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Annex 53-UK

Modelling Nitrate concentrations with variations in time

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ANNEX 53 - UK

Water Resources Management in Cooperation with Agriculture

MODELLING NITRATE CONCENTRATIONS WITH VARIATIONS IN TIME

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UK WATER INDUSTRY RESEARCH LIMITED

WATER RESOURCES MANAGEMENT IN COOPERATION WITH AGRICULTURE (WAgriCo)

MODELLING NITRATE CONCENTRATIONS WITH VARIATION IN TIME

Executive Summary

Objectives

As part of the WAgriCo (Water Resources in Co-operation with Agriculture) (EU LIFE 05-D-182) project, Entec UK Ltd were contracted by UK Water Industry Research Ltd to model how changes in nitrate leaching from different catchment management scenarios (or 'Programmes of Measures') would impact on nitrate concentrations in the eight selected WAgriCo catchments. The catchments are all to Wessex Water Services Ltd groundwater supplies located in the Frome, Piddle and Wey surface water catchments in Dorset, UK. Each of the eight supplies abstracts groundwater from the Chalk aquifer.

More detailed objectives are described, but in summary these were to provide: background information on flow processes and transport of nitrate in the Chalk; to describe likely historically leached nitrate and compare estimates for recent years with ADAS UK Ltd's NIPPER model predictions; to estimate travel times in the catchments, then compare simulated and measured nitrate concentrations at the groundwater supplies. With good model fits in place, the key part of the project was then to simulate future nitrate concentrations under baseline conditions and with the WAgriCo measures in place. The final element of work was to examine the mechanisms behind the short term spikes in nitrate concentration which will give Wessex Water significant challenges in meeting drinking water standards in the coming years and decades.

Conclusions

Groundwater catchments were defined for the WAgriCo abstractions. These are typically smaller than the larger areas in which farmer liaison has been undertaken as part of the WAgriCo project.

The concentration of historically leached nitrate, defined as part of a project in 2007/8 for Wessex Water compares well to ADAS' NIPPER model estimates for recent years. A refinement to the managed grassland trend and approach was made, but overall the two approaches produce similar results bringing confidence to the use of the historical trends in leached nitrate. There was a peak in nitrate leaching between ~1980 and ~1995.

An approach which combines GIS grids of land use and travel time with historically leached nitrate trends in Excel was developed for Wessex Water in 2007 to simulate past, present and future nitrate concentrations in groundwater. Good agreement was achieved between simulated and measured nitrate concentrations in six out of eight of the WAgriCo groundwater supplies; indicating the long term trend in nitrate concentration in these groundwater supplies is related to historically (~10-60 years old) leached nitrate. In a seventh catchment, the fit was moderately good and in the eighth (Langdon) the fit was poor due to the lack of groundwater level data and probably significant runoff recharge. The good model fits has given confidence in using the models /approach to evaluate the impact of the WAgriCo measures.

The model / approach has been used to simulate nitrate concentrations up to the year ~2040 assuming ADAS NIPPER model estimates for soil leaching under baseline conditions and under a best case with a number of WAgriCo measures in place. These simulations suggest that the WAgriCo measures will help maintain and improve water quality in a number of the catchments, although in others, will not be able to prevent the effect of historically leached nitrate leading to an exceedance of the drinking water standard.

The assessment of controls on short term spikes and seasonal variations in nitrate has not reached a firm conclusion. It appears likely that these variations in nitrate concentration are related to bypass recharge through the soil and fracture flow of bypass and infiltration recharge through the unsaturated zone. Further work is recommended. If a link can be established between shorter term nitrate concentrations, rapid recharge and this year's / month's leachable nitrate, then the more immediate benefit of the WAgriCo measures could be identified, measured and communicated to farmers.

Recommendations

Wherever focussed catchment management is to be undertaken, it is recommended that the groundwater catchments to the abstraction sources are re-evaluated. These groundwater catchments are likely to be smaller than the Environment Agency defined total catchment source protection zones (which conservatively were made larger to take into account uncertainties in capture zones) and so would allow more focussed effort.

Further application of the model / approach to simulating long term nitrate trends would provide additional checks on its robustness. With a robust validation in place, the approach could or should be applied to all catchments in which focussed catchment management is planned, as this will inform the timescale for the impact of any measures to be realised.

As noted above, further work is required to understand the link between today's land management and short term variation in nitrate concentrations; as such a link will provide more immediate feedback to catchment managers and farmers on the benefit of the measures applied.

Benefits

Integral to the implementation of catchment management measures is an understanding of how long it will take for their benefits to be realised. The approach developed for Wessex Water and applied to this WAgriCo project provides a tool to evaluate the influence of historically leached nitrate on concentrations today and in the coming decades. Without this understanding, catchment managers and farmers could feel the measures being implemented are having no effect or even a detrimental effect. With this understanding, other methods of evaluating reduced nitrate leaching can be explored to give feedback on the success of any measures.

The work has also improved the understanding of the likely link between short term nitrate variations in groundwater, bypass recharge and / or fracture flow of recharge in general, and today's land management. Further work is required, but this link would provide more immediate feedback to farmers and catchment managers on the success of any measures.

**For further information please contact UK Water Industry Research Limited,
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ANNEX 53 - UK

1 Introduction

1.1 Purpose of Report

As part of the WAgriCo (Water Resources in Co-operation with Agriculture) project, Entec UK Ltd (Entec) was contracted by UK Water Industry Research Ltd (UKWIR) to model how changes in nitrate leaching from different catchment management scenarios (or 'Programmes of Measures') would impact on nitrate concentrations in the eight WAgriCo catchments. The catchments are all to Wessex Water Services Ltd (Wessex Water) groundwater supplies located in the Frome, Piddle and Wey surface water catchments in Dorset, UK. Each of the eight supplies abstracts groundwater from the Chalk aquifer.

This report documents the results of Entec's work against this objective including briefly describing the conceptual understanding of transport processes in the Chalk, efforts to constrain the nitrate leached from the soil historically (last 50 – 100 years), and simulating historical trends in nitrate at Wessex Water's groundwater supplies. With the confidence gained from good model simulations of historical nitrate in groundwater trends, the report then describes predicted trends without and with a number of WAgriCo measures put in place. Impacts on the shorter term seasonality and spikiness of trends, as well as on the long term trends, are described.

This report therefore provides a basis to better understand how long measures may need to be in place before an improvement in groundwater quality is seen. This understanding is important, as where this timescale is long:

- **Farmers** and **catchment managers** involved in delivering the Programmes of Measures will need to find other (than groundwater, e.g. soil water) monitoring points to feedback and demonstrate reduced nitrate leaching is occurring.

- **Water Companies** will need to plan for deteriorating water quality for years to come despite implementation of the measures such as those developed during WAgriCo.

- **The Environment Agency** will need to factor these delays into the River Basin Management Plans due for completion in December 2009 and identify which groundwater bodies are likely to have deteriorating water quality despite implementation of any measures.

- **DEFRA** will need to inform the European Commission, under Water Framework Directive responsibilities, where deteriorating trends are anticipated beyond 2015 and 2027 because of historical nitrate inputs.

1.2 Project Objectives

Detailed objectives are set out in the Research Agreement between Entec and UKWIR (WR26D268). The main purpose of this work was to assess the impact on groundwater quality of achieving reductions in nitrate concentrations over time for various Programmes of Measures or changes to land-use management practices. The following objectives were set at the start of the project:

- To characterise flow in the Chalk and understand the importance of bypass flow in the observation of nitrate concentration peaks, using data to validate findings.

- Use the outputs from the ADAS NIPPER model, for four different catchment management scenarios, to provide a more informed soil nitrate leaching input to the Entec model of long term trends in groundwater nitrate concentrations.

- Use the subsequent modelled long term trends to mechanistically estimate the timescale of nitrate travel from soil-zone to abstraction and to quantify the impacts of the four different catchment management scenarios.

- Use the more detailed daily nitrate leaching outputs from the NIPPER model to assess seasonality in observed nitrate trends.

1.3 Report Contents

Following this introduction, Section 2 briefly describes the key aspects of the WAgriCo project relevant to this work, including a description of the measures developed by ADAS. For further background, Section 3 provides an outline of the science controlling the movement of water (and nitrate) in the Chalk and of existing nitrate transport modelling approaches.

Section 4 describes estimates of historically leached nitrate and ADAS's NIPPER model predictions of recent (2000-2006) and future nitrate leaching (with different WAgriCo measures in place). Section 5 describes Entec's approach and results on simulating long term trends historically and Section 6 looks at predictions of nitrate concentrations in the coming decades assuming the WAgriCo measures are put in place. Section 7 describes some important, but inconclusive work in which efforts were made to better understand shorter term (seasonal and daily/weekly) variation in nitrate from the long term trend.

A summary and recommendations section is provided in Section 8. Data and model calibrations have been illustrated in figures and tables either within the text or in the Appendices.

2 The WAgriCo Project

2.1 About the WAgriCo Project

WAgriCo (Water Resources in Co-operation with Agriculture) is an EC Life co-funded project aimed at developing best practice approaches for the control of diffuse water pollution (predominantly nitrates in groundwater) from agriculture. The project commenced in 2005 and was due for completion at the end of September 2008. It had German partners from Lower Saxony, and in the UK involved the cooperation of farmers as well as DEFRA, Wessex Water, the Environment Agency, ADAS, and the National Farmer's Union (NFU). Work in the UK focussed on eight 'pilot areas' within the river catchments of the Frome, Piddle and Wey near Dorchester, Dorset.

The project was managed through UKWIR. Entec became involved in the project formally in July 2008, following work they had done for Wessex Water on nitrate trend prediction between 2006 and early 2008.

The WAgriCo project is described in more detail in ADAS (2008). As a project it follows the Water4All (Lovett et al., 2006) and subsequent WaterCost (WaterCost, 2008) projects which were undertaken by Danish, Dutch, German and UK partners between 2003 and 2005. The project has also overlapped with the EC Life project AGWAPLAN (Nilsson, 2008) undertaken in Denmark between 2005 and 2008. Each project has been aimed at finding ways to reduce the impact of agriculture on the water environment and in particular, but not exclusively, nitrate on groundwater.

Much of the WAgriCo project's emphasis is in providing advice and support to farmers in order to reduce nitrate losses to groundwater, particularly with regards to use of fertilisers and manures. The project also seeks to reduce losses of nutrients to surface waters, which could indirectly affect groundwater.

The project has identified a 'Programme of Measures', or improvements in agricultural practices, to increase the efficiency of manure and fertiliser use, which farmers receive payment for implementing. Part of this EC Life project's requirements was to evaluate the impact of any measures on groundwater quality and this report was prepared in response to that requirement for work in the UK.

2.2 Selection and Location of the WAgriCo Catchments

The groundwater sources selected for catchment management as part of the WAgriCo project were identified by Wessex Water on the basis of rising nitrate levels, or concentrations already exceeding drinking water standards. The eight catchments are Eagle Lodge, Empool, Friar Waddon, Hooke, Langdon and Winterborne Abbas in the Frome catchment, and Dewlish and Milborne St. Andrew in the Piddle catchment. Further justification of catchment selection is given in Annex 16 of the Interim Technical Report for WAgriCo (September 2007, LIFE).

The WAgriCo catchment boundaries, as shown in Figure 1, are based on the Environment Agency's 'total catchment' source protection zone (SPZ 3). The SPZ 3 areas appear to take into account uncertainties in the catchment area and are thus conservatively large; an appropriate approach when these areas help guide the implementation of groundwater protection policy. For the WAgriCo catchments, these are also the areas of land in which there has been close liaison between farmers and farm advisors. Work by Entec, described in Section 5, redefined the groundwater catchments to the eight groundwater supplies using groundwater contour data. It is noted that these groundwater catchments are smaller than the SPZ 3 defined land areas and in some cases cover different land areas.

2.3 Outline of WAgriCo Measures Used in Nitrate Trend Predictions

Four WAgriCo measures, or management scenarios, were selected by ADAS for this project as representing those most likely to reduce nitrate leaching to groundwater. These measures are part of a list of 44 mitigation measures aimed at reducing diffuse water pollution from agriculture (DWPA) produced for DEFRA (2006). Details of the four measures are set out in Table 2.1.

Table 2.1 Summary of the WAgriCo Measures Evaluated in this Project

	Measure	Measure Detail
1*	Recommendations for fertiliser applications (crops) (Code GAP1)	Does not exceed optimum recommended rates. Takes full account of soil nitrogen supply.
2	Recommendations for fertiliser applications (manure) (Code GAP1)	Does not exceed optimum recommended rates. Takes full account of manure inputs.
3	Cover crops (Code EGAP1)	Establish a cover crop immediately post-harvest or, at the latest, by mid-September prior to the main crop. Retain the area uncultivated until at least 15th February the following year and follow with a spring crop.
		Alternatively, undersow crops with a cover crop that will be in place to take up nutrients and provide vegetation cover once the main crop has been harvested. Do not destroy the undersown cover crop before the 15th February the following year.
		Farm livestock can graze the cover crop once established, but must be removed to avoid poaching and loss of ground cover.
4	Manure timing (moving from autumn to spring application for slurries and poultry manures (Code EGAP3)	Spring application makes best use of manure N, therefore moving from autumn applications (application after October 15th) to spring application (application after January 31st) is suggested. This will cover the use of both slurries and poultry manures.

* Measures 1 and 2 are listed as part of one measure (code GAP1) in the DEFRA guidelines, but have been modelled separately by ADAS.

3 Water and Nitrate Movement between Soil and Abstraction Point

3.1 Introduction

This section describes the conceptual understanding of recharge and nitrate transport from the soil zone, through the unsaturated and saturated zones of the Chalk aquifer to the groundwater supplies. As such it provides a basis for predicting the delay between the implementation of the WAgriCo measures set out in Table 2.1 and an improvement in groundwater quality at the water table and at Wessex Water's groundwater supplies.

The descriptions provided are not intended to be an exhaustive review of all processes, but instead are intended to provide the reader with sufficient background to understand the processes modelled to generate the long and short term predicted nitrate concentration trends. A review of nitrate sources, leaching, transport and attenuation processes can also be found in the Environment Agency's (2005) Science Report: *Attenuation of nitrate in the subsurface environment*.

3.2 Soil Leaching

Leaching of nitrates from soils in the WAgriCo project catchments in recent years (from 2002) and in the future under the proposed 'Measures' (see Table 2.1) was examined by ADAS (2008). The processes controlling nitrate leaching are not described in detail here, but the key factors which influence the availability of nitrogen leaching from soil include:

- Availability of nitrogen (N) (a balance between uptake and supply).
- Availability of nitrate N in fertilisers applied to soil (manures/artificial fertilisers and slurries).
- Effective rainfall draining from the soil.
- Soil types and physical properties.
- Crops and crop cultivation – (e.g. in order of efficiency of nitrate uptake from soil sugar beet > winter wheat > potatoes > oil seed rape. Legumes add nitrogen to the soil).
- Land management practices – (e.g. autumn/winter crops absorb residual nitrate, ploughing of land release nitrate).

Prediction of nitrate leaching in recent years, and at the field scale, when there are good data on inorganic fertiliser and manure application rates and crop types, is possible using nitrate leaching models such as NIPPER (Gooday et al., 2007, Lord et al., 2007), but the estimates will have uncertainties. Prediction of nitrate leaching from soils over the previous century is made even more difficult due to uncertainties in historical fertiliser application rate, manure application, ploughing, land use, crop type etc. A discussion of the efforts used to constrain the historically leached nitrate concentration is discussed in Section 4.2.

Further reading on nitrate leaching can be found in Addiscott (1996), MAFF (1995) and MAFF (2000).

3.3 Recharge (and Runoff)

Recharge through the soil is the route for leachable nitrate within the soil to be carried down to the water table and from there onwards to the abstraction. Each of the WAgriCo catchments is predominantly on chalk soils and there is little, if any anticipated runoff to wash nitrates directly into surface waters. The main exception is the Langdon catchment, which is understood to receive a high proportion of runoff recharge from areas mapped as clay-with-flints (SPZ manual derivation notes held by Environment Agency South West).

A recharge model produced by Entec (2005) for the Environment Agency and Wessex Water has concluded that recharge in the areas typified by the WAgriCo catchments occurs as:

- **Infiltration recharge** (recharge which occurs when the moisture deficit in the soil is exceeded – occurs to all permeable strata except where groundwater discharges at the surface e.g. very close to rivers).

- **Bypass recharge** (recharge which occurs regardless of soil moisture deficit during periods of more intense rainfall – in the South Wessex area this tends to be limited to the Chalk and is empirically set in the recharge model (Entec, 2005) as 10% of all rainfall on outcrop Chalk in excess of 1 mm/day.

- **Runoff recharge** (recharge which occurs where runoff from lower permeability deposits (e.g. head deposits) run-offs and recharges adjacent permeable material – absent on outcrop Chalk).

The main soil type for the majority of WAgriCo catchments is a shallow well drained silty soil over chalk (NSRI - Procter et al., 1998).

3.4 Movement through the Chalk Unsaturated Zone

3.4.1 Overview

Water and nitrate movement down through the Chalk's unsaturated zone to the water table has the potential to occur via matrix or piston flow through the Chalk matrix or, much more rapidly via fissures and fractures in this dual porosity aquifer. Piston flow through the unsaturated chalk matrix is the dominant recharge mechanism providing the observed summer base-flow even during times of drought (Foster, 1993, Price et al. 2000). Fissure or bypass flow is assumed to occur when the saturated vertical hydraulic conductivity of the chalk matrix is exceeded by effective precipitation (Price et al. 1993, 2000; Lee at al. 2006; Matthias et al. 2006).

Seasonal variation in the volume of effective recharge is reflected in observed seasonality in groundwater level hydrographs of Chalk observation boreholes and Chalk fed stream and river flow hydrographs. The water table response to recharge events is partly controlled by matrix flow, with the most rapid responses to recharge events explained by fissure flow in the unsaturated zone (Lee et al., 2006).

The occurrence of by-pass flow (or fissure flow) is supported by evidence from water quality observations, e.g. bacteria count and pesticide and nitrate concentration spikes which often follow heavy rainfall events. Volumetrically, this recharge mechanism is not as important as piston flow via the chalk matrix, providing up to 30% of the total annual recharge to the water table (Mathias et al., 2006). By-pass flow in the unsaturated zone is also thought to occur closer to the water table, during steady-state winter recharge. As pore-water suctions decrease in the unsaturated chalk matrix (with increased piston flow recharge), pore water is released to narrower then wider fissures, close to the water table (Price et al., 2000).

3.4.2 Modelling Matrix Flow

Downward flow within the unsaturated chalk matrix is most commonly simulated by assuming that 'plug' or 'piston' flow occurs, where recharge added at the top of the unsaturated zone displaces water held in the pores of the unsaturated zone and leads to a release of water at the water table. Environment Agency models such as LandSim (Environment Agency, 2003) and ConSim (Environment Agency, 1999) use this approach and this approach has been used in the predictions of long-term annual average nitrate concentrations for this project. The equation describing plug flow is:

$$T_u = z \,.\, \theta / R_I \qquad \text{Eqn 1}$$

Where:

T_u= travel time (years) of a water particle or conservative ion (such as chloride and nitrate);

z = the thickness (m) of the unsaturated zone (or depth to the water table below the soil zone);

θ = the moisture content (fraction) of the strata (e.g. Chalk) in the unsaturated zone;

R_I = the infiltration recharge (m/yr) leaving the base of the soil zone.

Work undertaken by Imperial College, London, suggests that water may continue discharging from the unsaturated Chalk matrix to the saturated aquifer even during the summer and early autumn when there is no infiltration (and at times no bypass) recharge from the soil zone. The concept is that water in the unsaturated Chalk matrix takes on a higher pressure in winter below the soil zone and this pressure takes some time to dissipate fully down to the water table. Although this mechanism is important when trying to understand seasonal hydraulic responses, the rate of transport of nitrate through thick unsaturated zones is likely to average out at one calculated using equation 1 and the average annual infiltration recharge (R_I). For the Dorchester area, this rate will be of the order of 1.0 m/yr to 1.5 m/yr.

3.4.3 Modelling Bypass Flow

Assessment of groundwater and stream hydrographs, undertaken as part of the South Wessex Recharge Model (Entec, 2005) indicates that discharge from the unsaturated zone continues during times of no infiltration recharge through the soil. In addition to the ongoing steady discharge of water from matrix Chalk in the unsaturated zone postulated by Imperial College (see above), the presence of increased turbidity and occasional concentration spikes of pesticides and, more frequently, nitrates in some sources suggests that there is rapid transport of water and contaminants down fissures in the Chalk. There is typically no evidence of this process in more intergranular-flow aquifers in Wessex such as the Upper Greensand or where the Chalk is covered by drift (e.g. East Anglia).

Environment Agency models such as ConSim (Environment Agency, 1999) use an approach (after Price, 1987) of allowing rapid transmission through the unsaturated chalk when the infiltration/ recharge exceeds the saturated hydraulic conductivity of the chalk matrix.

The LandSim (Environment Agency, 2003) manual provides geometric mean saturated vertical hydraulic conductivity values (13 samples between 4 and 66 m bgl) of 5.07×10^{-8} m/s (4.4 mm/day) and (73 samples between 242 and 279 m bgl) 3.06×10^{-8} m/s (2.6 mm/day) for the Upper Chalk at Totford and Faircross in Hampshire respectively. No data for the Upper Chalk are given for Dorset.

3.4.4 Nitrate Transport through the Unsaturated Zone

The Chalk unsaturated zone in Hampshire and Dorset is highly likely to be fully aerobic / oxygenated meaning that bacterially mediated nitrate reduction will be unlikely below the soil zone. As in some other parts of England, where the Chalk is covered by clayey drift there will, conversely, be a potential for nitrate reduction within the drift (Environment Agency, 2005).

Due to the nature of piston flow within the chalk matrix, and the lack of vertical mixing, pore water nitrate (and tritium) profiles in the unsaturated zone (e.g. BGS, 2005) often preserve the concentrations historically leached from the overlying soils (Parker et al. 1990). It is noted that diffusion is likely to dampen any short term variability (weekly) over the centimetre scale in the chalk matrix over a year or so, and should smooth year to year changes over the 1 m scale after perhaps 10 years, but otherwise will not affect nitrate concentrations distributed through a thick (tens of metres) unsaturated zone.

Roy et al. (2007) have noted that the historically increasing trend in matrix pore water nitrate concentrations arriving at the water table is the most statistically significant control on nitrate concentrations in the Hampshire and Dorset Chalk saturated zone.

3.5 Movement in the Saturated Zone to the Abstraction Point

3.5.1 Processes

Water movement from the water table to the abstraction will be predominantly take place in the fissures of the Chalk, although there is a potential for diffusional movement of nitrate from the fissures into the chalk matrix and vice versa. The Environment Agency's Inner (SPZ 1) and Outer (SPZ 2) source protection zones for the WAgriCo catchments show the estimated 50 day and 400 day travel times from the water table to the point of abstraction. The 400 day travel time defined zone is not dissimilar to the total catchment for many of the catchments suggesting travel times (for contaminants such as nitrate) within the catchment of less than 1-2 years.

The source protection zones were defined assuming 1 or 2% fissure porosity, but ignoring diffusion from the Chalk's fissures into the matrix and vice versa. Work undertaken by Entec on other projects and using John Barker's (UCL) spreadsheet model DP1D and taking measurements on cores has shown that diffusion into the matrix is important where transmissivities are $\leq$~300 m^2/day. BGS (1997) report that transmissivities in this area of the Dorset Chalk are of the order of 500-1000 m^2/day and are locally (around Empool) as high as

2000 to 15 000 m^2/day. This suggests fissure flow will dominate the transport of the bulk of water and nitrate from the water table to the abstraction.

Preferential flow paths in the Chalk saturated zone typically develop along hardgrounds and flint nodule bands, which follow the dip of bedding strata (e.g. the Melbourne Rock). The Chalk aquifer hydraulic gradient is much shallower than the dip of main bedding horizons. Preferential flow paths can therefore only develop along bedding features for short distances before they dip beneath the main zone of groundwater circulation (the upper 50m). Flow-paths are assumed to step-up strata to the next developed bedding feature and the main flow remains within the shallow circulation closer to the water table (South Wessex Recharge Model, Entec 2005).

In catchments other than the Chalk, and in particularly those where flow is within intergranular aquifers (e.g. the Upper Greensand in Wessex) then travel times in the saturated zone may be significant.

Denitrification in the saturated Chalk is unlikely (Environment Agency, 2005).

3.5.2 Modelling Movement in the Saturated Zone

In the nitrate trend predictions for the WAgriCo catchments, movement through the saturated aquifer has not been modelled due to the likely lower significance of this process (in the Chalk) on nitrate concentrations compared to unsaturated travel times. This section is, however, provided for completeness and has formed the basis of successfully predicting long term trends in an Upper Greensand catchment for Wessex Water.

The most commonly used expression to calculate the rate of lateral movement of a water particle or conservative contaminant (including nitrate) in a saturated aquifer is[1]:

$$V_s = k \cdot i / n \qquad \text{Eqn 2}$$

Where

V_s = the rate of movement (m/day) of a water particle or conservative ion (such as chloride and nitrate);

k = the saturated hydraulic conductivity (m/day) of the aquifer (e.g. Chalk);

i = the hydraulic gradient;

n = the effective porosity of the aquifer (e.g. Chalk).

In strata such as the Upper Greensand where flow is intergranular, the effective porosity will be of the order of 20-30% compared to the Chalk aquifers 1-2% fissure porosity. This means for the same volume rate of flow, travel times will be ~20 times longer.

[1] This equation is an approximation based on Darcy's Law and for unconfined strata more accurately should be related to Dupuis' Law.

3.5.3 Nitrate Transport and Mixing in the Saturated Zone

Nitrate concentrations in the saturated zone are affected by mixing processes (as discussed previously) and by changes in redox potential with depth and age of water. The regional redox boundary between oxidizing and reducing conditions has been shown to be controlled by the position of preferential flow horizons in the Chalk (Schürch et al. 2004). The redox boundary position within the saturated zone controls the depth beneath which denitrification takes place and above which nitrate is the dominant dissolved nitrogen species. Schürch et al. (2004) suggest that the redox boundary forms a diffuse zone close to the preferential flow path mixing area, where groundwaters with low nitrate and high nitrate concentrations can mix. The consequences of changes in water table level are in relation to this boundary are not known. Although the position of the redox boundary has only been identified in investigations of the Chalk adjacent to the confining Palaeogene sediment cover, it could be present at depth throughout the saturated aquifer.

3.6 Effect of Groundwater Level Fluctuations

Groundwater levels in the Chalk respond seasonally to variations in recharge. In the vicinity of the WAgriCo catchments, groundwater levels vary seasonally from a few metres close to water courses to ~40 m in some of the higher interfluves (Entec, 2005).

Increases in groundwater level have two possible effects:

- The thickness of the unsaturated zone reduces.
- Flow velocities in the Chalk potentially increase as more highly developed / permeable fissures take part in the transmission of water, nitrate and other contaminants.

The science controlling the often observed seasonal variation in groundwater quality (including nitrate concentrations) is not well understood. Previously postulated concepts include: (1) water table rise flushing out contaminants (e.g. nitrate) in the unsaturated zone above and (2) variations in the dilution of recharge by older water in stratified aquifers. A third (3) possibility for the Chalk is that seasonal variations in water quality are caused by variations in the amount of bypass recharge (see Section 7). It is possible that there is a combination of effects (1) and (3) for the Chalk, whereby bypass recharge can reach the water table more quickly during periods of high groundwater levels (caused by significant piston flow infiltration recharge).

4 Nitrate Leaching – Historical Trends and Impact of the WAgriCo Measures

4.1 Introduction

This section describes the long term (1900 to 2007) trends for nitrate leaching derived by Entec (January 2008) in work for Wessex Water and the comparison of these against NIPPER model outputs for three areas in Dorset. The NIPPER model outputs were provided by ADAS as part of the WAgriCo project.

Entec's long term historical trends for nitrate leaching from the soil were influenced by data, but otherwise derived for arable and managed grassland areas using an empirical / model fitting approach. The NIPPER model outputs are based on significantly more data and detail in terms of fertiliser and manure use, cropping, livestock numbers and types, farm management etc for the period 2000-2006. This detail is not, however, available historically.

Before the NIPPER nitrate leaching values for each land use could be used in the Entec long term nitrate prediction models, any differences between the estimates of the two approaches needed to be understood and the associated uncertainties quantified. Comparison of nitrate leaching from the two approaches therefore gave an independent check on likely nitrate leaching in recent years and in turn some validation of Entec's historical nitrate leaching trends. Good comparison would increase the confidence in future trend predictions.

This section provides a discussion of this work and gives the model parameters, uncertainties and outputs of the combination of the two models.

4.2 Estimates of Historically Leached Nitrate in South Wessex

Historically (1900 – 2007) leached nitrate concentrations for the South Wessex Area were constrained by Entec (January 2008) through examination of (a) historical inorganic fertiliser inputs as reported in the British Survey of Agricultural Practice, (b) observation borehole nitrate concentration data, and through an iterative process to gain the best fit to a number of observed nitrate concentration trends in the modelled groundwater sources. Whilst not fully independent, the trends of historically leached nitrate appear plausible (see Figure 2 and 3).

To account for dilution effects, the method (Entec, January 2008) developed for Wessex Water, increased or decreased the historically leached nitrate concentrations depending on whether infiltration recharge was lower or higher for a particular catchment than the 440 mm/yr assumed for the trends shown in Figures 2 and 3.

For land uses other than arable or managed grassland, nitrate concentrations of 2.0 mg/l N and 0.5 mg/l N were assumed for semi-natural vegetation and woodland and forestry respectively. None of the catchments modelled had significant urban areas.

4.3 ADAS NIPPER Baseline values – 2000-2006

The reader is referred to the ADAS report (ADAS, 2008) for a full description of the NIPPER modelling work undertaken to produce estimates of annual average nitrate concentrations for the period 2000-2006 in the WAgriCo catchments. Three NIPPER model areas were selected to allow examination of changes in nitrate leaching from areas with different recharge; recharge reducing generally from southwest to the northeast. The model areas shown on Figure 1 are as follows:

- Area 1 in the vicinity of Dorchester and encompassing WagriCo catchments – Eagle Lodge, Empool, Friar Waddon and Winterborne Abbas.
- Area 2 to the south of Blandford Forum and encompassing the catchments to Wessex Water's Shapwick and Sturminster Marshall groundwater sources.
- Area 3 to the north of Salisbury and encompassing the Deans Farm source.

The size of the model areas were selected by ADAS to ensure they were sufficiently large for outputs not to be skewed by individual farms, but sufficiently small enough so that the effects of spatial variations in recharge or land use/ management were not lost in the averaging process.

Details of NIPPER model assumptions made by ADAS and provided to Entec for this project are set out in Table 4.1.

The area weighted manure and fertilizer applications and the different stock types in the land-uses in each of the NIPPER modelled areas are set out in Table 1. This illustrates the variation in agricultural practices in each of the modelled areas.

NIPPER model predictions for nitrate leaching (from chalky soils) from this (2000-2006) baseline period are set out in Table 4.2.

Table 4.1 Area Weighted Manure and Fertilizer Loading Rates and the Different Stock Types in the Land-Uses in each of the NIPPER Modelled[a] Areas

Area	Land Use	Inorganic Fertiliser	Manure	Cut Grass (Grazed)	Covered by Dairy Stock	Covered by Sheep & Beef Grazing
		kg/ha	kg/ha	% of Area	% of Area	% of Area
1	Arable	168.2	14.6			
1	Grassland	91.0	56.8	48.6	28.8	22.6
2	Arable	156.2	40.3			
2	Grassland	96.8	105.4	48.4	30.0	21.7
3	Arable	173.3	22.2			
3	Grassland	38.8	79.5	41.1	19.4	39.5

Notes:

The constant NIPPER model run parameters for all scenarios were as follows:

- Period 01 September 2000 to 31 August 2006 was modelled using actual rainfall data inputs, but with recharge estimates which do not allow for bypass flow recharge.
- Manures were applied on the 01 September, 01 January and 01 March.
- Inorganic fertilisers were applied throughout the Spring at different times to different crops. Most commonly the timing was on 21 February and 14 March to cereals, 14 February and 21 March to grass and slightly later to potatoes, beef etc.
- Area 1 and 2 are broadly similar in terms of different types of cropping occurring, although Area 1 has slightly less arable and more grassland than Area 2. Cattle numbers are similar, but Area 1 has more sheep, whilst Area 2 has more poultry. From a "cursory look", ADAS commented that "Area 1 is more representative, as sheep and grassland appear to increase as you head west, whilst there is more poultry to the north and east".

4.4 Comparison of NIPPER and Entec Leached Estimates

Table 4.2 presents a comparison of baseline (i.e. current practices) ADAS NIPPER leached nitrate concentrations for the three model areas with those assumed / used by Entec (January 2008) in work for Wessex Water.

Table 4.2 Comparison of Entec UK Ltd and NIPPER Leached Nitrate Concentrations

		Entec Model			ADAS NIPPER Model		
Area	Land Use	Infiltration Recharge (mm/yr)		Assumed Nitrate (mg/l N)	Infiltration Recharge (mm/yr)	Leached Nitrate (mg/l N)	Comment
		1971-2000 LTA[1]	Sept 00 – Aug 06 Average	2001-2006 Average[2]	Sept 00 – Aug 06 Average	2001-2006 Average	
1	Arable	440	382	7.77	358	7.79	
2	Arable	373	322	9.17	313	9.23	
3	Arable	292	297	11.72	187	11.19	The NIPPER recharge value appears low.
1	Grassland	436	382	9.60	369	7.06	
2	Grassland	333	322	12.69	309	8.43	
3	Grassland	272	297	15.53	177	7.03	The NIPPER recharge value appears low.

Notes:

1. The Long term averages (LTA) are as outputs from Entec's (2005) South Wessex Recharge Model runs for Eagle Lodge (= Area 1), Sturminster Marshall (= Area 2) and Deans Farm (= Area 3) – see Figure 4 for locations of catchment areas.

2. The averages for Area 1 (arable and grassland) are the average concentration for the years 2001 to 2006 as shown on Figures 2 and 3 for a reference infiltration recharge of 440 mm/yr. The averages for Areas 2 and 3 are calculated by multiplying the Area 1 average nitrate concentration by 440 mm/yr and dividing by the 1971-2000 long term average infiltration recharge. This is a dilution / concentration effect.

For **arable land use**, the Entec and ADAS NIPPER approaches yield very similar leached nitrate concentrations. It is possible that the Entec approach overestimates arable leaching in areas of lower recharge, but, given the discrepancies between recharge estimates for Area 3 (Table 4.2), there is insufficient evidence to modify the approach for arable land use. Also, none of the WAgriCo catchments are in areas with particularly low recharge.

For **managed grassland**, there is a significant difference between the outputs of the Entec and ADAS NIPPER approaches for both the Area 1 baseline value and the change in concentration with recharge. For the Area 1 baseline values, the Entec assumed leached nitrate of 9.6 mg/l N is significantly higher than the ADAS NIPPER estimate of ~7.1 mg/l N. In addition, the ADAS NIPPER model estimates for Areas 2 and 3 (8.43 and 7.03 mg/l N respectively) do not show the expected increased leached nitrate concentration with lower recharge. This makes the difference between the Entec and NIPPER estimates of leached nitrate very large (>50%) for Areas 2 and 3.

Although the dataset is very small (3 data points for each land use), comparison of leached nitrate concentrations with infiltration recharge estimates shows very poor correlation ($R^2 = <0.05$) for managed grassland compared to the good correlation ($R^2 = >0.9$) for arable. Conversely, comparison of leached nitrate concentrations with total N or manure N inputs is much better for managed grassland ($R^2 = 0.86$ and 0.80 respectively) than for arable ($R^2 = 0.61$ and 0.04 respectively). Correlation of leached nitrate concentration with inorganic fertiliser inputs is poor for both arable ($R^2 = 0.14$) and grassland ($R^2 = 0.31$). This suggests leaching from grassland is much more sensitive to manure inputs than recharge.

4.5 Reasons for Differences in Nitrate leached on Managed Grassland

As part of this work, Entec and ADAS discussed the differences in nitrate leaching from grassland. The following paragraph is based on the feedback from ADAS on these differences.

Despite the assumed greater leaching of nitrate from arable compared to managed grassland, the high organic content and application of manure and return excreta would ensure that there is a high turnover of nitrate during the winter months. Therefore even after high levels of rainfall, a chalky soil would still retain significant mineralised nitrate content, as the rate of replenishment would be close to that of leaching. Hence the drop off in leached nitrate concentrations expected from managed grassland would not be as high. For a poorly drained clay soil, denitrification in a wet winter could significantly decrease the amount of available leachable nitrate, whilst the wet conditions could retard the process of mineralization of nitrate from organic matter. It is likely that the managed grassland nitrate leaching trend developed by Entec (January 2008), overestimates the drop off in nitrate leaching in winter periods.

4.6 Modifying the Entec (January 2008) Managed Grassland Estimates

Entec’s (January 2008) approach developed for Wessex Water does not allow for spatial variations in manure application and excreta rates to be taken into account. Instead it applies a single assumed nitrate leaching trend modified only by spatial variations in recharge.

To improve the compatibility with the NIPPER baseline leached nitrate concentrations, the following modifications were made to Entec’s approach:

- Leached nitrate concentration for managed grassland (at reference infiltration recharge of 440 mm/yr) modified as shown on Figure 3 to be compatible with NIPPER Area 1 grassland leaching (and its assumptions with regard to manure and excreta inputs).

- The modification to leached nitrate concentrations with spatial changes in infiltration recharge was removed for managed grassland, but maintained for arable land use.

4.7 Remaining Uncertainties

The comparison described in the previous sections suggests that catchments[2] with significant managed grassland, and which have different animal numbers and types (and hence manure and excreta inputs) to the NIPPER Area 1 catchments (i.e. around Dorchester) may be less well simulated in terms of long term nitrate trends using the Entec UK Ltd approach.

Taking into account changes in historical livestock numbers and types and making estimates of historical manure and excreta application would allow the Entec methodology to be improved for areas with significant managed grassland.

5 Simulating Historical Nitrate Trends at Groundwater Abstractions

5.1 Introduction

This section describes the simulation of historical nitrate concentration trends at the eight WAgriCo Wessex Water groundwater supplies. A good comparison between simulated and measured (data for 1976 to 2007) brings confidence to the approach and assumptions used, and to any predictions of future nitrate concentrations using the WAgriCo measures (see Section 6).

5.2 Overview of Approach

The approach, which is based on that developed for Wessex Water (Entec, January 2008), has the following key elements:

- Constraint of leached nitrate concentrations from arable and managed grassland for the period 1900 to 2007 (discussed in Section 4).

- Checking and refining catchment areas to selected PWS groundwater supplies through consideration of groundwater contours and an approximate water balance (typical abstraction rate = average recharge × catchment area).

[2] Of the sources evaluated for Wessex Water (Entec UK Ltd, January 2008), only their Chirton source could fall into this category. That source however has unsaturated travel times estimated at predominantly in excess of 75 years and so the existing model fit to measured concentrations is not overly sensitive to more recent changes in manure and fertiliser use or to recharge differences. It is possible however, that the forward predictions for Chirton could be overly pessimistic due to the assumed higher grassland leached nitrate concentrations arising from its low (1971-2000) infiltration recharge estimate (~280 mm/yr).

- Determining travel times through the unsaturated zone of the Chalk for the South Wessex area using a GIS grid of unsaturated zone depth, multiplied by a derived chalk matrix porosity, and divided by a GIS grid of infiltration recharge. The 250 m x 250 m GIS grids were outputs from a South Wessex Recharge Model study (Entec, 2005) undertaken for the Environment Agency and Wessex Water (consent for the grids use being given by both parties).

- Simulating long trends in nitrate concentration at the selected PWS groundwater sources by combining (in Microsoft Excel, 2002) GIS outputs, from defined catchment areas, the proportions of flux (recharge × area) of different unsaturated zone travel times for different land uses (based on the Environment Agency's simplified land use 2000 grid) with the historically leached nitrate concentrations.

- Simulating seasonal trends in nitrate on top of the long term trend by linking to groundwater level variation time series; an empirical rather than mechanistic approach.

- Simulating 'spikes' in nitrate concentration on top of the combined seasonal and long term trends by linking to Entec's 4R South Wessex Recharge Model (Entec, 2005) outputs of daily bypass flow for the defined PWS groundwater sources' catchments. Bypass flow bypasses the soil moisture deficit during heavier rainfall.

The following subsections provide more detail on the above summarised approach.

5.3 Delineation of the WAgriCo Groundwater Catchments

5.3.1 General Approach

The groundwater catchment boundary to each of the WAgriCo groundwater abstractions was defined by hand through consideration of the existing Environment Agency Source Protection Zone (SPZ), but modified to (1) better honour groundwater level gradients and contours, and (2) achieve an area which when multiplied by the typical recharge gave the typical (as provided by Wessex Water) abstraction rate.

5.3.2 Significant Uncertainties for the Hooke and Langdon Catchments

Groundwater level contour data from the area surrounding the Hooke and Langdon sources was not available for this project. These sources are located at the western edge of the Chalk aquifer and in terms of groundwater levels are not covered in any detail by either the Hydrogeological Map of the Chalk and UGS aquifers (IGS, 1979) or by the more recent Environment Agency observation borehole network. The lack of information on groundwater levels in this area brings significant uncertainty into the definition of the groundwater catchments, and also means that there is no depth of unsaturated zone component on which to base travel time estimates.

Further efforts had previously (Entec, June 2008a) been made to estimate groundwater levels (using stream head elevations) in the vicinity of Hooke and redefine the catchment, but the outcome was still poorly constrained.

Groundwater level contours for the area surrounding the Langdon Springs SPZ were drawn by hand using groundwater levels from boreholes recorded in the BGS Wellmaster database and from spring head elevations. The contours were used in conjunction with the SPZ to estimate the catchment boundary. In doing so the following information from the SPZ designation notes (Environment Agency, South West Region) was taken into account:

- Part of the catchment for Langdon Springs is likely to contain an east-west trending dry valley feature, which is in turn fed by run-off recharge from head deposits on the surrounding elevated areas.

- The run-off recharge from head deposits which cover most of the catchment probably lead to the dry valley feature acting as a recharge mound, and the hydraulic gradient will locally go against topography.

- Simulating seasonal trends in nitrate on top of the long term trend by linking to groundwater level variation time series; an empirical rather than mechanistic approach.

- Inferred faulting in the Chalk is likely to connect the dry valley feature to the Langdon Springs source.

Reversal of the hydraulic gradient contrary to topographic slope is confirmed by groundwater levels measured in and surrounding the dry valley feature (Figure 4).

The complexity of the recharge system for this catchment (i.e. run-off to the dry valley combined with flow along the dry valley and potential input from the Upper Greensand aquifer) means that the conceptual model used for other WAgriCo catchments will not be representative of the groundwater flow system at Langdon. The calculation of the age of water arriving at the water table, based on vertical downward piston flow through the unsaturated zone, is therefore unsound. Head-deposits, which cover a large proportion of the catchment will prevent direct infiltration. Run-off recharge will lead to higher infiltration rates in a more localised area at the edge of the head deposits. These higher infiltration rates will lead to much shorter travel times through the unsaturated zone. Overall the model fit for Langdon was anticipated to be poor.

5.3.3 Outputs

Best estimate groundwater catchments for each of the eight WAgriCo sources are shown in Figure 5. The significant uncertainties in the definition of the Hooke and Langdon catchments are re-iterated. It is also noted that some catchment boundaries could move seasonally in response to changes in recharge and abstraction, as well as due to variations in hydraulic conductivity of the Chalk at different depths of water table.

The defined groundwater catchments are smaller than the Environment Agency's source protection zones and are therefore smaller than the catchment areas over which ADAS has been liaising with farmers regarding agricultural methods and measures. In the case of Eagle Lodge, some of the groundwater catchment appears to be outside the farmer liaison WAgriCo catchment. This illustrates the importance of evaluating the extent of groundwater catchments before significant effort is invested in land management.

5.4 Land-use and Land-use Changes

The simplified map (250 m × 250 m GIS grid) of land-uses in 2000 was used with permission from the Environment Agency to define which areas of the modelled catchments should apply the historically leached nitrate trends for arable, managed grassland, woodland (and forestry) or semi-natural vegetation. This approach assumes there have been no changes to land use for the period of any travel time delay through the unsaturated zone.

To inform this assumption, land use maps for 1930, from the First Land Utilisation Survey of Great Britain (http://www.visionofbritain.org.uk/maps/map_lib_page.do) were compared to the gridded year 2000 simplified land use (see Figure 6) for the WAgriCo catchments. Although the Hooke and Langdon catchments appear to have changed from managed grassland to arable, land use in the other catchments appears not to have changed significantly since 1930.

5.5 Recharge Variations

The concentration of nitrate leached from arable land depends on the amount of recharge; being lower where recharge is higher. This effect is factored into the use of the Entec historical trends and in ADAS' NIPPER model assumptions (see Sections 4.2 and 4.4).

Recharge also drives the movement of water through the unsaturated zone.

A 250 m × 250 m GIS grid of annual average (1971-2000) infiltration recharge estimates were taken from outputs of the South Wessex Recharge Model (Entec, 2005) and used with permission of the Environment Agency and Wessex Water.

Bypass recharge estimates (used in simulating spikes) were generated by running the South Wessex Recharge Model (Entec, 2005) for the gridded area of each of the WAgriCo groundwater catchments.

5.6 Delays through the Unsaturated Zone

An unsaturated zone travel time GIS grid (250 m × 250 m) for the South Wessex Recharge area was produced as part of Entec's (January 2008) work for Wessex Water. This grid was produced by multiplying unsaturated zone depths (ground level elevation minus groundwater level in mAOD) by a moisture content of 30% for the Chalk (as constrained by unsaturated zone profile data, BGS, 2005), and then dividing by the estimated annual average (1971-2000) infiltration recharge. This is consistent with the approach described in Section 3.4.2.

Six of the eight WAgriCo catchments fall within the gridded area (see Figure 7). Due to the absence of groundwater level contour data in the vicinity of Hooke and Langdon, this grid does not, however, extend to these catchments. Instead groundwater levels and their contours were estimated and unsaturated zone travel times were manually derived.

Appendix A of this report shows histograms of different unsaturated zone travel times within each of the eight WAgriCo defined groundwater catchments. Different land uses are differentiated in these histograms. The significant uncertainties in the Hooke and Langdon catchments are re-iterated. For most catchments, the typical water age is 10-40 years. This means, with reference to Section 5.4, that land use changes before the 1960s-1970's will not affect the nitrate trend predictions for these catchments.

5.7 Delays between the Water Table and the Abstraction

As discussed in Section 3.5.2, any delay between water and nitrate arriving at the water table and moving to the abstraction source in the saturated zone has not been modelled. This is because delays in the saturated zone are likely to be insignificant compared to those between the soil and the water table.

5.8 Seasonal Variations

In work for Wessex Water (Entec, January 2008), close correlation between seasonal variations in nitrate concentrations and groundwater levels were noted (see Figure 8). The factors controlling the seasonal variations in nitrate have not been constrained as part of this or previous work by Entec. Instead, seasonal variations in nitrate have been simulated by modifying the long term trend predictions with a visually fit multiple of groundwater level variation (at two Environment Agency observation boreholes – Woodyates and Ashton Farm – see Figure 1 for locations). In a number of cases the seasonal nitrate trend fit has been improved by inclusion of a delay of up to 60 days on the water level variation.

5.9 Short Term Spikes

Nitrate concentration spikes were simulated (Entec, January 2008) by empirically linking nitrate variations to estimates of bypass recharge; made by running the South Wessex Recharge Model (Entec, 2005) for the defined WAgriCo catchment areas. As for the seasonal variations, the process behind this empirical relationship is currently not clear, but has been postulated to be due to current leachable nitrate being taken rapidly down to the water during periods of heavy rainfall. Such a mechanism is consistent with occasional pesticide detections and turbidity in the raw abstracted water. A further discussion of the effects of bypass recharge is provided in Section 7.

5.10 Simulating Historical Trends in Nitrate at Groundwater Abstractions

By combining the unsaturated travel time estimates illustrated for the WAgriCo catchments in the histograms of Appendix A of this report with the historically leached nitrate trends for arable and managed grassland (modified for consistency with NIPPER) (Figures 2 and 3), long term trends have been simulated for comparison with the measured nitrate concentrations in Wessex Water's raw abstraction water. As noted, seasonality and "spikiness" have been simulated empirically as factors of measured groundwater level and bypass recharge. The nitrate concentration modelled on a given date is therefore given by the equation:

$$NO_3 = [\text{Piston flow } NO_3] + [\text{Multiple of Water Level}] + [\text{Multiple of Bypass Recharge}]$$

For each WAgriCo catchment, Table 5.1 provides a summary of model input and best fit parameters. Charts showing modelled versus measured nitrate concentrations at the Wessex Water abstraction supplies are provided in Appendix B of this note.

Visually good fits are apparent for Eagle Lodge, Empool, Friar Waddon, Milborne St Andrew and Winterborne Abbas. The fit for Hooke is also good, although this is only achieved by simulating a change (as supported by 1930's and 2000 land use maps) from semi-natural vegetation to managed grassland in the nominal year of 1977 (discussed in Entec, June 2008). The shape of the modelled long term trend for Dewlish is steeper than observed and so is not as good as the trends for the other catchments, although still not a poor match.

As expected, due to the poor groundwater level data coverage (and so poor constraint of unsaturated travel times), the Langdon model fit is very poor. Measured annual average nitrate concentrations (~12 mg/l N) at Langdon also exceed the maximum nitrate concentrations on the long term historical trends, suggesting that, in addition to the poorly constrained travel times, the model assumptions are not valid in this catchment.

As part of this project, Entec and ADAS liaised over other possible reasons for a poor fit for the Langdon catchment. ADAS briefly reviewed their data for the Langdon catchment and compared these with their Area 1 model assumptions. ADAS noted that:

- The Langdon catchment is far too small for their agricultural census data to inform exactly what is going on in it, but looking at a 3x3 km square around it, animal numbers per ha are comparable to those in Area 1.
- Theoretically all the animals in the 9 km^2 area could be located in one farm within the catchment, thus having much higher stocking densities in Langdon, than is typical for Area 1, but ADAS doubt this as land use within that 9 km^2 area is almost 60% grassland and 10% rough grazing, so the animals must be fairly well spread.
- According to ADAS's soils data, most of Langdon is on a more clayey soil, and although it is not as organic as the typical soils for Area 1, ADAS note that would not explain such high concentrations.
- It is such a small catchment that without some detailed observed field data ADAS would not try and model it.

gTable 5.1 Summary of Model Input and Best Fit Parameters

Public Water Supply				Land Use (% of model grid area)			Recharge (mm/yr) Direct to Chalk[2]			Seasonal Nitrate Variation Related to Water Levels						Spikiness Relationship to Bypass Flow	
										Woodyates			Ashton Farm				
Source Name	Map ref	Abs. Rate[1] (Ml/d)	Geology	Arable	Managed Grass	Woodland & Forestry	Arable	Managed Grass	Assumed Moisture Content	Ref Date[2]	k[3]	Lag[4] (days)	Ref Date[2]	k[3]	Lag[4] (days)	Multiple of Bypass Recharge	Lag on Bypass Recharge (days)
Dewlish	3	5.0	Upper Chalk	90.6	9.4	0.0	459	437	0.30	20/06/1975	0.06	45	04/07/1998	0.24	30	0.50	0
Eagle Lodge	5	7.0	Upper Chalk	84.5	15.5	0.0	440	436	0.30	20/06/1975	0.04	30	04/07/1998	0.16	30	0.60	-30
Empool	6	11.8	Predominantly Upper Chalk	50.0	50.0	0.0	414	401	0.30	20/06/1975	0.03	60	04/07/1998	0.12	45	0.60	0
Friar Waddon	7	7.0	Upper Chalk, Portland & Purbeck Beds	61.0	39.0	0.0	442	441	0.30	10/09/1975	0.10	10	01/09/2003	0.4	10	1.00	0
Hooke	2	2.0	Upper, Middle and Lower Chalk	56.3	43.8	0.0	532	508	0.30	20/11/1974	0.04	0	06/02/1998	0.14	0	0.50	0
Langdon	1	0.6	Middle & Lower Chalk & UGS?	77.8	22.2	0.0	525	541	0.30	20/06/1975	0.06	10	04/07/1998	0.24	30	0.60	0
Milborne St Andrew	4	5.0	Upper Chalk	81.0	19.0	0.0	444	443	0.30	20/06/1975	0.08	25	04/07/1998	0.32	25	0.70	0
Winterboune Abbas	8	2.8	Upper Chalk	28.9	71.1	0.0	500	488	0.30	10/09/1975	0.09	60	01/09/2003	0.36	60	0.30	0

Notes:
1 Typical abstraction rate as provided by Wessex Water
2 This is the date of the water levels on which the long term trend is based and so provides the starting water level from which variations are calculated.
3 This is the multiple of water level variation from that on the reference date to give the nitrate concentration.
4 This is the lag that nitrate concentrations change after a change in water level.

Potentially there could be an influence from ploughing in the past 20-30 years, or there may be a significant point source in the catchment. Another possible mechanism is runoff recharge washing off more fertiliser and manure based nitrate.

6 Predicting the Long Term Impacts of Different WAgriCo Measures

6.1 Introduction

This section describes the prediction of future nitrate concentrations in each of the eight WAgriCo Wessex Water groundwater supplies assuming either nitrate leaching remains at the 2007 baseline condition or that land is managed under a number of WAgriCo measures.

6.2 Assumed Soil Leaching

In addition to the baseline nitrate leaching discussed in Sections 4.3 and 4.4, ADAS provided NIPPER model run outputs (for Areas 1 to 3) for the following WAgriCo measures:

1. Cover Crop (Code EGAP1);
2. Adjust Fertiliser for Crops (Code GAP1);
3. Adjust Fertiliser for Manure (Code GAP1);
4. Manure Timing (Code EGAP3); and
5. Measures 1 to 4 combined (ADAS's view of the best case of WAgriCo measures).

A description of the individual measures and the assumptions made for their NIPPER models are provided in the main ADAS report for this project (ADAS, 2008) and summarised in Table 2.1 of Section 2 of this report.

As Area 1 is likely to be the most representative for the WAgriCo catchments, only results from Area 1 are discussed further. Table 6.1 provides the NIPPER model outputs for these measures.

6.3 Modelling the Effect on Long Term Trends

The NIPPER model outputs of Table 6.1 relate to how nitrate leaching from the soil could be reduced soon after implementation of the measures, but given the long travel times (see Appendix A) for 80-90% of the water leaving the soil and arriving at the water table (and then the groundwater supply), there will be a delay before the benefits of these measures are fully realised at Wessex Water's groundwater abstractions.

To illustrate the maximum impact of the measures on each of the sources, NIPPER model predictions for nitrate leaching from the combined WAgriCo scenarios 1-4 were selected. Compared to the baseline, this equates to a ~ 15% reduction on arable (in the Dorchester, 440 mm/yr infiltration recharge area) and a 5% reduction on managed grassland anywhere in the South Wessex area.

Table 6.1 NIPPER Predicted Leached Nitrate Concentrations for ADAS Selected WAgriCo Measures

Scenario	Code	NIPPER Predicted Leached Nitrate Concentration (mg/l N)			
		Arable		Managed Grassland	
		mg/l N	As % of baseline	mg/l N	As % of baseline
0. Baseline		7.79		7.06	
1. Cover Crop	EGAP1	6.78	87.0%	6.94	98.3%
2. Adjust Fertiliser for Crops	GAP1	7.77	99.7%	6.99	99.0%
3. Adjust Fertiliser for Manure	GAP1	7.71	99.0%	7.06	100%
4.Manure Timing	EGAP3	7.75	99.5%	6.83	96.7%
5. Best Case (1-4 Combined)		6.65	85.4%	6.71	95.0%

These percentage reduction factors were applied to the assumed concentration (in the Entec approach Excel workbooks) of leached nitrate from arable (when 440 mm/yr recharge) and grassland trends from 2008 onwards. Arable areas still having their leached nitrate concentrations modified where infiltration recharge annual (1971-2000) averages differ from 440 mm/yr, but the managed grassland nitrate concentrations do not change with recharge.

6.4 Modelling the Effect on Seasonal Trends

The controlling mechanism on seasonal variations in nitrate is unclear (see Sections 3.6 and 5.8). Reduction in nitrate leaching from the soil could reduce the amplitude of the seasonal variations with time (years if related to bypass flow or decades if related to younger water at depth in the Chalk matrix). However, without the controlling mechanism being resolved, it was inappropriate to simulate a change in seasonal variations from the empirical relationship used to match historical nitrate concentration data at the Wessex Water abstraction.

To illustrate the effect of seasonal variations in nitrate on top of the long term trend modelled with the baseline and best case WAgriCo measures, daily groundwater level data from the Ashton Farm borehole for the period June 1992 to May 2006 were replicated twice to cover the period up to 2038. There is no difference between the modelled amplitude of variation between these two scenarios.

6.5 Modelling the Effect on 'Spikiness'

Future nitrate concentration spikes for the baseline case have been simulated by repeating twice the bypass recharge estimates for June 1992 to May 2006 (the same period for the groundwater levels on which future seasonal trends are based), and modified with the same empirical factor used to match historical measured nitrate data, to cover the period up to 2038.

For the WAgriCo best case measures, 'spikiness' has been reduced by the percentage reduction in total leaching as shown in Table 6.1 (i.e. 15% reduction for arable and 5% reduction for managed grassland). The reduction in spikiness has been applied pro rata to the proportions of arable and grassland in the modelled catchments e.g. for a catchment with 50% arable land the spikiness was reduced by 7.5%.

Charts illustrating future predictions of nitrate concentration in the Wessex Water abstracted groundwater under the baseline and best case WAgriCo measures are provided in Appendix C of this report.

6.6 Likely Effectiveness of Measures in Reducing Nitrate for Wessex Water

The model predictions suggest that the catchments in which the WAgriCo measures may make the greatest difference to Wessex Water's need or not for nitrate treatment or blending are Dewlish, Eagle Lodge, Friar Waddon, Milborne St Andrew and Winterborne Abbas (see Appendix C).

The measures would also provide additional safety for Empool, but on the basis of the model predictions do not appear necessary for the Hooke catchment; although not forgetting that travel times are poorly constrained in this catchment.

The poor model fit at Langdon, means that there is no confidence in the time taken for any measures to take effect, but the high concentrations measured in groundwater to date suggest that implementation of measures to reduce nitrate would be sensible, until an improved model fit and understanding of historically leached nitrate is achieved.

7 The Influence of Rapid Recharge on Nitrate Concentrations

7.1 Introduction

This section describes the measured short term variations in nitrate concentrations at selected Wessex Water sources, and suggests possible controlling mechanisms. The availability of information and model outputs to support these hypothetical mechanisms is discussed, and a summary is provided which focuses on the implications for the long term trend predictions discussed in Section 6. The need for further work on the influence of bypass recharge and rapid fracture flow through the unsaturated zone on pumped water quality is highlighted.

7.2 The Problem of Short Term Nitrate Variations for Water Companies

For Wessex Water, or any other Water Company, nitrate concentrations must be below the drinking water standard for close to 100% of the time. Whereas the occasional (once per year) spike above the drinking water standard may be tolerated by the Drinking Water Inspectorate

(DWI), two or three spikes per year would likely require blending or treatment to be put in place.

This means that, although land management measures may achieve an average nitrate concentration much less than the drinking water standard (see Table 6.1), significant variation from this average in soil leaching would lead to significant blending or treatment related costs if that variability is transmitted to the pumped groundwater quality.

7.3 Short Term Variations in Nitrate Concentration Measured in Pumped Water

Measurements of nitrate concentrations in pumped groundwater (and spring discharges) from Wessex Water sources show evidence of fluctuations on a number of timescales, from the long term (usually rising) trend (modelled in Section 5), through seasonal variations, to short term transient variations (or "spikes"). Spikes being defined here as one or two successive measurements which have a concentration of >~1 mg/l greater than the average concentration for the two data points before and two after. Figures 9 to 11 show records of nitrate concentrations at the Friar Waddon, Eagle Lodge and Empool sources for the period 1995 to 2007 to illustrate these points.

The spikes seen in measurements of nitrate concentration may be positive (transient increases in concentration of up to 3 mg/l N) or negative (transient decreases in concentration of up to 6 mg/l N). Visual inspection of Figures 9 to 11 shows that for the average concentration measured (all boreholes) there is a range in responses from:

- Fewer spikes on a more pronounced seasonal response at Friar Waddon (Figure 9).
- More numerous spikes on a much less pronounced seasonal response at Empool (Figure 11).
- Something in between these two cases for Eagle Lodge (Figure 10).

Nitrate spikes are therefore more frequent and/or larger at some abstraction supplies than at others.

7.4 The Influence of Sampling Different Boreholes

At many public water abstractions there is more than one borehole (often for security of supply) and nitrate concentration data are collected for both the raw and treated water as well as for the combined water. Figures 9 to 11 also show concentrations of nitrate in individual boreholes (regardless of whether the water was raw or treated i.e. chlorinated rather than treated to remove nitrate). Excluding anomalously low values, the two boreholes at Friar Waddon have very similar (<0.5 mg/l N difference) concentrations and variations, the two at Eagle Lodge boreholes have differences of up to 1.8 mg/l N and the four Empool boreholes have differences of up to 1.5 mg/l.

Where there are differences in nitrate concentration between boreholes at an abstraction supply a spike in the data could be purely related to the average concentration being dominated by one then another borehole's nitrate concentration. This effect means that more detailed assessment of the data sets are required before controlling natural mechanisms can be explored on such sources. Conversely, the variation at Friar Waddon (Figure 9) is suitable for exploring natural mechanisms.

7.5 Improved Model Prediction of Short Term Variations

Differences in concentration between the two boreholes at the Friar Waddon source are sufficiently low to allow data for any borehole or their combination to be used together as a more continuous dataset for evaluation of short term variability or 'spikiness'. Figure 12 shows the combined measured nitrate concentration dataset for Friar Waddon, plus:

- (1) the Entec model prediction for long term trend and function of groundwater level.
- (2) recharge model (Entec, 2005) estimates for total recharge arriving at the water table (infiltration recharge and bypass recharge).
- (3) a new model prediction of nitrate concentration which (disregards any double counting and) adds a multiple of the total recharge (1) to the combined long term trend and function of water level (2).
- (4) recharge model (Entec, 2005) estimates for bypass recharge – an estimate which assumes 10% of all rainfall exceeding a rate of 1 mm/day.

The modelled nitrate (3), which combines the long term trend, the seasonal response based on water level and on top of that adds a multiple of the total (infiltration plus bypass) recharge produces a very good fit to the measured nitrate concentrations. A number of spikes [S] in nitrate are however not simulated, although there are rainfall (and bypass recharge) events prior to these.

On a separate project, Entec commenced work in late September 2008 with Wessex Water to try and improve the recharge models so that increases in flows in streams and rivers measured during the summer month are better simulated. This is likely to require an increase in the amount of predicted bypass recharge and the routing of some recharge rapidly to the water table by fracture flow through the unsaturated zone. The recharge model estimates are therefore by no means perfect and this compromises the ability to check if nitrate spikes are related to bypass recharge. Bypass recharge or rapid fracture flow through the unsaturated zone therefore remains a plausible but unproven cause of nitrate spikes.

The improved model fit of Figure 12 still has empirical elements such as adding a multiple of groundwater level and of total recharge to the mechanistically estimated long term trend. Possible mechanisms for this improved fit are discussed in Section 7.7.

7.6 Variability in Leached Nitrate During a Year

Figure 13 shows the predicted nitrate concentration in soil drainage from the ADAS NIPPER model for arable land in Area 1 (see Figure 1), which includes the Eagle Lodge, Empool and Friar Waddon catchments, for hydrological years 2002-3 and 2003-4. A similar variation is evident in NIPPER model predictions for managed grassland.

NIPPER does not model bypass recharge and so predicts no soil drainage during the summer months while a soil moisture deficit is established. There are therefore no predictions of nitrate concentrations during these periods. Assumptions used in the NIPPER models have been discussed in Section 4.3.

Predicted nitrate concentrations in soil drainage are highly variable for both arable and managed grassland land use. Although time-averaged concentrations for arable are well within the drinking water standard, rarely exceeding 7 mg/l NO_3-N, predicted concentrations on individual days can exceed 20 mg/l NO_3-N. Should bypass recharge carry such variable nitrate concentrations through the soil and then rapidly via fractures through the unsaturated zone, it is likely that this will then result in transient increases in nitrate concentration in pumped water.

7.7 Possible Mechanisms for Short Term Variability

A discussion of mechanisms controlling water and nitrate movement in the unsaturated zone has been provided in Section 3. This section provides an overview of the mechanisms which could affect short term variations (including spikes) in nitrate concentrations:

- Infiltration recharge caused by lower intensity rainfall onto soils in which there is no moisture deficit will reach the top of the Chalk unsaturated zone.

- Infiltration recharge at a rate in excess of the saturated vertical hydraulic conductivity of the chalk matrix (~1 to 5 mm/day) could move rapidly via fissures to the water table. Infiltration at a rate less than this will drive piston flow through the unsaturated zone – moving historically leached nitrate downwards.

- In summer and early autumn, the upper 5 m of unsaturated chalk may have higher suction pressures than at greater depth (Price, 1987) due to the moisture deficit developed in the overlying soil. The deeper chalk matrix is likely to be effectively saturated. The presence in the top 5 m of higher suction pressures during summer and early autumn could lead to some bypass recharge being drawn into the matrix in this zone thus not reaching the water table.

- In winter and spring, the whole of the chalk matrix is likely to be saturated and intense rainfall is likely to lead to fracture flow movement of recharge to the water table.

- Both infiltration recharge moving to the water table via piston flow and bypass recharge moving rapidly via fissures will lead to a rise in water level.

- An increase in water level will lead to water of a younger age in the chalk matrix being released to the saturated fissure system of the Chalk aquifer and subsequently transported to the public water supply abstraction. At least some of the seasonal variation in nitrate concentration at the public water supply could be related to this process.

- Infiltration and bypass recharge events in excess of ~ 1mm/day will transmit water via fractures to the water table more quickly in winter when the water table is at a higher elevation. Recharge events in excess of 1 mm/day are also more likely in winter.

- Nitrate leached from the soil either in infiltration recharge or bypass recharge therefore has the potential to be transmitted rapidly to the water table. The concentration of nitrate leachable from the soil varies through the year and so this variability could also be transmitted to the water table.

- Short term variations in the concentration of nitrate in groundwater (and at the public water supply) are therefore likely to depend on (1) the volume and concentration of old piston flow water driven to the water table by infiltration recharge, (2) the volume and concentration of (infiltration and bypass) recharge arriving via fractures, (3) the depth to the water table and (4) seasonal variability in soil leachable nitrate.

7.8 Ability of Existing Models to Simulate Short Term Variability

Entec's (2005) recharge model includes bypass flow as 10% of any rainfall in excess of 1 mm/day and infiltration recharge when there is no soil moisture deficit. In the recharge model this recharge is combined at the base of the soil zone into a recharge store and is then released as recharge to the water table at a more gradual rate and after a delay which depends on the depth to the groundwater level as mapped during autumn. The recharge model does not currently allow rapid movement of recharge through the unsaturated zone via fractures.

The empirical model simulation of nitrate concentrations at Friar Waddon (Figure 12) includes a long term trend prediction, a function of water level and then a separate function of total recharge to achieve a very good fit to measured nitrate concentration data. Conceptually, however, a water level rise is linked directly to recharge and so there may be an element of double counting. To help resolve this, there would be a need to separately track recharge as (1) piston flow through the matrix and (2) as fracture flow. Revisions to Entec's 4R recharge model were not possible within the scope and budget of this project. However, to provide some feel for the possible amounts of fracture flow, in the Friar Waddon catchment, about 18% of recharge (infiltration plus bypass) exceeds an equivalent matrix saturated hydraulic conductivity of 5 mm/day and 49% exceeds 2 mm/day. These proportions of possible fracture flow are sufficiently large to have a measurable effect on nitrate concentrations.

7.9 Uncertainty

From the previous sections, there are significant uncertainties in both measurements and model predictions of short term variations in nitrate concentrations in pumped water. This section describes some of those uncertainties, and suggests further work which could reduce or eliminate them. To better constrain the presence and simulation of short term spikes in nitrate concentration, the following steps are recommended:

- There are a number of details of the operational regime at the sources which are not currently known, and which could influence pumped water quality. Several of the sites include more than one borehole, which may operate with differing pumping rates or at different depths. Details such as these should be considered to ensure that any apparent transient fluctuations in nitrate concentrations cannot be explained by operational differences.

- Further data analysis should also consider the varying frequency of the data records for individual boreholes; time series of data from different boreholes at a source may be fortnightly or less frequent, whilst the analysis carried out to date has considered data averaged across all boreholes at a source, to provide, in many cases, weekly data. This may mask significant variations between boreholes.

- It is understood that water temperature data are collected daily in a number of boreholes by data logging of water levels and temperature. Groundwater in Wessex should reflect the average air temperature at least below a few metres depth. With increasing depth there will be a temperature gradient typically 3°C/100 m in the UK. Rapid fracture flow of recent recharge has the potential to carry cooler or warmer water to the water table and cause a temperature effect. Temperature data will therefore provide a much more continuous data set to check for bypass recharge / fracture flow events. The less frequent nitrate concentration data can then be compared against this.

- As well as uncertainty in the measured nitrate concentration data, there is uncertainty in the NIPPER and 4R model estimates. For NIPPER, a significant step would be to provide estimates of leachable nitrate throughout the year and not just when the soil moisture deficit has been satisfied. The sensitivity of the model to some underlying assumptions (such as, for example, the timing of applications of manure and fertiliser) should also be investigated.

- The 4R recharge model could also be modified to take into account the potential for rapid transmission of recharge via fractures when the recharge rate exceeds the saturated hydraulic conductivity of the chalk matrix. It would also be useful to track the proportion of recharge which bypasses the soil moisture deficit in the fracture flow movement through the unsaturated zone.

- With results from the above points combined, the ultimate aim would be to demonstrate, if present, the link between fertiliser or manure application, leachable nitrate in the soil and seasonal and short term fluctuations in nitrate concentration at the water table.

At the end of September 2008, Wessex Water commissioned Entec to undertake further investigation of bypass recharge, in particular the effect on river flows during summer. Some examination of the above recommendations will take place within this work.

7.10 Summary and Re-iteration of Importance of Shorter Term Variability / Spikiness

Fluctuations in observed nitrate concentrations in pumped water occur on several timescales. It is suggested that long term trends are related to historical fertiliser inputs to agricultural land, seasonal variations at least in part to fluctuations in groundwater level, and transient variations (spikes) to incidences of bypass recharge and or fracture flow.

The mechanisms controlling the shorter term variability requires further investigation and an approach has been suggested. The ultimate goal is to understand to what extent both seasonal and spike variations in nitrate are related to concurrent land management i.e. this year’s or month’s land management activities. If this is better understood the more immediate effect of the WAgriCo measures could be identified, measured and communicated to farmers.

8 Conclusions and Recommendations

8.1 Catchments

Groundwater catchments to the WAgriCo Wessex Water abstractions have been defined. These are smaller than the 'WAgriCo catchment' area over which ADAS and Wessex Water have been liaising with farmers regarding catchment management measures.

It is recommended that groundwater catchments are evaluated wherever focussed catchment management measures, specifically aimed at groundwater abstractions, are to be implemented.

8.2 Entec's Models for Long Term Trends and Uncertainties

A GIS/ Excel based approach, developed for Wessex Water (Entec, January 2008), has been used to simulate historical nitrate concentrations for each of the defined groundwater catchments. The approach takes into account likely travel times through the unsaturated zone of the Chalk and best estimates of historically leached nitrate, and adds seasonality and 'spikiness' empirical factors.

Comparison with ADAS' NIPPER model outputs for leached nitrate over the years 2000-2006 has broadly validated Entec's assumptions for arable land for this period, but has also allowed refinements to be made to the approach for managed grassland. In particular, for grassland, livestock numbers and types and manure management appear to be far more important spatial variables than recharge.

Good agreement has been achieved between simulated and historically measured nitrate concentrations in Wessex Water's groundwater abstraction data supplied for six of the eight WAgriCo catchments; the two exceptions being Dewlish, where the fit is reasonable, and Langdon where poor constraint of groundwater levels significantly affects it's catchment delineation and calculated unsaturated zone depths and there is a very poor model fit.

The approach and model predictions have a number of uncertainties, but the general good agreement between simulated and historically measured nitrate concentrations provides improved confidence on how historically leached nitrate is manifesting itself in the current water quality measured at Wessex Water's groundwater supplies.

Further application of the model / approach to simulating long term nitrate trends would provide a check on its robustness. This could be done within the South Wessex Recharge area, but a greater test would be its application in other parts of the unconfined Chalk of Southern England and Yorkshire, the drift covered Chalk of East Anglia and ultimately moving to other aquifers. With a robust validation in place, the approach could or should be applied to all catchments in which focussed catchment management is planned, as this will inform the timescale for the impact of any measures to be realised.

8.3 Ages of Water in the WAgriCo Catchments

Histograms showing the estimated ages of the bulk (80-90%) of the water in the WAgriCo groundwater catchments are provided in Appendix A. These show that groundwater is typically less than 60 years old, predominantly less than 30 years old for Eagle Lodge, Empool, Hooke, and Milborne St Andrew. Friar Waddon has waters in the 30-60 year age range and the other sources have a broader mixture. The implication of this is that changes in land management need to be considered over decades before benefits will be fully realised.

8.4 WAgriCo Measures and NIPPER Outputs

ADAS have provided NIPPER model estimates for leached nitrate from arable and grassland under a number of measures. The best case, with four WAgriCo measures combined, represents reductions in leached nitrate from arable of ~15% and from managed grassland of 5%, when compared to the current baseline.

8.5 Impact of the Measures on Long Term Trends in Wessex Water's Supplies

The review of Entec's model predictions suggests that the best case use of WAgriCo measures:

- Will help, but water quality for Wessex Water will still exceed drinking water standards at the Friar Waddon, Milborne St Andrew and Winterbourne Abbas sources.
- Will help maintain and improve water quality with nitrate concentrations below the drinking water standard at the Dewlish, Eagle Lodge, Empool, and Hooke sources.
- Will have an uncertain (due to poor model fit), but likely beneficial effect at the Langdon source.

8.6 Impact of the Measures in the Shorter Term

It has not been possible to fully resolve the cause of seasonal or short term spikes in nitrate concentration, although an improved empirical model fit has been achieved for the Friar Waddon source. Recommendations have been made to investigate the cause of the spikes and seasonal variations further, but bypass recharge and / or fracture flow movement during high recharge events should be investigated as likely causes.

The mechanism controlling the spikes requires further investigation and an approach has been suggested. The ultimate goal is to understand to what extent both seasonal and spike variations in nitrate are related to concurrent (i.e. this year's / month's) land management. If this is better understood the more immediate effect of the WAgriCo measures could be identified, measured and communicated to farmers.

If this is the case, then a link could be established between this year's / month's farming practices and spikes in nitrate concentration at Wessex Water's supplies; spikes being the main driver behind the need for treatment or blending. With that link established, the more immediate effect of the WAgriCo measures could be identified, measured and communicated to farmers.

8.7 Comparison with other Models and Sensitivity Analysis

Finally, in order to validate the work carried out here it is recommended that a review of the strengths and weaknesses of other models used in the prediction of long-term trends in nitrate concentrations in groundwater is carried out. An analysis of the sensitivity of the results to uncertainties in the data and to uncertainties in the conceptual models would also improve the confidence in this work.

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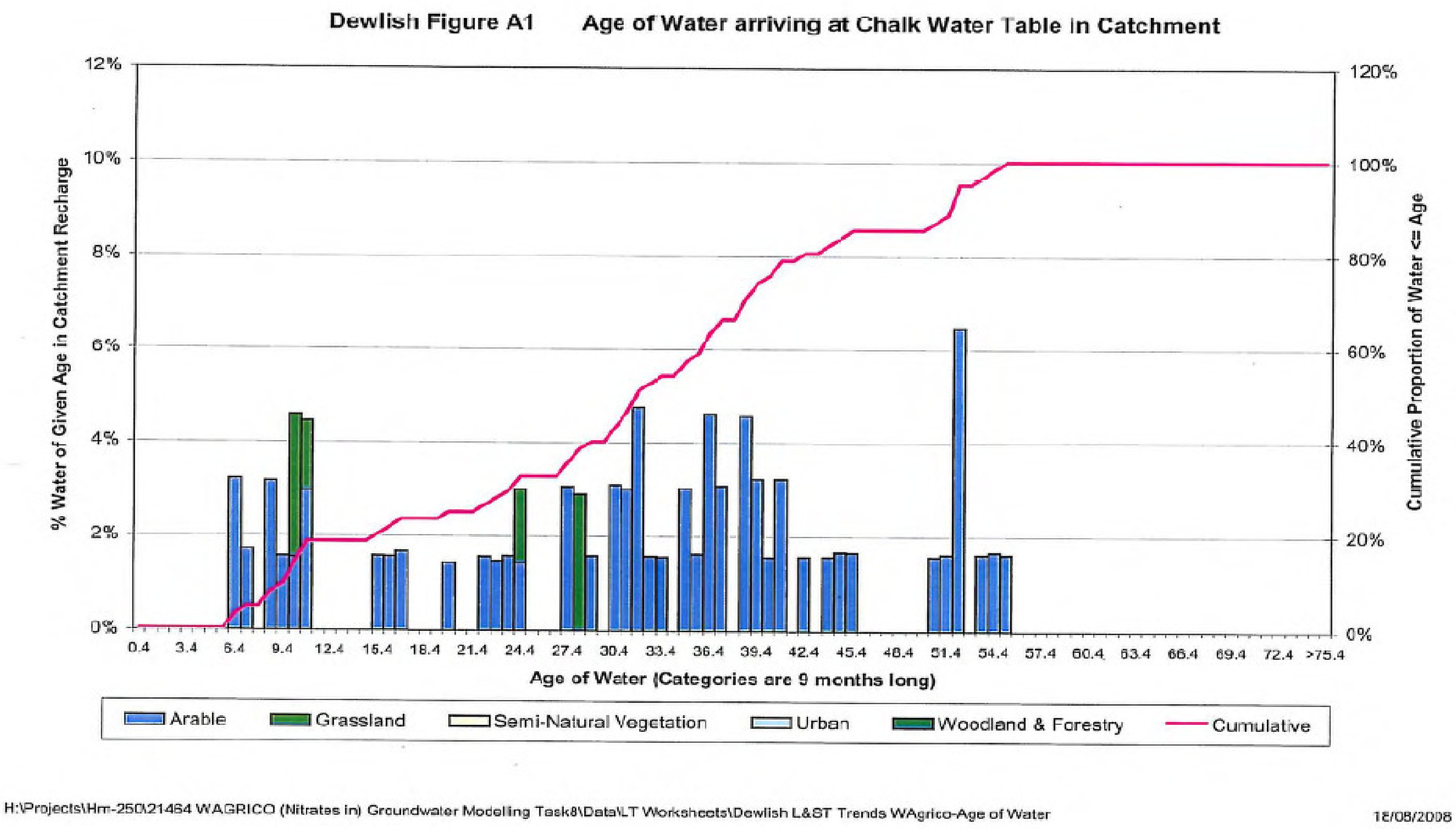
Appendix A

Histograms of water ages arriving at WAgriCo catchments.


Dewlish Figure A1 Age of Water arriving at Chalk Water Table in Catchment
% Water of Given Age in Catchment Recharge
Cumulative Proportion of Water <= Age
Age of Water (Categories are 9 months long)
Arable
Grassland
Semi-Natural Vegetation
Urban
Woodland & Forestry
Cumulative
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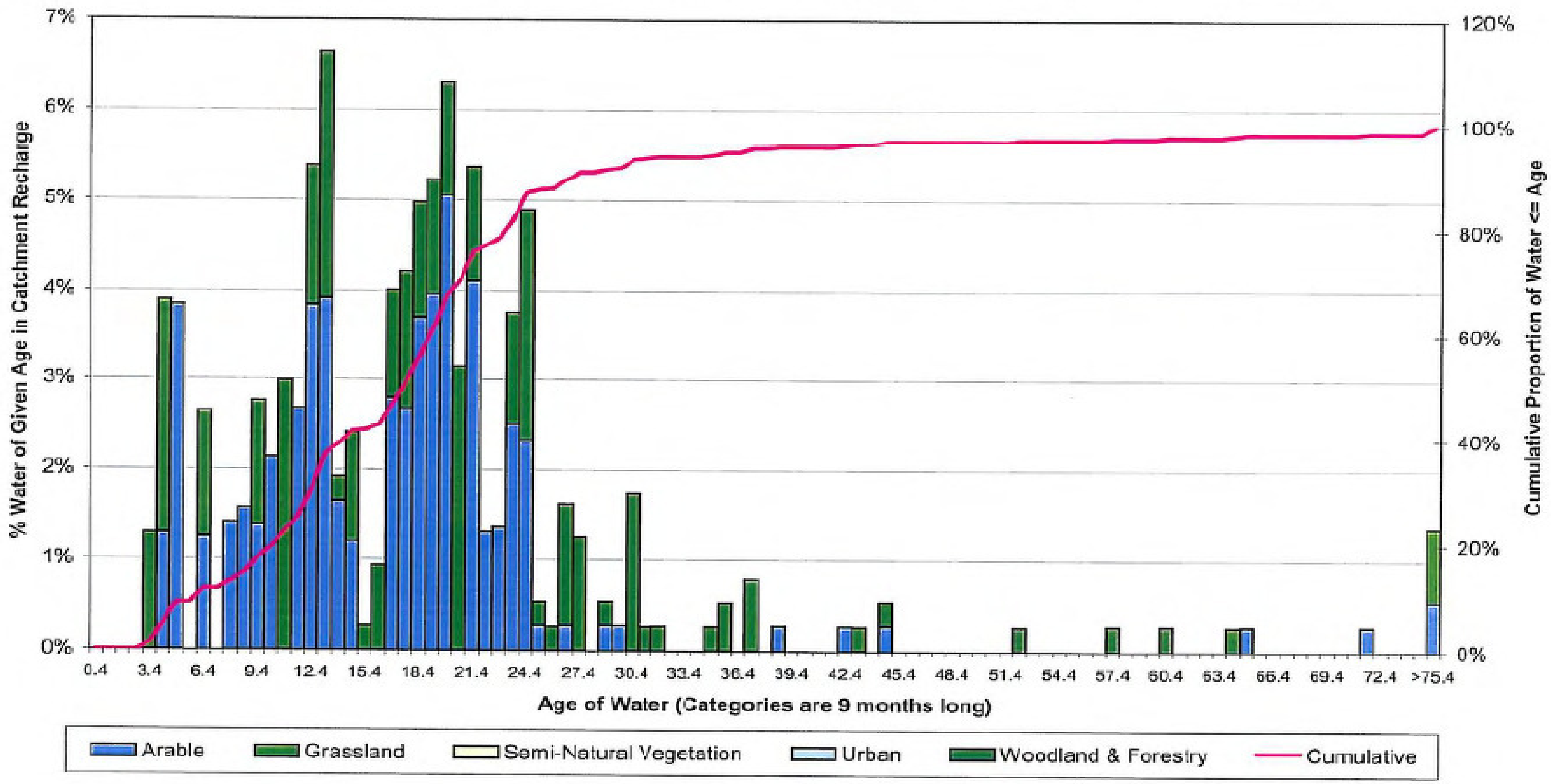
18/08/2008

Empool Figure A1 Age of Water arriving at Chalk Water Table in Catchment



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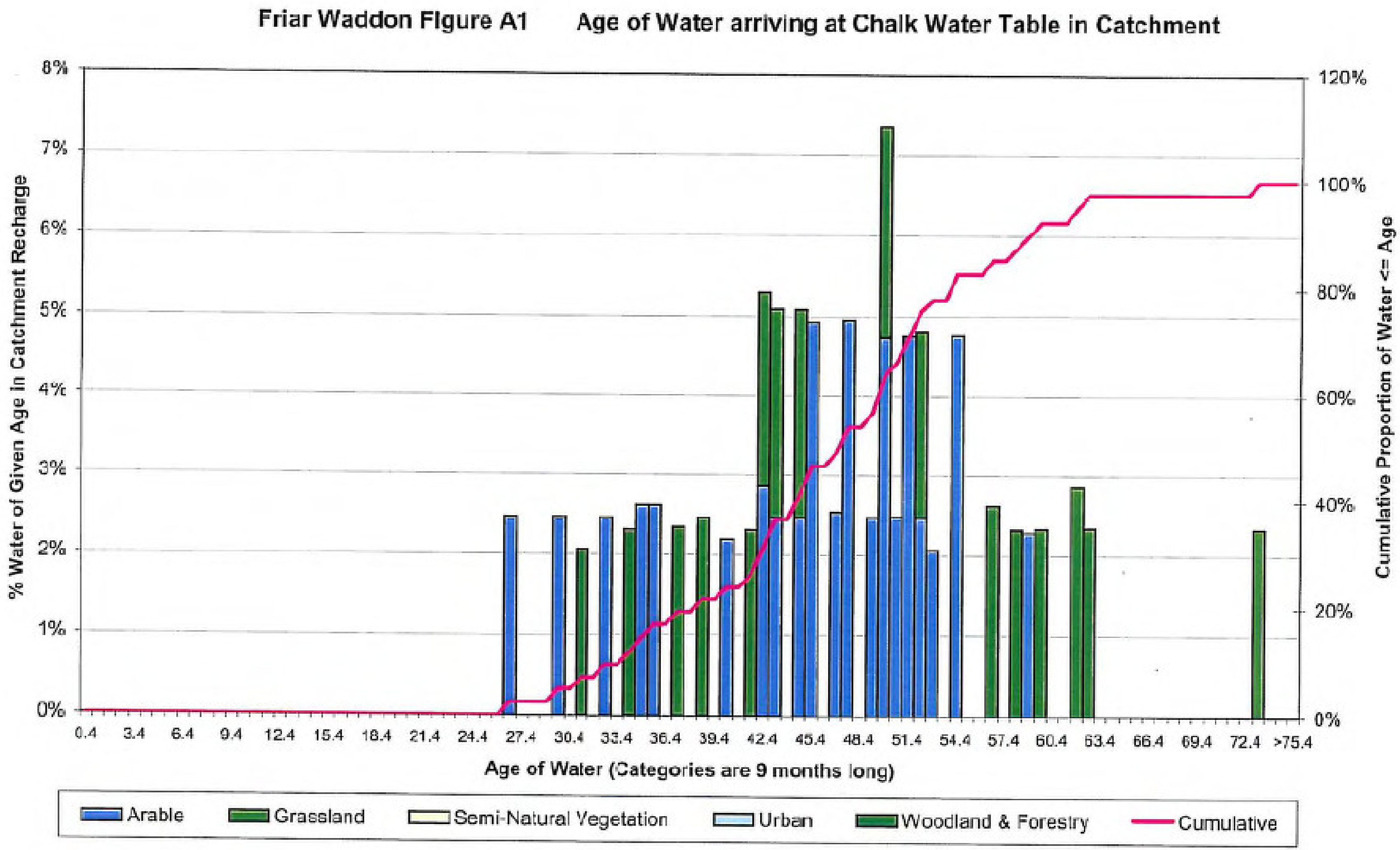

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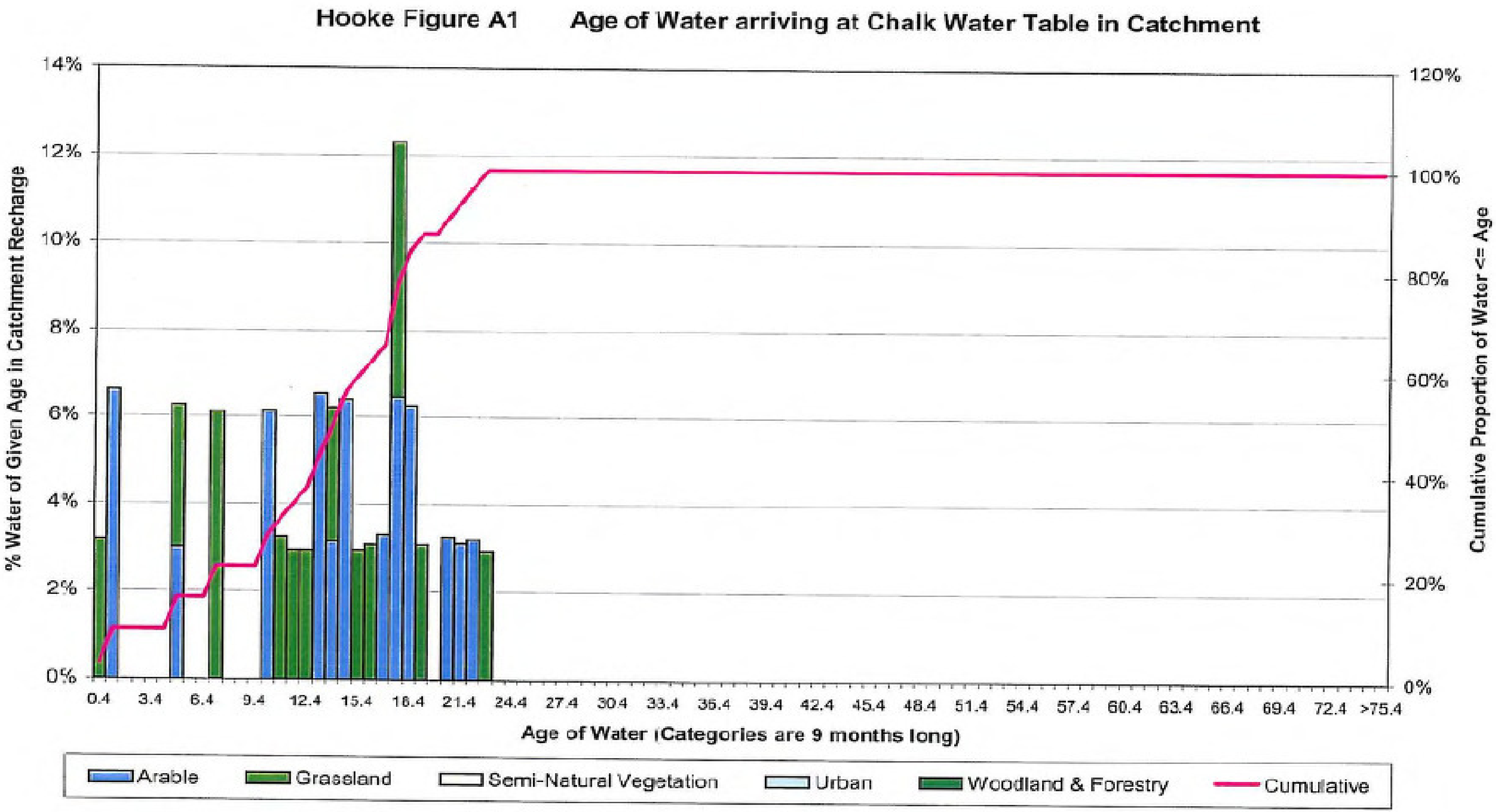

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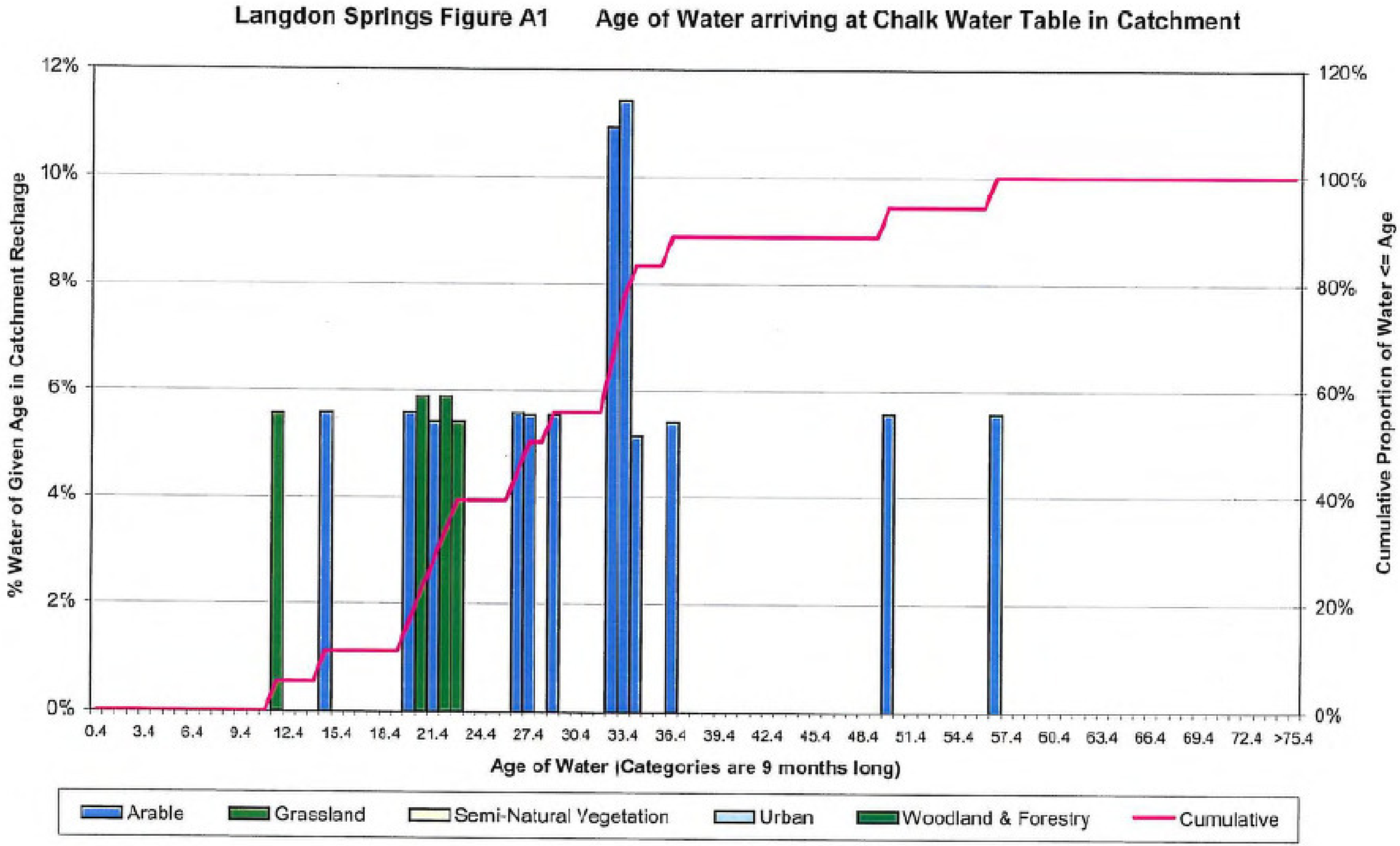

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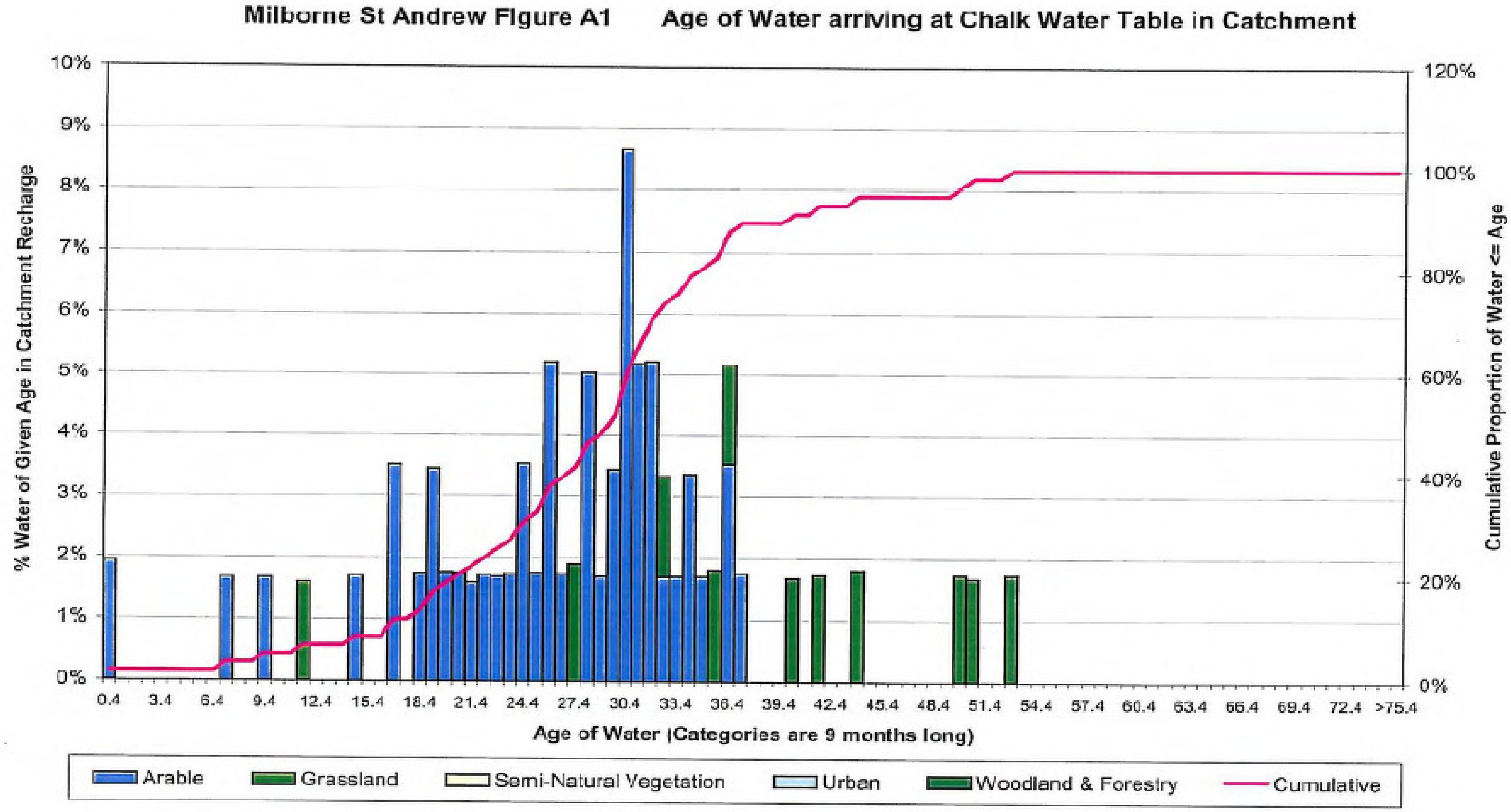

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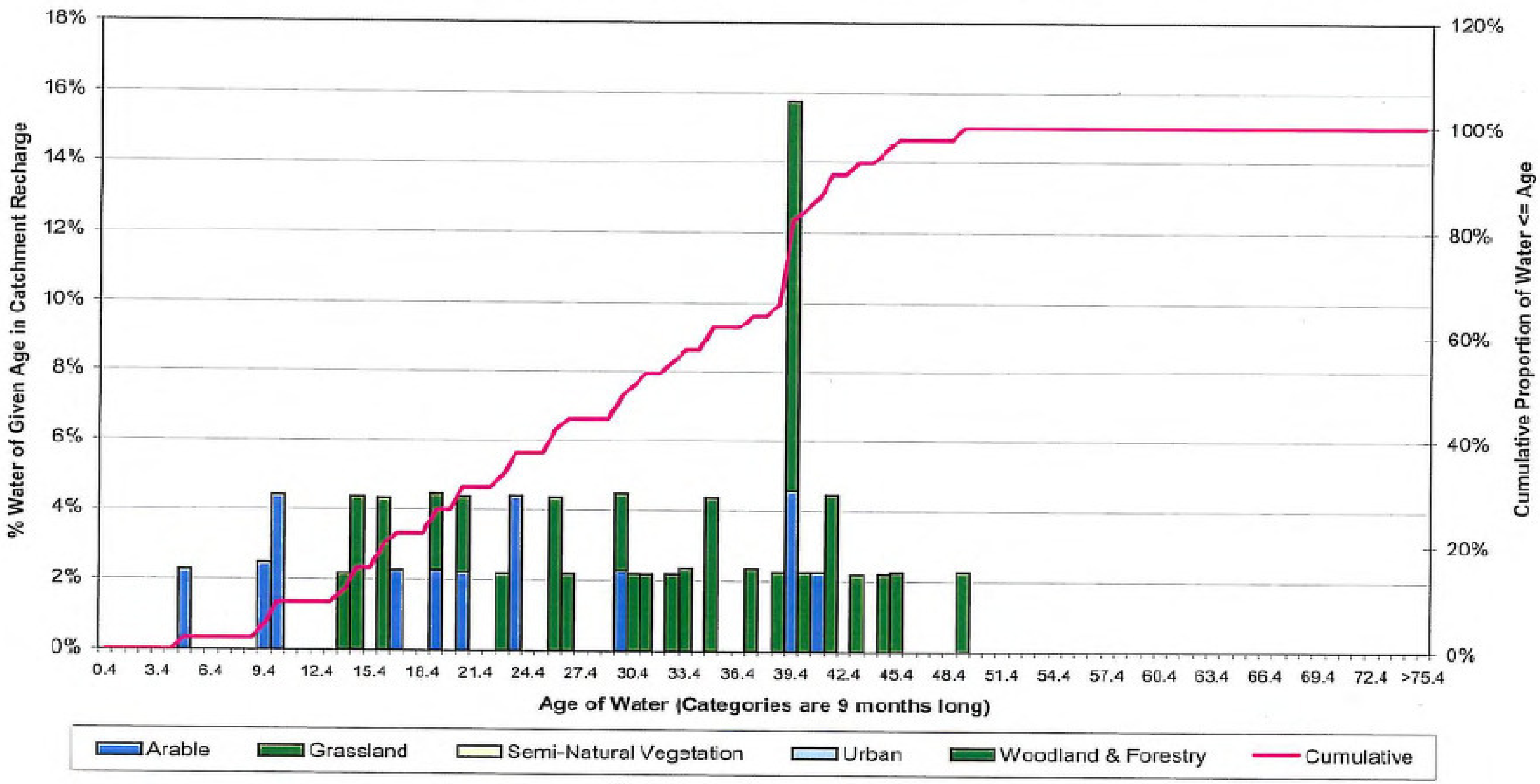
Winterborne Abbas Figure A1 Age of Water arriving at Chalk Water Table in Catchment



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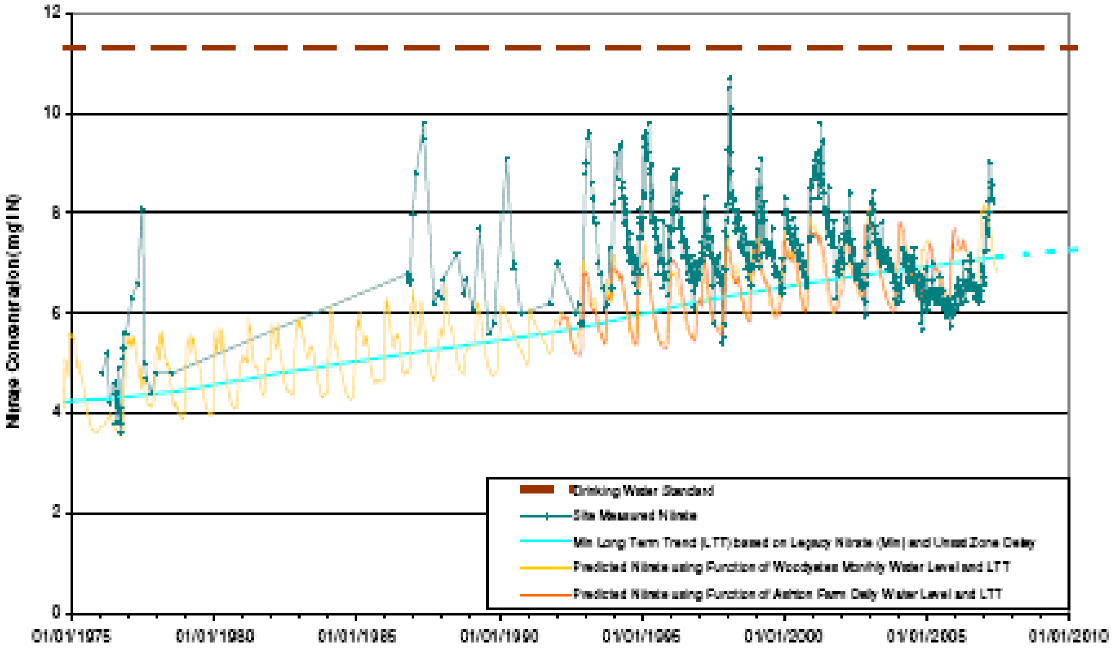
Appendix B

Figures showing modelled versus measured nitrate concentrations at the Wessex Water abstraction supplies.

Dewlish Figure B1   Comparison of Modelled Trend (Long Term + Seasonal) with Measured Nitrate



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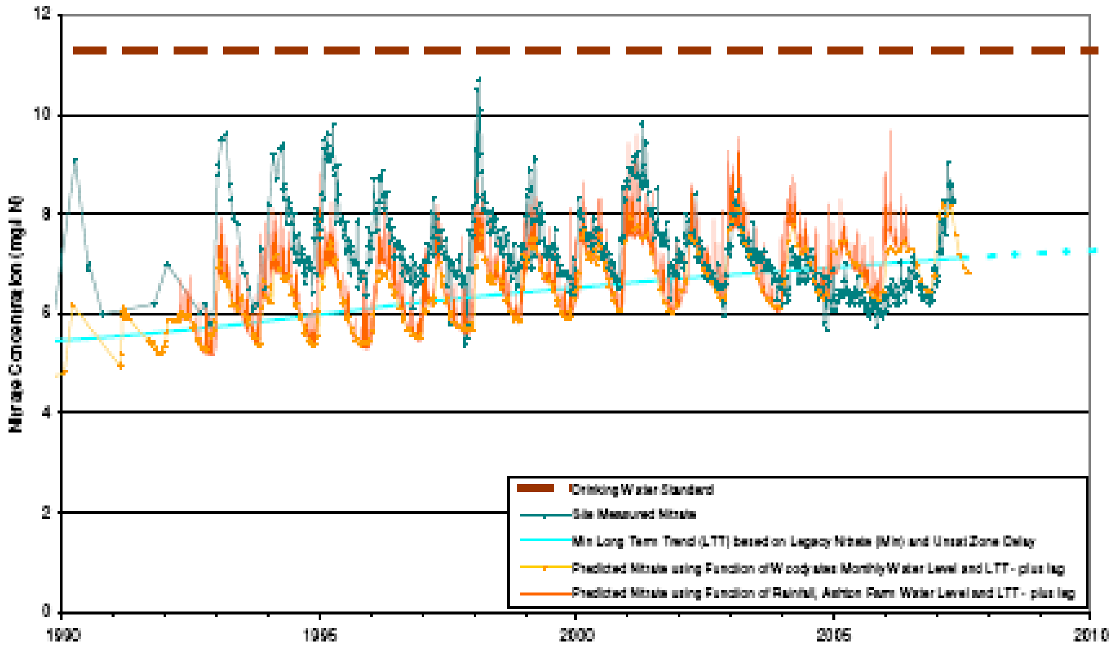
Dewlish Figure B2   Zoom-In of Model with Bypass Flow, Lagged (by 30 days) Seasonal Variation and Long Term Prediction



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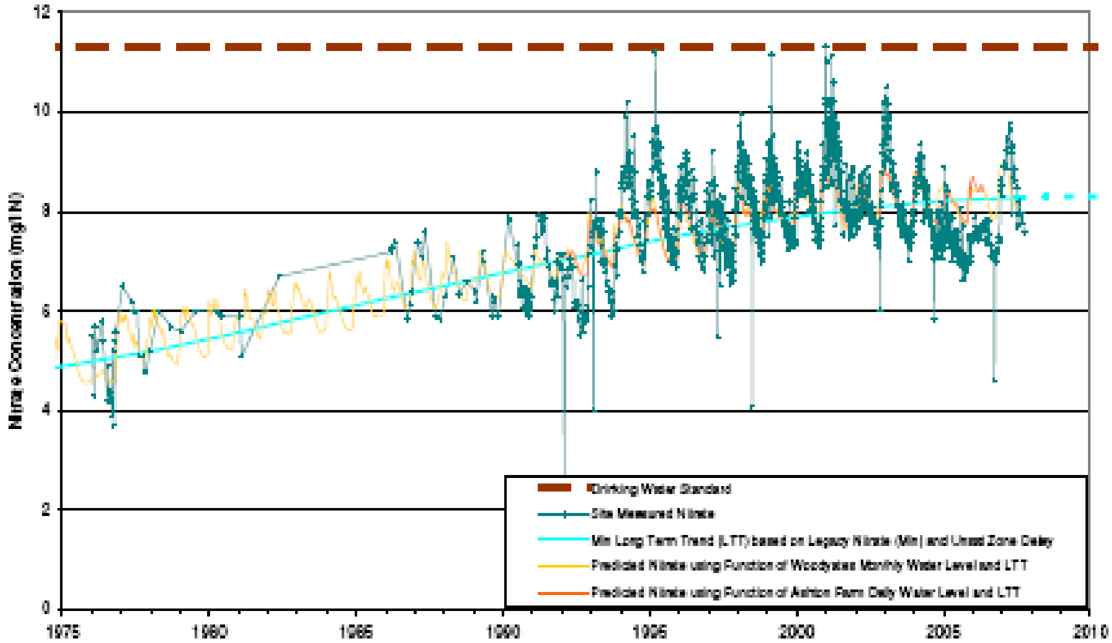
Eagle Lodge Figure B1 Comparison of Modelled Trend (Long Term + Seasonal) with Measured Nitrate



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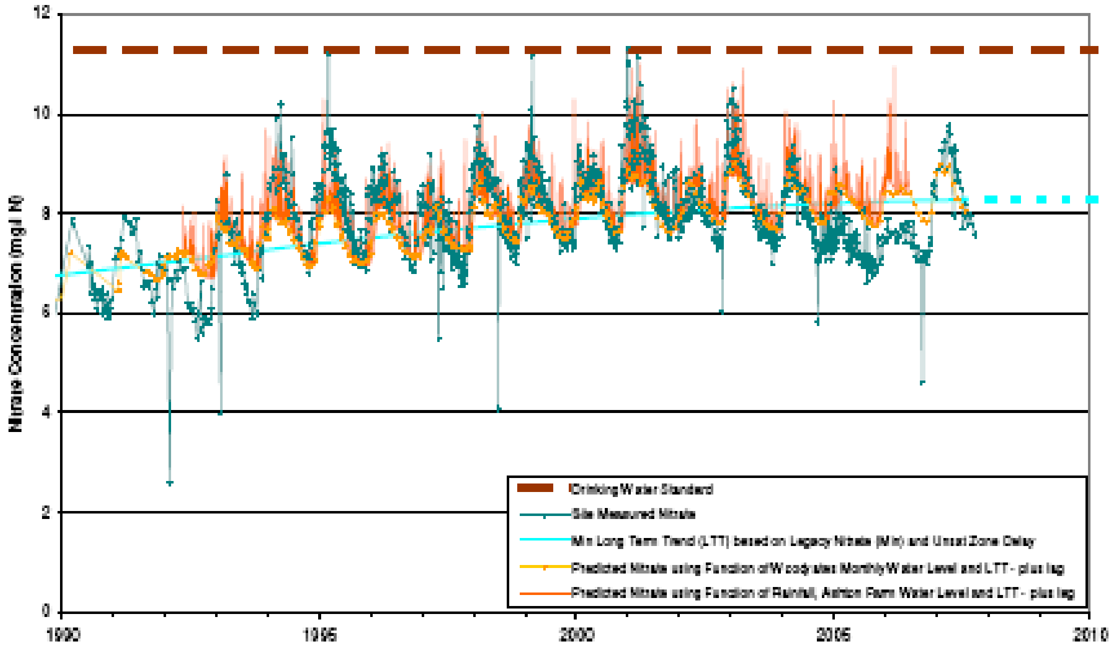
Eagle Lodge Figure B2 Zoom-in of Model with Bypass Flow, Lagged (by 30 days) Seasonal Variation and Long Term Prediction



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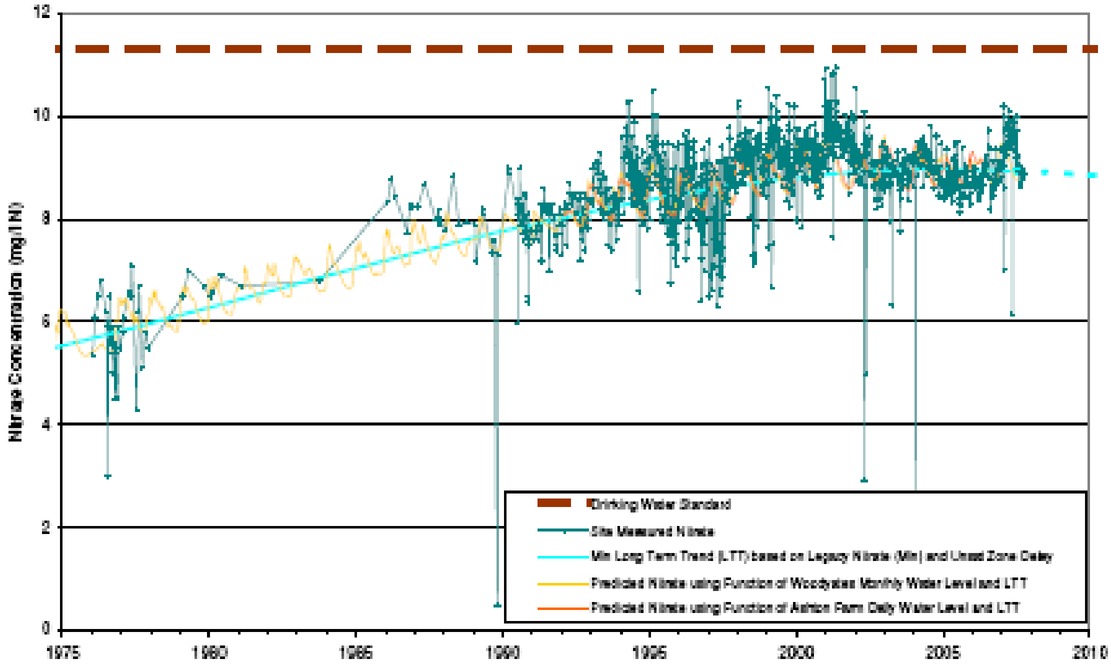
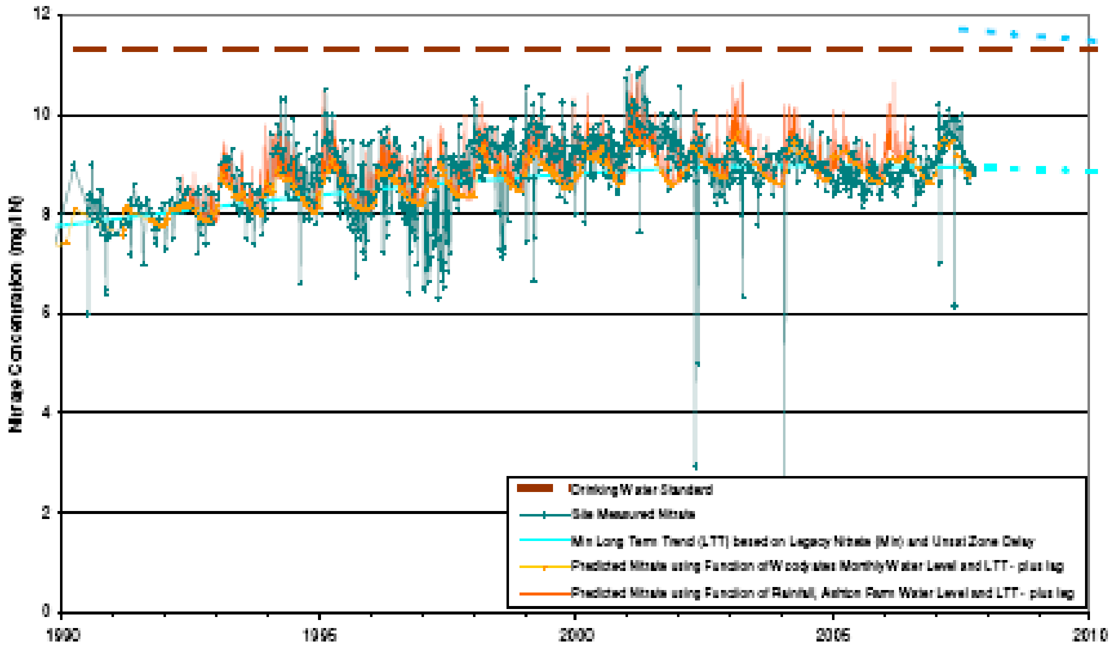
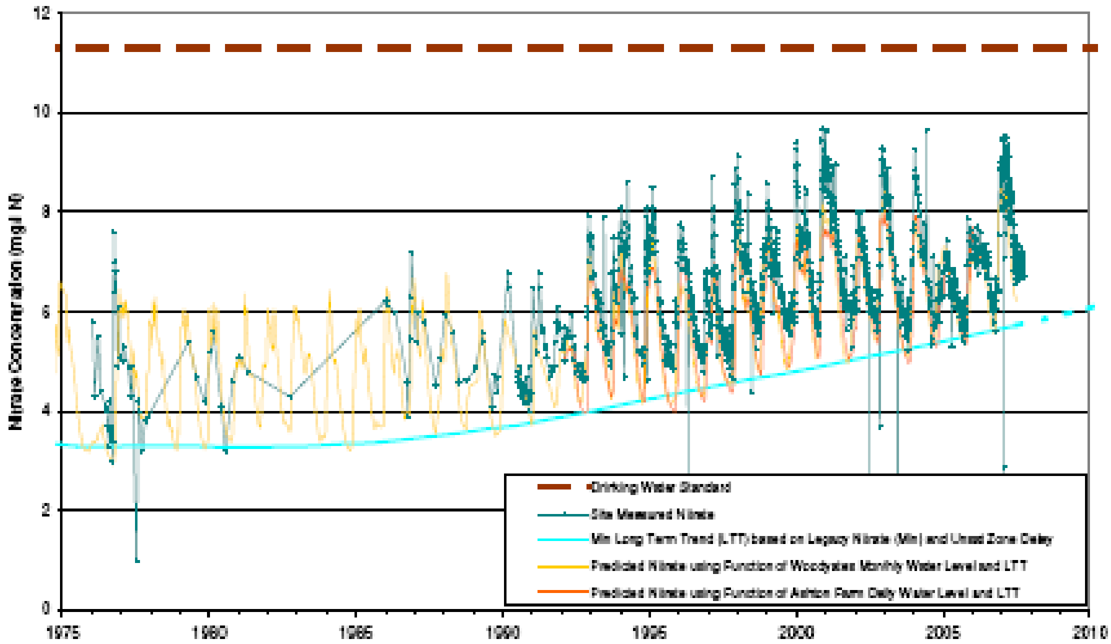
Empool Figure B1 Comparison of Modelled Trend (Long Term + Seasonal) with Measured Nitrate



Empool Figure B2 Zoom-in of Model with Bypass Flow, Lagged (by 45 days) Seasonal Variation and Long Term Prediction



Friar Waddon Figure B1 Comparison of Modelled Trend (Long Term + Seasonal) with Measured Nitrate



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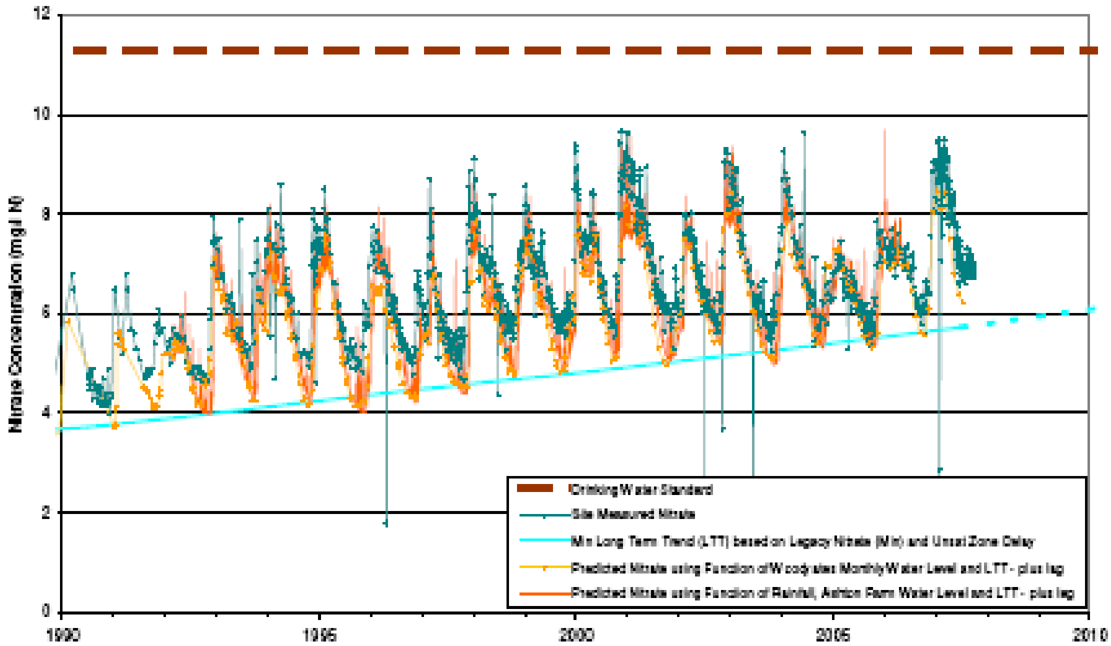
Friar Waddon Figure B2 Zoom-in of Model with Bypass Flow, Lagged (by 10 days) Seasonal Variation and Long Term Prediction



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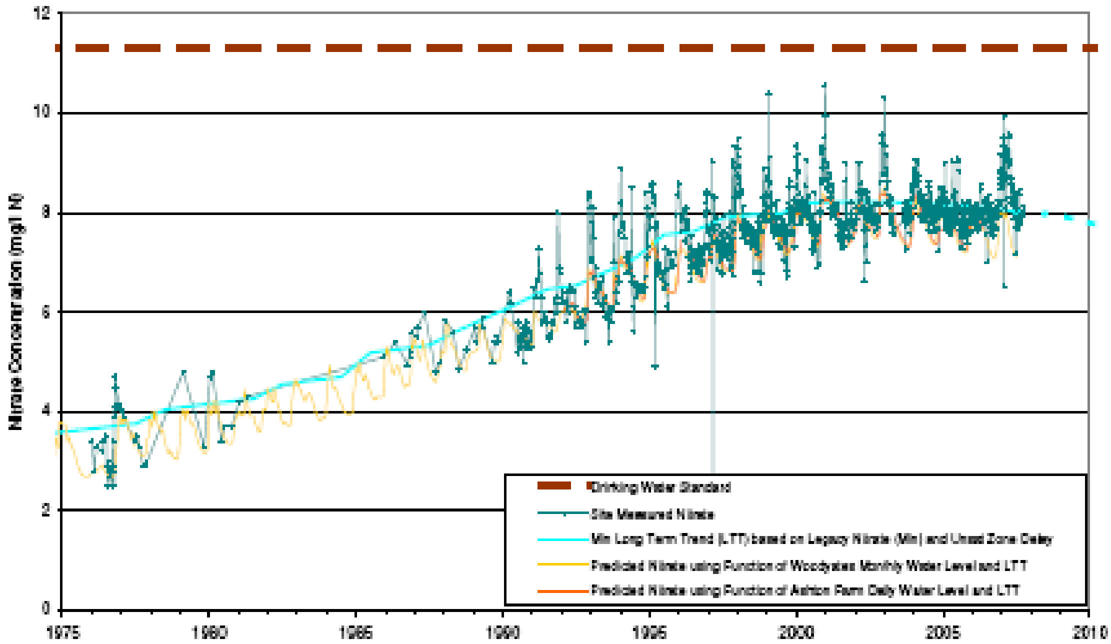
Hooke Figure B1 Comparison of Modelled Trend (Long Term + Seasonal) with Measured Nitrate



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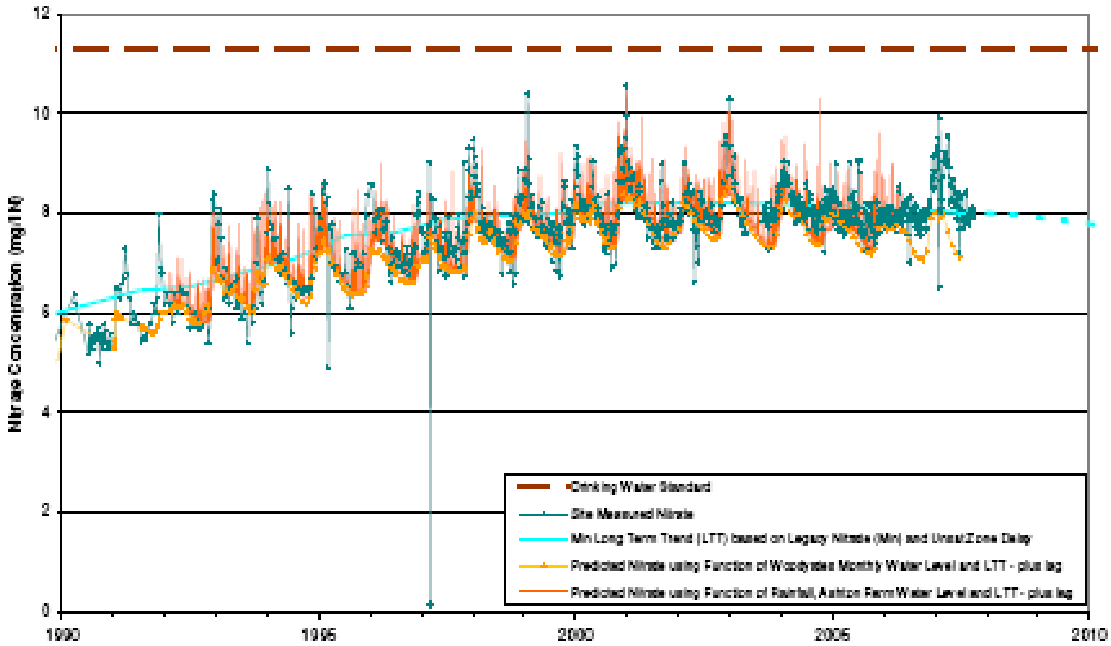
Hooke Figure B2 Zoom-in of Model with Bypass Flow, Lagged (by 0 days) Seasonal Variation and Long Term Prediction



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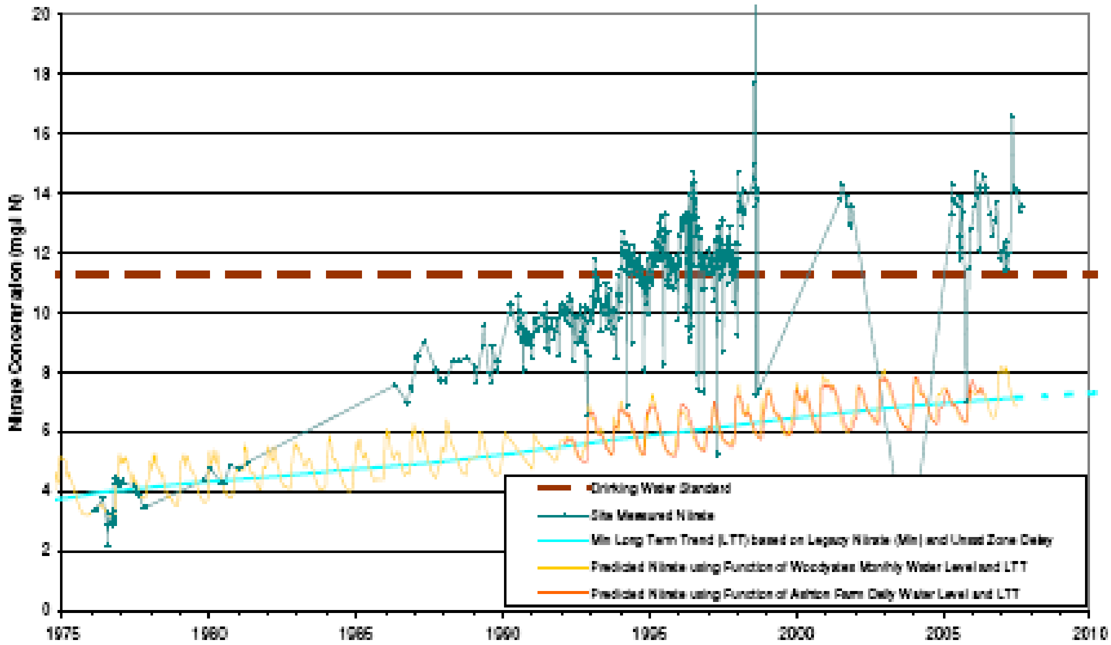
Langdon Springs Figure B1 Comparison of Modelled Trend (Long Term + Seasonal) with Measured Nitrate



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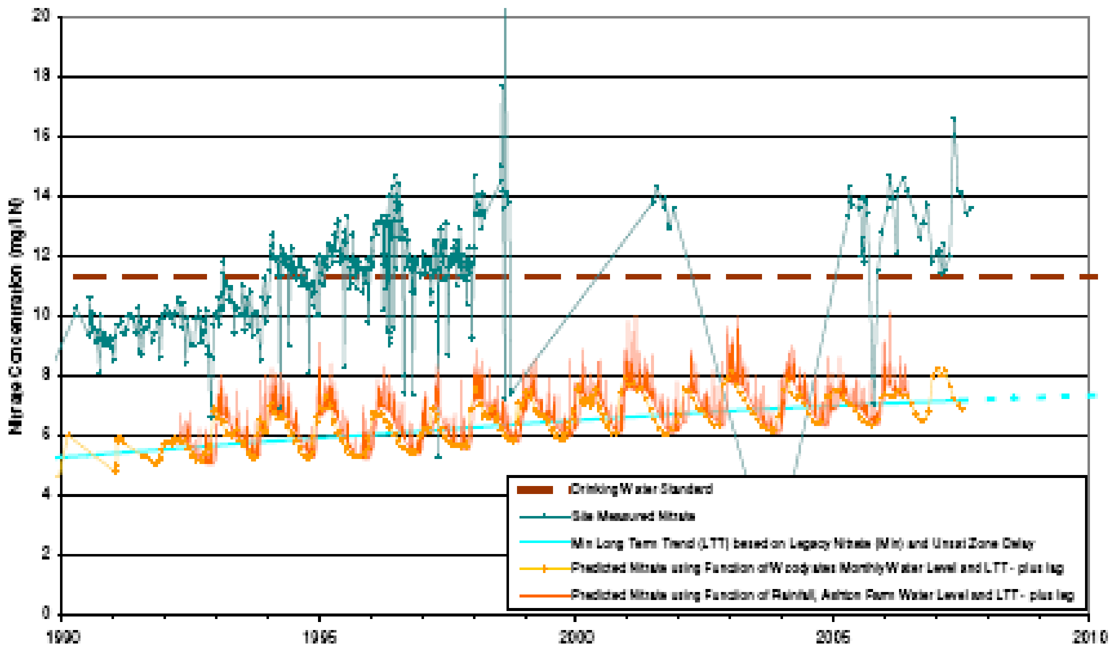
Langdon Springs Figure B2 Zoom-In of Model with Bypass Flow, Lagged (by 30 days) Seasonal Variation and Long Term Prediction



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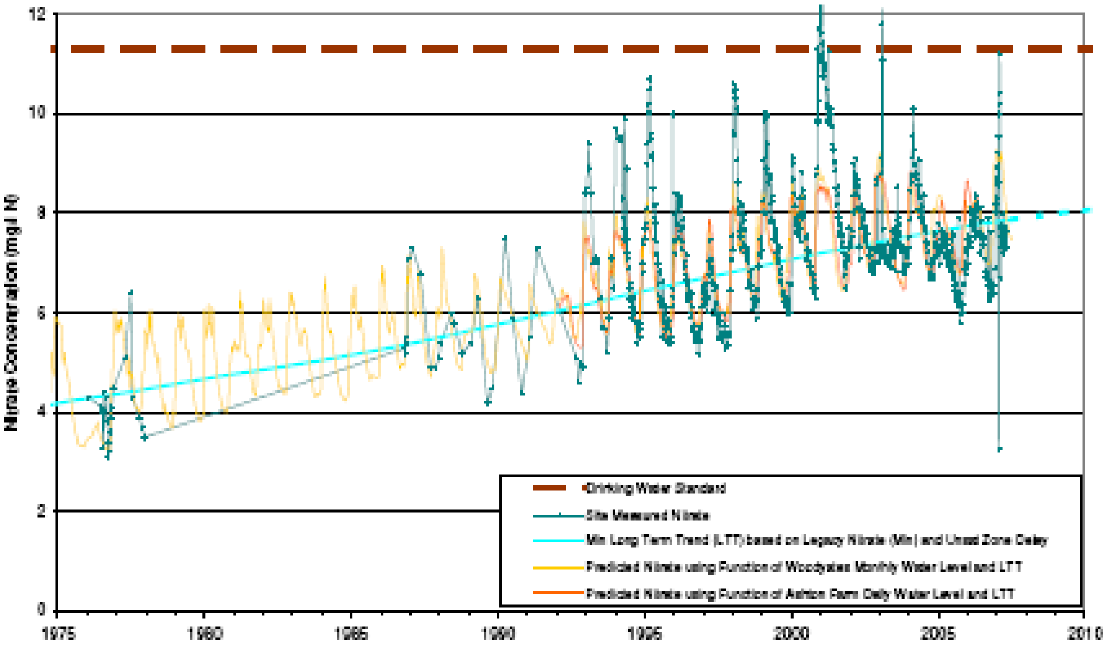
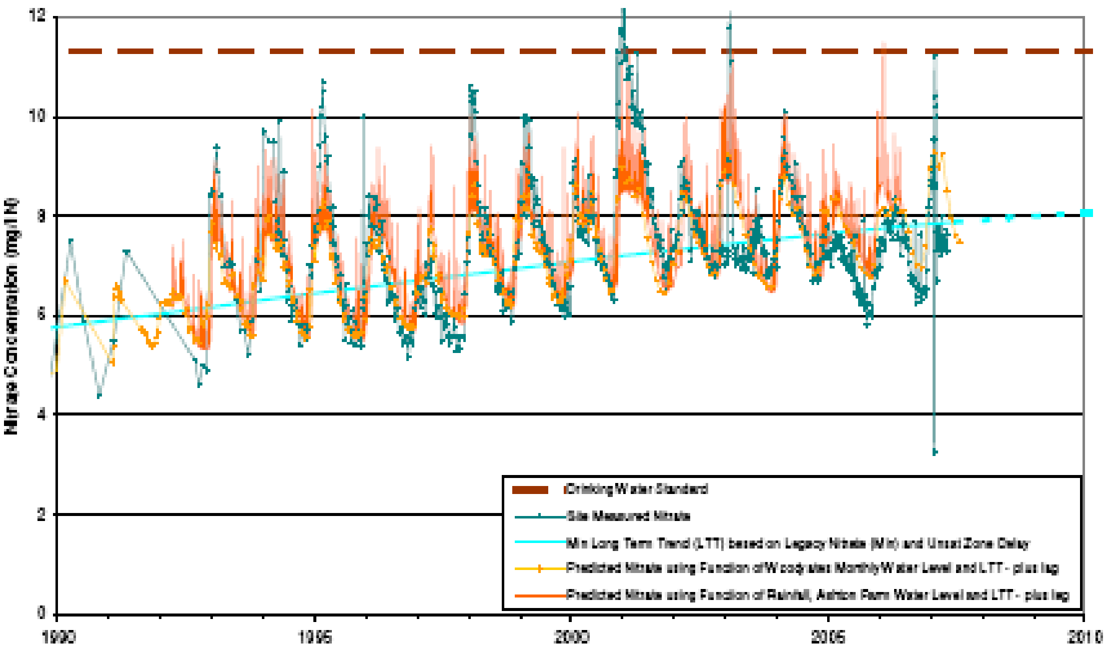
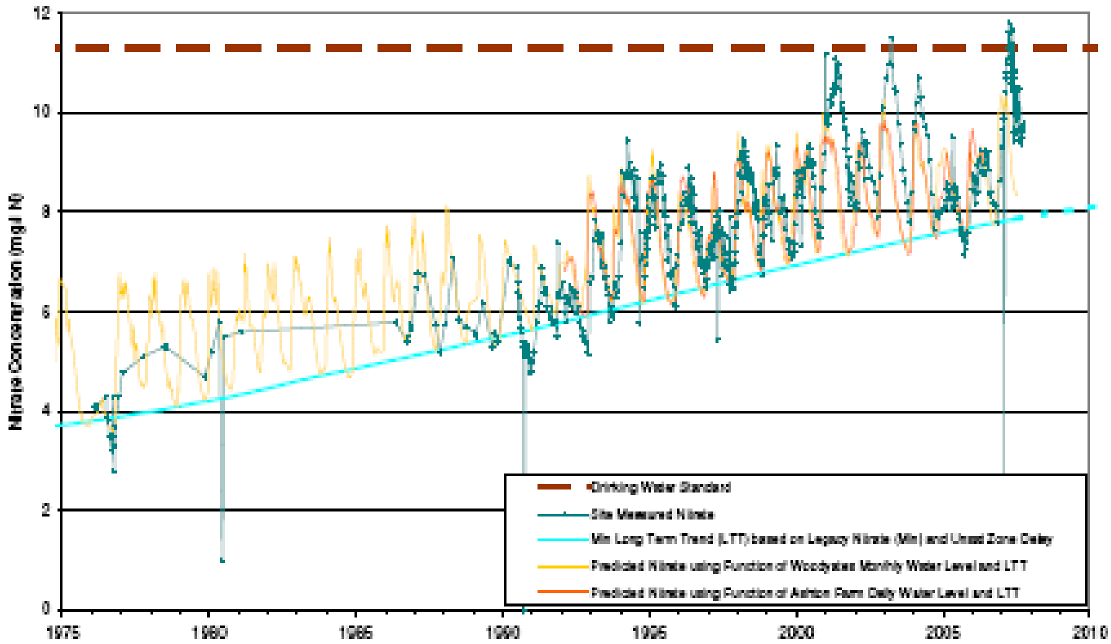
Milborne St Andrew Figure B1 Comparison of Modelled Trend (Long Term + Seasonal) with Measured Nitrate



Milborne St Andrew Figure B2 Zoom-in of Model with Bypass Flow, Lagged (by 25 days) Seasonal Variation and Long Term Prediction



Winterborne Abbas Figure B1 Comparison of Modelled Trend (Long Term + Seasonal) with Measured Nitrate



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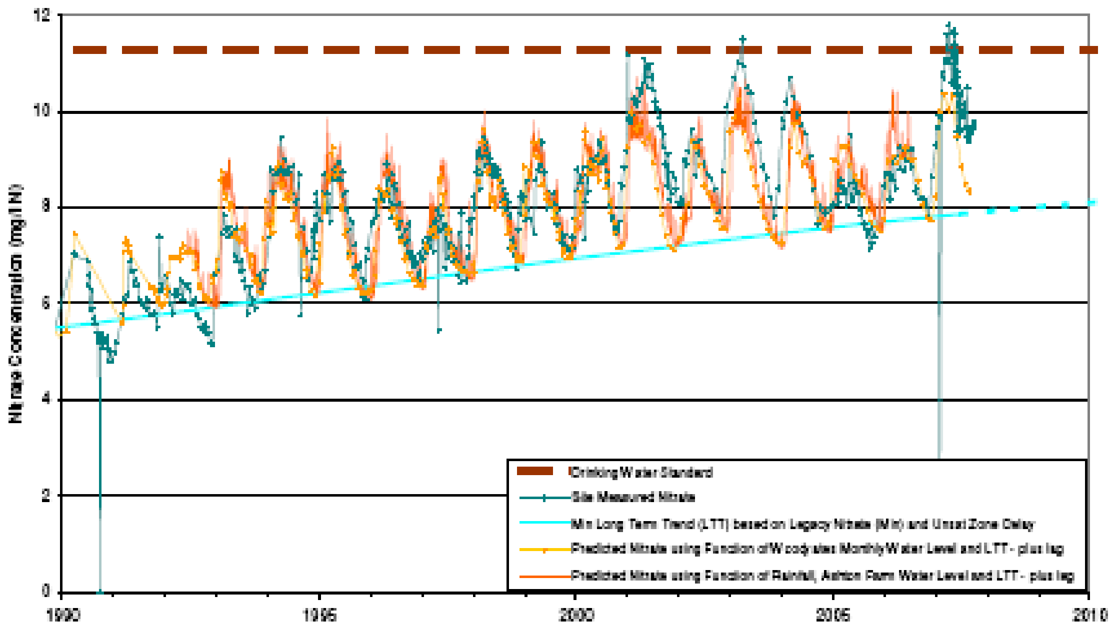
Winterborne Abbas Figure B2 Zoom-in of Model with Bypass Flow, Lagged (by 60 days) Seasonal Variation and Long Term Prediction



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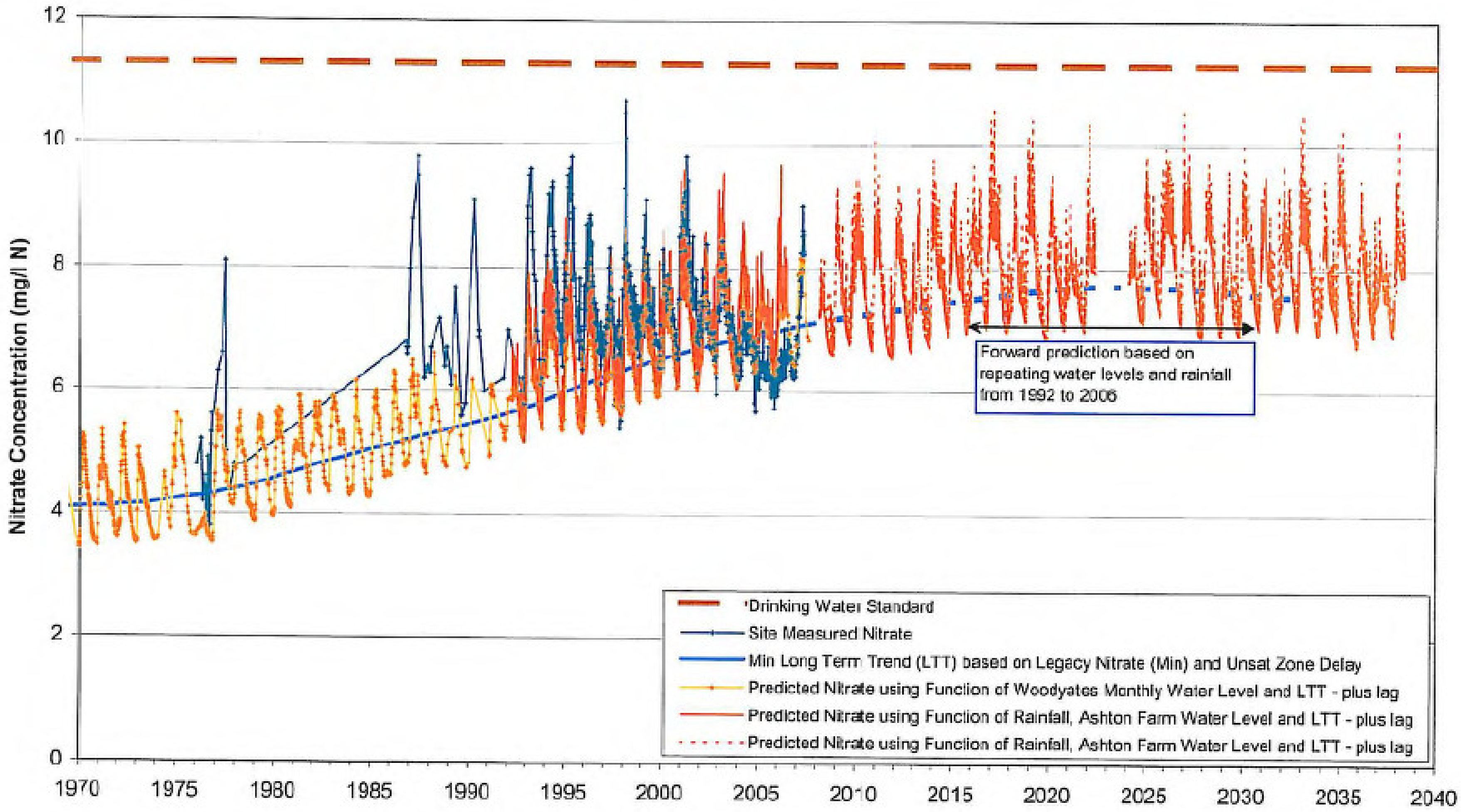
Appendix C

Future predictions of nitrate concentrations in the Wessex Water abstracted groundwater under the baseline and best case WAgriCo measures.

Dewlish Forward Prediction of Nitrate at PWS Assuming 'Baseline' Leaching Scenario



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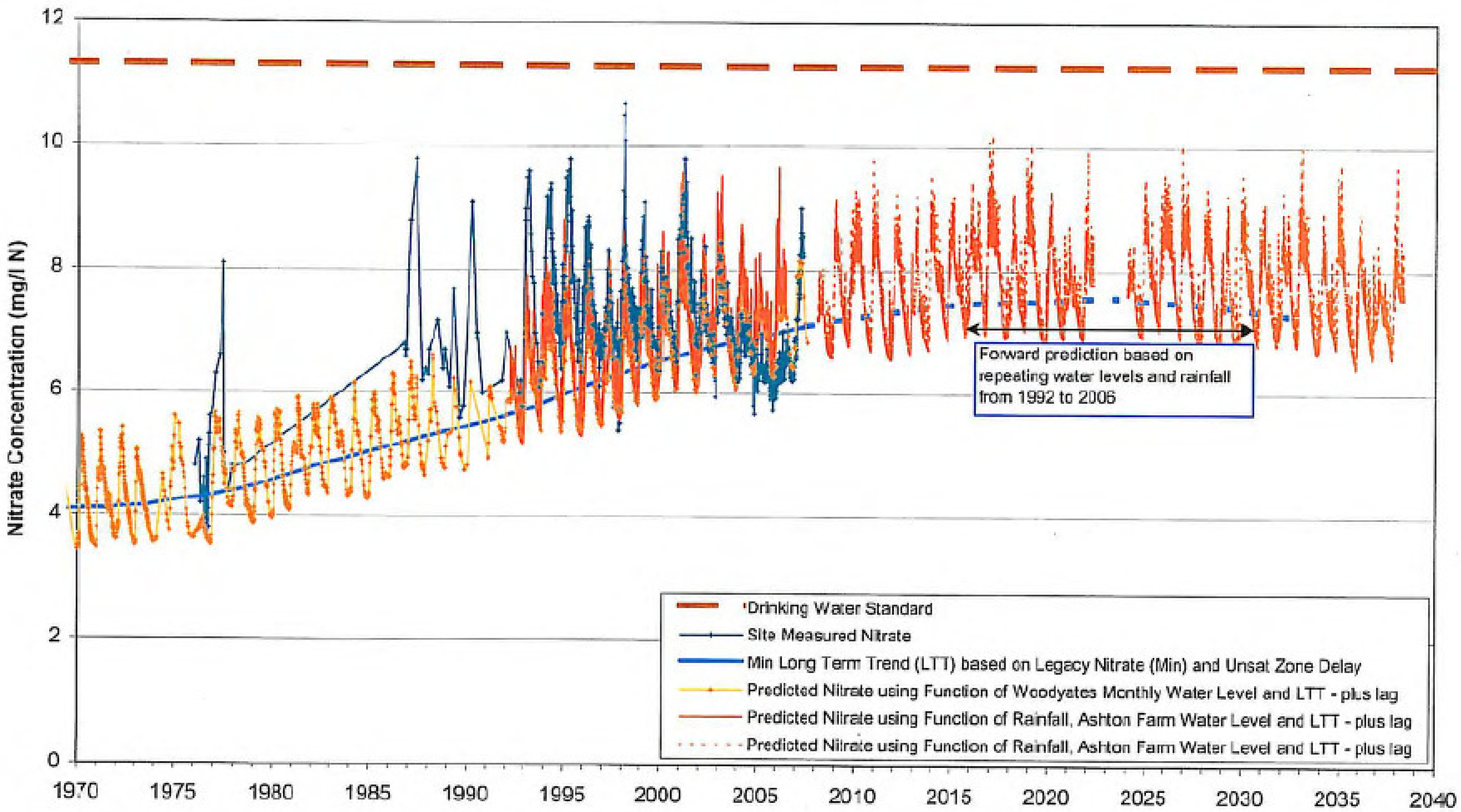
Dewlish Forward Prediction of Nitrate at PWS Assuming 'Best Case' Leaching Scenario



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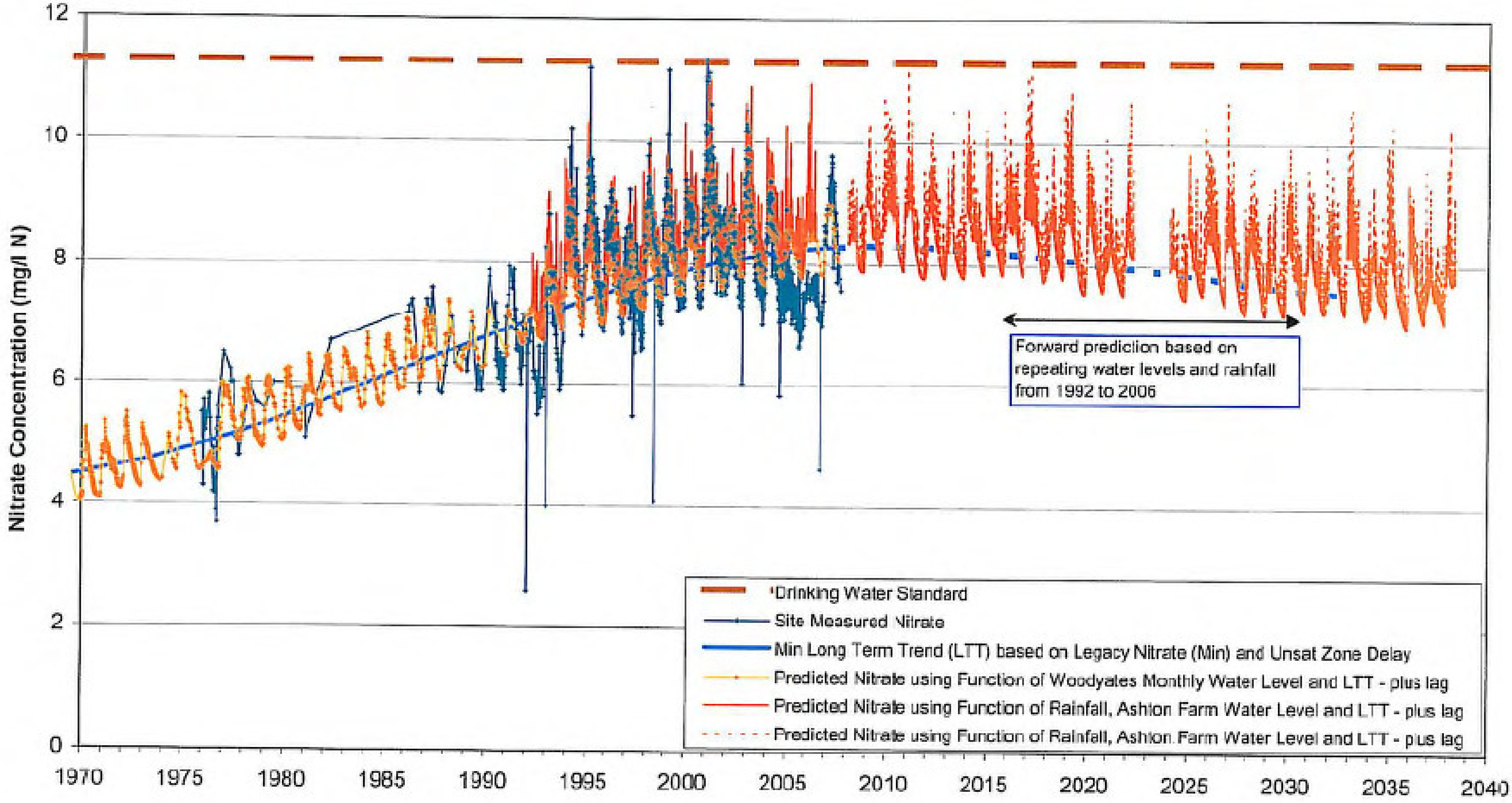
Eagle Lodge Forward Prediction of Nitrate at PWS Assuming 'Baseline' Leaching Scenario



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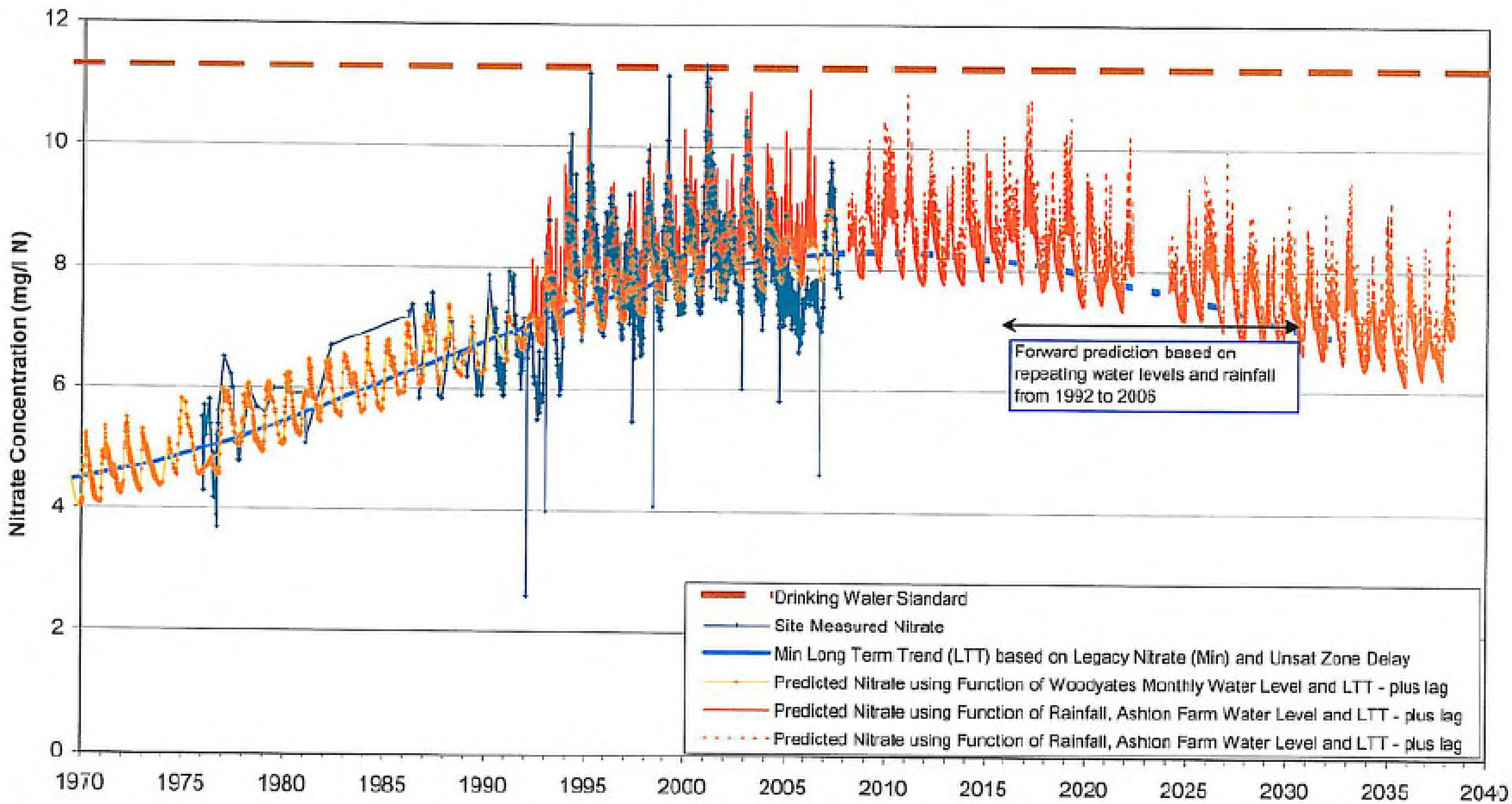
Eagle Lodge Forward Prediction of Nitrate at PWS Assuming 'Best Case' Leaching Scenario



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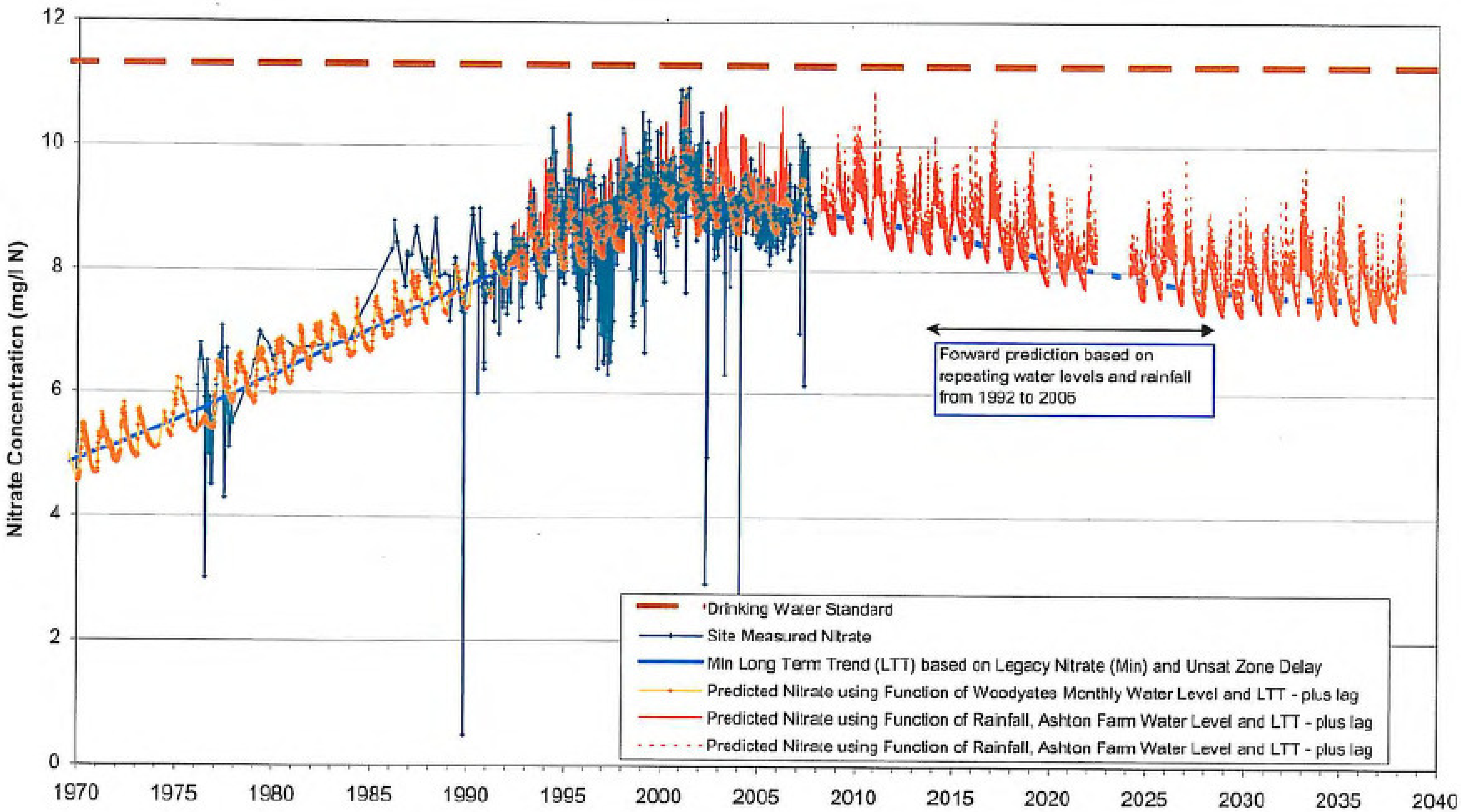
Empool Forward Prediction of Nitrate at PWS Assuming 'Baseline' Leaching Scenario



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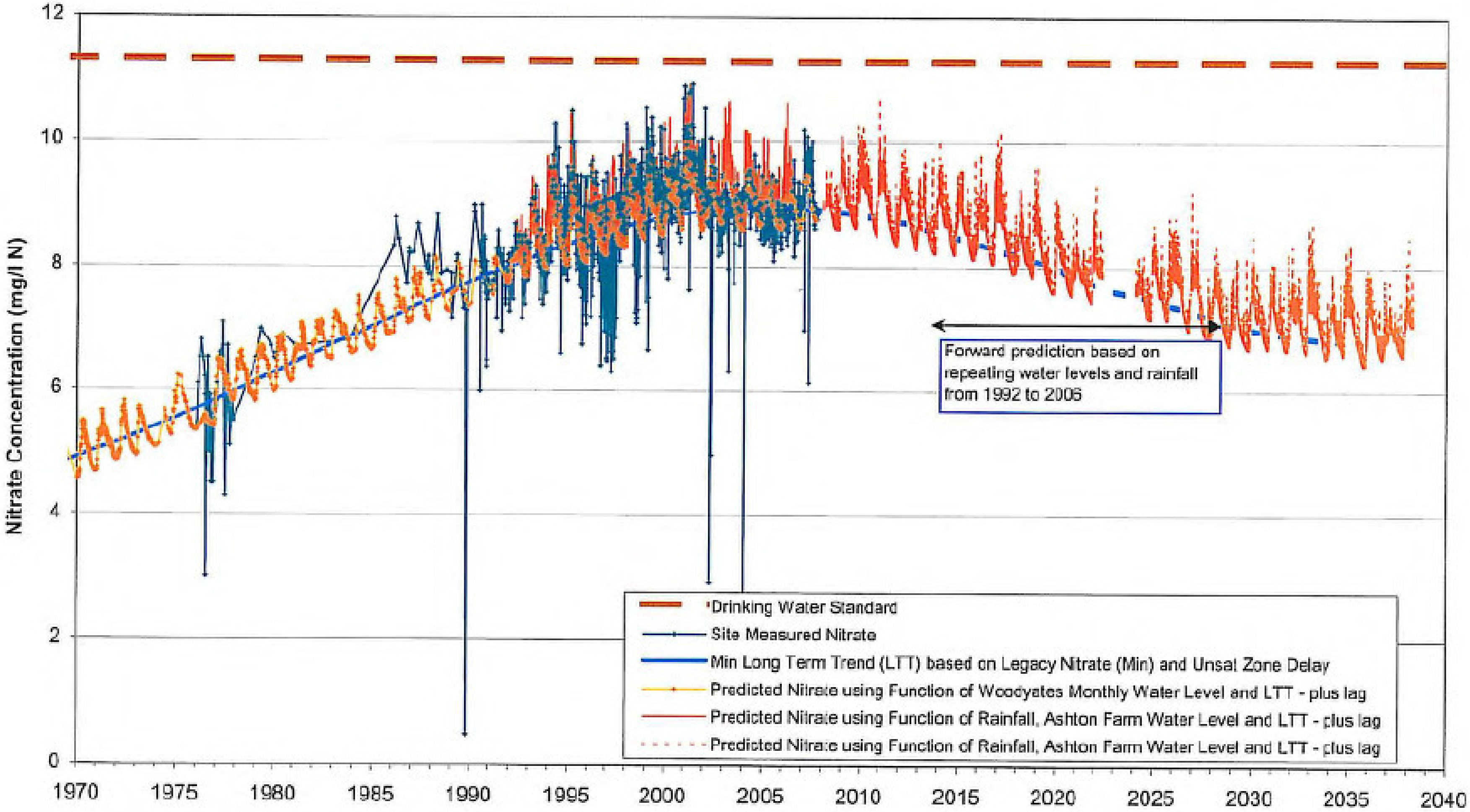
Empool Forward Prediction of Nitrate at PWS Assuming 'Best Case' Leaching Scenario



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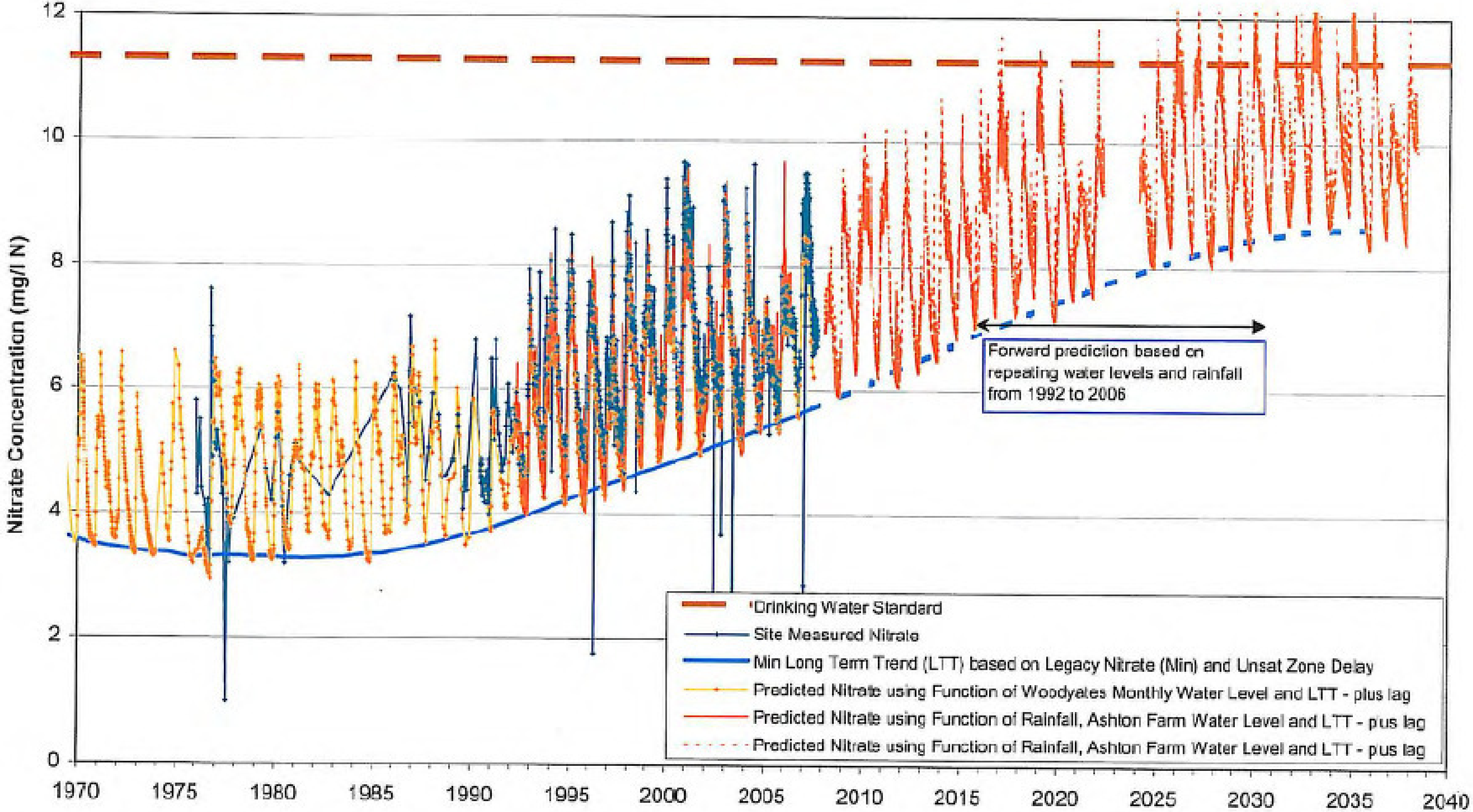
Friar Waddon   Forward Prediction of Nitrate at PWS Assuming 'Baseline' Leaching Scenario



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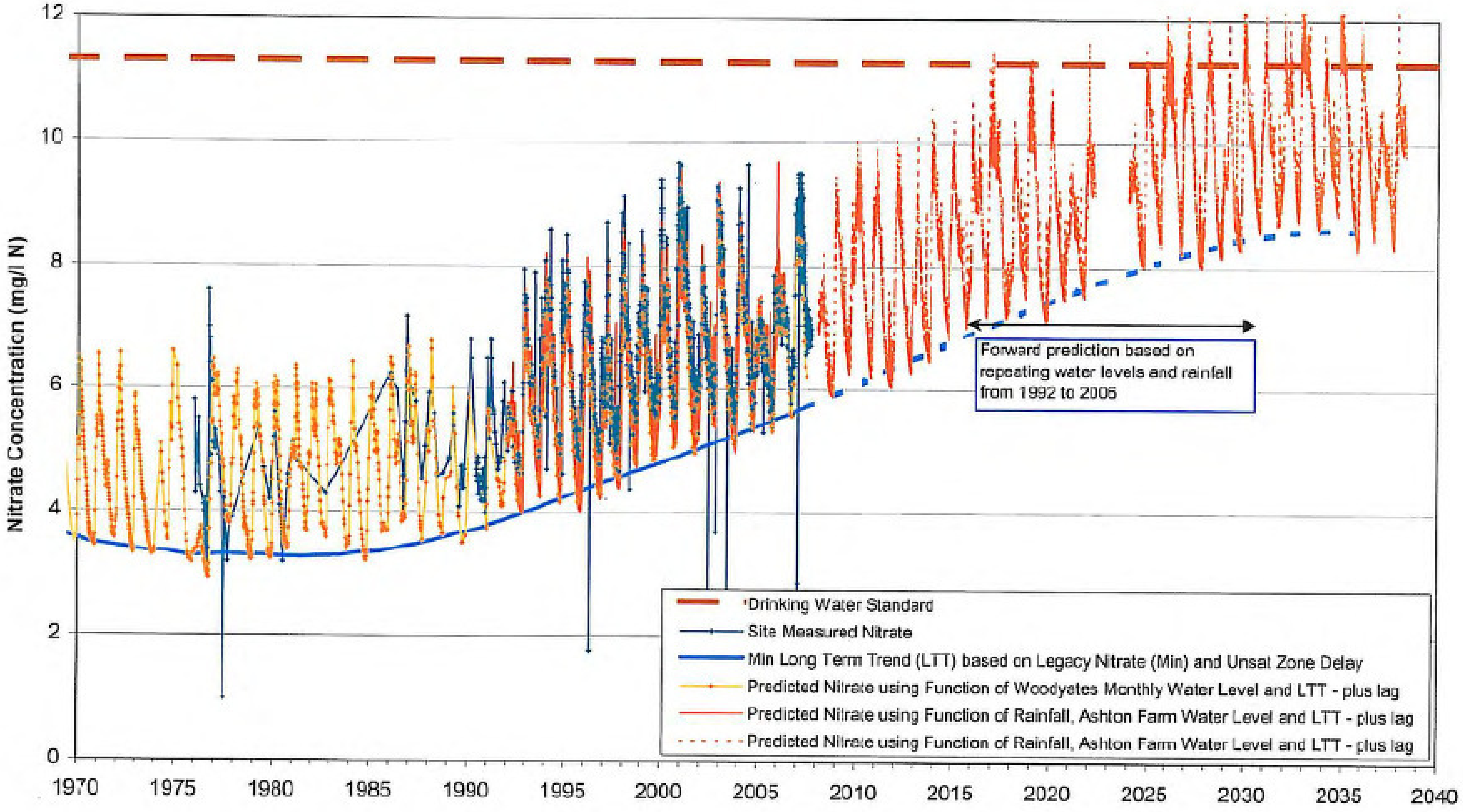
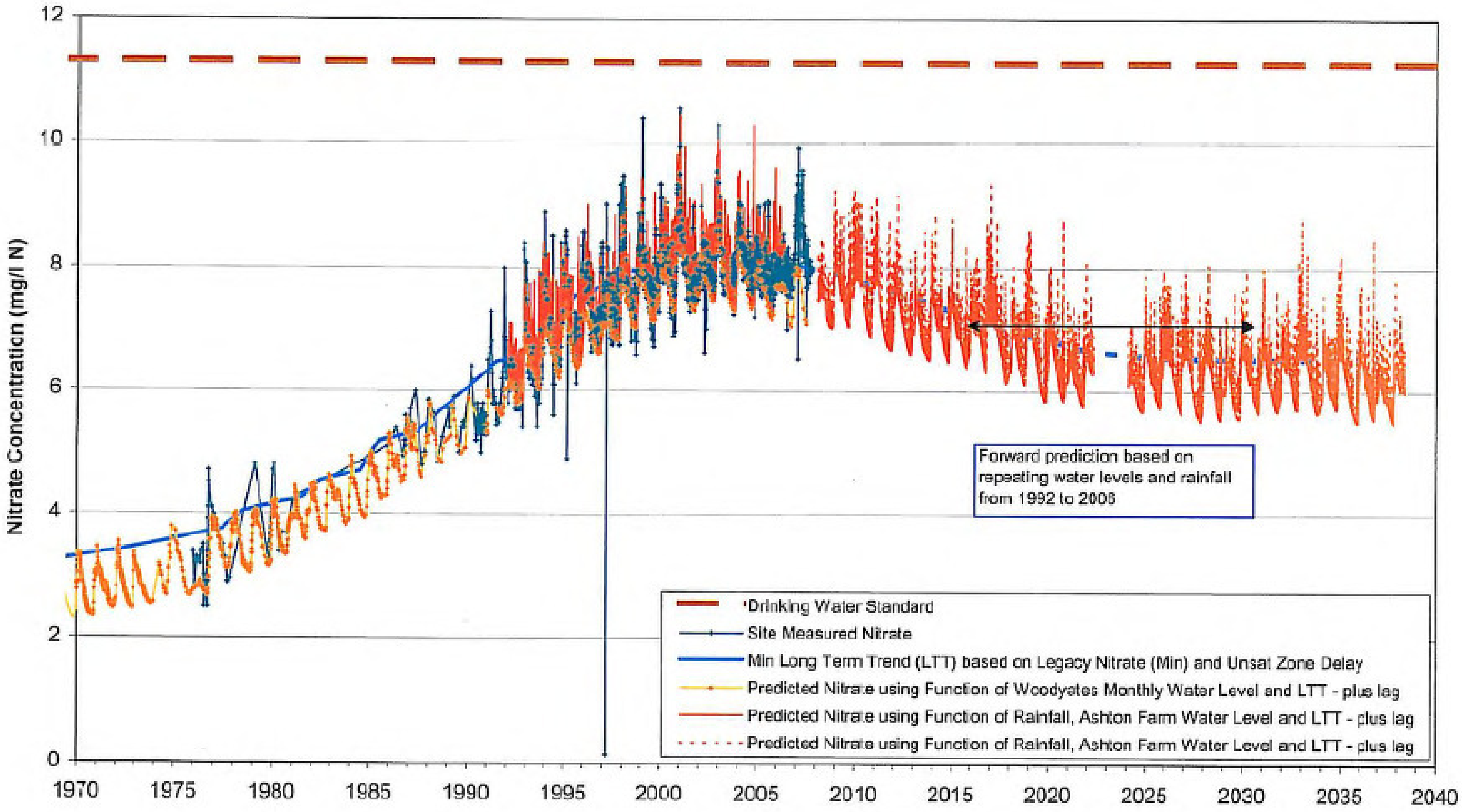
Friar Waddon   Forward Prediction of Nitrate at PWS Assuming 'Best Case' Leaching Scenario



Hooke Forward Prediction of Nitrate at PWS Assuming 'Baseline' Leaching Scenario



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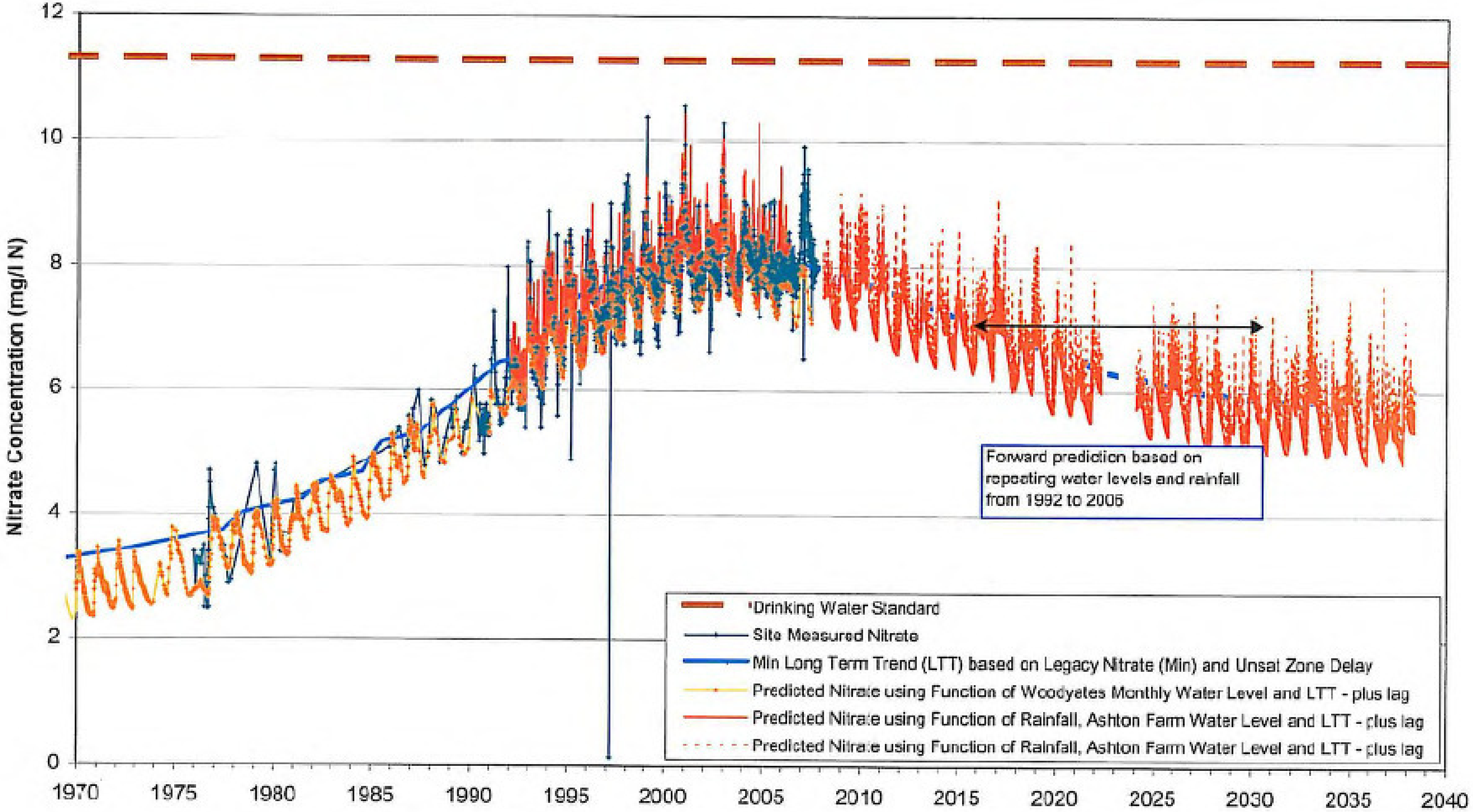
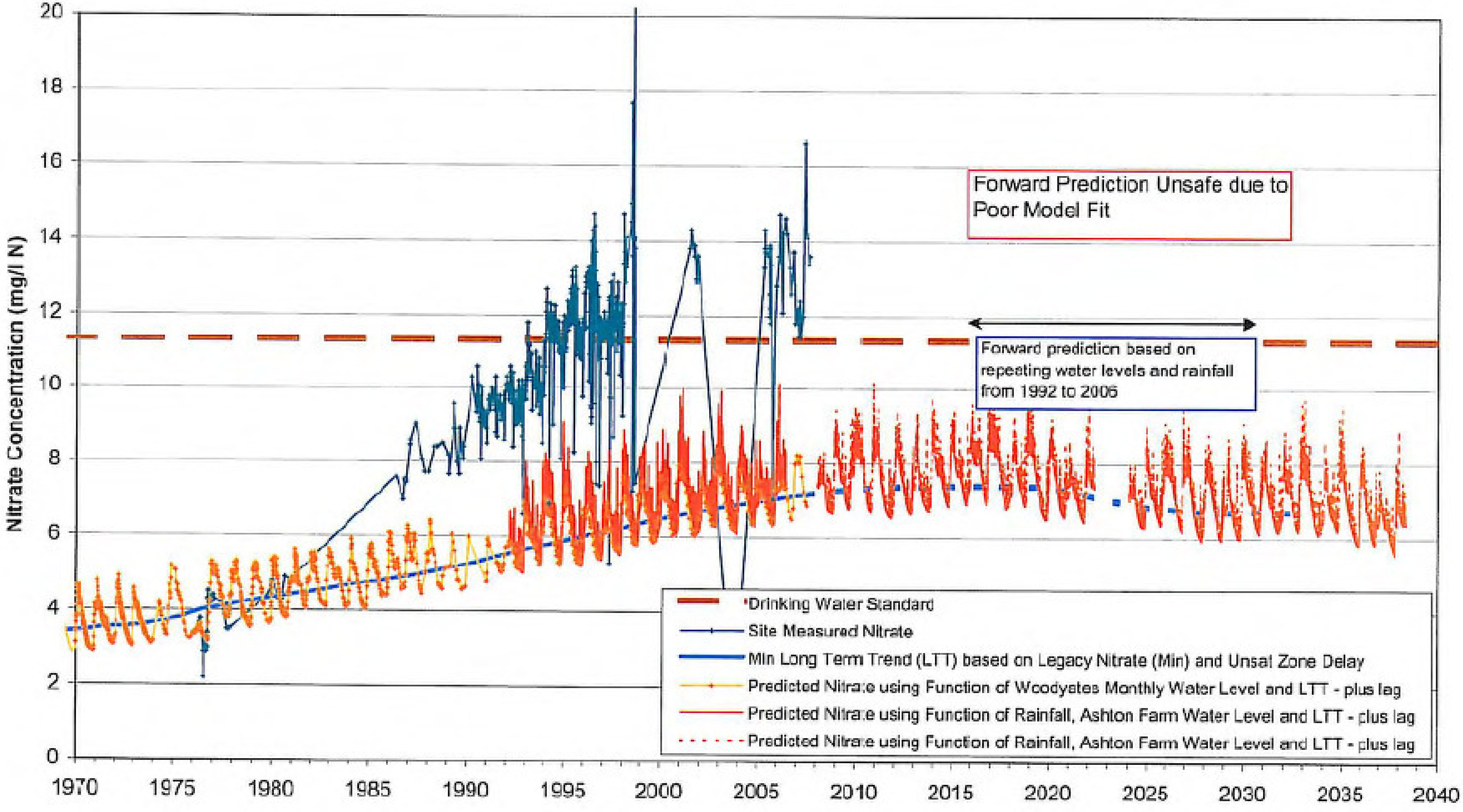
Hooke Forward Prediction of Nitrate at PWS Assuming 'Best Case' Leaching Scenario



Langdon Springs   Forward Prediction of Nitrate at PWS Assuming 'Baseline' Leaching Scenario



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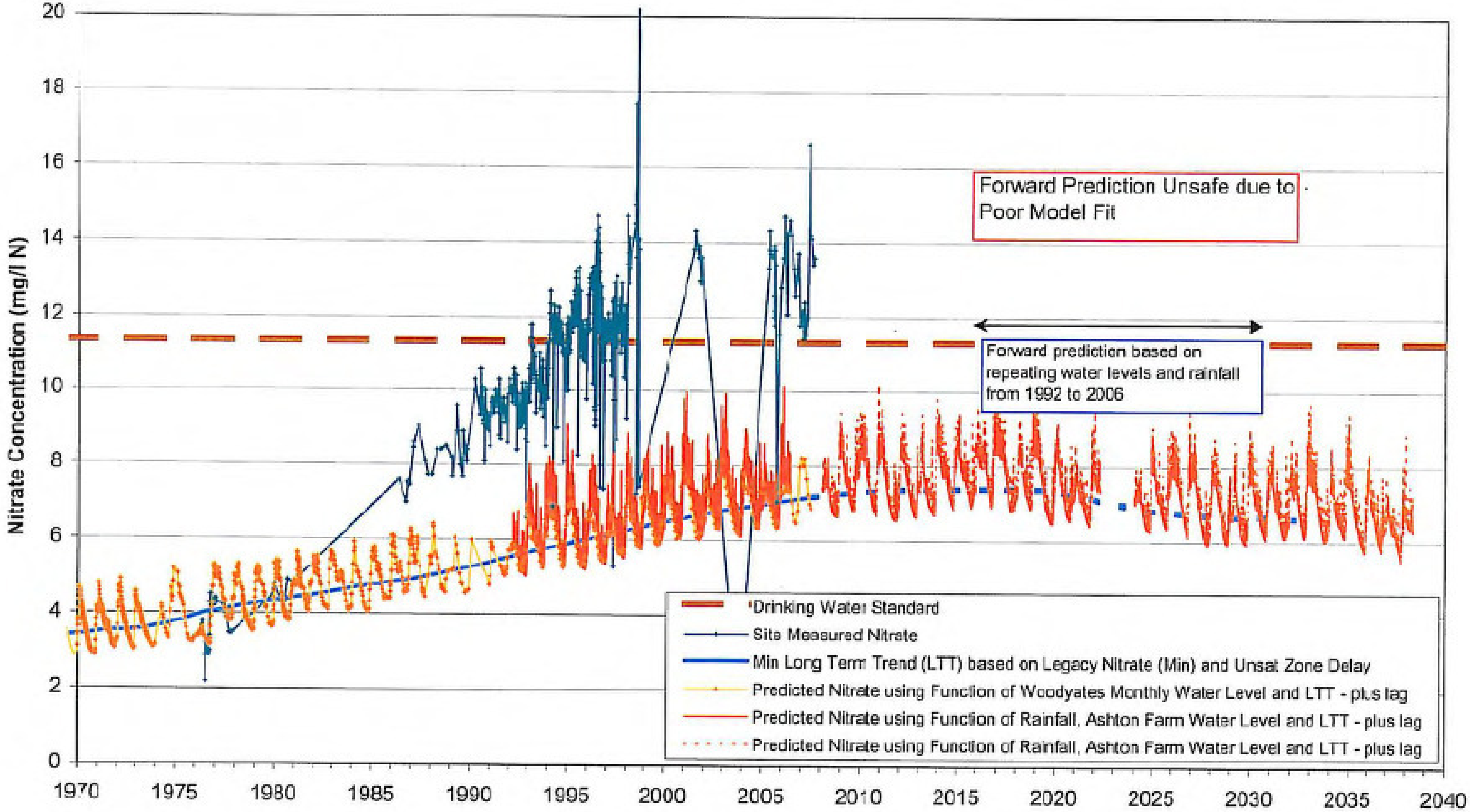
Langdon Springs Forward Prediction of Nitrate at PWS Assuming 'Best Case' Leaching Scenario



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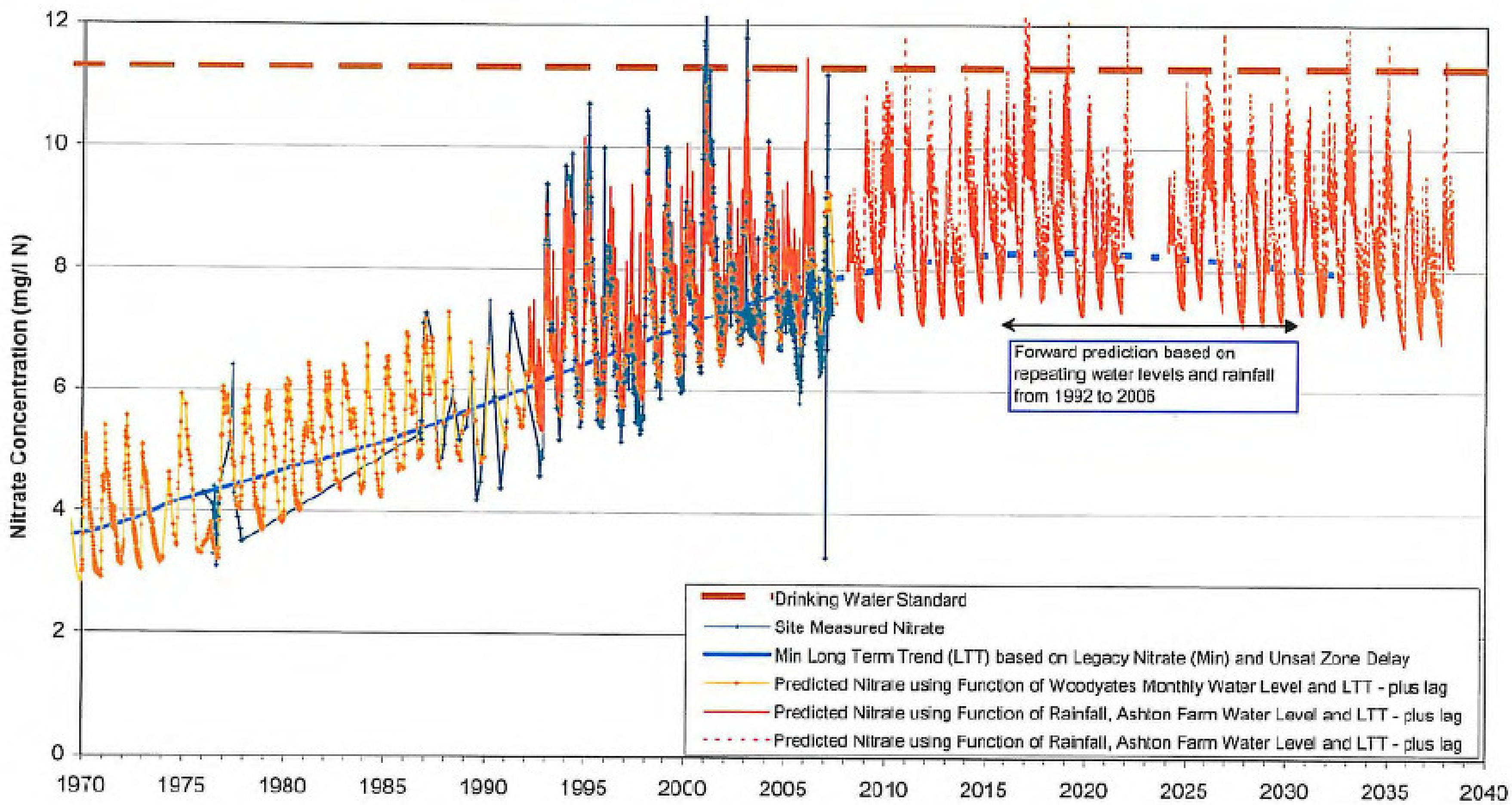
Milborne St Andrew Forward Prediction of Nitrate at PWS Assuming 'Baseline' Leaching Scenario



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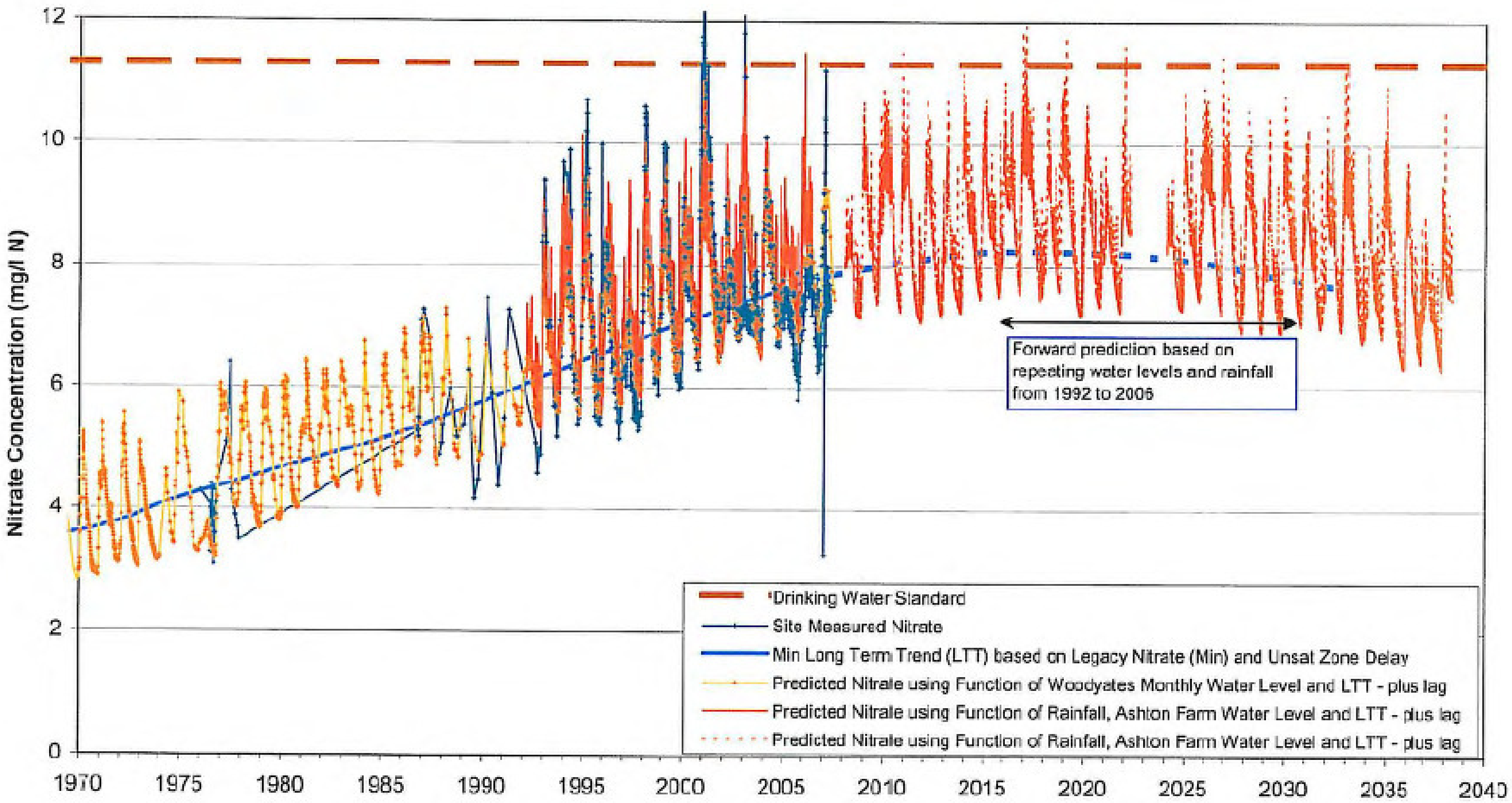
Milborne St Andrew Forward Prediction of Nitrate at PWS Assuming 'Best Case' Leaching Scenario



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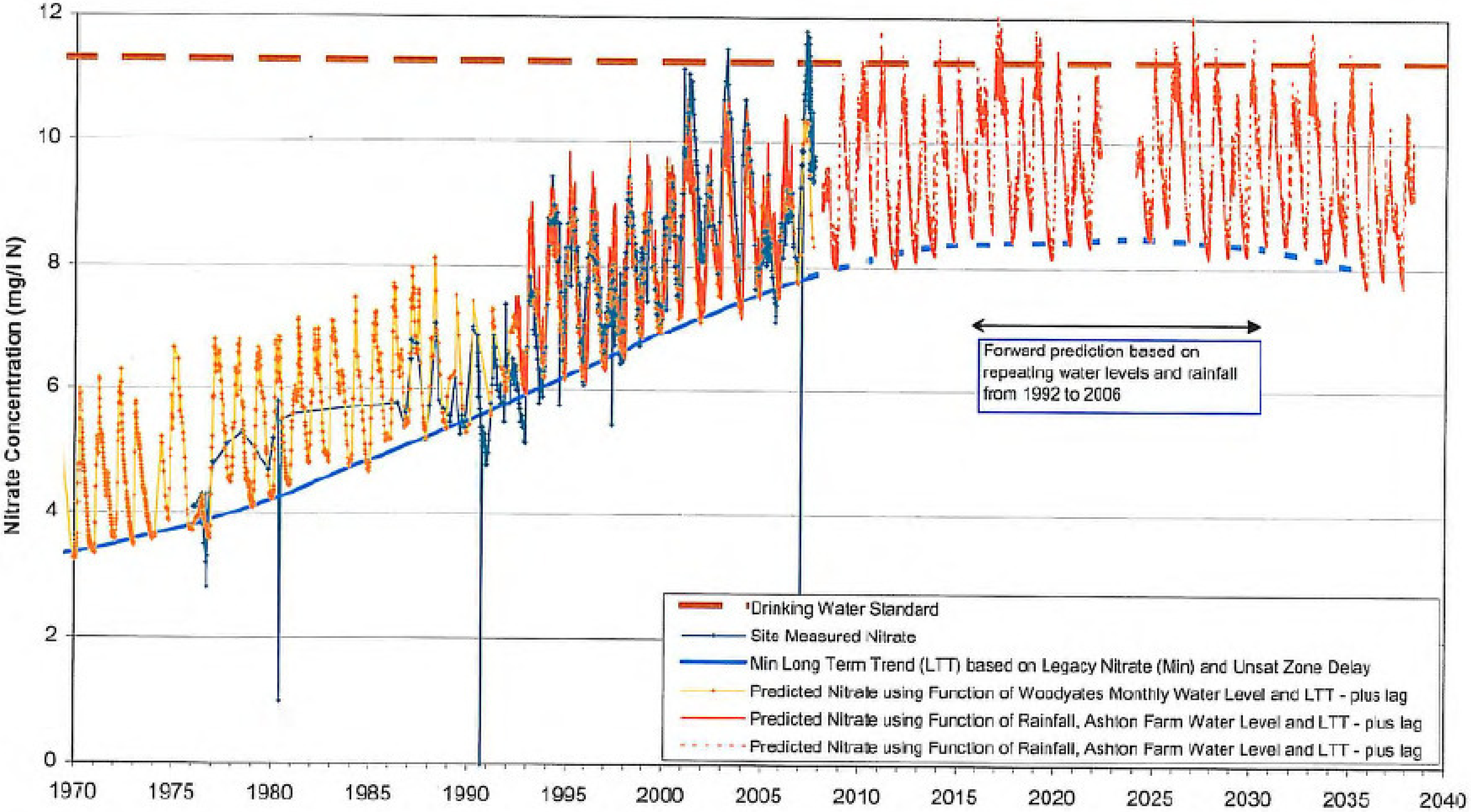
Winterborne Abbas   Forward Prediction of Nitrate at PWS Assuming 'Baseline' Leaching Scenario



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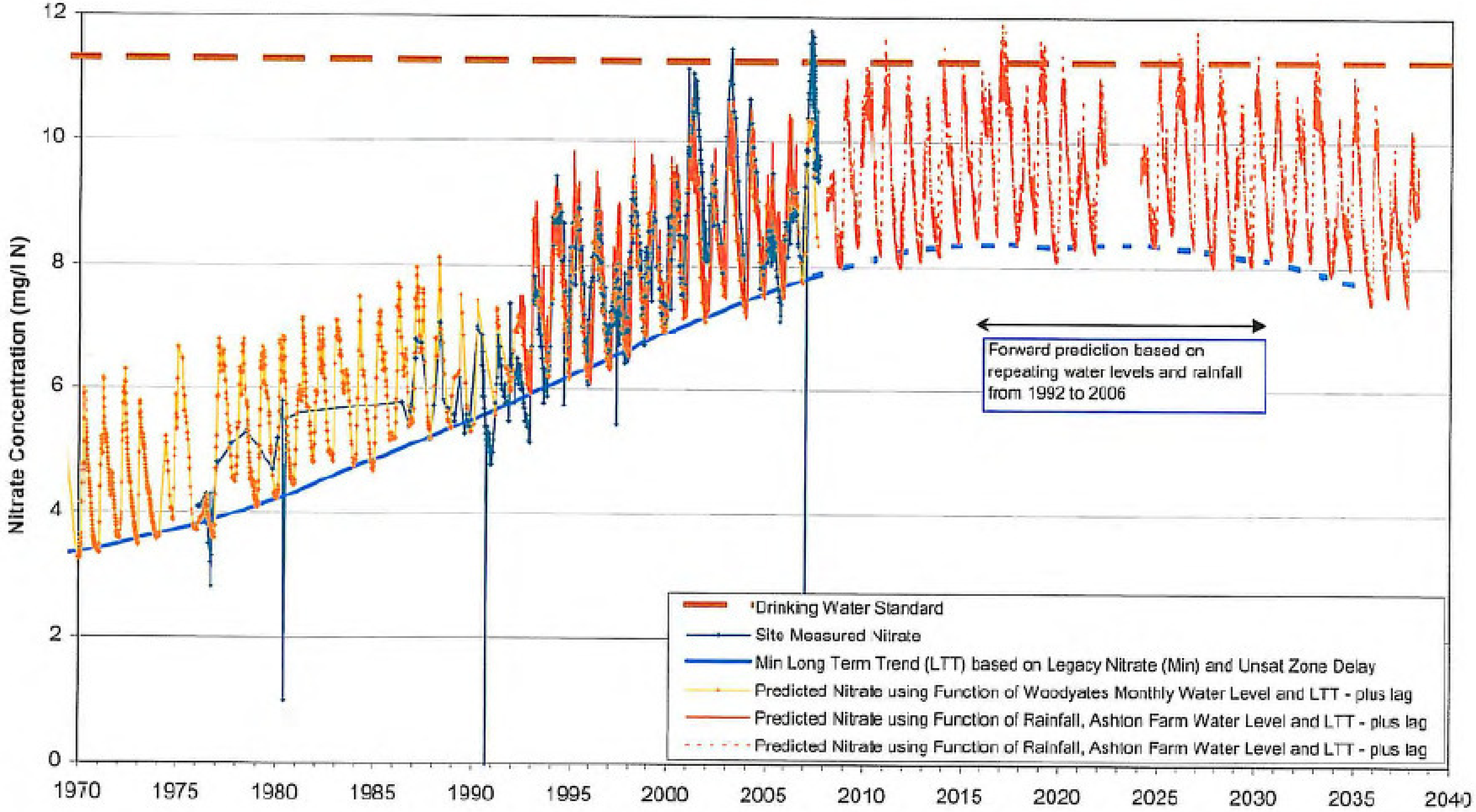
Winterborne Abbas Forward Prediction of Nitrate at PWS Assuming 'Best Case' Leaching Scenario



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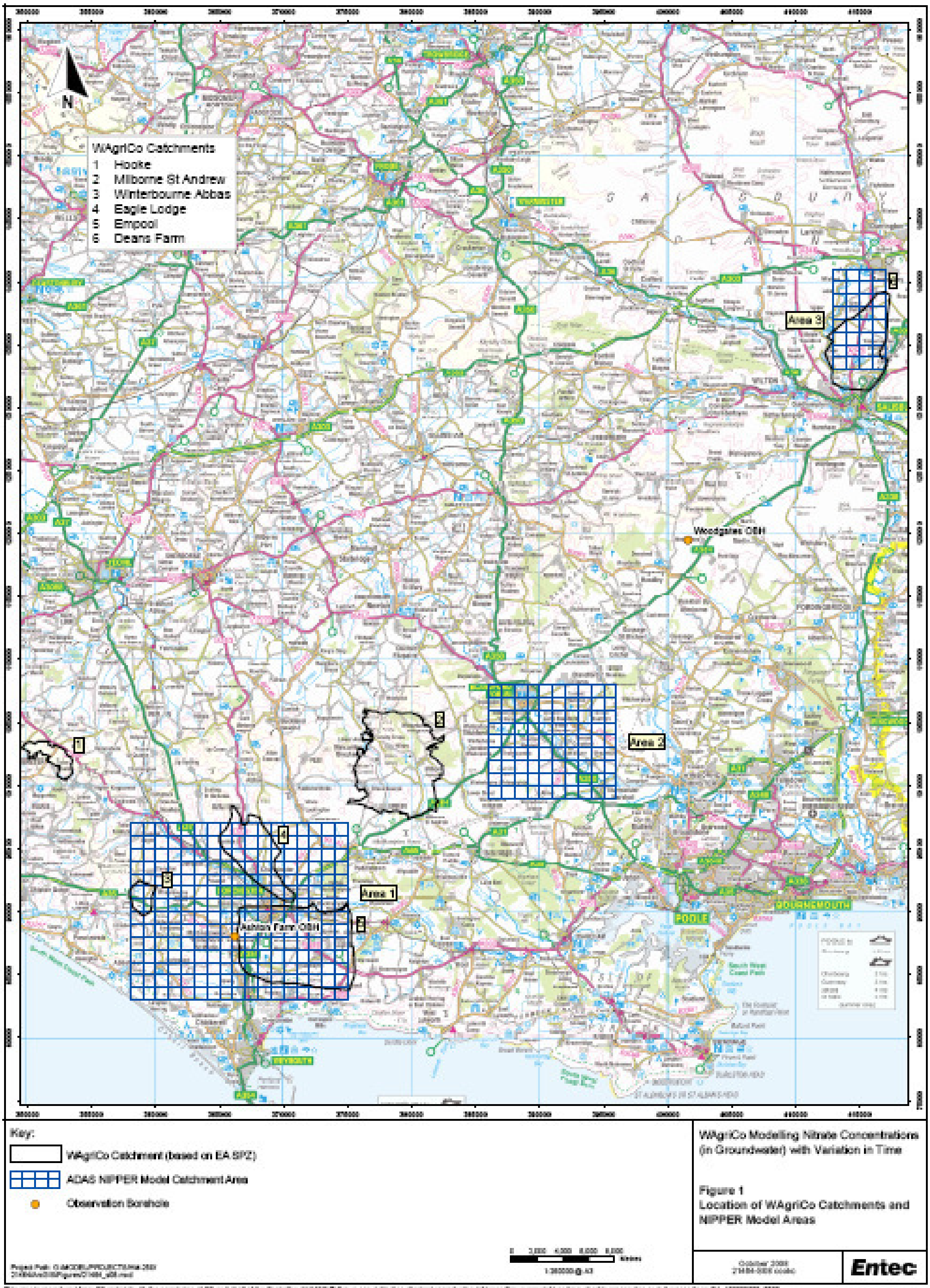
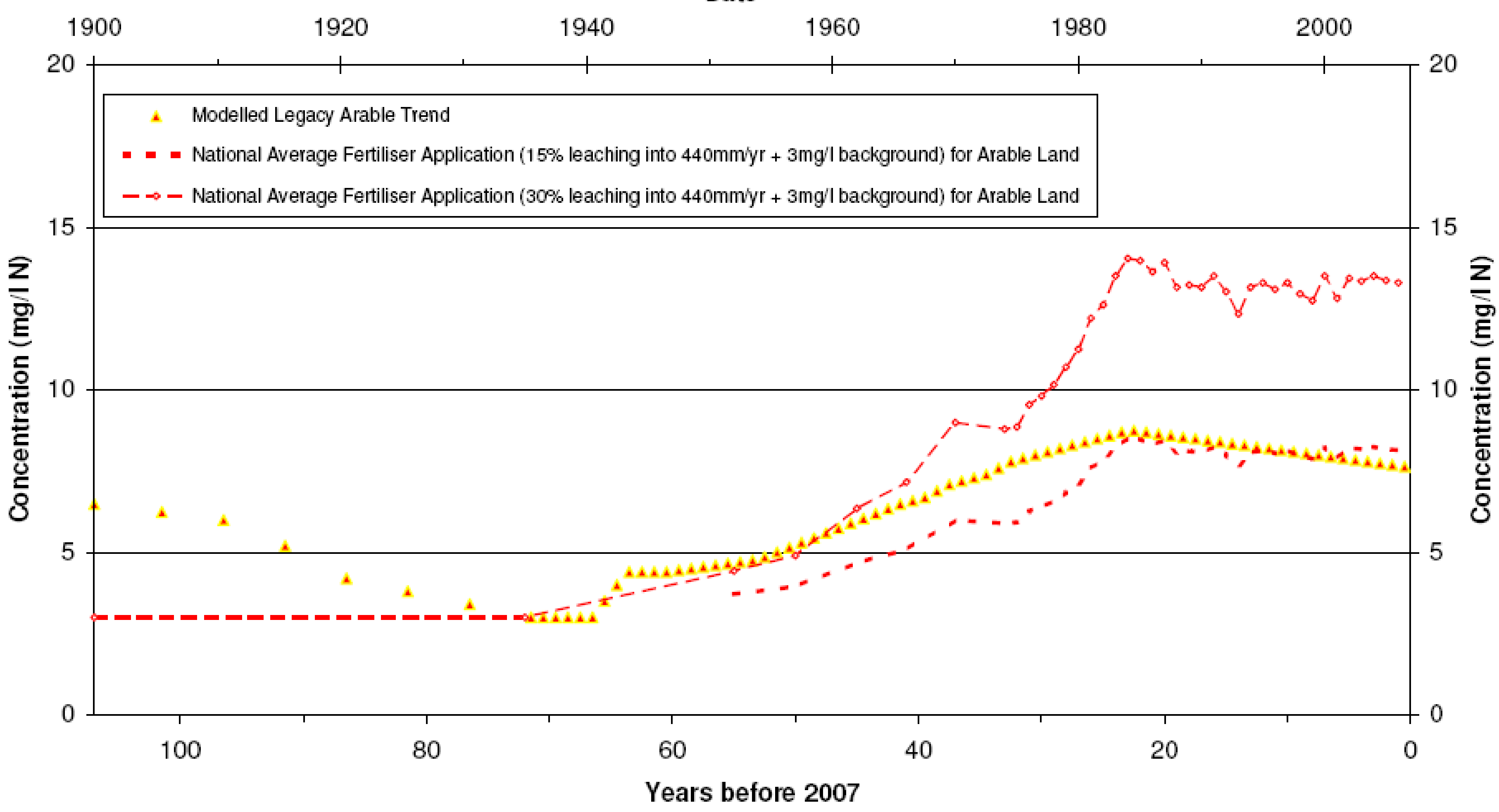
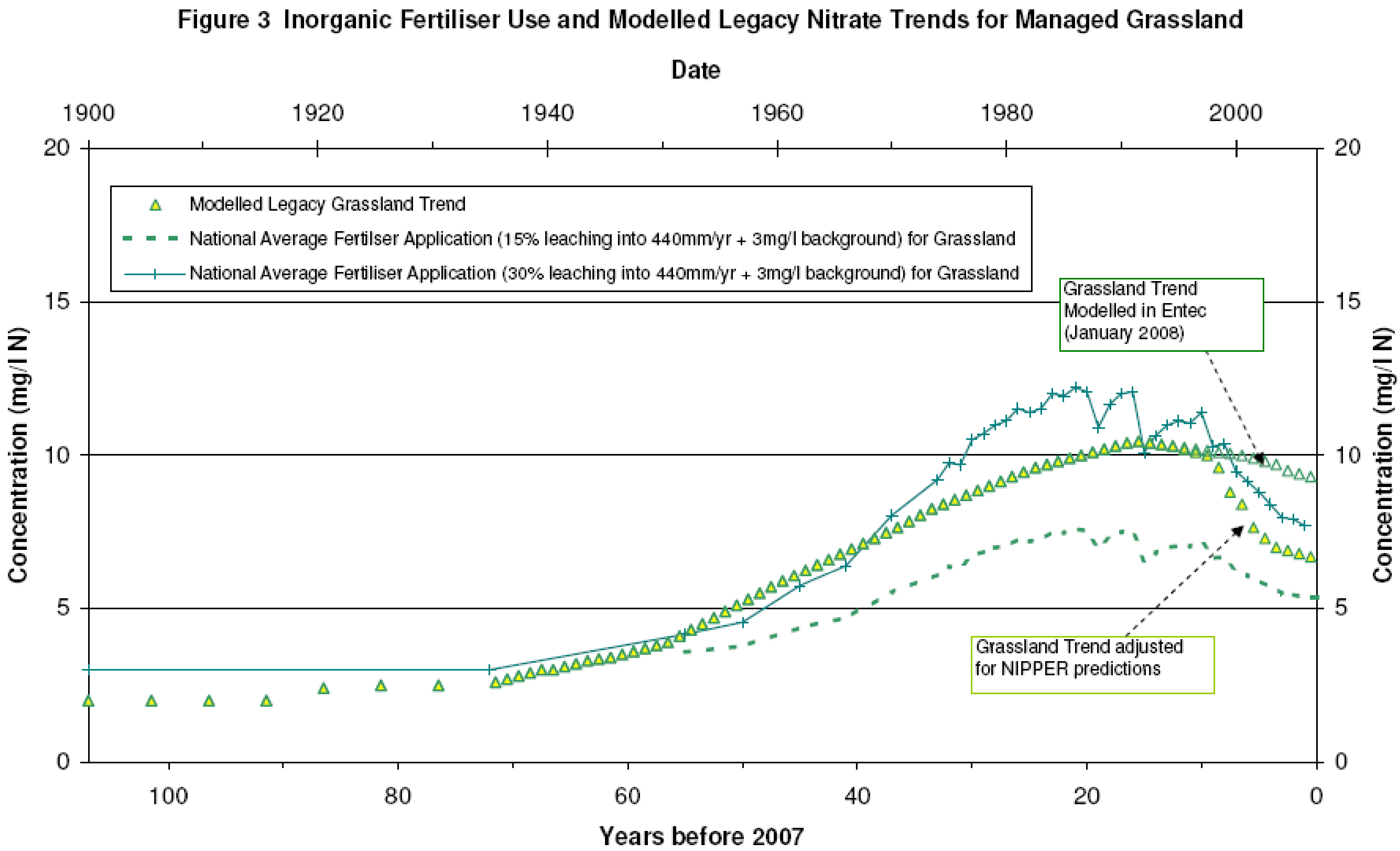

N
WAgriCo Catchments
1 Hooke
2 Milborne St Andrew
3 Winterbourne Abbas
4 Eagle Lodge
5 Empool
6 Deans Farm
Area 1
Area 2
Area 3
Woodgates OBH
Ashton Farm OBH
POOLE
BOURNEMOUTH
WEYMOUTH
Key:
WAgriCo Catchment (based on EA SPZ)
ADAS NIPPER Model Catchment Area
Observation Borehole
WAgriCo Modelling Nitrate Concentrations (in Groundwater) with Variation in Time
Figure 1
Location of WAgriCo Catchments and NIPPER Model Areas
Entec

Figure 2 Inorganic Fertiliser Use and Modelled Legacy Nitrate Trends for Arable Land



H:\Projects\Hm-250\21464 WAGRICO (Nitrates in) Groundwater Modelling Task8\Data\LT Worksheets\Nitrate Trends OBHs.xls-Figure 3 (ar)



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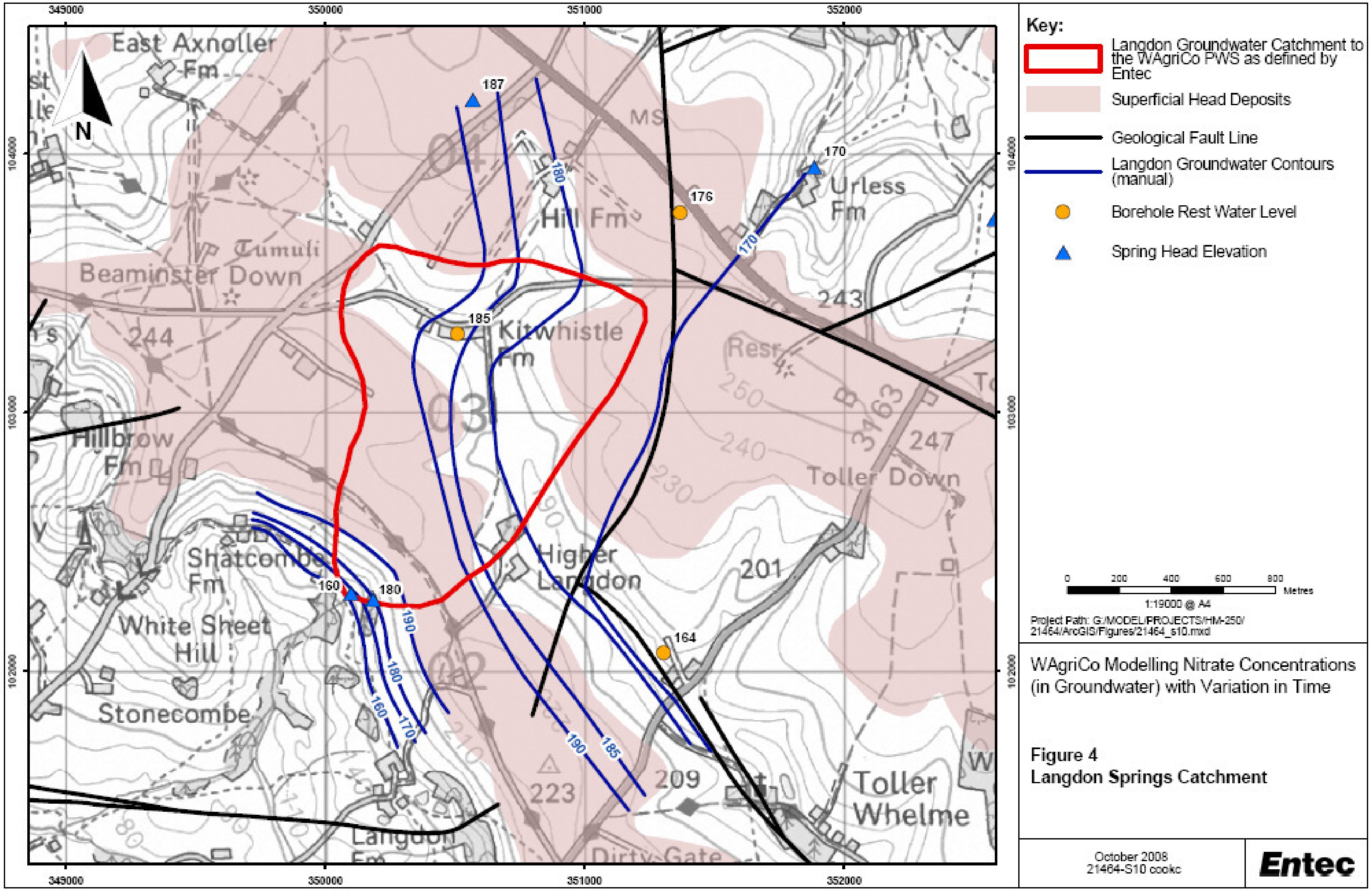
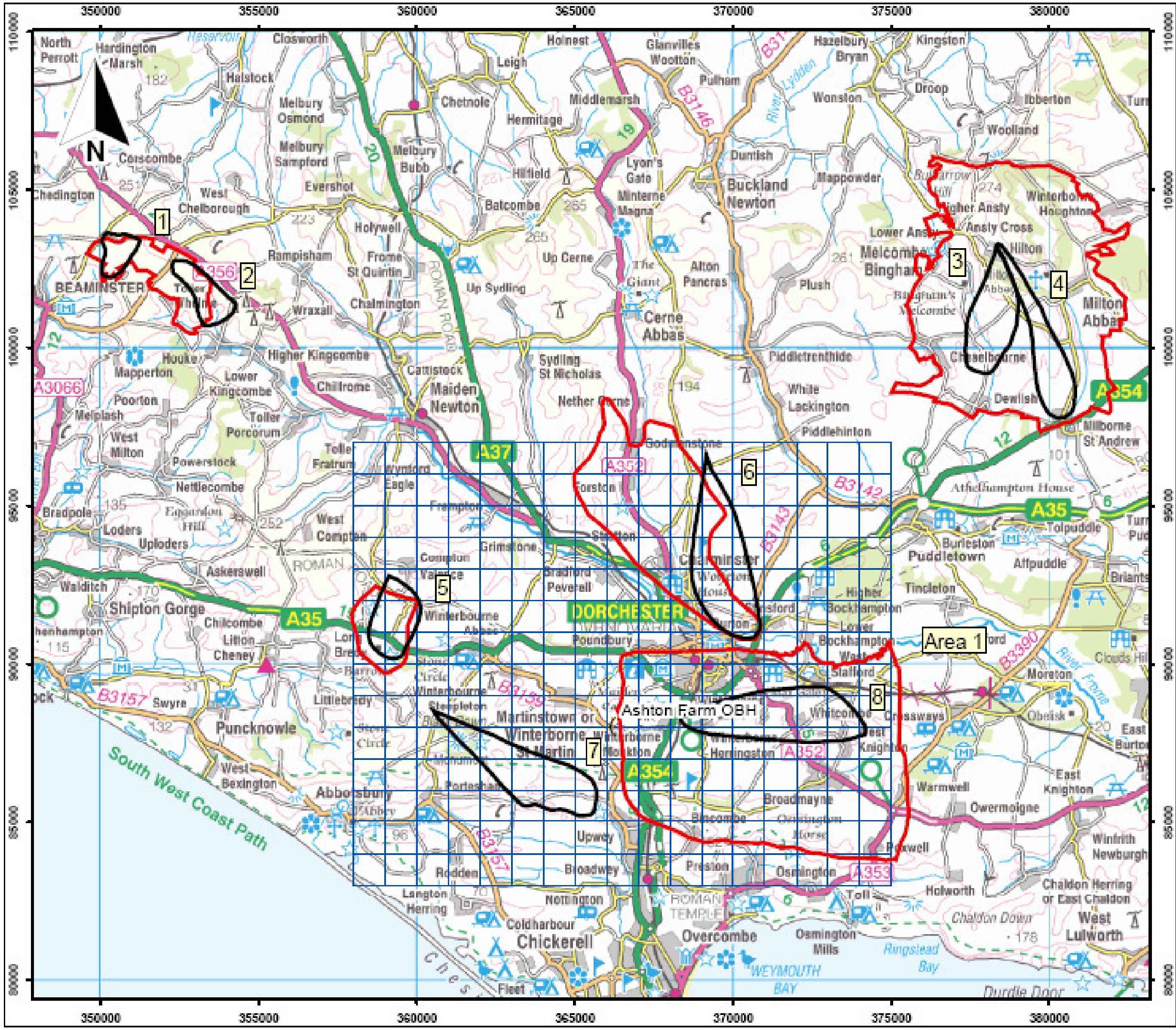


WAgriCo Modelling Nitrate Concentrations (in Groundwater) with Variation in Time

Figure 4
Langdon Springs Catchment

October 2008
21464-S10 cookc

Entec



Key:

- Groundwater Catchments to the WAgriCo PWS as defined by Entec
- WAgriCo Catchment (based on EA SPZ)
- ADAS NIPPER Model Catchment Area
- Observation Borehole

Groundwater Catchments to the WAgriCo PWS

1 Langdon Springs
2 Hooke
3 Dewlish
4 Milborne St Andrew
5 Winterbourne Abbas
6 Eagle Lodge
7 Friar Waddon
8 Empool Catchment

See Figure 1 for WAgriCo catchment names

0 2,000 4,000 6,000 8,000 Metres

1:180000 @ A4

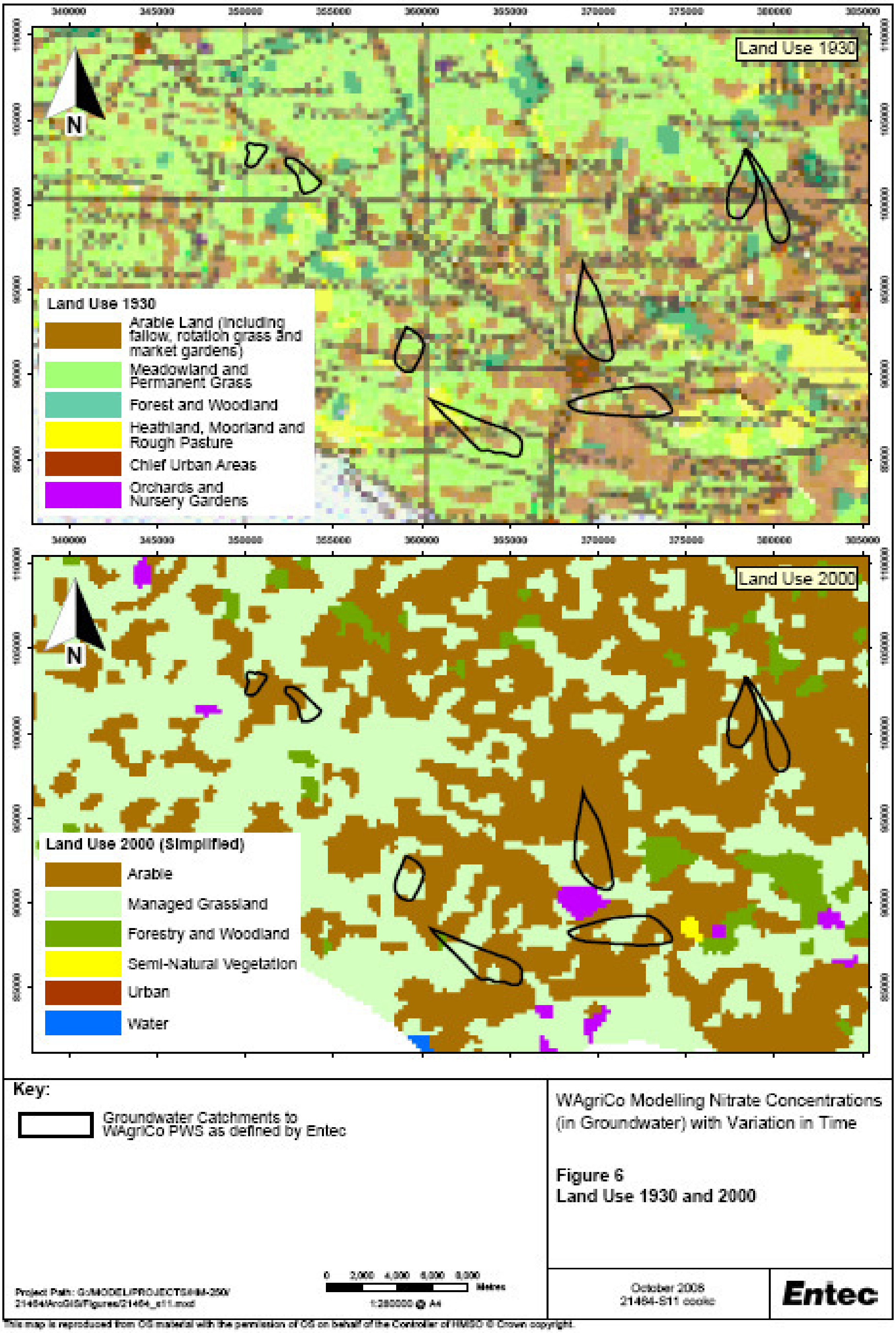
Project Path: G:/MODEL/PROJECTS/HM-250/21464/ArcGIS/Figures/21464_s09.mxd

WAgriCo Modelling Nitrate Concentrations (in Groundwater) with Variation in Time

Figure 5
Groundwater Catchments to the WAgriCo PWS as defined by Entec

October 2008
21464-S09 cookc

Entec



Land Use 1930
Land Use 1930
Arable Land (including fallow, rotation grass and market gardens)
Meadowland and Permanent Grass
Forest and Woodland
Heathland, Moorland and Rough Pasture
Chief Urban Areas
Orchards and Nursery Gardens
Land Use 2000
Land Use 2000 (Simplified)
Arable
Managed Grassland
Forestry and Woodland
Semi-Natural Vegetation
Urban
Water
N
Key:
Groundwater Catchments to WAgriCo PWS as defined by Entec
WAgriCo Modelling Nitrate Concentrations (in Groundwater) with Variation in Time
Figure 6
Land Use 1930 and 2000
0 2,000 4,000 6,000 8,000 Metres
1:280000 @ A4
October 2008
Entec

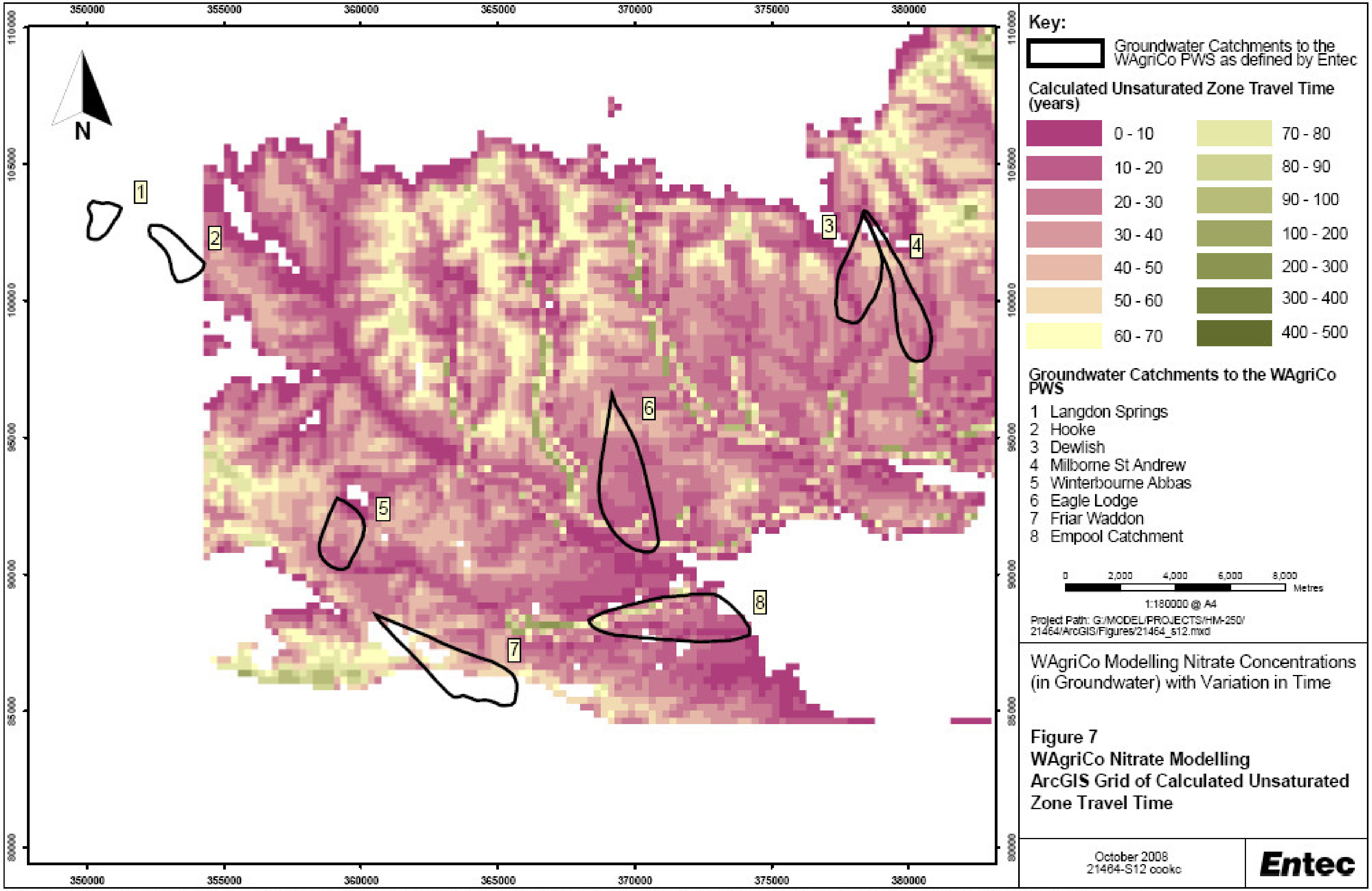

350000
355000
360000
365000
370000
375000
380000
110000
105000
100000
95000
90000
85000
80000
N
1
2
3
4
5
6
7
8
Key:
Groundwater Catchments to the WAgriCo PWS as defined by Entec
Calculated Unsaturated Zone Travel Time (years)
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 100
100 - 200
200 - 300
300 - 400
400 - 500
Groundwater Catchments to the WAgriCo PWS
1 Langdon Springs
2 Hooke
3 Dewlish
4 Milborne St Andrew
5 Winterbourne Abbas
6 Eagle Lodge
7 Friar Waddon
8 Empool Catchment
0 2,000 4,000 6,000 8,000 Metres
1:180000 @ A4
Project Path: G:/MODEL/PROJECTS/HM-250/21464/ArcGIS/Figures/21464_s12.mxd
WAgriCo Modelling Nitrate Concentrations (in Groundwater) with Variation in Time
Figure 7
WAgriCo Nitrate Modelling
ArcGIS Grid of Calculated Unsaturated Zone Travel Time
October 2008
21464-S12 cooke
Entec

Figure 8 Nitrate Variations at Eagle Lodge and Groundwater Levels

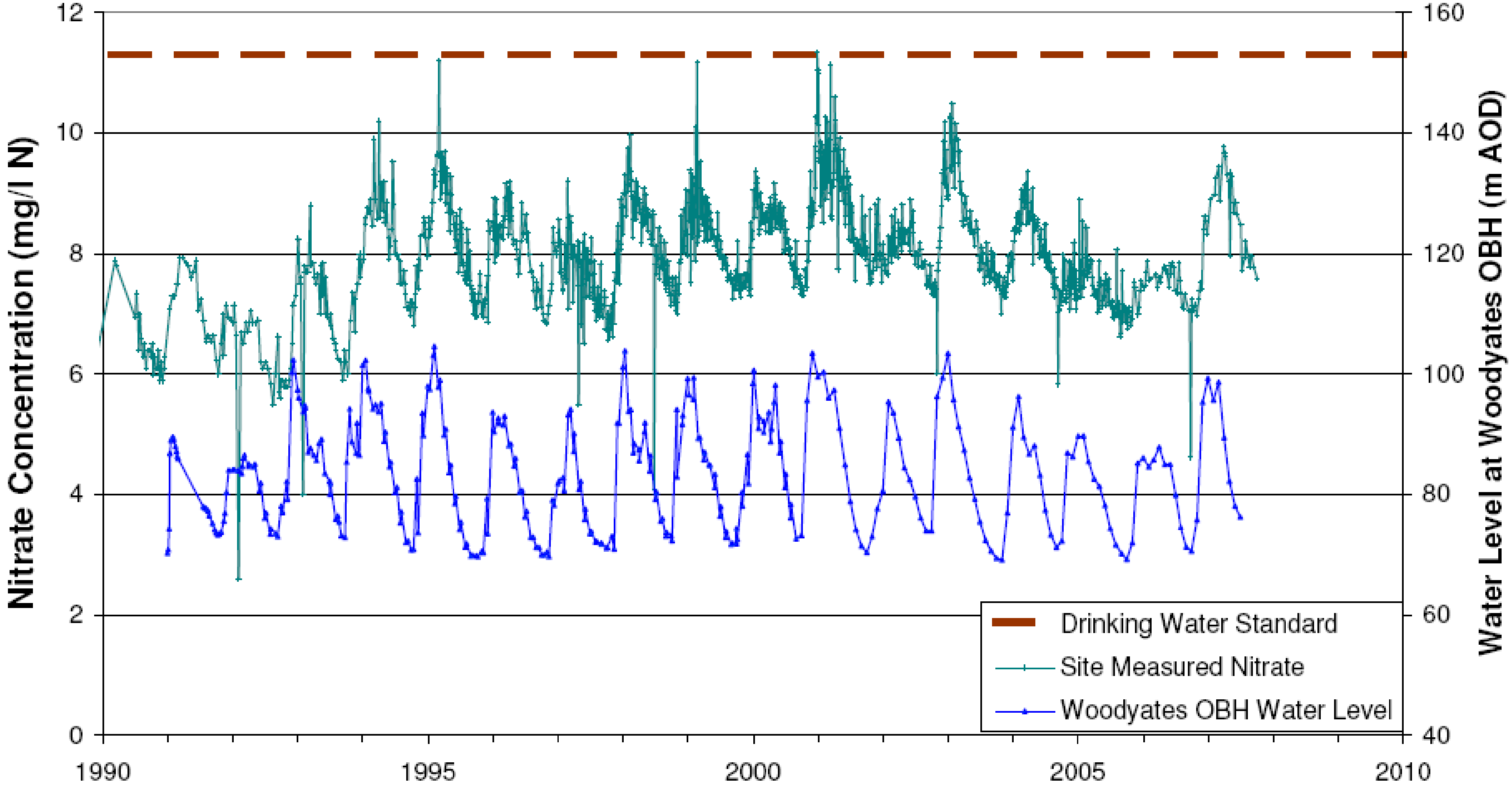


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Figure 9 Shorter Term Variability in Nitrate Concentration at the Friar Waddon Supply

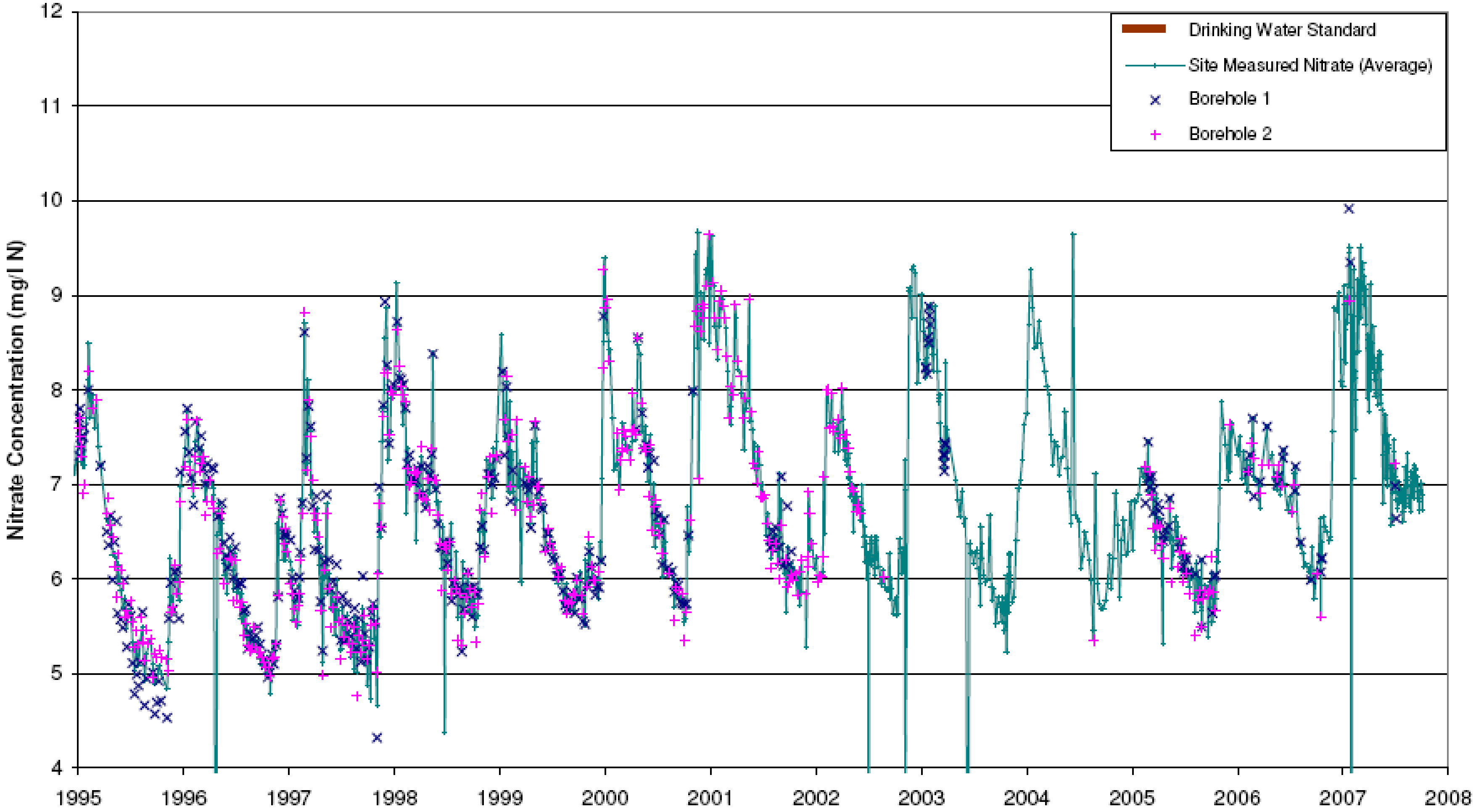

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Figure 10 Shorter Term Variability in Nitrate Concentration at the Eagle Lodge Supply

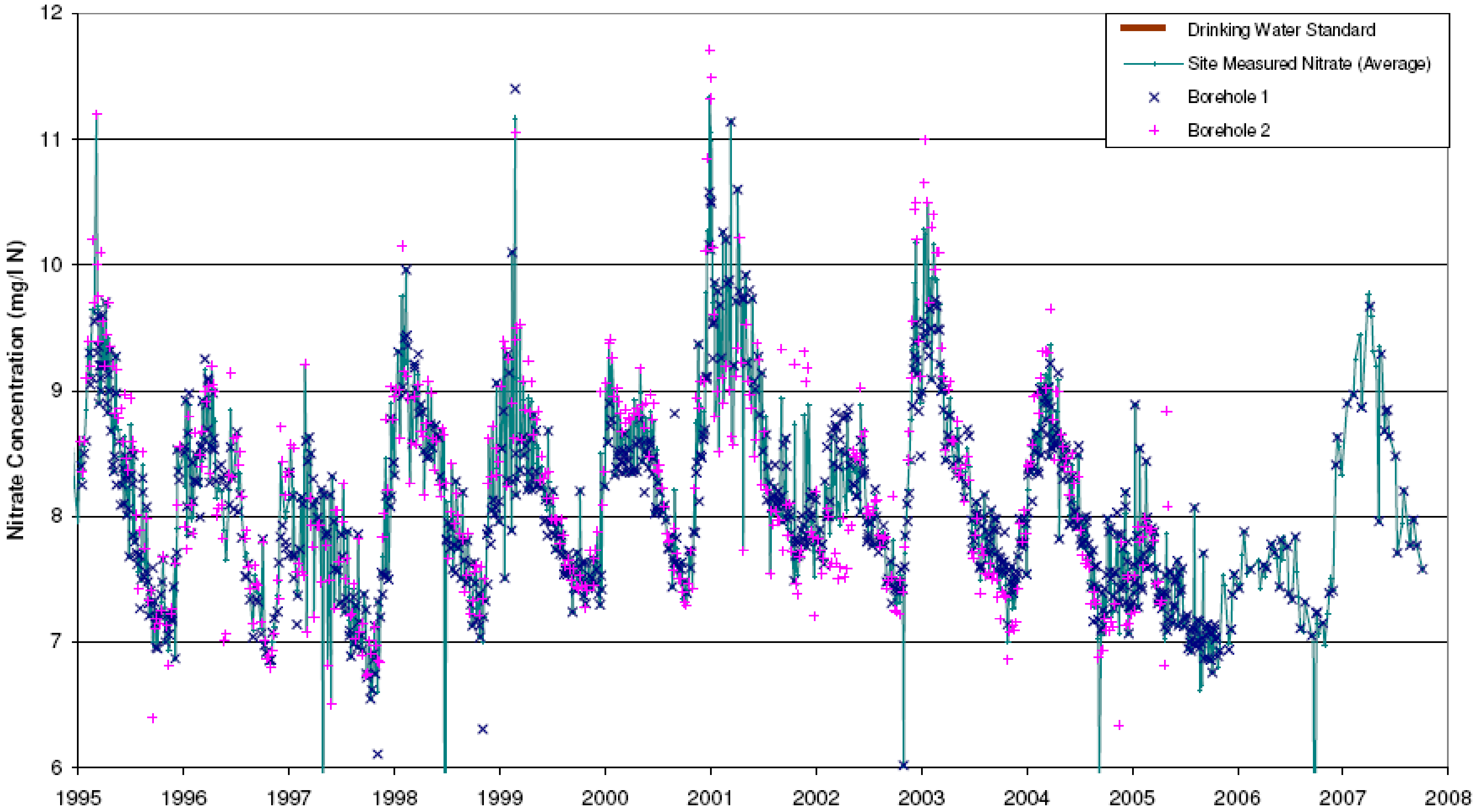

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Figure 11 Shorter Term Variability in Nitrate Concentration at the Empool Supply

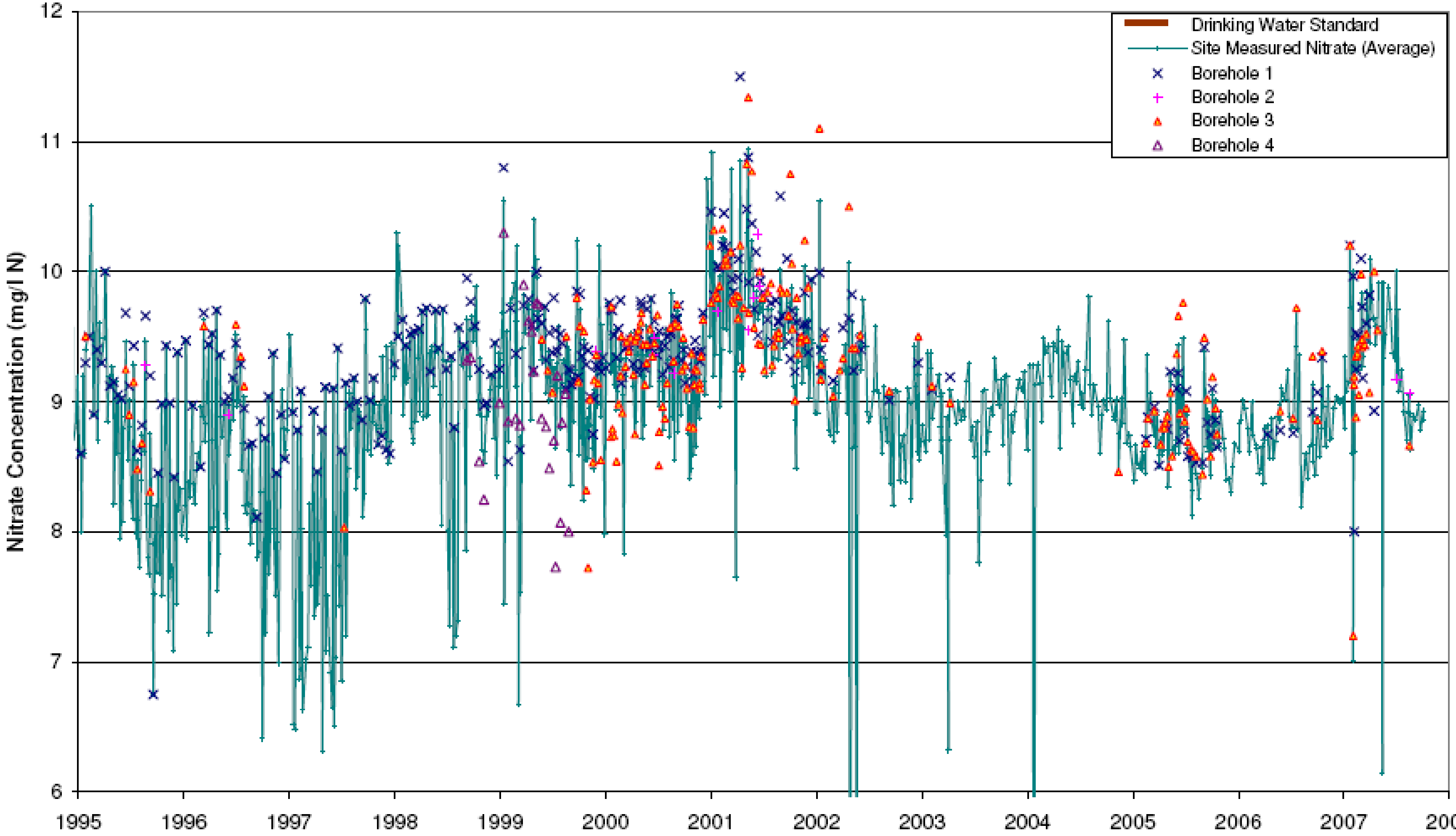

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Figure 12 Spikes and Improved Simulation of Nitrate Concentrations at the Friar Waddon Supply

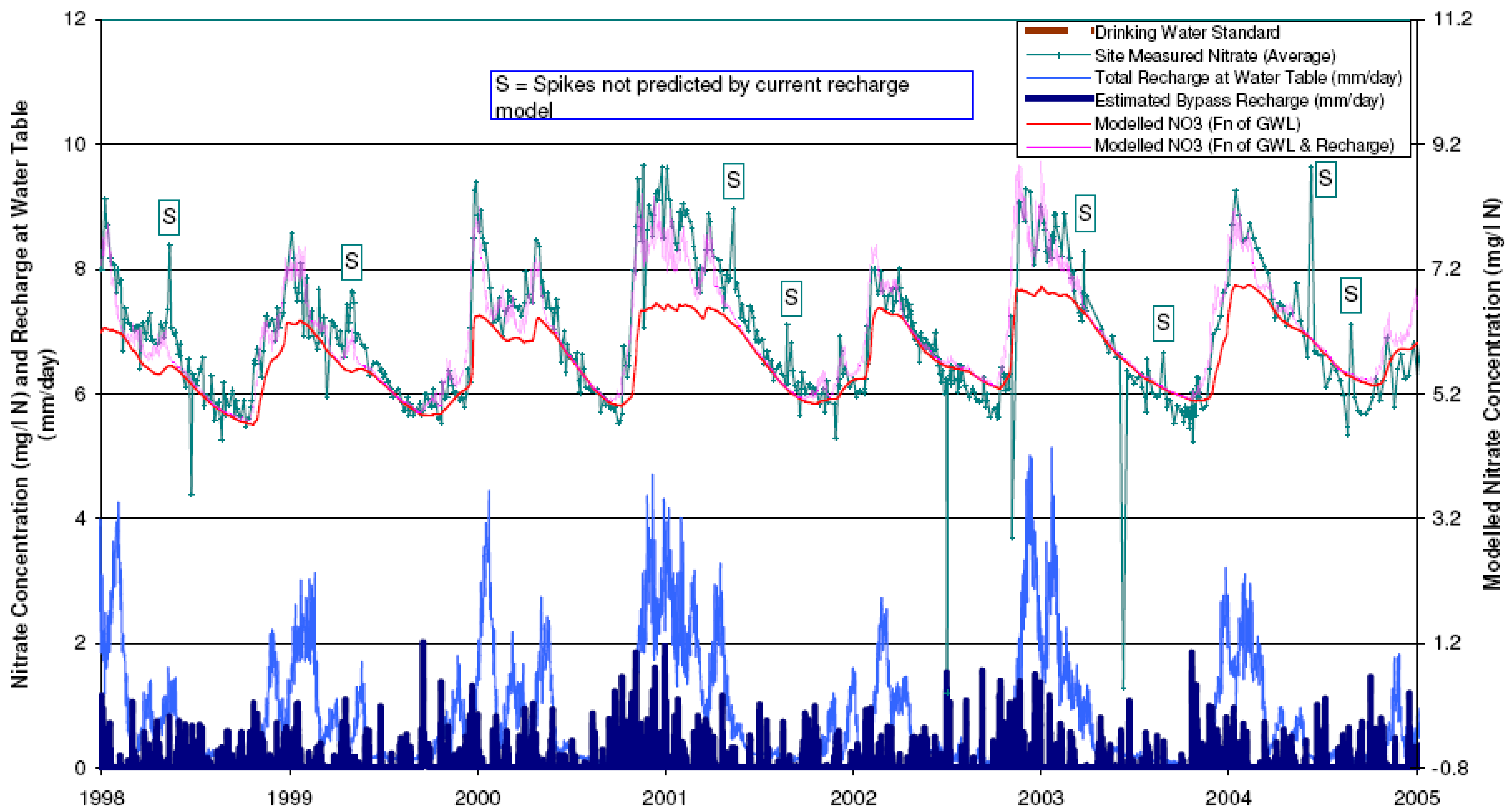

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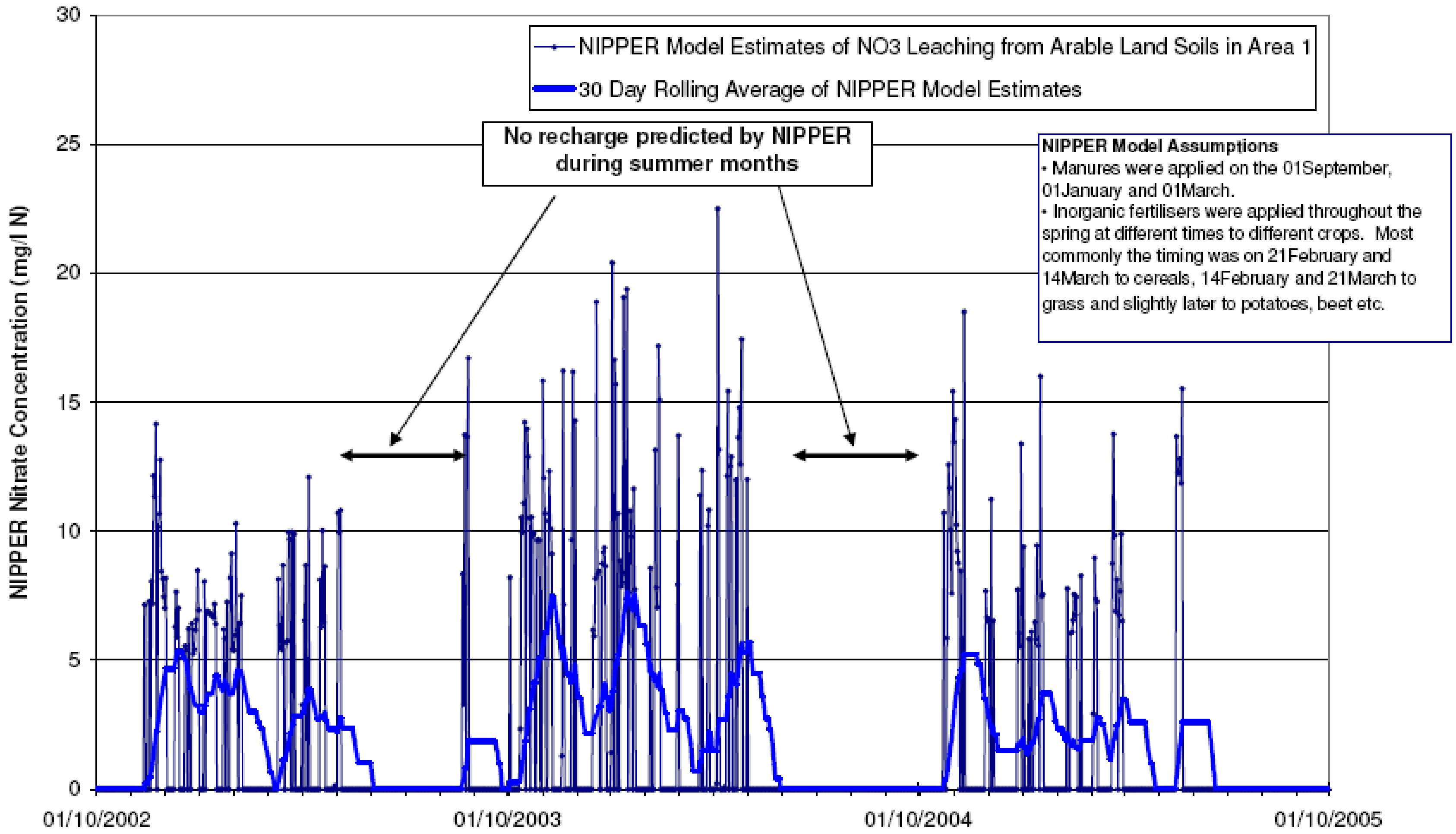
Figure 13 ADAS' NIPPER Model Predictions of Nitrate concentration in Arable Soil Drainage



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