067m/d. Higher bedrock permeability has been inferred in other local boreholes (0.1m/d) however these locations included components of flow from the overlying higher permeability drift deposits and these locations are considered to be biased.

**Source**: From Groundwater Science (2016) report Section 2.8.

The ability of the model to reproduce groundwater levels measured in the piezometers (discussed in Section 2) and Radnor Hills' abstraction boreholes was tested. This was done in February / March 2106 before the piezometers were surveyed-in in August 2016. The maximum difference in piezometer dipping datum elevation between the two approaches is 0.6 m. Groundwater Science (2016) reported that: "*The 'residual mean' (average difference between observed and simulated groundwater levels) is 28cm. For typical Environment Agency Regional Scale models, when used for SPZ purposes, the standard target is to be within 2m of observed groundwater levels*."

So the model achieved a high level of fit with measured groundwater levels suggesting the combination of assumed recharge, hydraulic conductivities and connection between drift and bedrock and drift and the river are all consistent.

### 3.2.6 Sensitivity Analysis

A sensitivity analysis was undertaken on the parameters which are simulated to exert the greatest control on the distribution of abstraction capture zones, namely the horizontal hydraulic conductivity and recharge to groundwater. Further details are provided in Box 3.2.

**Box 3.2 – SPZ Model Sensitivity Analysis (after Groundwater Science, 2016)**

A sensitivity analysis was undertaken on the parameters which are simulated to exert the greatest control on the distribution of abstraction capture zones, namely the horizontal hydraulic conductivity and recharge to groundwater.

These parameters are linked and acceptable calibration to measured groundwater levels can be obtained by increasing recharge and, in turn, increasing hydraulic conductivity, or, reducing both recharge and hydraulic conductivity. While this therefore unsatisfactorily results in the potential for multiple configurations of the model parameters to produce 'equally good calibrations to observed groundwater levels' the resultant flows and water balances do change between these alternative realisations.

It is for this reason that an initial water balance assessment and catchment scale recharge and through-flow study was of particular importance in constraining the model parameterisation. This study helps to fix the modelled flows and recharge so piezometer based observed groundwater levels can then be used to further constrain the hydraulic conductivity without the difficulties of equi-finality in recharge.

The water balance assessment however contains uncertainties and so a sensitivity analysis was therefore undertaken with two sensitivity runs to assist in bracketing the area of the potential capture zones. The hydraulic conductivity of the model was increased from the calibrated base value of 11.22m/d by 50% and within the same run the recharge to groundwater was increased from 225mm/yr. by 20% to 270mm/yr. Similarly the hydraulic conductivity was decreased by 50% and the recharge decreased by 20% for an opposing simulation.

**Source**: From Groundwater Science (2016) report Section 2.9.

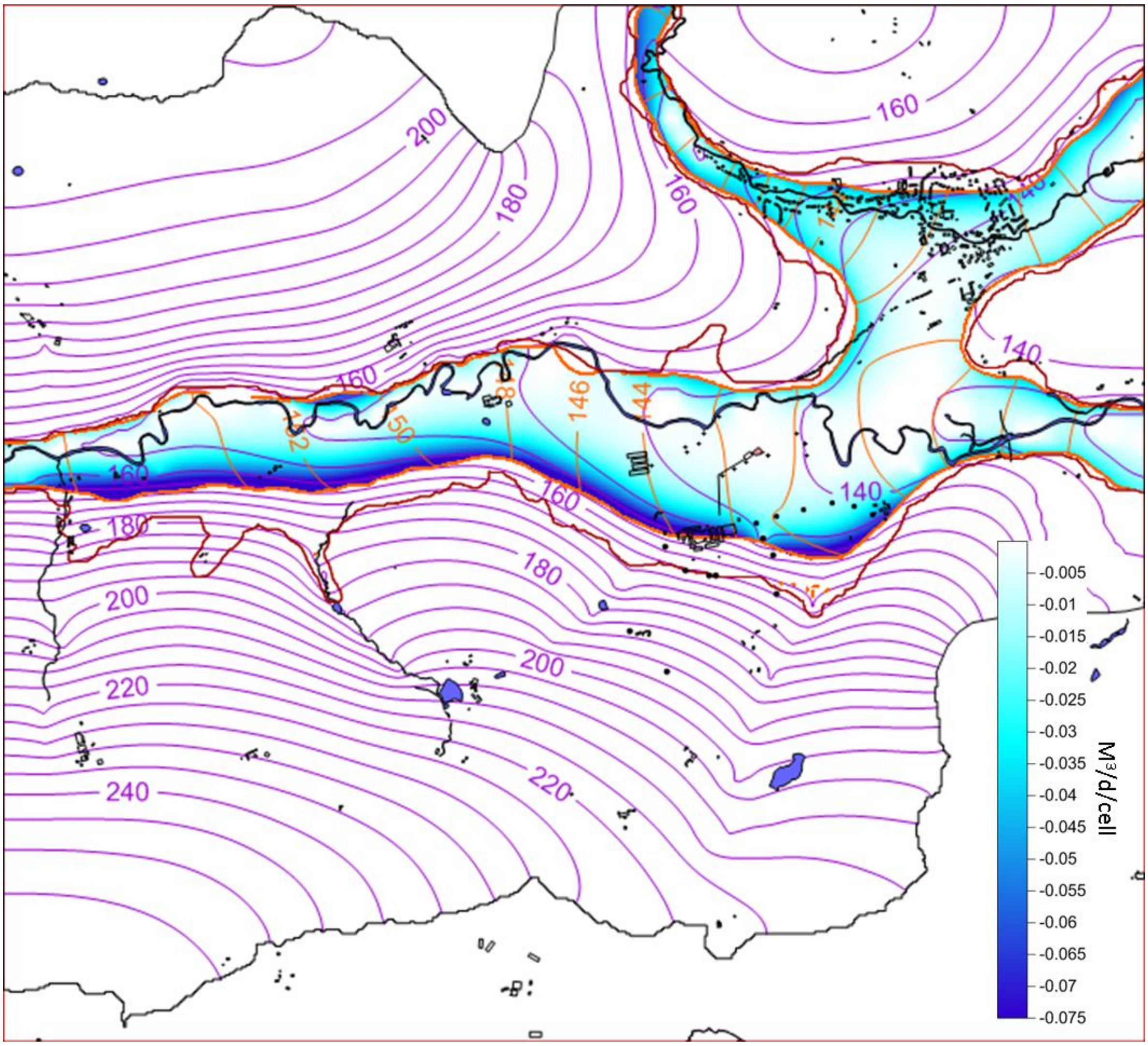
The model parameterisation as shown in Table 3.2 was viewed as the most likely based on available information at the time of model construction. Its construction pre-dates the evaluation in Section 2.5.4 regarding evidence of lagoon discharge dilution from background groundwater flow and knowledge and quantification of losses from the River Teme between Milebrook and Lingen Bridge discussed in Section 4. The implications of these on the SPZ model are discussed in Section 5.

### 3.2.7 Model Outputs

A large number of post processed model datasets have been generated and retained within ESRI GIS and Surfer. Only key datasets pertinent to the abstraction capture scenarios are presented in the Groundwater Science (2016) report.

One example is shown on Figure 3.4, which visualises the simulated up-flow of groundwater from the bedrock to the drift deposits. It demonstrates that the majority of lateral and vertical flows to the drift filled valley are relatively shallow and concentrated on the valley margin.

**Figure 3.4. Simulated heads and flow to the drift from the bedrock (after Groundwater Science, 2016)**




**Notes**: Contains Ordnance Survey data © Crown Copyright and database right [2016].

Dark red polygon is the extent of the Glacial-Alluvial deposits as inferred from Environment Agency groundwater vulnerability mapping. Black circles are abstractions (larger circles are bedrock; smaller circles are from the glacial deposits). Black crosses are piezometer or percolation test locations which have inferred groundwater levels.

Orange contours are the Glacial-Alluvial, layer 1, simulated groundwater levels (m AOD). The purple contours are the simulated groundwater levels (m AOD) for the Bedrock.

The shaded blue colour scale represents the magnitude of flow from the bedrock to drift. The image denotes significant volumes of seepage at shallow depths where bedrock head intersects with the valley's drift material. (Adapted from Groundwater Science (2016) Figure 6).

## 3.3 Proposed New SPZs for Operational Use

### 3.3.1 Scenarios Modelled

In discussion with Rukhydro and Radnor Hills, Groundwater Science modelled the following three scenarios to support the delineation of SPZs:

1) **Simulation 'RDR011'** – this most closely represents **'current' operation** as defined by 2015 rates. Abstractions G2 and G3 are inactive and the discharge to the soakaway is 160m$^3$/d.
2) **Simulation 'RDR012'** - this aims to represent a possible **'future' operation** with maximum abstraction rates and soakaway discharge rates. It is the same as for RDR011 except the G2 and G3 abstractions are active at the rate of 280 and 180 m$^3$/d respectively and the discharge to the soakaway is increased to 240 m$^3$/d.
3) **Simulation 'RDR013' –** this is as for RDR012 but considers relocation of the soakaway to north of the chicken farm. To do this the existing soakaway discharge is reduced to a 0 m$^3$/d discharge and the 240m$^3$/d is discharged to a new, areally larger, soakaway to the north west of the site.

### 3.3.2 Presentation of Outputs

Groundwater Science's (2016) discussion on presentation of SPZs is repeated in Box 3.3.

**Box 3.3 – Source Protection Zone Presentation (after Groundwater Science, 2016)**

The typical metric for SPZ delineation is a travel time with the SP Zone 1 being the area which corresponds to abstraction within 50 days (red). SP Zone 2 is extended to 400days (green) and SP Zone 3 represents the total capture area without time limitation (blue).

In recent years additional datasets have been incorporated into the delineation process to take account of the volumetric significance of flow pathways. As the character of abstraction capture and groundwater chemistries differ between the bedrock and drift deposits the joint travel time and volumetric datasets are presented as contributions from each of these two aquifers independently. Consequently, Groundwater Science (2106) presents figures of the 50, 400 and Total travel time plots alongside the 'Volume Through' datasets.

Groundwater Science recommends that the red areas of the Volume Through plots are taken as 'illustrative' only as the volumes presented are extremely low (~0.01 m$^3$/day) and approaching the precision of the model. There is greater confidence in the higher flow volume areas of the delineated capture zones.

**Source**: From Groundwater Science (2016) report Section 3.3.

Groundwater Science's (2016) report presents 12 maps on six figures; 6 maps each for the 'current' (RDR011) and 'future' (RDR013) scenarios as summarised in Box 3.4 and reproduced at a small scale in Figures 3.5 and 3.6.

**Box 3.4 – Six Different Maps for Each Scenario**

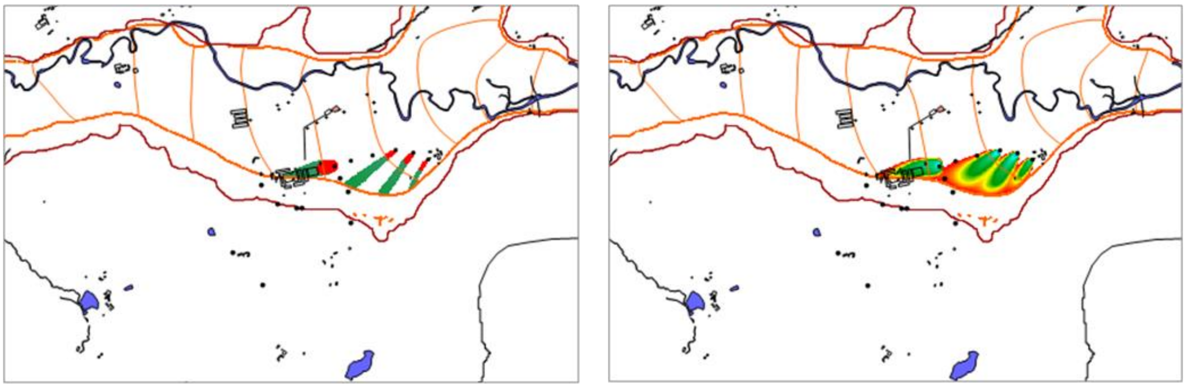
- SPZs in the drift deposits for the abstractions from the drift deposits;
  - Simulated time of travel for water within the glacial deposits to get to the abstractions from the drift;
  - Volume of water passing through the drift deposits which is simulated to be abstracted from the wells in the drift;
- SPZs in the bedrock for the abstractions from the drift deposits;
  - Simulated time of travel for water within the bedrock to get to the abstractions from the drift;
  - Volume of water passing through the bedrock which is simulated to be abstracted from the wells in the drift;
- SPZs in the bedrock for the abstractions from the bedrock;
  - Simulated time of travel for water within the bedrock to get to the abstractions from the bedrock;
  - Volume of water passing through the bedrock which is simulated to be abstracted from the wells in the bedrock.

**Source**: Rukhydro summary of the maps available in Groundwater Science (2016).

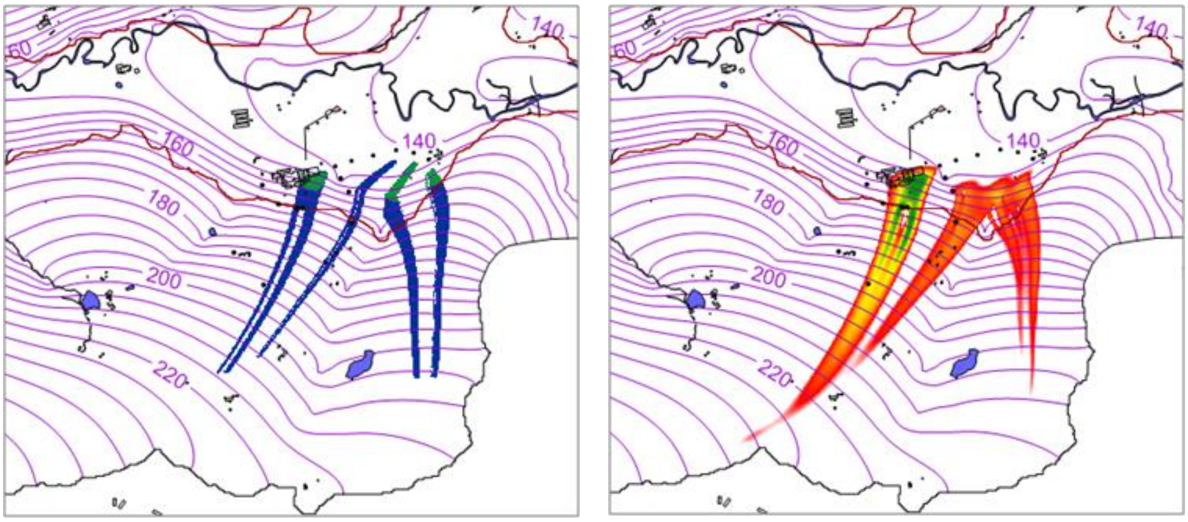
## Figure 3.5 Components of the ‘Current’ Situation SPZ Maps (Groundwater Science, 2016)

| Travel Time Maps on this Left Side | Where the water comes from Maps on this side |
|---|---|
| (Red is within 50 days, green is within 400 days, blue is total catchment) | (Blue = 50m$^3$/d to green 5 m$^3$/day to yellow 1 m$^3$/day to red 0.1m$^3$/d) |

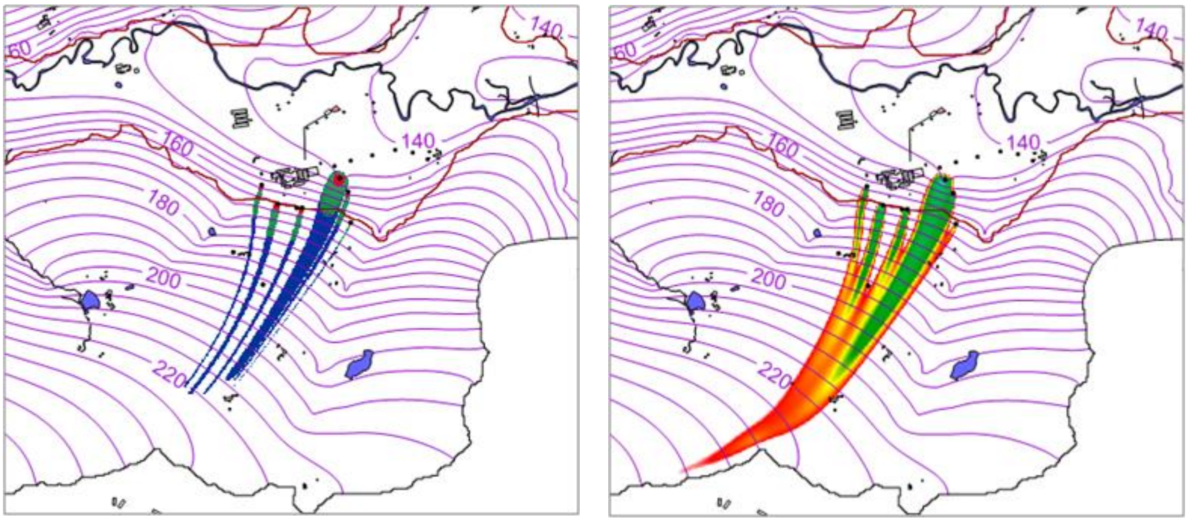
**(a) SPZs in the drift for the drift wells**



**(b) SPZs in the bedrock for the drift wells**




**(c) SPZs in the bedrock for the bedrock wells**

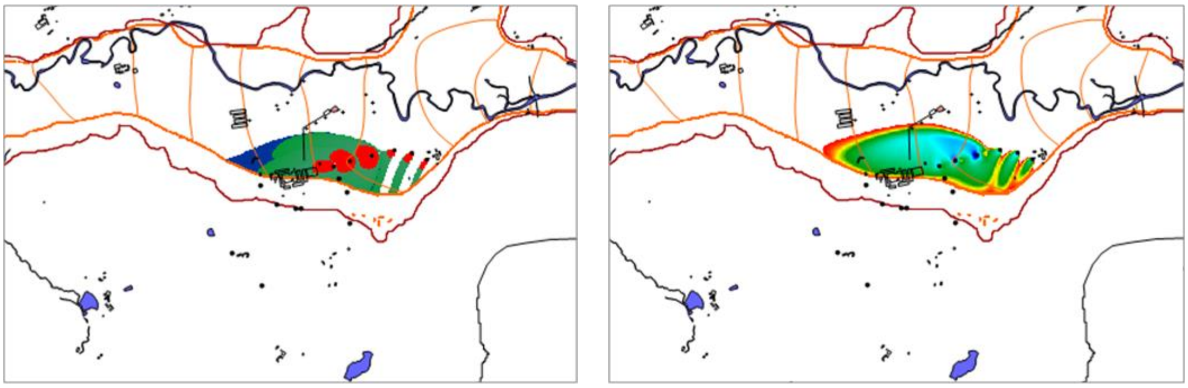



**Notes**: Contains Ordnance Survey data © Crown Copyright and database right [2016]. Taken from Groundwater Science (2016) report – see that report for further explanation of figures.

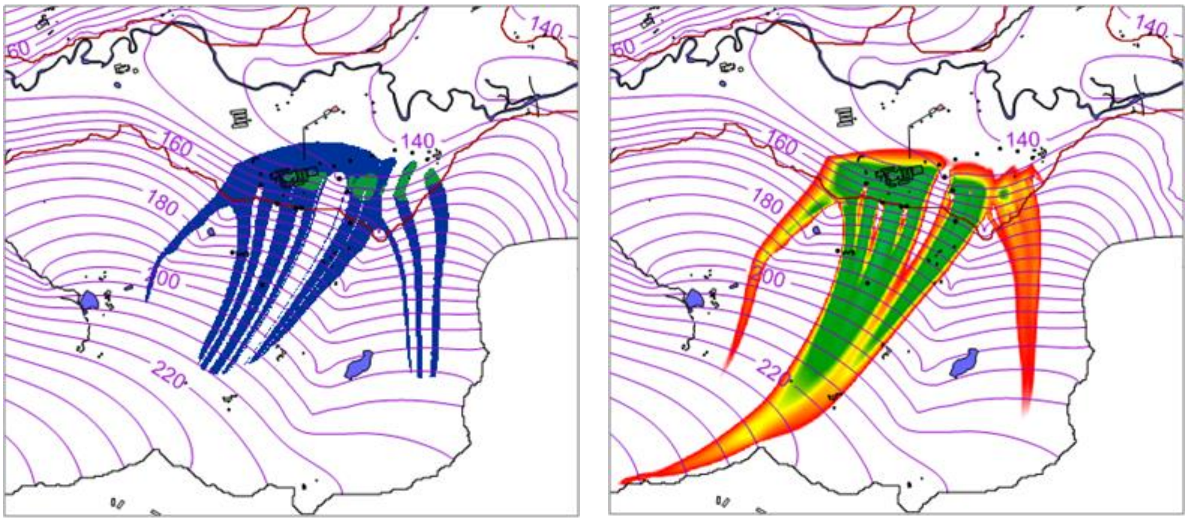
**Figure 3.6 Components of the 'Future' Situation SPZ Maps (Groundwater Science, 2016)**

| **Travel Time Maps on this Left Side** | **Where the water comes from Maps on this side** |
|---|---|
| (Red is within 50 days, green is within 400 days, blue is total catchment) | (Blue = 50m$^3$/d to green 5 m$^3$/day to yellow 1 m$^3$/day to red 0.1m$^3$/d) |

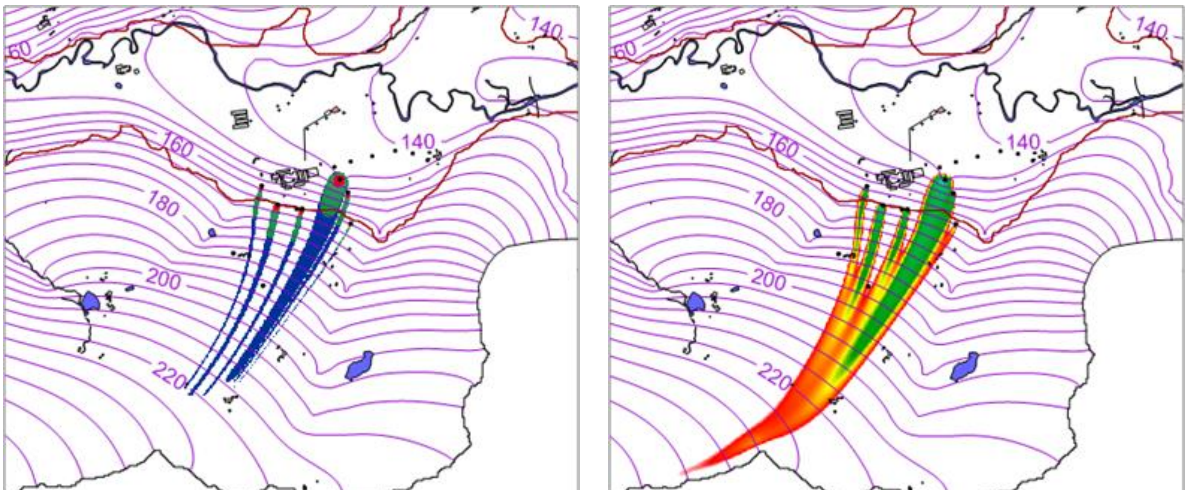
**(d) SPZs in the drift for the drift wells**



**(e) SPZs in the bedrock for the drift wells**




**(f) SPZs in the bedrock for the bedrock wells**



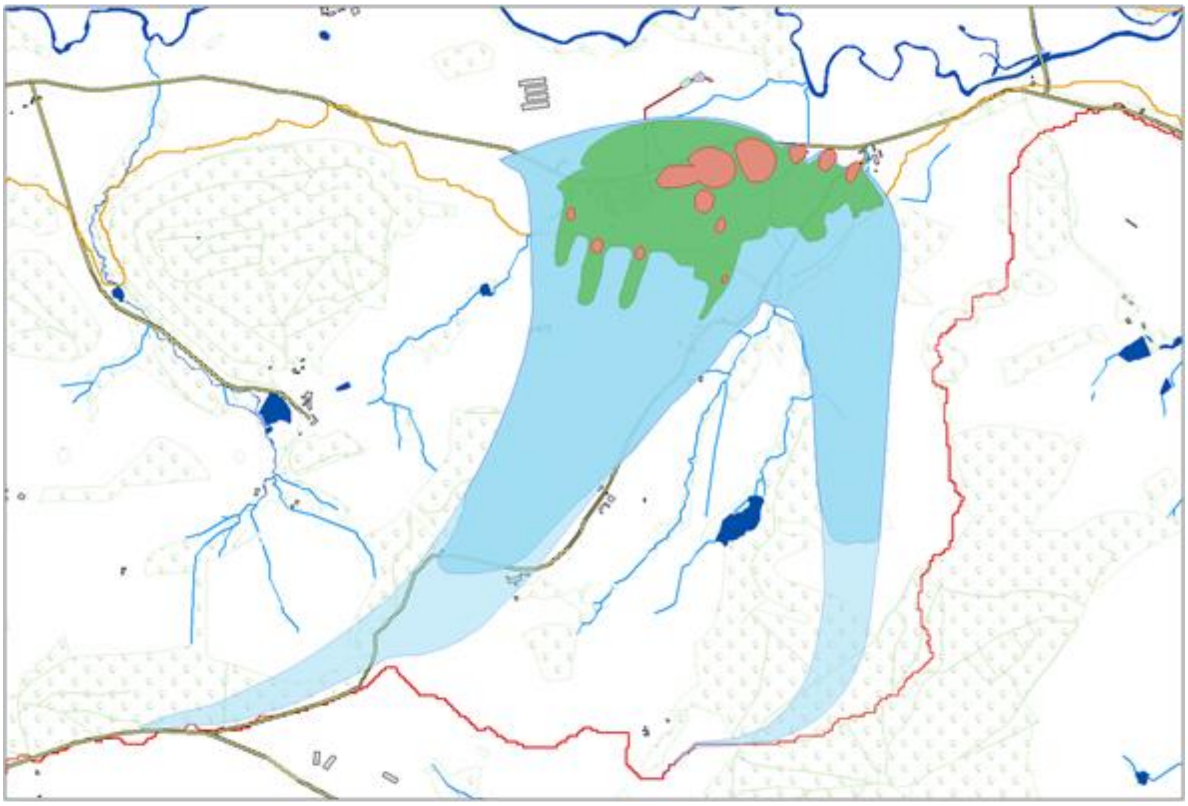

**Notes**: Contains Ordnance Survey data © Crown Copyright and database right [2016]. Taken from Groundwater Science (2016) report – see that report for further explanation of figures.

### 3.3.3 Proposed Amalgamated SPZ for Future Operation

The output maps illustrated in Figures 3.5 and 3.6 are produced in the software package Surfer. To provide a single source protection zone as a shapefile for overlaying on other maps in GIS, Groundwater Science amalgamated the maps for the future situation as shown and described on Figure 3.7.

**Figure 3.7 Proposed Source Protection Zones for the Radnor Hills operation (after Groundwater Science, 2016)**

The map below shows the amalgamated source protection zones (SPZs) for all Radnor Hills supplies under the predicted future abstraction rates detailed in Table 3.3. The different travel time zones (in groundwater and not from the land surface) are as follows: Red = SPZ1 (Inner, 50 days), Green = SPZ2 (Outer, 400 days) and Blue = Total Catchment (unlimited time). Extension of light blue denotes simulated travel times in excess of a decade.



**Notes**: Contains Ordnance Survey data © Crown Copyright and database right [2016]. Red polygon is the Teme surface water catchment, Orange polygon is the extent of the Glacial-Alluvial deposits as inferred from Environment Agency groundwater vulnerability mapping. See previous figures or Groundwater Science (2016) for key to other mapped features.

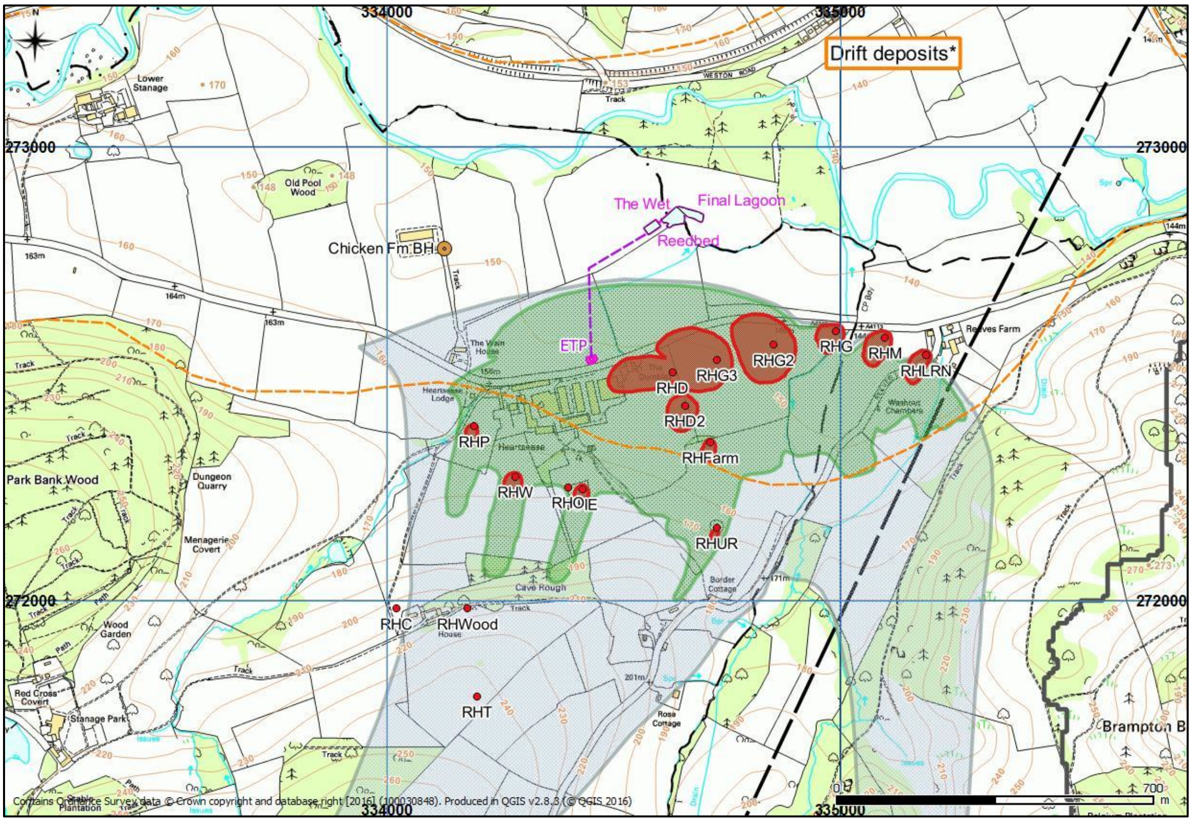
**Approach**: The proposed SPZs are provided in the shapefile pgn_RadnorHills_SPZones.shp. These areas have been delineated by amalgamating all travel time plots presented in Figure 3.6, and analogous data from run RDR012. From these collective datasets the fastest travel times simulated for each and every cell is applied to guide the 50day, 400day and total capture zones.

In addition, the zones have been extended to include the pathways as implied by the volumetric outputs. This results in broader, more joined-up zones. The final extents are deliberately manually drawn and do not map exactly to simulated data. The simulated data are supporting datasets which guide the delineation. Local hydrogeological interpretation and conservatism in areas of greater uncertainty additionally contribute to the final zones

An amalgamated map has not been produced for the current abstraction regime.

A zoomed in version of the SPZ map for the future situation is shown overlain on 1:10,000 scale mapping on Figure 3.8.

**Figure 3.8 – Zoomed-in Version of SPZ Map (Future Situation) on 1:10000 Base Mapping**




**Source**: Contains Ordnance Survey data © Crown Copyright and database right [2016] (100030848) including 1:50k scale topographic contours. Also contains Environment Agency extent of Minor Aquifer Intermediate groundwater vulnerability (orange dashed line, used here to show the extent of drift deposits) and BGS mapped faults from DiGMapGB-625, with the permission of the British Geological Survey.

**Legend**: The map below shows the amalgamated source protection zones (SPZs) for all Radnor Hills supplies under the predicted future abstraction rates detailed in Table 3.3. The different travel time zones (in groundwater and not from the land surface) are as follows: **Red** = SPZ1 (Inner, 50days), **Green** = SPZ2 (Outer, 400 days) and **Blue** = Total Catchment (unlimited time).

## 3.4 Use of Water Quality for Further Validation

Groundwater Science extracted the proportions of bedrock and drift water that the SPZ model predicted to be present under the 'current' situation abstraction regime for boreholes on the drift. The information is provided in Table 3.4 together with selected water quality data collated by Rukhydro. Figure 3.9 graphically presents the same data.

Although there is uncertainty regarding the composition of completely bedrock-free drift water (because bedrock water could be rising into the drift throughout the valley), then Table 3.4 and Figure 3.9 suggest:

- There are clear differences between drift and bedrock groundwaters, with 100% bedrock groundwaters containing higher concentrations of sodium, alkalinity and fluoride and lower concentrations of chloride.
- The SPZ model prediction for Borehole RHD (81% contribution from the bedrock) appears too high compared to water quality which suggests 40-60%.
- The SPZ model prediction for Borehole RHD2 (100% contribution from the bedrock) appears too high compared to water quality which suggests ~80%.

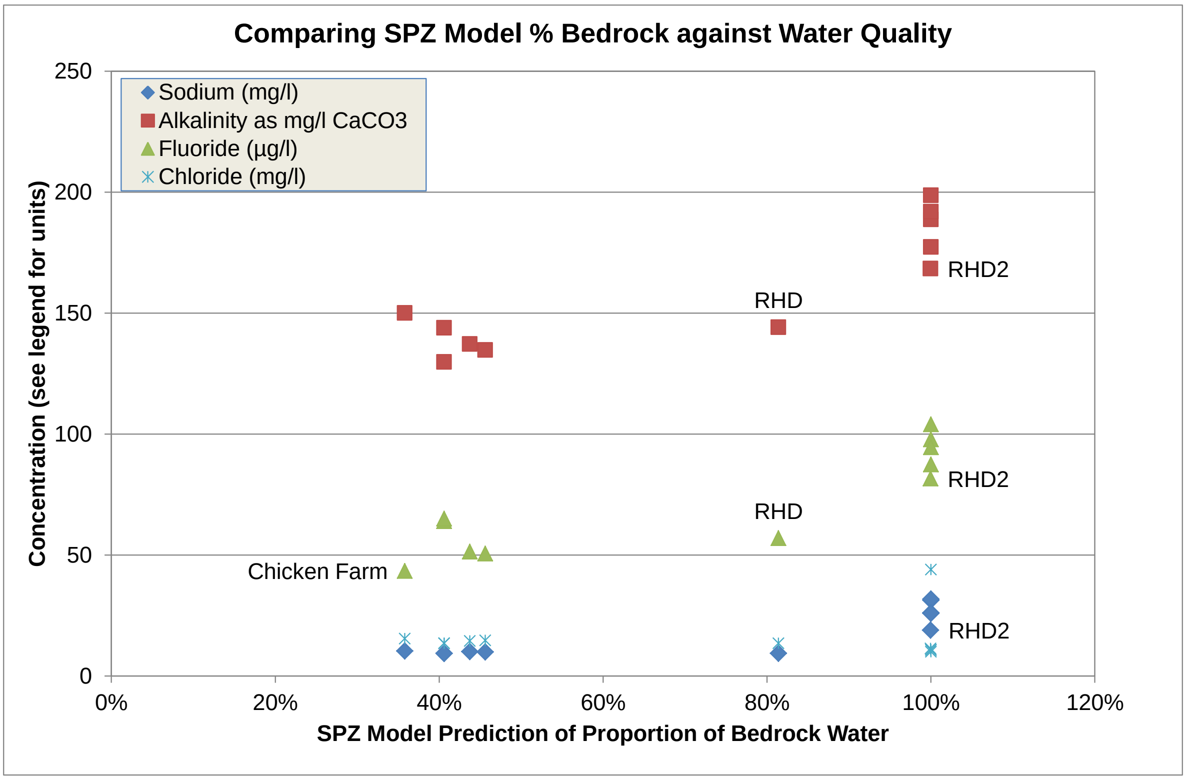
**Table 3.4 SPZ Model Predictions of % Bedrock versus Water Quality**

| Bore-hole | Model Rate[1] m³/day | From Drift[1] m³/day | From[1] Bedrock m³/day | Bedrock Water[1] % | Chloride mg/l | Sodium[2] mg/l | Alkalinity[2] mg/l $CaCO_3$ | Fluoride[2] mg/l |
|---|---|---|---|---|---|---|---|---|
| Chicken Fm | 60.0 | 38.5 | 21.5 | 36% | 15.40 | 10.30 | 150.0 | 43.4 |
| LRN[3] | 25.6 | 15.2 | 10.4 | 41% | 13.49 | 9.37 | 143.9 | 64.0 |
| LRO[3] | 25.6 | 15.2 | 10.4 | 41% | 13.50 | 9.26 | 129.8 | 65.0 |
| RHM | 52.8 | 29.7 | 23.1 | 44% | 14.45 | 10.10 | 137.2 | 51.4 |
| RHG | 47.7 | 25.9 | 21.8 | 46% | 14.69 | 9.90 | 134.8 | 50.6 |
| RHD | 83.2 | 15.5 | 67.7 | 81% | 13.53 | 9.35 | 144.1 | 57.0 |
| RHD2 | 81.2 | 0.0 | 81.2 | 100% | 11.38 | 18.90 | 168.4 | 81.6 |
| RHE | 24.4 | | | 100% | 10.79 | 31.30 | 198.7 | 87.4 |
| RHP | 19.2 | | | 100% | 10.71 | 31.80 | 177.3 | 104.0 |
| RHUR | 5.0 | | | 100% | 9.97 | 26.10 | 188.7 | 97.8 |
| RHW | 33.9 | | | 100% | 43.97 | 25.90 | 191.9 | 94.5 |

Notes:

1) As provided by Groundwater Science (except RHE, RHP, RHUR and RHW which are in areas without drift cover). Rates are average abstraction rates for 2015. Boreholes are shown in order of increasing proportion of bedrock water and alphabetical thereafter.
2) From samples taken on 21/09/2015 except for the Chicken Farm which is for 23/02/16 (and 13/03/2013 for fluoride).
3) These are modelled as a combined abstraction of 25.6 $m^3$/day, but the individual rates are LRN (20.6 $m^3$/day) and LRO (5 $m^3$/day)

**Figure 3.9 – SPZ Model Predictions of % Bedrock versus Water Quality**



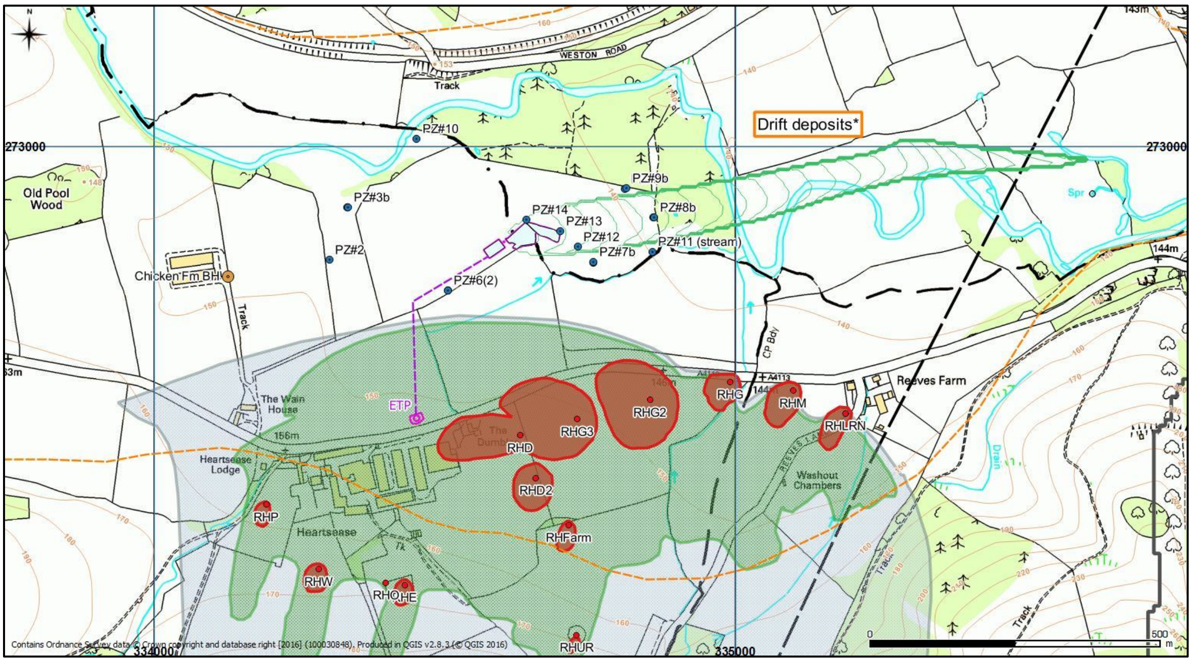

**Source**: Graphically presents data from Table 3.4. Water quality data from Radnor Hills.

## 3.5 SPZ Model Predicted Soakaway Plumes

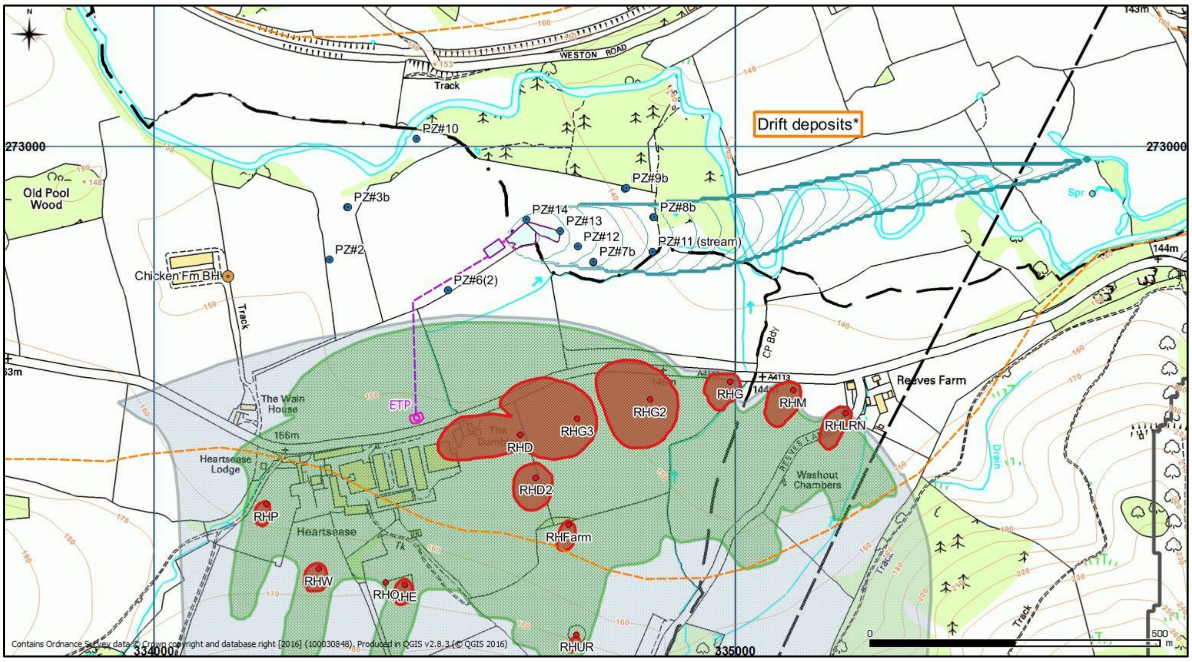
Figure 3.10 shows the predicted direction of plumes from the lagoon / soakaway under 'current' and future abstraction and discharges scenarios (see Table 3.3).

**Figure 3.10 – SPZ Model Predictions of Plumes from Modelled Discharges**

**(a) Predicted Plume from Current Lagoon Discharge of 160 m³/day (but with Future SPZ)**




**(b) Predicted Plume from Future Lagoon Discharge of 240 m³/day and Future SPZ**




**Source**: Contains Ordnance Survey data © Crown Copyright and database right [2016] (100030848) including 1:50k scale topographic contours. Also contains Environment Agency extent of Minor Aquifer Intermediate groundwater vulnerability (orange dashed line, used here to show the extent of drift deposits) and BGS mapped faults from DiGMapGB-625, with the permission of the British Geological Survey.

**Legend**: See Figure 3.8 for Source Protection Zone (SPZ) legend details (Red = SPZ1 (Inner, 50days), Green = SPZ2 (Outer, 400 days) and Blue = Total Catchment (unlimited time)). The plumes are contoured with 30 day travel time steps.

The plume shapes were produced by Groundwater Science using the SPZ model and FlowSource to forward track discharges. With each of the contours on the plumes equating to 30 days travel time for a conservative unretarded parameter (e.g. chloride or bromide), both simulated plumes suggest travel times of:

- 150 to 180 days to piezometer PZ#8b;
- 240 to 270 days to the River Teme.

For the current situation, the direction and cross groundwater flow width (~85 m) of the plume matches the water quality impact detailed in Section 2.5.4 with the main impact (10-20% lagoon water) at PZ#8b, lesser impact (7-9%) at PZ#14 and more minor impact (4-6%) at PZ#9b and PZ#11b. The modelled plume also shows PZ#7b, closest to the lagoon, to be not in the direct path of the plume; although this is less consistent with the monitored water quality which suggests 7-9% lagoon water. Samples are yet to be collected from PZ#13 (immediately downgradient and centre of plume) and PZ#12, due to these piezometers being dry during the August 2016 sampling round.

Importantly for both ‘current’ and ‘future’ abstraction scenarios, the model suggests there is negligible risk of the plume water being intercepted by Radnor Hills’ abstraction boreholes. Under the future scenario the modelled cross groundwater flow plume width is ~120 m wide.

## 3.6 Uncertainties

All models are a mathematical simplification of often heterogeneous strata and rely on using a few parameters to represent averages of spatially variable properties (e.g. recharge, hydraulic conductivity).

Groundwater Science note that, when compared to many Source Protection Zone models, the Radnor Hills one has a very fine grid (5 m rather than 200 m) and has received relatively large amounts of validation and checking. The model’s simulation of groundwater levels is very good and the direction and width of the modelled soakaway plumes tallies well with water quality data.

There are however uncertainties and these will only be reduced in time as the model is used and tested over time.

## 3.7 Summary

A detailed MODFLOW model (with 5 m grid) has been set up of the Radnor Hills area by Groundwater Science and calibrated against groundwater levels. This has been used with FlowSource to define new source protection zones for Radnor Hills' operational use. It has also been used to examine the potential for the soakaway’s plumes to impact upon Radnor Hills’ abstracted water.

The model suggests there is negligible risk to the Radnor Hills abstractions under the current and anticipated future abstraction and soakaway discharge scenarios.

# 4. River Teme Flows and Dry Reaches

## 4.1 Purpose of this Section

This section presents available information on flows in the River Teme and on reaches of the river which are prone to drying out in drought conditions. This information is important for examining the feasibility of a treated discharge to river as well as the general conceptual understanding of the area.

## 4.2 Available Information

Following discussions with NRW, the Environment Agency was contacted and the following information was made available:

- ESI (2007) Report. Hydrological and hydrogeological assessment of flows in the Upper Teme. Consultant report for the Environment Agency, Midlands Region);
- Spot flow measurements on the River Teme 1995 to 2011 including notes on locations where the river dries up.
- Daily river stage measurements for the Teme at Knighton and Leintwardine (downstream of confluence with the River Clun) and daily flow measurements for the River Teme at Tenbury (the nearest flow gauge on the Teme) and two other gauged rivers in the area (River Arrow at Titley and River Lugg at Byton).
- Environment Agency's local fisheries officer's (Peter Giles) maps of reaches prone to drying up; provided to Radnor Hills on 03 March 2016.

## 4.3 Dry River Reach Assessment

### 4.3.1 ESI (2007) Report

ESI (2007) undertook an evaluation of which reaches of the River Teme dry out using information from a site visit on 13 August 2007 and from Environment Agency staff (Peter Giles, fisheries officer). The reaches they mapped are shown on Figure 4.1.

ESI noted the earliest place to go dry, when flows are declining, is reported to be at a point on the River Teme near Weston footbridge (NGR 4329 3731), approximately 1.2 km ('as the crow flies') upstream of the Radnor Hills site at Heartsease.

### 4.3.2 Environment Agency Local Fisheries Officer Maps

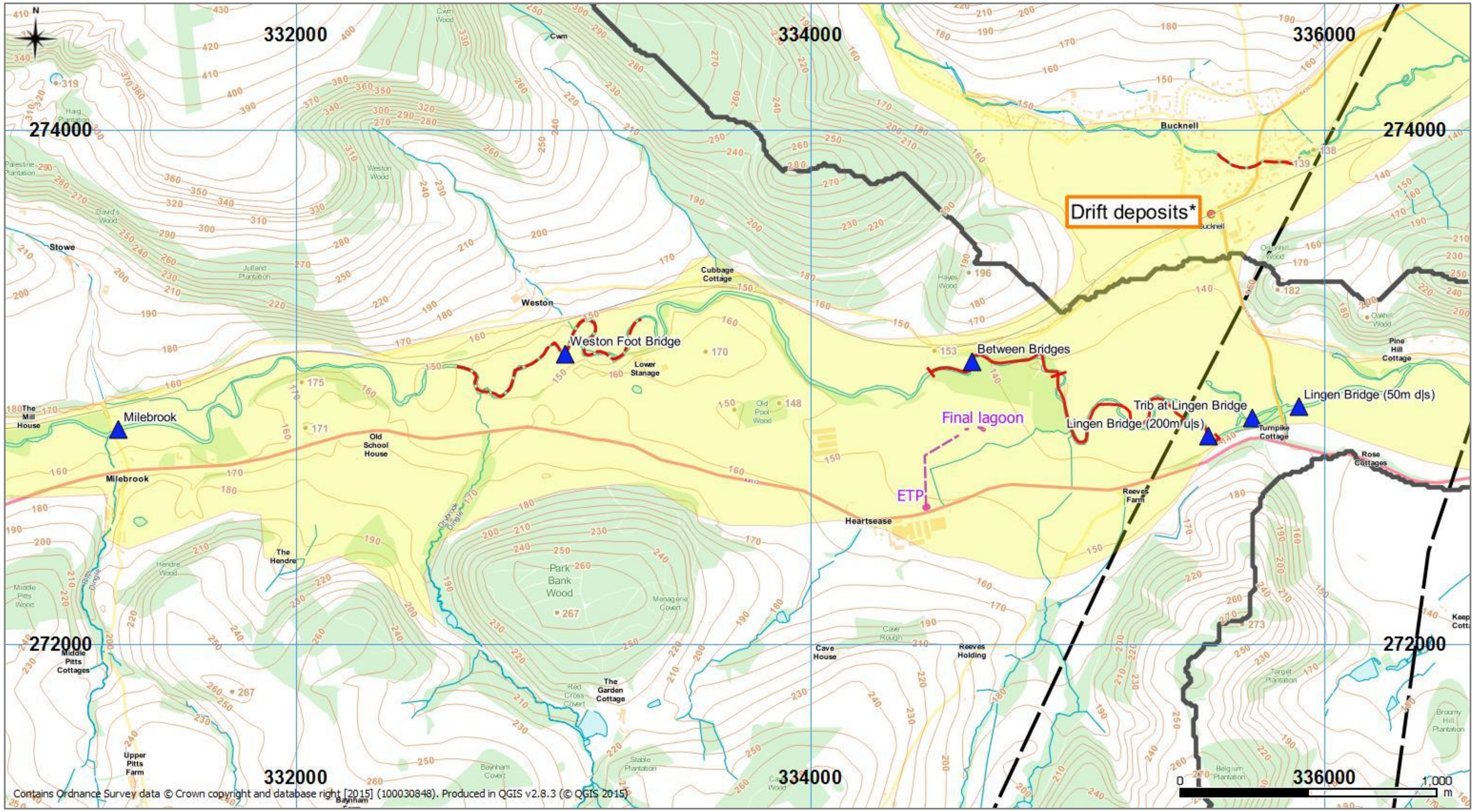
The Environment Agency's local fisheries officer (Peter Giles) was contacted and on 03 March 2016, kindly provided a map annotated with the river reaches which dry up. The map was provided to Radnor Hills in paper copy and is reproduced in Appendix B. The dry reaches from this are also shown on Figure 4.1.

### 4.3.3 Overview of Dry Reaches

Figure 4.1 shows that the River Teme dries up for about 600 m of river length upstream and 600 m downstream of Weston footbridge. There is then a ~1700 m river length of permanent river down to north of Heartsease. This is then followed by an ~1800 m length of river which is prone to drying up. The lower ~1160 m dries up before the upper ~620 m of this reach.

Peter Giles' (EA) map (Appendix B) notes that normal flow occurs from ~260 m (river length) upstream of Lingen Bridge. Recommencing of "normal" flow broadly coincides with a geological fault and change in bedrock strata and constriction of the valley and width of the drift. The normal flow also occurs in an area where springs are mapped (see Figure 4.2).

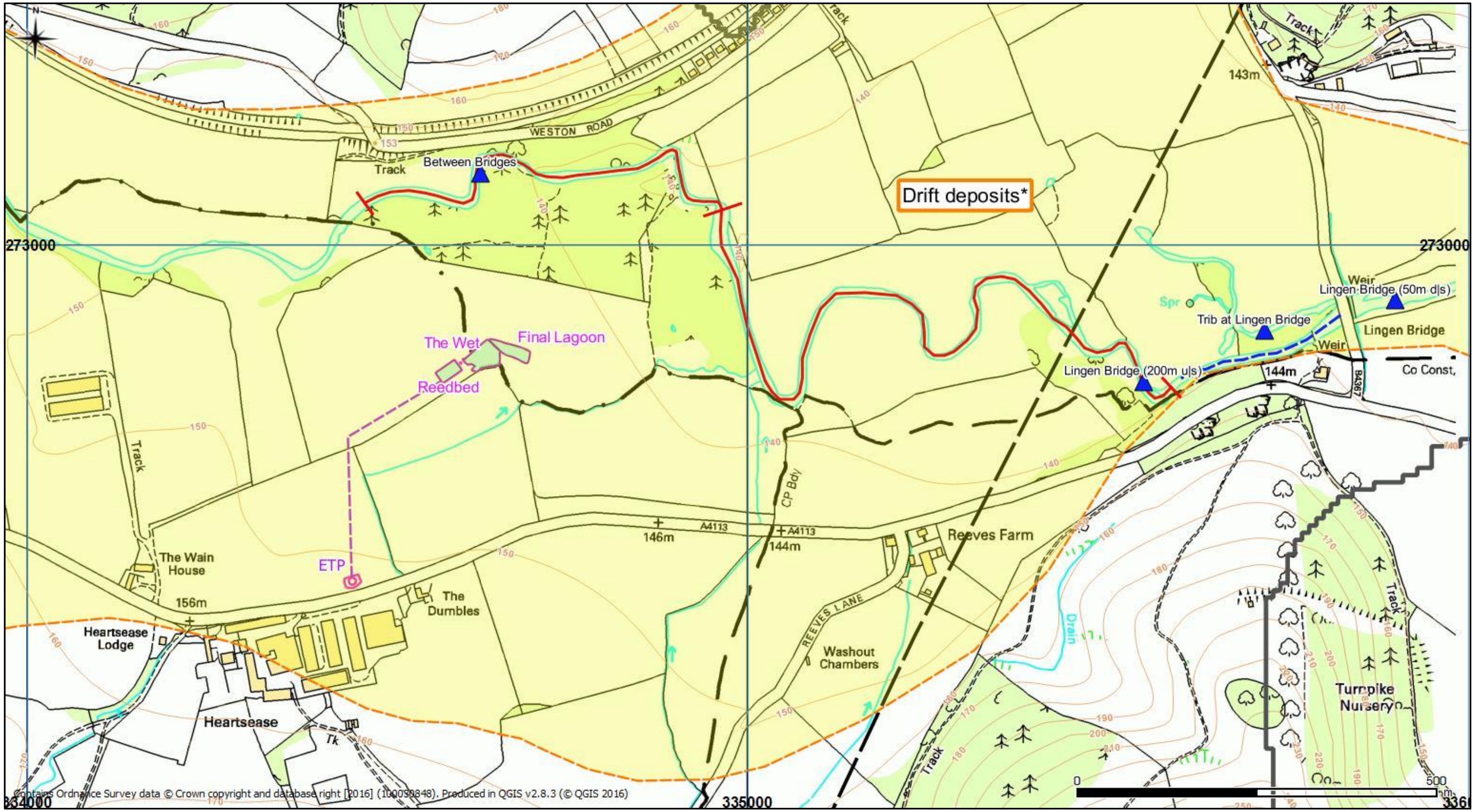
**Figure 4.1 – River Reaches Prone to Drying up and Location of Spot Flow Gauging Sites**




**Source:** Contains Ordnance Survey data © Crown Copyright and database right [2016] (100030848) including 1:50k scale topographic contours. Also contains Environment Agency extent (yellow area) of Minor Aquifer Intermediate groundwater vulnerability (used here to show the extent of drift deposits) and BGS mapped faults (black dashed lines) from DiGMapGB-625, with the permission of the British Geological Survey.

**Notes: Blue triangles**: locations of spot river flow measurement sites. Red reaches: Reaches prone to drying up after ESI (2007, dashed) and P Giles (EA, 03 March 2016, solid). The red reaches have been digitised from 1:10,000 scale mapping, but are overlain on 1:25,000 scale mapping above. This leads to some mismatch downstream of Heartsease.

**Figure 4.2 – River Reaches Prone to Drying up and Location of Spot Flow Gauging Sites (Zoomed-In)**




**Source:** Contains Ordnance Survey data © Crown Copyright and database right [2016] (100030848) including 1:50k scale topographic contours. Also contains Environment Agency extent (yellow area) of Minor Aquifer Intermediate groundwater vulnerability (used here to show the extent of drift deposits) and BGS mapped faults (black dashed lines) from DiGMapGB-625, with the permission of the British Geological Survey.

**Notes: Blue triangles**: locations of spot river flow measurement sites. Red reaches: Reaches prone to drying up after P Giles (EA, 03 March 2016). Blue dashed reach – reach with near Lingen Bridge with normal flow and not prone to drying up.

## 4.4 River Teme Flows and Dry Periods near Heartsease

### 4.4.1 Purpose of this Sub-Section

There are no continuous flow measurements for the River Teme near Heartsease. Flows and periods of no flows therefore need to be estimated using continuous measurements from elsewhere on the Teme or in nearby river catchments correlated to spot flow measurements for the Teme near Heartsease. The following sections provide these correlations.

### 4.4.2 Continuous Flow and River Stage Gauging

Table 4.1 provides information on catchments and sub-catchments (Water Framework Directive water bodies) and river gauging stations for the River Teme. Details of river gauges on the River Lugg and River Arrow to the south of the Teme valley are also provided. Locations of gauges, River Teme sub-catchments to Leintwardine and other gauged catchments are shown on Figure 4.3.

**Table 4.1 Catchment Areas for Flow Measurements and Estimates**

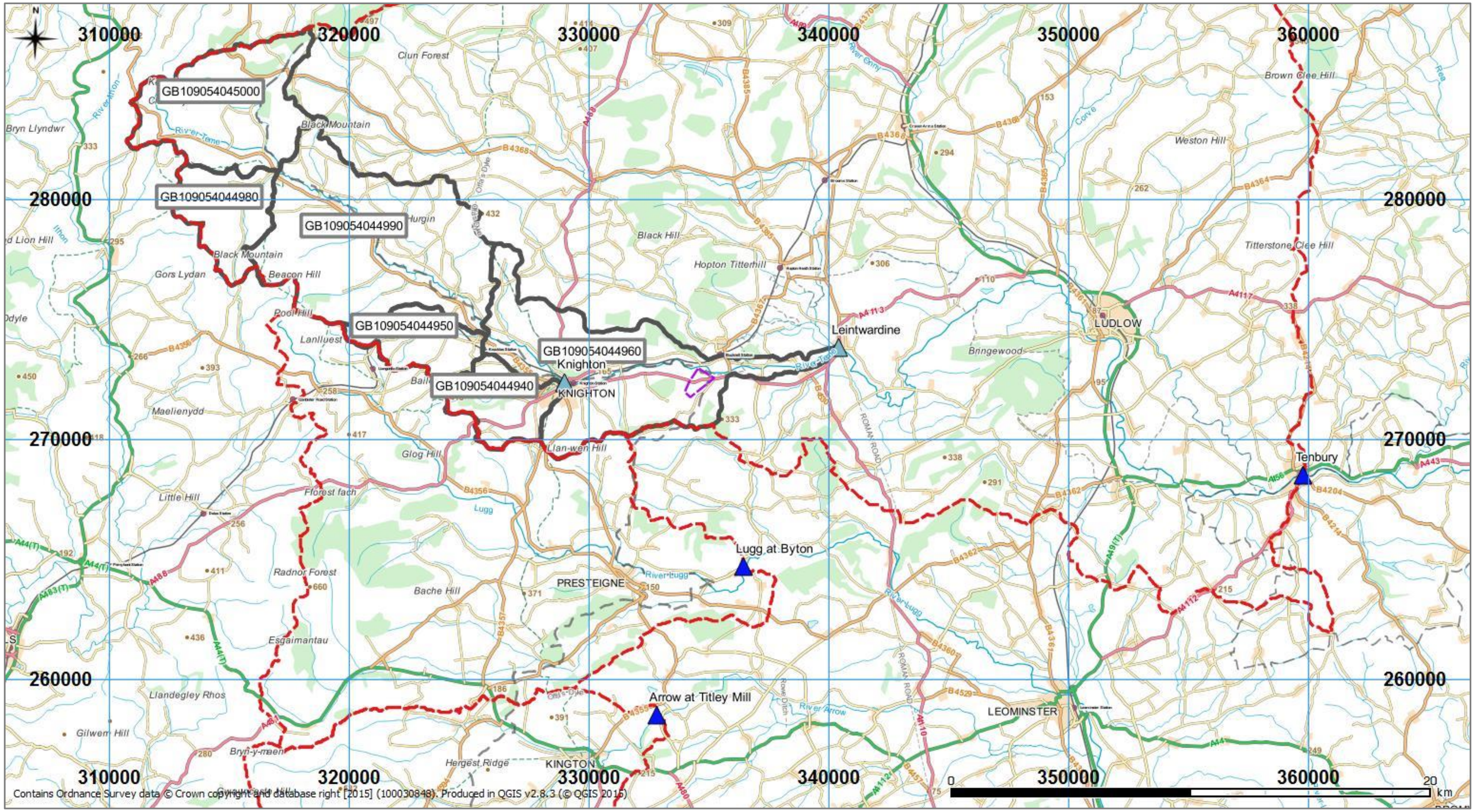
| Water Body ID | Water Body Name | Water Body Area ($km^2$) | Assumed Proportion in Catchment to Teme at Lingen Bridge | Source of Information |
|---|---|---|---|---|
| GB109054045000 | Teme - source to conf Deuddwr Bk | 29.88 | 100% | Environment Agency |
| GB109054044980 | Deuddwr Bk - source to conf R Teme | 13.53 | 100% | “ |
| GB109054044990 | Teme - conf Deuddwr Bk to conf Ffrwdwen Bk | 55.03 | 100% | “ |
| GB109054044950 | Ffrwdwen Bk - source to conf R Teme | 11.30 | 100% | “ |
| GB109054044940 | Wylcwm Bk - source to conf R Teme | 11.22 | 100% | “ |
| GB109054044960 | Teme - source to conf Ffwdwen Bk to conf R Clun (at Leintwardine) | 44.53 | 90% | “<br>(90% estimate by Rukhydro, 2015) |
| | Teme to confluence with Clun at Leintwardine | 165.49 | | Calculated |
| | Teme at Milebrook | 150.00 | | Estimated |
| | Teme at Lingen Bridge | 161.01 | | Calculated |
| **Catchment to Gauge at** | **Grid Ref of Gauge** | **Catchment Area ($km^2$)** | **Type of Gauge** | **Source of Information** |
| Knighton (Teme) | 328980,272370 | 119 | Stage | ESI, 2007 |
| Leintwardine (Teme)[1] | 340430, 273810 | 430 | Stage | ESI, 2007 |
| Tenbury (Teme) | 359770, 268510 | 1135 | Flow | ESI, 2007 |
| Byton (Lugg) | 336432, 264689 | 202.5 | Flow | Environment Agency[2] |
| Titley Mill (Arrow) | 332821, 258500 | 125.9 | Flow | Environment Agency[2] |

Notes:
1) The gauging station at Leintwardine is downstream of where the River Clun enters the Teme.
2) Data and grid reference from the Environment Agency, but catchment area calculated in QGIS2.8.3 using catchment areas downloaded from National River Flow archive.

### 4.4.3 River Teme at Tenbury

There are no continuous flow gauging sites on the River Teme upstream of Tenbury and the flows at Tenbury include significant inflows from rivers Clun, Corve and Onny. The catchment to Tenbury is reported in ESI (2007) as 1135 $km^2$ and the catchment to the Teme (based on upstream water body areas – see Table 4.1) before the confluence with the Clun at Leintwardine is 165.5 $km^2$ and so represents less than 15% of the catchment to Tenbury.

**Figure 4.3 – River Teme Catchment to Leintwardine and Referenced Gauging Stations**




**Source:** Contains Ordnance Survey data © Crown Copyright and database right [2016]. Also contains Water Framework Directive water body boundaries (grey solid) downloaded from the Environment Agency's Geostore website on 03 November 2015 and catchment boundaries (red-dashed) from the CEH website (Data owned by NERC – centre for Ecology and Hydrology © Database Right/Copyright NERC – Centre for Ecology and Hydrology. Downloaded on 29 March 2016). The full catchments are not shown.

**Notes:** **Blue triangles**: locations of continuous river flow measurement sites. **Grey-blue triangles**: locations of continuous river level measurements. Only gauges used in this study are shown. **Small purple area** is the general location of Radnor Hills at Heartsease.

### 4.4.4 River Teme at Leintwardine

ESI (2007) report on flow estimates for the Teme at Leintwardine based on a provisional stage / discharge relationship derived by the Environment Agency. ESI (2007) also note that the flows in the River Teme at the Leintwardine (stage) gauge "*are greatly influenced by flows in the River Clun, which flows into the Teme just upstream of the gauging site and may not be an accurate reflection of the conditions in the River Teme upstream of Leintwardine.*"

The Clun catchment is 272 $km^2$ (EA & NE, 2014) and the Teme to Leintwardine is 165.5 $km^2$ (see Table 4.1). ESI (2007) report the catchment to Leintwardine, including the Clun, Pember's Ditch and the Teme is 430 $km^2$ (so broadly consistent). The Teme catchment and flows at Leintwardine therefore represent a ~38% contribution from the Teme and so, as noted by ESI (2007), are strongly influenced by flows in the Clun.

### 4.4.5 River Teme at Knighton

From Table 4.1, the catchment to the river (stage) gauging station at Knighton is 119 $km^2$ compared to an estimated catchment area for the Teme to Heartsease of 161 $km^2$. So the catchment at Knighton is ~74% of that at Heartsease, making the Knighton stage gauge more likely to represent relative variability of flows (and stage) in the Teme than either at Leintwardine or Tenbury. Available river stage data for Knighton is shown on Figure 4.4.

There are, however known losses from the River Teme to groundwater between Knighton and Lingen Bridge. ESI (2007, Table 5.7) report losses of 18,600 to 20,800 $m^3$/day between Milebrook and Weston Footbridge (see Figure 4.1 for locations) for three dates in September 2007. The losses from the river between Milebrook to Lingen Bridge for the same dates are reported to be 17,500 to 22,700 $m^3$/day.

### 4.4.6 Environment Agency Spot Flow Measurement Data

ESI (2007) examined spot flow measurement data up to and including 05 October 2007 and reported it in their Appendix B. Environment Agency data provided for this 2016 evaluation include 5 additional dates for Weston footbridge between May and October 2011.

Available spot flow measurements for the River Teme between Weston footbridge (upstream of Heartsease) and around Lingen Bridge (downstream of Heartsease) are shown on Figure 4.4. Locations of spot flow gauged sites are shown on Figure 4.1.

### 4.4.7 River Flows for the Teme at Milebrook versus those on the River Arrow

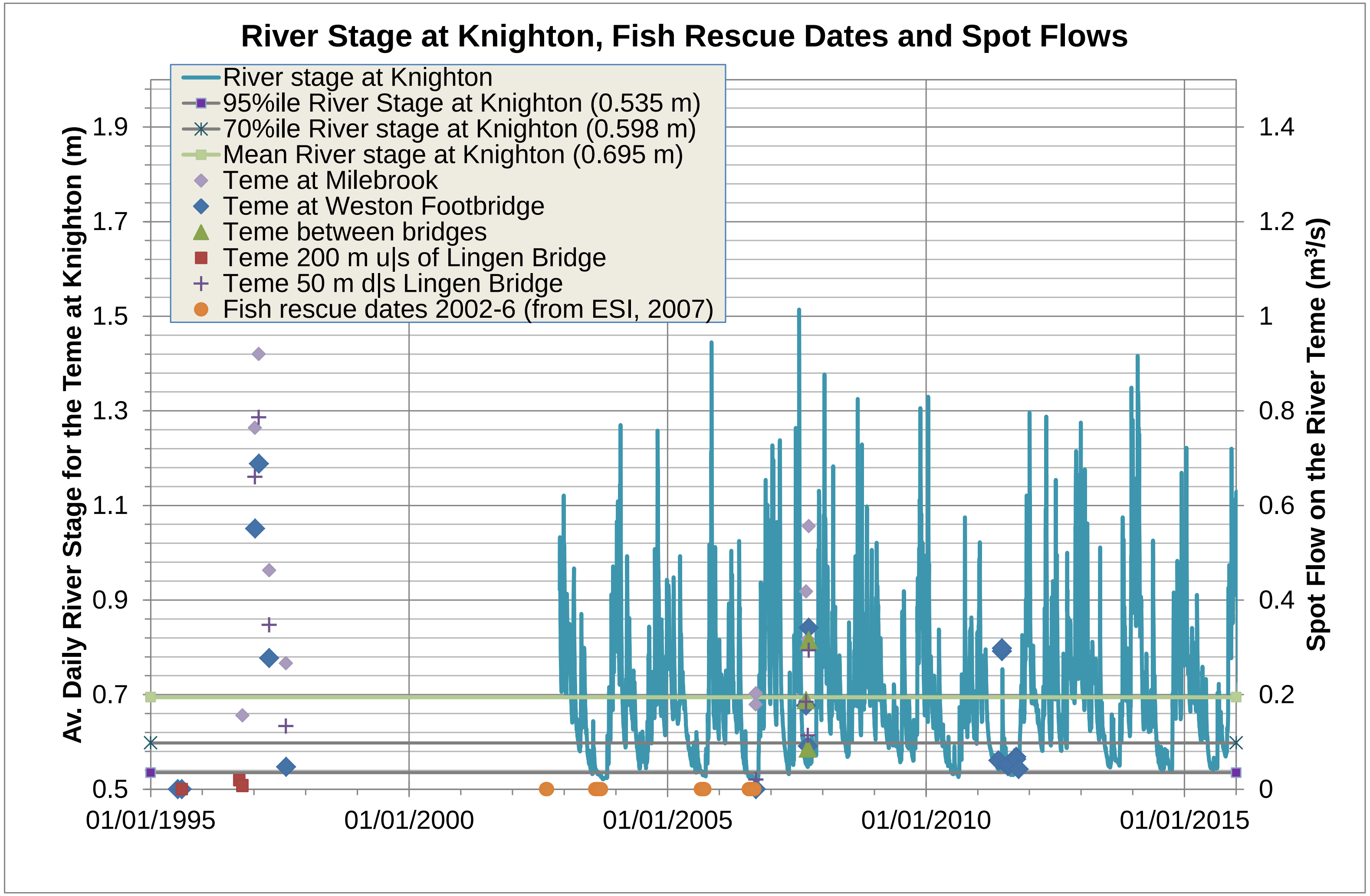
Figure 4.4 shows there are spot flow data for the Teme near Heartsease from before stage measurements started being recorded at Knighton in 2002. This means a stage flow relationship just using the Knighton data will be poorly constrained for higher flows. Instead therefore Figure 4.5 compares flows on the Teme at Milebrook (upstream of the drying up reaches, estimated catchment area ~150 $km^2$) with flows at Titley Mill on the River Arrow (catchment area = 125.9 $km^2$). Like the Teme to Milebrook, the valley of the River Arrow catchment to Titley Mill also has significant areas of superficial deposits ("*Minor Aquifer Intermediate*" groundwater vulnerability as mapped on the Environment Agency's what's in my backyard website) and plausibly has similar rainfall and flow variability.

The relationship $y = 0.9736x^{1.0567}$ is derived between flows on the Teme at Milebrook (y) and on the River Arrow at Titley Mill (x).

## 4.5 Downstream Changes in Flow near Heartsease

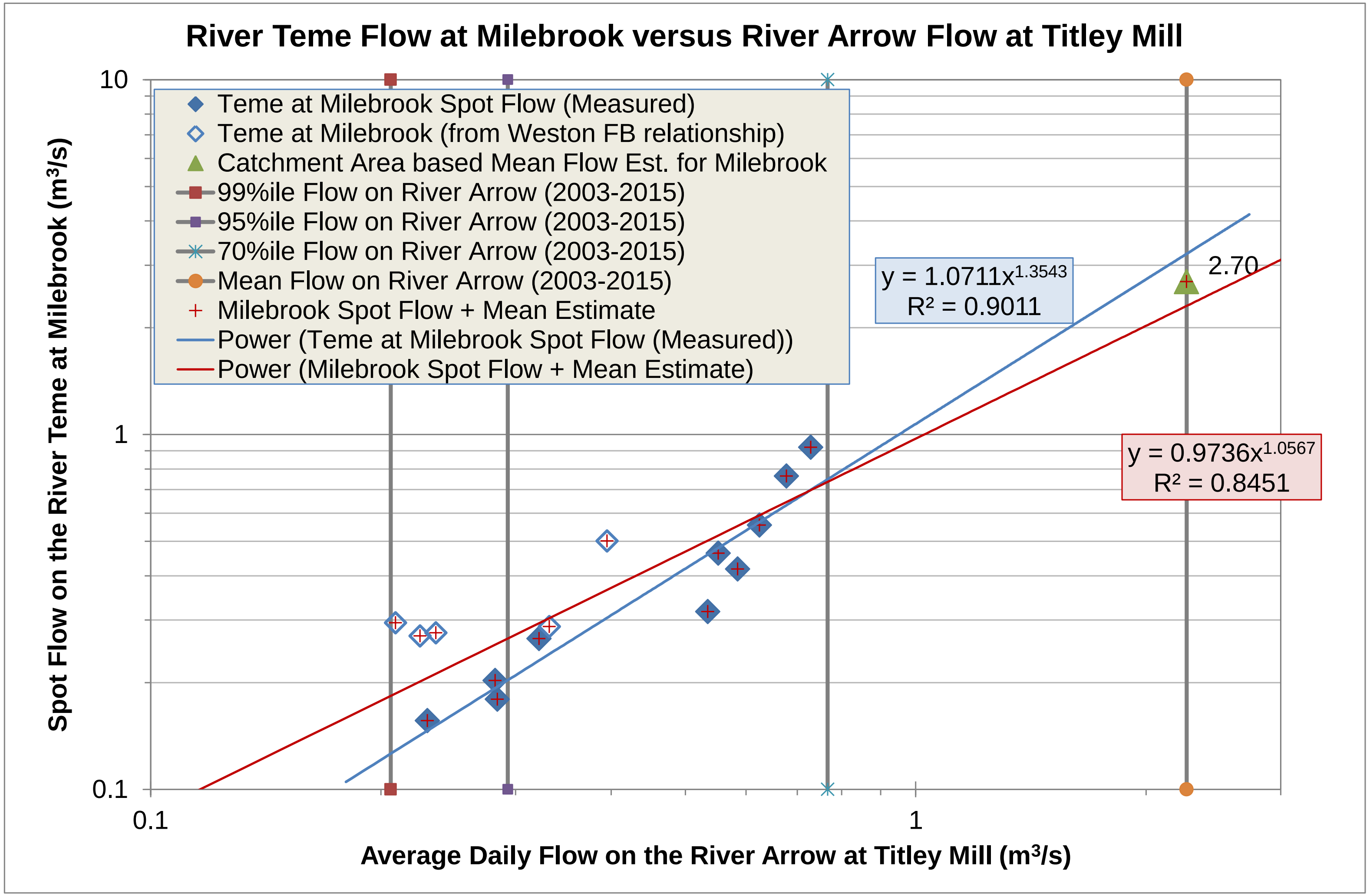
Figure 4.6a shows downstream changes in flow recorded at five locations near Heartsease between January 1997 and September 2007. Locations are shown on Figure 4.1. Figure 4.6b compares spots flows at different locations against those at Milebrook.

**Figure 4.4 – River Stage Variation at Knighton, Fish Rescue Dates and Spot Flow Measurements for the Teme near Heartsease**



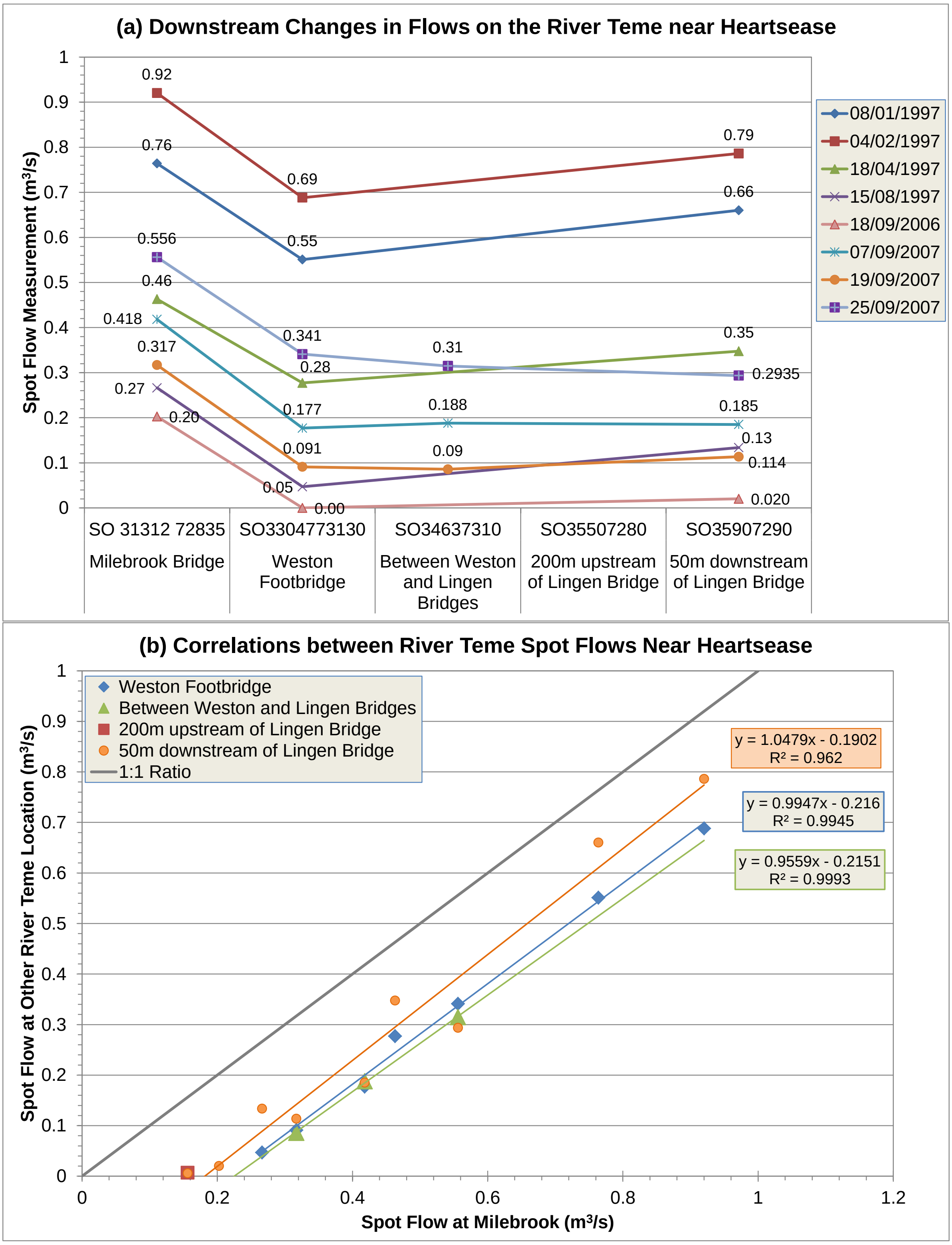

**Source:** River stage and spot flow measurements data provided by the Environment Agency (*Contains Environment Agency information © Environment Agency and database right*). Fish rescue dates (for the period 2002 to 2006) and a few additional spot flow measurements from ESI, 2007.
**Notes:** Percentiles and mean for river stage are for the 13 year period 01/01/2003 to 31/12/2015. The two vertical scales have no relationship to each other.

**Figure 4.5 – Relationship between River Teme Flows at Milebrook and on the River Arrow at Titley Mill**




**Source:** Daily river flow and spot flow measurements data provided by the Environment Agency (*Contains Environment Agency information © Environment Agency and database right*).
**Notes:** Percentiles and mean for river flow are for the 13 year period 01/01/2003 to 31/12/2015. The catchment area based mean flow estimate for Milebrook uses the average of the mean flow per $km^2$ of catchment area for the Arrow at Titley Mill (0.0179 $m^3/s/km^2$, 125.9 $km^2$) and the River Lugg at Byton (0.0180 $m^3/s/km^2$, 202.5 $km^2$) multiplied by the estimated catchment area for the Teme at Milebrook of ~150 $km^2$. The red trend line uses both the spot flows and this mean flow estimate.

## Figure 4.6 – Downstream Changes in River Teme Flows Near Heartsease




**Notes**: Spot flow measurements data provided by the Environment Agency (*Contains Environment Agency information © Environment Agency and database right*) and from ESI (2007, Appendix B and Figure 5.9). Zero flow measurements are not used here as they would incorrectly modify the derived relationships with flows at Milebrook. That is, because a zero flow could occur at a range of low flows below a given threshold flow at Milebrook.

Figure 4.6 illustrates the significant (~0.2 $m^3/s$ = 17,280 $m^3/day$) loss in river flow between Milebrook and Weston Footbridge which has been occurring at least since 1997 (before Radnor Hills abstraction commenced). They also show a gain of 0.02 to 0.10 $m^3/s$ (1,728 to 8,640 $m^3/day$) between Weston Footbridge and Lingen Bridge, with the gain increasing as upstream flows increase. Of note, when the river is dry at Weston Bridge, flows at Lingen Bridge are at least 0.02 $m^3/s$ (1,728 $m^3/day$).

Figure 4.6b derives the following relationships between flows near Heartsease (y) and flows at Milebrook (x) on the River Teme:

- Weston Bridge flow (y = 0.9947x - 0.216);
- Lingen Bridge flow (y = 1.0479x - 0.1902).

These relationships are poorly constrained at medium to high flows.

## 4.6 Lingen Bridge Flows for Use in Discharge Evaluation

Evaluation of the impact of a consented discharge to a river requires input of average (mean) flows and dry weather (95th percentile) flows.

The relationship between flows on the River Teme at Milebrook and on the River Arrow at Titley Mill derived in Section 4.4.7 and those between Weston Bridge and Milebrook and Lingen Bridge and Milebrook allows long-term continuous flow data for the River Arrow at Titley Mill to be used to provide flow statistic estimates for the River Teme near Heartsease. These estimates are provided in Table 4.2. For information the corresponding river stage statistics at Knighton are also provided and Figure 4.7 compares the flow estimates and measurements with river stage at Knighton.

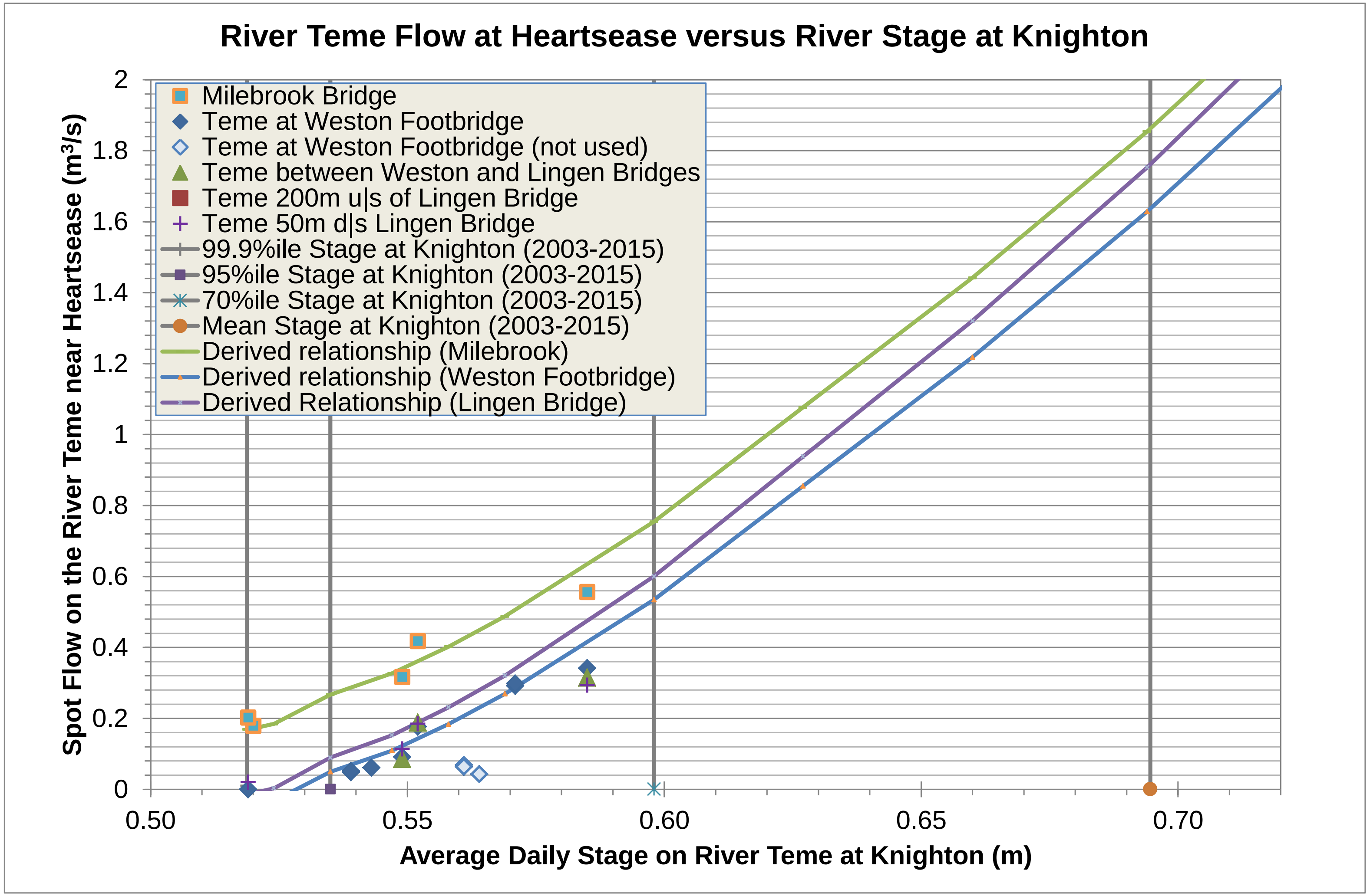
**Table 4.2 Estimated Percentile Flows for the River Teme at Lingen Bridge**

| Percentile[1] | River Flow on the Arrow at Titley Mill[2] | River Stage at Knighton[2] | Estimated Flow on the River Teme ($m^3/s$) at | | |
|---|---|---|---|---|---|
| | $m^3/s$ | m | Milebrook | Weston Footbridge | Lingen Bridge |
| 99.9 | 0.191 | 0.519 | 0.169 | 0.000 | 0.000[4] |
| 99.5 | 0.197 | 0.521 | 0.175 | 0.000 | 0.000[4] |
| 99 | 0.207 | 0.524 | 0.185 | 0.000 | 0.003[4] |
| 95 | 0.294 | 0.535 | 0.267 | 0.050 | **0.090** |
| 90 | 0.356 | 0.547 | 0.327 | 0.109 | 0.153 |
| 85 | 0.433 | 0.558 | 0.402 | 0.184 | 0.231 |
| 80 | 0.520 | 0.569 | 0.488 | 0.269 | 0.321 |
| 70 | 0.786 | 0.598 | 0.754 | 0.534 | 0.600 |
| 60 | 1.100 | 0.627 | 1.077 | 0.855 | 0.938 |
| 50 | 1.450 | 0.660 | 1.442 | 1.218 | 1.321 |
| 40 | 1.840 | 0.694 | 1.854 | 1.629 | 1.753 |
| 30 | 2.390 | 0.738 | 2.445 | 2.216 | 2.372 |
| 20 | 3.220 | 0.797 | 3.350 | 3.116 | 3.320 |
| 10 | 5.350 | 0.899 | 5.728 | 5.482 | 5.813 |
| 5 | 7.827 | 0.989 | 8.563 | 8.302 | 8.783 |
| 1 | 14.100 | 1.157 | 15.950 | 15.649 | 16.524 |
| Mean | 2.316 | 0.695 | 2.365 | 2.136 | **2.288** |

Notes:

1) Percentage of the flow record that the corresponding flow is exceeded.
2) Based on measured flow or stage (river levels) for the period 01/01/2003 to 31/12/2015 inclusive. The river stage for Knighton corresponds to the percentile for Knighton rather than being linked directly to the flow on the River Arrow.
3) To the nearest percentile except 99.5th and 99.9th percentiles.
4) It is understood the River Teme does not dry up at Lingen Bridge.

**Figure 4.7 – Relationship between River Stage Variation at Knighton and Spot Flow Measurements for the Teme near Heartsease**




**Source:** River stage and spot flow measurements data provided by the Environment Agency (*Contains Environment Agency information © Environment Agency and database right*).
**Notes:** Percentiles and mean for river stage are for the 13 year period 01/01/2003 to 31/12/2015. The derived relationships relate to the relationships derived between flows on the River Arrow and spot flow measurements for the River Teme as provided in Table 4.2, but then using the corresponding (e.g. 95%ile) stage at Knighton as opposed to flow on the River Arrow.

This evaluation suggests the following flow statistics for use in evaluation of a discharge to the River Teme near (±100 m) Lingen Bridge (see Figure 4.8):

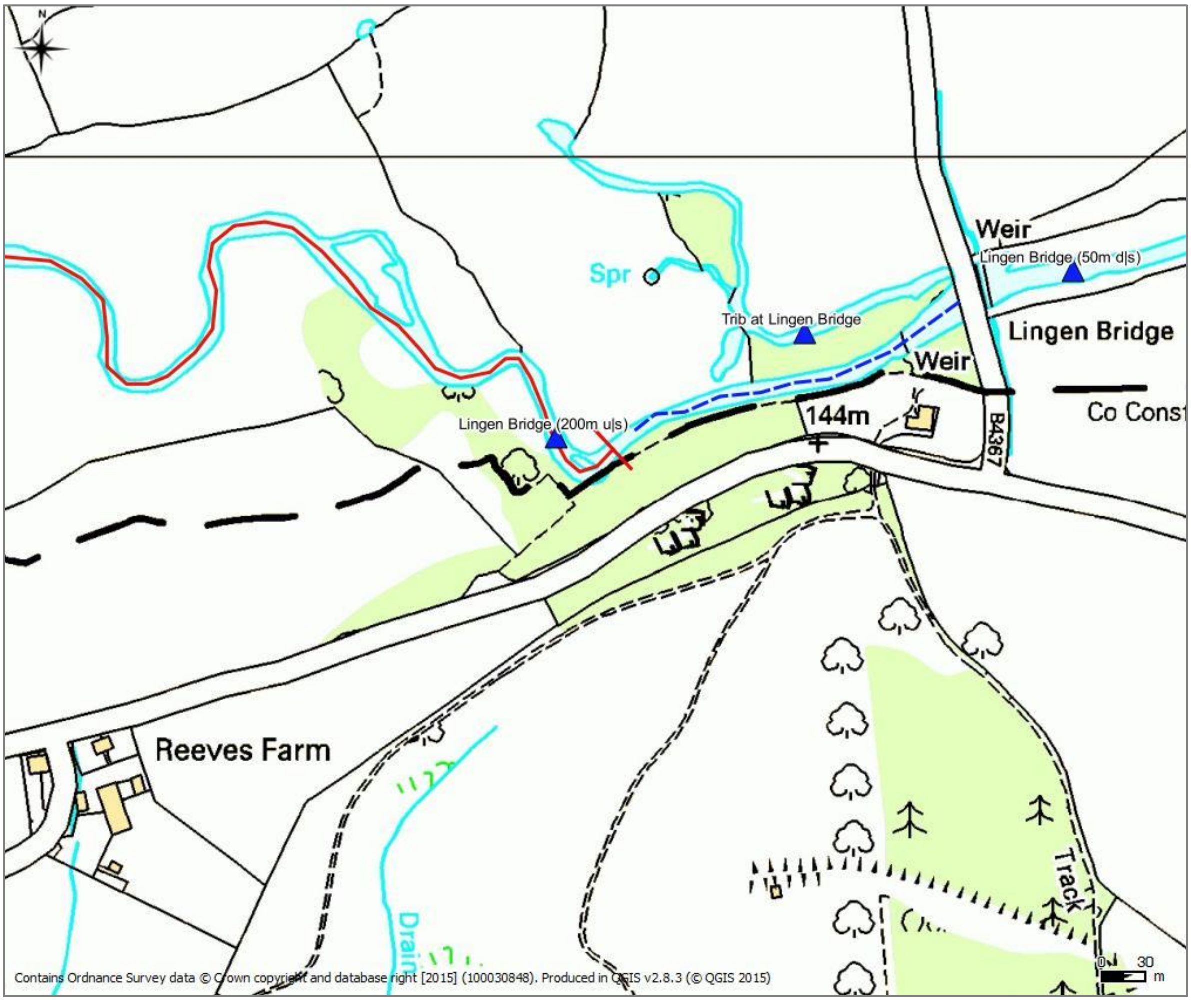
95 percentile (stage at Knighton = 0.535 m): 0.09 $m^3/s$ (7,776 $m^3$/day);

50 percentile (stage at Knighton = 0.660 m): 1.32 $m^3/s$ (114,048 $m^3$/day);

Mean flow (stage at Knighton = ~0.738 m*): 2.29 $m^3/s$ (197,856 $m^3$/day).

**Note:** * As flow does not typically increase linearly with river stage, the mean flow does not occur at the mean river stage (depth). Percentile flows and river stages should however correlate. Table 4.2 shows that the mean flow on the River Arrow occurs at ~30 percentile flow conditions, and the corresponding 30 percentile stage at Knighton is 0.738 m.

**Figure 4.8 – Reach for Surface Water Discharge near Lingen Bridge**




**Source**: Contains Ordnance Survey data © Crown Copyright and database right [2016] (100030848).
**Notes**: **Blue triangles**: locations of spot river flow measurement sites. Red reaches: Reaches prone to drying up after P Giles (EA, 03 March 2016). **Blue dashed reach** – target reach for treated discharges to surface water.

## 4.7 Stage and Flow Estimates for Fish Rescue Dates

To provide a check on the predicted flows, Table 4.3 repeats the fish rescue dates provided in ESI (2007, Table 6.1) and puts these against the river stage at Knighton, the percentile that stage corresponds to, and the estimated flows in the Teme near Heartsease.

**Table 4.3 Stage and Flow Estimates for Fish Rescue Dates at Knighton**

| Date of Fish Rescue[1] | Flow on the River Arrow at Titley Mill | | River Stage at Knighton Gauge | | Estimated Flow ($m^3/s$) in the River Teme near Heartsease[3] | | |
|---|---|---|---|---|---|---|---|
| | $m^3/s$ | Percentile[2] | m | Percentile[2] | Milebrook | Weston Footbridge | Lingen Bridge |
| 27/08/2002 | 0.294 | 95.0% | #N/A | #N/A | 0.267 | 0.050 | 0.090 |
| 28/08/2002 | 0.293 | 95.0% | #N/A | #N/A | 0.266 | 0.049 | 0.089 |
| 03/09/2002 | 0.288 | 96.0% | #N/A | #N/A | 0.261 | 0.044 | 0.084 |
| 09/08/2003 | 0.263 | 97.0% | 0.544 | 92.0% | 0.237 | 0.020 | 0.059 |
| 21/08/2003 | 0.23 | 98.0% | 0.535 | 95.0% | 0.206 | 0.000 | 0.026 |
| 02/09/2003 | 0.232 | 98.0% | 0.532 | 96.0% | 0.208 | 0.000 | 0.028 |
| 19/09/2003 | 0.192 | 99.9% | 0.526 | 99.0% | 0.170 | 0.000 | 0.000 |
| 25/08/2005 | 0.387 | 90.0% | 0.539 | 93.0% | 0.357 | 0.139 | 0.184 |
| 31/08/2005 | 0.341 | 91.0% | 0.538 | 94.0% | 0.312 | 0.095 | 0.137 |
| 01/09/2005 | 0.333 | 92.0% | 0.537 | 94.0% | 0.305 | 0.087 | 0.129 |
| 07/09/2005 | 0.300 | 95.0% | 0.530 | 97.0% | 0.273 | 0.055 | 0.096 |
| 16/09/2005 | 0.341 | 91.0% | 0.531 | 97.0% | 0.312 | 0.095 | 0.137 |
| 19/09/2005 | 0.299 | 95.0% | 0.530 | 97.0% | 0.272 | 0.054 | 0.095 |
| 29/07/2006 | 0.385 | 90.0% | 0.528 | 98.0% | 0.355 | 0.137 | 0.182 |
| 30/07/2006 | 0.389 | 90.0% | 0.527 | 98.0% | 0.359 | 0.141 | 0.186 |
| 14/08/2006 | 0.298 | 95.0% | 0.526 | 99.0% | 0.271 | 0.053 | 0.094 |
| 15/08/2006 | 0.296 | 95.0% | 0.526 | 99.0% | 0.269 | 0.052 | 0.092 |
| 06/09/2006 | 0.298 | 95.0% | 0.521 | 99.5% | 0.271 | 0.053 | 0.094 |
| Mean | 0.303 | 95.0% | 0.531 | 97.0% | 0.276 | 0.058 | 0.099 |

Notes:
1) From Table 6.1 of ESI (2007).
2) To the nearest percentile except $99.5^{th}$.
3) Where a negative flow is predicted a value of 0.000 is shown.
4) Based on trend line from Figure 4.5 using Weston Footbridge data.
5) Based on trend line from Figure 4.5 using all flow measurements near Heartsease (i.e. Weston Footbridge to Lingen Bridge).

Table 4.3 shows that fish rescues in the years 2002 to 2006 occurred under conditions of $92^{nd}$ to $99.5^{th}$ percentiles river level and on average under $97^{th}$ percentile river level. The corresponding predicted flows for these dates at Lingen Bridge are typically <0.1 $m^3/s$. This analysis provides independent support to the derived flow estimates.

## 4.8 Summary

Flow data for the River Teme near Heartsease are limited and some sections of the river are prone to drying out. Through careful evaluation of available information, the reaches prone to drying out have been mapped out and flow statistics for the River Teme at Lingen Bridge have been estimated. Section 4.6 provides these flow estimates for use in evaluating a discharge to river near Lingen Bridge.

The flow estimates have been checked against dates on which fish results took place and suggest fish rescues occur under plausible low ($92^{nd}$ to $99.5^{th}$) river level conditions.

# 5. Risk Assessment for Treated Discharge

## 5.1 Purpose of this Section

Based on the additional understanding of the area around the Radnor Hills discharge presented in this addendum to the Rukhydro (2015) report, this section evaluates the likely impact from the discharge of effluent from the to-be-permitted and built effluent treatment plant. This section makes reference to earlier sections in this addendum report.

## 5.2 Context

### 5.2.1 Context from Groundwater Level Monitoring

Groundwater level data described in Section 2 show the direction of groundwater flow in the gravels which underlies the lagoon is, as expected, down the valley in an approximate west to east direction. The average hydraulic gradient between piezometer PZ#6(2), through PZ#8b to the River Teme is ~0.008, whereas between PZ#8b and the River Teme is 0.015. These gradients are for groundwater levels recorded in February 2016.

Groundwater levels are typically no more than 2 m below ground level and in places at less than 1 m depth. Levels vary seasonally and have declined by ~0.5 m since February 2016.

### 5.2.2 Context from Water Quality Sampling Data

Stream and groundwater sample data discussed in Section 2 provide the measured risk from the current effluent discharge to ground (via "The Wet" and the final lagoon). Hazardous substances[3] have not been detected in the most impacted groundwater (PZ#8b), but concentrations of some trace metals are elevated (particularly manganese and zinc).

The water quality data has been used:

- To calculate the proportion of lagoon water in groundwater (and stream) samples. The average proportion of lagoon water in the most affected piezometer (PZ#8b) is 16%. With an average current effluent discharge of 160 $m^3$/day, this implies the effluent is diluted downgradient by an average of 840 $m^3$/day to give total average flows of 1000 $m^3$/day;
- To provide evidence for natural attenuation of the current effluent loading. This suggests that, at the current discharge rate of 160 $m^3$/day, an effluent filtered BOD of ~50 mg/l $O_2$ could be accommodated by aerobic oxidation using background groundwater dissolved oxygen. If beneficial nitrate reduction was also considered then an effluent filtered BOD of ~100 mg/l $O_2$ could be accommodated without releasing dissolved metals from the aquifer materials or generating methane gas.

### 5.2.3 Context from SPZ Modelling of Discharge Plumes

Plumes from the discharge (under current and future abstraction and discharge scenarios) have been modelled using the Radnor Hills source protection zone (SPZ) model and are discussed in Section 3.5. The modelled plumes are consistent with groundwater sampling data in terms of width and extent of the plume and suggest negligible risk to the Radnor Hills abstraction under current and future abstraction and discharge scenarios.

[3] Cadmium concentrations of up to 0.117 to 0.237 µg/l have been detected on one occasion in piezometers PZ#8b, PZ#9b andPZ#11b shortly after their installation, but otherwise cadmium concentrations have been less than the limit of detection of 0.1 µg/l.

The cross groundwater flow width (w) for the current situation (160 $m^3$/day discharge) plume is ~85 m and that for the future scenario (modelled discharge was 240 $m^3$/day) is ~120 m. The SPZ model was calibrated with plausible recharge and groundwater level data and deduced a hydraulic conductivity (k) of 11.22 m/day and an aquifer depth (z) of up to 35 m.

Using the measured February 2016 hydraulic gradient from PZ#8b to the River Teme (i = 0.015) and calculating groundwater flow (Q) using Darcy's Law (Q = k.i.w.z), with inputs of "k", "w" and "z" from the above paragraph, then the calculated groundwater flow is (11.22 x 0.015] x 85 x 35=) 500 $m^3$/day. This is less than the 1000 $m^3$/day estimated using water quality data, although in hydrogeological terms is a broadly similar number.

Hydraulic gradients may be steeper (between the lagoon and piezometer PZ#8b) in summer when the river dries up and thus stops constraining groundwater levels near the river. Alternatively, the hydraulic conductivity of the gravels may be higher closer to the river.

### 5.2.4 Context from the River Flow and Dry River Reach Assessment

Section 4 of this addendum has evaluated likely river flows in the River Teme near Heartsease and also highlighted river reaches that dry up. River flow estimates have been used in the separate evaluation of the impact of the treated effluent on the River Teme when / if that discharge occurs directly (via pipe).

Section 4 has shown there is good evidence for a consistent significant (~0.2 $m^3$/s = 17,280 $m^3$/day) loss in river flow between Milebrook and Weston Footbridge which has been occurring at least since 1997 (before Radnor Hills abstraction commenced). Section 4 has also shown a gain of 0.02 to 0.10 $m^3$/s (1,728 to 8,640 $m^3$/day) between Weston Footbridge and Lingen Bridge, with the gain increasing as upstream flows increase. Of note, when the river is dry at Weston Bridge, flows at Lingen Bridge are at least 0.02 $m^3$/s (1,728 $m^3$/day). This information suggests a net loss in river flow to the gravels between Weston Footbridge and Lingen Bridge of between (17,280-8,640=) 8,640 $m^3$/day at high river flows and (17,280-1,728=) 15,552 $m^3$/day during dry (low river flow) periods.

If the 8,640 $m^3$/day to 15,552 $m^3$/day loss from the river is assumed to flow in the gravels along the general course of river valley across a width of 400 m[4], then this equates to a flow per metre width of 21.6 $m^3$/day/m to 38.9 $m^3$/day/m.

The calculated diluting groundwater flow based on water quality data in Section 5.2.2 is ~1000 $m^3$/day including 160 $m^3$/day of effluent discharge, so 840 $m^3$/day of upgradient groundwater flow. The SPZ modelled current plume width is 85 m wide, so this equates to ~10 $m^3$/day/m width of background groundwater flow. This is less than the 21.6-38.9 $m^3$/day/m estimated from the river flow loss to the gravels and so suggests the dilution is not only plausible but conservative. It also suggests the hydraulic conductivity of the gravels may be greater close to the river.

## 5.3 Assumptions for the Proposed Discharge

### 5.3.1 Assumed Discharge Rate and Quality

Table 5.1 presents the assumed discharge rate and treated effluent quality following installation and commissioning of the proposed treatment plant.

[4] This is the approximate cross valley distance that the River Teme takes between Weston Road and where it intersects with the English-Welsh border.

**Table 5.1 Assumed Discharge Rate and Quality for the Proposed Treated Effluent**

| Parameter | Units | Design Average | Minimum | Maximum |
|---|---|---|---|---|
| **Discharge Quality from the Main Effluent Treatment plant** | | | | |
| Instantaneous Flow Rate | $m^3$/hour | 7.6 | | 12.1 |
| Daily Flow Rate | $m^3$/day | 183 | | 290 |
| Temperature | °C | 18.17 | 15 | 25 |
| pH | pH | 7.5 | 6.0 | 9.0 |
| Total Suspended Solids | mg/l | 5 | <1 | 10 |
| BOD concentration | mg/l $O_2$ | 5 | <1 | 10 |
| Ammoniacal nitrogen | mg/l $NH_4$ | 0.5 | <0.5 | 5 |
| | mg/l N | 0.39 | <0.39 | 3.89 |
| Phosphorus | mg/l $PO_4$ | 0.2 | <0.2 | 1 |
| | mg/l P | 0.065 | <0.065 | 0.326 |
| **Discharge Quality from the Klargester septic tank** | | | | |
| Daily Flow Rate | $m^3$/day | 8 | | |
| Total Suspended Solids | mg/l | 30 | | |
| BOD concentration | mg/l $O_2$ | 30 | | |
| Ammonia as $NH_4$-N | mg/l N | 20 | | |
| Phosphorus as P | mg/l P | 10[1] | | |
| **Assumed Combined Quality[2] and Infiltration Rates** | | | | |
| Daily Flow Rate | $m^3$/day | 100[2a] | 8[2b] | 298[2c] |
| Average infiltration rate through “the Wet” (1267 $m^2$) and final lagoon (779 $m^2$) | $m^3$/day/$m^2$ | 0.049 | 0.004 | 0.146 |
| Temperature | °C | 18.17 | 15 | 25 |
| pH | pH | 7.5 | 6.0 | 9.0 |
| Total Suspended Solids | mg/l | 7.0 | 30 | 10.5 |
| BOD concentration | mg/l $O_2$ | 7.0 | 30 | 10.5 |
| Ammonia as $NH_4$-N | mg/l $NH_4$ | 2.0 | 20 | 4.3 |
| Phosphorus as $PO_4$-P | mg/l $PO_4$ | 0.9 | 10 | 0.6 |

Notes:
1) Based on data in SEPA et al (2010; Table 6.4).
2) Calculated weighted (to flow rate) average assuming the Klargester effluent always goes to ground and the main effluent treatment plant discharges at:
   a. 290 $m^3$/day less 40% reuse = similar to the design average of 183 $m^3$/day ~ then 50% (~92 $m^3$/day) plus the Klargester effluent (8 $m^3$/day) gives 100 $m^3$/day to groundwater (as an average over the year);
   b. This assumes only the Klargester effluent goes to ground. As there is no data for the Klargester, the temperature and pH of the minimum for the main effluent treatment plant is assumed.
   c. 290 $m^3$/day with no re-use and 100% to groundwater for periods of less than a year.

## 5.3.2 Assumed Operational Scenarios

It is intended that the 8 $m^3$/day discharge to “the Wet” and final lagoon will always occur from the Klargester septic tank via the reedbed. It is assumed that the discharge from the main effluent treatment plant will:

- Routinely send 40% for re-use in the bottling plant (not in products) – meaning a maximum (290 $m^3$/day x 60% =) 174 $m^3$/day discharged to the environment. For the purposes of this risk assessment, this 174 $m^3$/day is assumed to be the same as the treatment plant designers “design average” of 183 $m^3$/day;
- On average through the year send 50% to groundwater and 50% to the river by piped discharge – meaning an annual average discharge to ground from the main treatment plant of (183 $m^3$/day x 50% =) ~92 $m^3$/day;

- As a worst case, the full maximum (290 $m^3$/day) flow would go to ground;
- As a best case, only the Klargester (8 $m^3$/day) would go to ground.

Table 5.1 shows the combined effluent quality assumed for these different scenarios.

## 5.4 Source – Pathway – Receptor

The risk linkage is:

- Source – the discharge of treated effluent to ground / groundwater via infiltration through "the Wet" and the final lagoon;
- Pathway – via groundwater flow[5];
- Receptors:
  - Groundwater in the alluvium / gravels between the soakaway and the 320 m of Radnor Hills land to the River Teme.
  - The River Teme (the most sensitive receptor) by discharge of groundwater;
  - Groundwater abstracted by Radnor Hills (ruled out as a result of the SPZ model work).

## 5.5 Tiered Risk Assessment Approach

The Environment Agency (2011, Section 3.1) guidance recommends a tiered approach as set out in Box 5.1. The outcome from each tier is also specified.

**Box 5.1 – Guidance Recommendation for a Tiered Approach to Risk Assessment**

The guidance recommends a tiered approach to a risk assessment:

- Risk screening;
- Generic quantitative risk assessment;
- Detailed quantitative risk assessment details of the type and source of effluent (for example, domestic sewage);

It notes that the outcome from each stage should be one of the following:

a) There is sufficient information to determine that the discharge does not present an unacceptable risk.

b) Further assessment is required (by moving to the next assessment tier with additional information) or alternatively, modifications need to be made to the activity such as improved treatment of the effluent or changes to the drainage field or its location.

c) The activity presents an unacceptable risk and a permit will not be granted.

This tiered approach to risk assessment should ensure that the effort required is consistent with the complexity of the activity and its setting. The assessment should be as simple as these factors allow and summarised in the conceptual model.

**Source**: From Environment Agency (2011, Section 3.1).

## 5.6 Risk Screening

The Environment Agency (2011, Section 3.2.1) provides examples of factors to be used for risk screening a discharge to ground. These factors are used to evaluate the Radnor Hills discharge in Table 5.2.

[5] It is assumed that bunding of the final lagoon / soakaway prevents surface water flow towards the local stream or into flood waters.

**Table 5.2 Risk Screening of the Radnor Hills Soakaway Discharge**

| Factor / Criteria | Assessment | Outcome |
|---|---|---|
| Are hazardous substances sufficiently close to the relevant minimum reporting values? | Assume no hazardous substances in the treated effluent from either the main treatment plant or the Klargester septic tank[1] (package treatment plant). | Pass |
| Non-hazardous substances at concentrations less than the relevant environmental standard or background level in groundwater | Concentrations of ammoniacal nitrogen (2 to 20 mg/l N) and BOD (7 to 30 mg/l $O_2$) in excess of background and could potentially cause release of metals from gravels if not attenuated. | Fail, although pass for Klargester effluent as is a standard package treatment plant effluent. |
| No aquifers beneath or near the activity? | The alluvium / gravels provide important baseflow to the River Teme and nearby are providing water for bottling at Radnor Hills. | Fail. |
| The volume discharged is very small compared to flow in underlying groundwater. | The 8 $m^3$/day from the Klargester is within the Guidance screening upper limit of 25 $m^3$/day, but this limit is exceeded by the normal operation annual average (100 $m^3$/day) and maximum (298 $m^3$/day) combined effluent flows. | Pass for Klargester<br>Fail for Normal operation and maximum discharge. |

Notes:

1) Environment Agency guidance (2011) suggests there may occasionally be low concentrations of toluene in septic tank discharge. Data in Environment Agency (2007) indicates concentrations of 26 µg/l and 110 µg/l were detected in two septic tanks, but toluene was not detected in downgradient groundwater.

The combined discharge fails the risk screening on the grounds of size and quality of the discharge and so from Box 5.1 above: "*Further assessment is required (by moving to the next assessment tier with additional information) or alternatively, modifications need to be made to the activity such as improved treatment of the effluent or changes to the drainage field or its location*."

## 5.7 Quantitative Risk Assessment

### 5.7.1 Approach

This section examines the likely impact of the discharges under their different scenarios taking into account infiltration rates, likely attenuation in the unsaturated zone and dilution, dispersion and attenuation in groundwater flow. This is consistent with detailed quantitative risk assessment rather than generic risk assessment.

### 5.7.2 Discharge and Infiltration Rates

***Guidance Requirements***

Environment Agency (2011) and Building Regulations (2010, Section H2, para 1.38) note septic tank discharges to ground should have:

- percolation rates (Vp) of between 12 and 100 secs/mm;
- a drainage floor area calculated as the product of:
  - the equivalent number of people (p = discharge rate [q] divided by 0.18 $m^3$/day);
  - the percolation rate (Vp);
  - a factor of 0.25;
  - (and so equating to [q/0.18] x Vp x 0.25)
- The drainage floor should be spread over a drainage field with pipe centres at least 2 m wide in trenches a maximum of 0.9 m wide meaning that the drainage field needs to be at least 2.0/0.9 (=2.2) times larger than the calculated drainage area.

- The Environment Agency (2011, Box 1.5, p25) guidance notes the drainage field area can be reduced by 20% for package treatment plants.
- All this translates into the drainage field for a package treatment plant discharge should be [q/0.18] x Vp x 0.25 x 2.2 x 80%.
- For permitted Vp values of 12 to 100 mm/secs, the above equation means that the drainage field area ($m^2$) should be between 29.3 and 244.4 times the discharge rate in $m^3$/day.

***Klargester Discharge alone***

Under the scenario that only the Klargester effluent is discharged to ground (the main effluent going to river via pipe), then this discharge would require a drainage field area of 234.4 to 1,955 $m^2$ for the 8 $m^3$/day leading to average infiltration rates of 0.034 to 0.004 $m^3/day/m^2$.

The "Wet" and final lagoon have basal areas of 1267 $m^2$ and 779 $m^2$ respectively; totalling 2046 $m^2$ and providing an area greater that required by the guidance. The average infiltration rate through "the Wet" and the final lagoon would be 0.004 $m^3/day/m^2$; consistent with the minimum required rate. It is likely the discharge would infiltrate just through the base of "the Wet" (1267 $m^2$) leading to an infiltration rate of 0.006 $m^3/day/m^2$ (6 mm/day).

The low discharge rates would allow significant time for aeration and attenuation of contaminants.

Overall, the Klargester discharge to "the Wet and final lagoon" is consistent with Environment Agency (2011) and Building Regulations (2010) requirements and so the impact to groundwater should be acceptable from an infiltration stand-point.

***Under "Normal" and Maximum Operating Conditions***

Under "normal" operating conditions with 100 $m^3$/day combined discharge to ground, the system would lead to an average infiltration rate through "the Wet" and final lagoon base of 0.049 $m^3/day/m^2$; in excess of the 0.034 $m^3/day/m^2$ from the guidance. To meet the guidance requirements, the drainage field would need to be (100 x 29.3 to 244.4=) 2,930 to 24,440 $m^2$ in area.

Infiltration rates under normal and therefore maximum infiltration rates will be in excess of guidance requirements and mean therefore that further evaluation of risks is required.

### 5.7.3 Ability to Infiltrate Water and the Need for Desludging

The Rukhydro (2015) report notes that up to circa 2013 the discharge was to "the Wet" only, but thereafter as effluent discharge rates rose above ~130 $m^3$/day, it was necessary to construct the final lagoon. The final lagoon was constructed by removal of top soil and 4 or 5 shallow pits (4x4x4 ft.) were dug through the clay into the underlying gravels. Bund heights of 0.5 m were constructed using the excavated clay.

Together "the Wet" and the final lagoon have soaked away on average ~160 $m^3$/day since ~2013, although in 2016 there has been evidence that the system is at its limit. 160 $m^3$/day is in excess of the "normal" operation scenario of 100 $m^3$/day so it is known the current areas can infiltrate this rate. It would appear highly unlikely however, that the current system could infiltrate the maximum discharge rate of 298 $m^3$/day.

Over time it is likely that both "the Wet" and the final lagoon have silted up with the moderately high suspended load of the effluent (122 mg/l average in the lagoon). 160 $m^3$/day of 122 mg/l suspended solid equates to 19.52 kg/day (~7.130 tonnes/year) of sediment. Assuming a sediment density of ~1.0 kg/l (or tonnes/$m^3$) and a lagoon area of 779 $m^2$, then the 7.13 tonnes/year equates to covering of (7.130 / [1.0 x 779] =) 9.2 mm/yr., so perhaps a build-up of ~3 cm of fine sediment since 2013. A visit to site in May 2016, suggested the sediment could be thicker than this and closer to perhaps 10 cm. This could plausibly impede percolation into the gravels. (It is noted there is also visual evidence of gas bubbles and water quality evidence of methane production in the lagoon sediment. Gas bubbles are likely to occupy some pore spaces in the sediment and this will cause a reduction in hydraulic conductivity of the sediment and so also reduce the infiltration rate).

The SPZ model has derived a saturated hydraulic conductivity for the gravels of ~10 m/d (11.22 m/day). Under a vertical hydraulic gradient of 1 (so fully saturated), then the theoretical infiltration rate to the gravels without the overlying fine sediment is 10 m/day (10 $m^3$/day/$m^2$) and this is far in excess of the infiltration rate of 0.149 $m^3$/day/$m^2$ calculated for the maximum discharge scenario.

This assessment suggests it will be necessary to de-sludge “the Wet” and final lagoon before the system could accept the maximum discharge scenario rate of 298 $m^3$/day. With Table 5.1 indicating the discharge will have an average of 10.5 mg/l of suspended solids, then this will lead to the deposition of (0.0105 kg/$m^3$ x 298 $m^3$/day=) 3.13 kg/day or 1.14 tonnes per year. Over the combined area (2046 $m^2$) of “the Wet” and the final lagoon, and again assuming a density of 1.0 tonnes/$m^3$, then the suspended solids will lead to the build-up of 0.6 mm/year. This suggests desludging is unlikely to be required more frequently than say every 10-20 years.

### 5.7.4 Attenuation in the Unsaturated Zone

***What is attenuation?***

Attenuation is the general term for a number of processes including retardation (through sorption and precipitation) and where applicable degradation, in particular biodegradation.

***Equations for calculating attenuation factors***

The Environment Agency (2011) guidance provides slightly more complicated formula for calculating unsaturated zone attenuating factors, but if dispersivity is ignored (as it will have a minor effect only here), then attenuation can be broken down into three components as provided in Box 5.2.

**Box 5.2 – Attenuation Factor Equations for the Unsaturated Zone**

The main attenuation factor calculations are:

- Unretarded travel time, Tu = D x θ / Inf.
- Retarded travel time Tr = u x (1+[Kd x ρ/θ])
- Attenuation factor = 0.5^(T½/Tr)

Where:

D = unsaturated zone thickness / depth to water table (m);

θ = unsaturated zone moisture content (this is less than the porosity; fraction);

Inf = soakaway infiltration rate (m/d, so infiltration rate in $m^3$/day divided by area of soakaway);

Kd = is a contaminant and strata specific partition coefficient (l/kg);

ρ = soil bulk density (kg/l or g/$cm^3$ of tonnes/$m^3$);

T½ = degradation rate half-life (the time it takes for half to degrade; days).

**Source**: Adapted from Environment Agency (2011).

***Unretarded travel times***

Table 5.1 has calculated infiltration rates of 0.049 $m^3$/day/$m^2$ under the “normal” operation scenario. Assuming a moisture content for the gravels of 0.05 to 0.1 (5 to 10%) and a depth to water table of 0.5 to 1.5 m translate into:

- Minimum unretarded travel time = ([0.5m x 0.05]/0.049 m/day =) 0.51 days;
- Maximum unretarded travel time = ([1.5m x 0.1]/0.049 m/day =) 3.1 days;

These travel times are relatively short.

***Retarded travel times***

Retardation factors for some contaminants can be large (1000's), but for ammoniacal nitrogen and organic acids in the gravels (with likely low clay and organic contents) retardation factors are likely, from experience, to be less than 10 to 20 meaning retarded travel times are currently likely to be no more than 5 to 60 days.

***Biodegradation rates***

Biodegradation of contaminants such as ammoniacal nitrogen and organic acids will be much shorter under aerobic conditions than anaerobic conditions. For example, Environment Agency guidance (2003) suggests a biodegradation rate half-life (T½) of 1 to 6 years in sands and gravels under aerobic conditions but no degradation under anaerobic conditions. Given retarded travel times for ammoniacal nitrogen of 5 to 60 days, its degradation in the unsaturated zone is likely to be minimal.

### 5.7.5 Dilution in Groundwater

***Dilution Calculation***

Evidence for significant background groundwater flow has been provided in Section 2 and is summarised in Section 5.2. Water quality data for a piezometer (PZ#8b, 260 m downgradient of the upgradient end of "the Wet") indicate that the current 160 $m^3$/day discharge is diluted and dispersed into ~840 $m^3$/day of upgradient background flow. SPZ modelling suggests the plume width for this current situation is ~85 m wide and for a modelled future scenario of 240 $m^3$/day discharge is ~120 m wide assuming discharge to the whole area of "the Wet" and final lagoon. This therefore suggests a plume width of ~0.5 times the discharge rate. From this it is calculated that diluting flows will be as shown in Table 5.3.

**Table 5.4 Dilution Calculation for Discharges to Ground**

| Discharge Scenario | Discharge Rate ($m^3$/day) | Estimated Plume Width (m)[1] | Estimated Upgradient Diluting Flow ($m^3$/day) | Estimated Downgradient Total Flow[3] ($m^3$/day) | Dilution Factor Multiple[4] |
|---|---|---|---|---|---|
| SPZ Model current situation | 160 | ~85 | 860[2] | 1000 | x16.0% |
| SPZ Model future scenario | 240 | ~120 | 1186 | 1426 | x16.8% |
| Klargester only scenario[5] | 8 | 40 | 405 | 413 | x1.9% |
| "Normal" operations[5] | 100 | 50 | 506 | 606 | x16.5% |
| Maximum scenario[5] | 298 | ~150 | 1518 | 1816 | X16.4% |

Notes:

1) For the SPZ model scenarios, these are modelled plume widths and for the other scenarios it is assumed, based on the SPZ modelled plumes that the plume width (m) is 0.5 x the discharge rate ($m^3$/day). The exception is for the Klargester only discharge which is assumed to infiltrate through the full area of "the Wet" which has a cross flow width of ~40 m.
2) This is based on bromide concentration data and generally supported by a Darcy Flow calculation using SPZ model calibrated input parameters.
3) Discharge rate plus up-gradient diluting flow;
4) Discharge rate divided by downgradient flow. This is the multiple of concentrations in the lagoon to predict increases in concentration (above background) in downgradient groundwater.
5) See Table 5.1 for discharge scenarios.

***Dilution for the Klargester only discharge***

Table 5.4 shows that dilution factors for the Klargester effluent only (8 $m^3$/day) discharge to full area of "the Wet" are high, leading to concentrations in the effluent being reduced to a downgradient concentration increase of 1.9%. From the assumed effluent quality in Table 5.1, this suggests that regardless of any attenuation, downgradient concentration increases would be as follows:

- $BOD_{5ATU}$ (30 x 1.9%=) 0.57 mg/l $O_2$;
- Ammoniacal nitrogen (20 x 1.9%=) 0.38 mg/l N (less than the drinking water standard of 0.39 mg/l N);
- Phosphorus (10 x 1.9% =) 0.19 mg/l P.

***Dilution under the Normal Operating Conditions***

From Table 5.4, dilution under normal operating conditions would be x16.5%, and assuming normal operating effluent quality from Table 5.1, downgradient concentrations would be as follows:

- $BOD_{5ATU}$ (7 x 16.5%=) 1.16 mg/l $O_2$;
- Ammoniacal nitrogen (2 x 16.5%=) 0.33 mg/l N (less than the drinking water standard of 0.39 mg/l N);
- Phosphorus (0.9 x 16.5% =) 0.15 mg/l P.

Concentrations are therefore similar to the Klargester impact above.

***Dilution Funder Maximum Operating Conditions***

From Table 5.4, dilution under maximum operating conditions would be x16.4%, and assuming maximum operating conditions effluent quality from Table 5.1, downgradient concentrations would be as follows:

- $BOD_{5ATU}$ (10.5 x 16.4%=) 1.7 mg/l $O_2$;
- Ammoniacal nitrogen (4.3 x 16.4%=) 0.71 mg/l N (in excess of the drinking water standard of 0.39 mg/l N);
- Phosphorus (0.6 x 16.4% =) 0.1 mg/l P.

Concentrations are again similar to the Klargester and “normal” operations impact above, although predicting slightly higher $BOD_{5ATU}$ and ammoniacal nitrogen concentrations.

### 5.7.6 Attenuation in the Saturated Zone

***Similarities with the unsaturated zone***

As for the unsaturated zone, the (conservatively assumed) likely low clay and organic matter content of the alluvium / gravels means that sorption and retardation of contaminants during movement in the groundwater will not be large. Retardation factors for e.g. ammoniacal nitrogen perhaps being of the order of 10 to 20.

***Attenuation of BOD and Ammoniacal Nitrogen***

With significant up-gradient diluting groundwater flow there is the potential for degradation of the organic matter associated with the BOD and of ammoniacal nitrogen. Section 2 and summarised in Section 5.2.2 has noted that there is good evidence from the water quality data that at the current discharge rate of 160 $m^3$/day the groundwater system could accommodate an effluent BOD of 50 mg/l $O_2$ by use of dissolved oxygen in groundwater and if required an additional BOD of 50 mg/l $O_2$ by use of dissolved nitrate in groundwater.

Ammoniacal nitrogen oxidation to nitrate is a two stage process (Environment Agency, 2003), but overall can be summarised by the formula:

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+$$

This means one mole of ammoniacal nitrogen requires 2 moles of dissolved oxygen. Or in terms of mass concentration units 1 mg/l N ammoniacal nitrogen requires (1 x 32/14=) 2.29 mg/l $O_2$ of dissolved oxygen; an equivalent BOD of 2.29 mg/l $O_2$.

Section 5.7.5 has calculated the increase in $BOD_{5ATU}$ and ammoniacal nitrogen in downgradient groundwater assuming dilution only. The maximum increase is for the maximum discharge scenario with increases of 1.7 mg/l $O_2$ $BOD_{5ATU}$ and 0.71 mg/l N ammoniacal nitrogen. With the ammoniacal nitrogen conversion factor from above this translates into a total BOD increase of (1.7 + [0.71x2.29] =) 3.33 mg/l $O_2$. This would lead to a decrease in dissolved oxygen concentrations from the upgradient average of 10.65 mg/l $O_2$ to (10.65-3.33=) 7.32 mg/l $O_2$. At >7 mg/l $O_2$ dissolved oxygen, conditions in groundwater would still be very much aerobic and this would mean a low likelihood of manganese and iron reduction that has to date being causing increases in dissolved metal concentrations.

***Attenuation of Phosphate***

Phosphate tends to absorb strongly to iron and manganese oxides and can form low solubility calcium phosphate compounds. It can also be used my microbes as a nutrient. SEPA (and Environment Agency, 2010) guidance suggests that at 1 m depth beneath septic tanks the reduction in phosphate can be of the order of 67-100%. Dissolved orthophosphate concentrations in downgradient piezometers are <0.02 mg/l P with the current discharge. An impact from phosphate therefore appears unlikely.

### 5.7.7 Travel times to the river

Unretarded travel times ($T_{gw}$) in the alluvium / gravels for the distance (L = 300 m) between the final lagoon and the river can be calculated as:

$$T_{gw} = (L \times n) / (k \times i)$$

Where: "n" and "k" are the effective saturated porosity (0.2) and hydraulic conductivity (~11 m/day) of the gravels and "i" is the hydraulic gradient (0.015).

The unretarded travel time is therefore calculated as 364 days. This is the time taken for an unretarded parameter such as chloride to move from underneath the lagoon to the river. It also provides an indication of the time that will be needed to flush existing impacted groundwater from the system once the new discharge regime commences. (There may also be some delay if dissolved oxygen is consumed by currently reduced metals in the aquifer).

Retarded travel times are likely to be no more than 10 to 20 times longer. Under aerobic conditions, these travel times would allow degradation of many contaminants.

## 5.8 Summary of Groundwater Risk Assessment

Installation of piezometers around the existing discharge and collection of water level and water quality data has helped constrain the impact of the current 160 $m^3$/day discharge in terms of its dilution and attenuation in groundwater. A source protection zone model has been used to constrain hydraulic parameters and predict the extent of plumes from the current discharge and a modelled future scenario. The modelled extent of the current discharge is consistent with water quality monitoring data and brings added confidence to the understanding of the hydrogeology of the area. This understanding is further enhanced by an evaluation of losses of river water to groundwater up-valley from the discharge.

Discharge rates and quality have been defined for the future discharge scenarios including Klargester ("septic tank") only (8 $m^3$/day), normal operations (100 $m^3$/day) and maximum (298 $m^3$/day). In terms of infiltration rates, discharge of the Klargester only to "the Wet" and final lagoon would meet Environment Agency and Building Regulations guidance, but the other scenarios would exceed this capacity.

Under normal operating conditions (100 $m^3$/day), “the Wet” and the final lagoon have a proven current capacity to accept this (and up to ~160 $m^3$/day), but this capacity will be insufficient to accept the maximum discharge scenario (298 $m^3$/day). It is likely that the infiltration capacity of “the Wet” and final lagoon have reduced as a result of sediment deposition, but in theory the gravels have the capacity to accept this higher discharge rate. Desludging is therefore likely to be required before this higher rate could be accepted.

Attenuation of contaminants in the unsaturated zone may be significant for the Klargester only scenario, but would be minimal for the other scenarios.

Dilution of all the discharges would be significant leading to a large reduction in Klargester concentrations (x1.9%) and ~x16.5% concentrations for both of the other scenarios. The worst case is diluted concentration increases in downgradient groundwater of 1.7 mg/l $O_2$ $BOD_{5ATU}$, 0.71 mg/l N ammoniacal nitrogen and 0.1 mg/l P phosphorus / phosphate.

The $BOD_{5ATU}$ and ammoniacal nitrogen are likely to be oxidised by dissolved oxygen from the upgradient groundwater and leave a downgradient dissolved oxygen concentration of >7 mg/l $O_2$. This means conditions in groundwater will remain aerobic and there is unlikely to be release of dissolved metals associated with iron and manganese reduction.

Phosphate attenuation is likely to be significant in the groundwater environment.

Unretarded travel times between the final lagoon and the River Teme are likely to be of the order of 1 year. This is also the likely timescale for flushing of currently impacted groundwater from the system, although there may be some delay if reduced metals need to be oxidised and re-precipitated in the alluvium / gravels.

# 6. Recommendations

## 6.1 On-going Monitoring

A monitoring plan has been previously been submitted to NRW. This is to keep under observation the quality through the existing treatment system including the current lagoon discharge quality and to monitor groundwater quality.

Low groundwater levels prevented sampling of piezometer PZ#13 which is immediately downgradient of the final lagoon and a number of other piezometers. Sampling should be reconvened as per the agreed schedule once groundwater levels recover. A link has been made between groundwater levels likely to be suitable for sampling the piezometers and the river stage at Knighton.

## 6.2 Monitoring the Impact of the Proposed Discharge

Monitoring of the proposed discharge to groundwater should include monitoring of:

- Daily flows discharged to “the Wet and final lagoon;
- Discharge quality under a range of operational regimes;
- Groundwater levels to check the impact of seasonal water level variations and different discharge rates;
- Groundwater sampling to check the predicted improvement in groundwater quality from the proposed discharges under a variety of seasons and operational regimes.

The need for long-term monitoring should be reviewed if it can be demonstrated water quality is stable, predictable and acceptable.

## 6.3 Desludging and Bunds

It is likely that “the Wet” and the final lagoon require desludging before the maximum discharge rates could be infiltrated. Currently the sludge may be providing protection to groundwater against toluene that is being generated in the final lagoon. For this reason, desludging should be undertaken once the main treated discharge can be diverted under permit to the river. It may then be appropriate to let the lagoon largely dry out before desludging.

Once the desludging is done, it is recommended that the bunds around “the Wet” and the final lagoon are re-instated / stabilised and the system gradually tested at higher and higher discharge rates during a period when discharge to river is still acceptable and further remedial measures or lagoon extensions can be considered.

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| | |
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# Appendix A
# Borehole Log for Chicken Farm

1 Pages

The following page provides the drilling log as provided by Radnor Hills for a borehole drilled at the Dumbles Poultry Limited at approximate grid reference (334127, 272776).

30/12/2010 18:39 01686440654 POWYSDRILLINGSERVICE PAGE 03

# POWYS DRILLING SERVICES

## BOREHOLE CONSTRUCTION RECORD

**Customer Name** Will

**Site Address** Radnor Hills
Knighton

POULTRY UNIT

N.G.R.

**Location of B/Hole** Close to hedge by chicken sheds

**Borehole Dia.** 200 Dia. from 0 to 10½ m
Dia. from to m

**Casing Details** Solid Steel 200 mm from 0 to 10½ m
mm from to m

**Liner Details** (mdpe - 100mm) Plain from 0 to 4½ m
Slotted from 4½ to 10½ m

**Borehole Chamber Constructed?** ~~Yes / No~~ no chamber needed

**Strata Log**

| From | To | Description of Strata |
|---|---|---|
| 0ft | 4ft | Made up ground |
| 4ft | 15ft | Sandy gravel. |
| 15ft | 24ft | gravel lot's of water in it |
| 24ft | 37ft | 309lplmin |
| | | 4 bages pea gravel used |
| | | 4 bages Cement for grout. |

Date Drilling Commenced 2-3-09 Date Completed Drilling 3-3-09.

Water Struck at 24ft

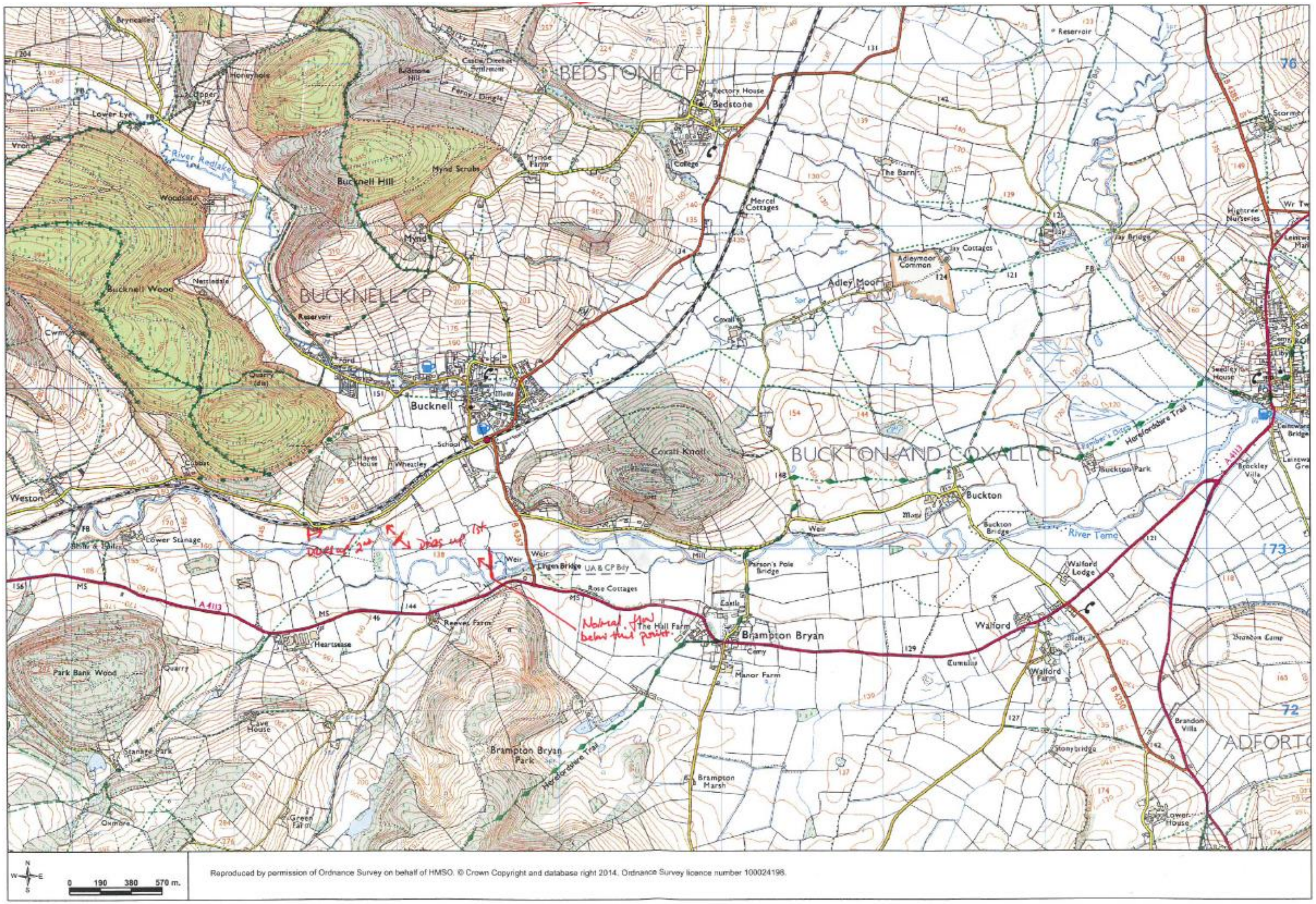
Flow Rates 309l/min Rest Level 19ft

Driller Signature N. R. Nickell

# Appendix B
# Dry River Reaches Map

1 Page

The following page reproduces a scanned version of a map provided by Peter Giles (Environment Agency fisheries officer) 03 March 2016.


BEDSTONE CP
Bedstone
Bucknell Hill
Bucknell Wood
BUCKNELL CP
Bucknell
Coxall Knoll
Adley Moor
BUCKTON AND COXALL CP
Buckton
River Teme
A 4113
Brampton Bryan
Walford
Brampton Bryan Park
Park Bank Wood
ADFORT
76
73
72
0 190 380 570 m.