Alston Licence Renewals: Alston Plumsgate Road AN/34/0009/008 and Alston Ludham Road AN/34/0009/009.

Response to the Broads Authority on Concerns Relating to the Groundwater Investigations and Modelling Work

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1. Overview

This document represents part of the Environment Agency response to the Broads Authority consultation response on the Appropriate Assessment for the Alston abstraction licence renewal.

The Environment Agency response to the Broads Authority is in three parts:

- General document prepared by the Environment Agency
- Response to detailed points made by Professor Rushton prepared by AMEC (this document)
- Overall view of the work undertaken by AMEC and of the points made by Professor Rushton prepared by Jan van Wonderen.
- Professor Rushton's main concerns have been described under three headings:
- "misleading" interpretation of pumping tests, and use of derived values in the regional model
- Inadequacy of the 200m grid used in the regional model
- Failure to represent hydrological functioning of the fens

This document addresses these three main concerns. The analysis of pumping test data using a radial flow model, and subsequent use of parameters in the regional model is covered in section 2. It is easiest to combine our response to the latter two concerns, and so section 3 covers both of these.

Section 4 provides a response to certain comments made by Professor Rushton on the Summary Report, which have not yet been responded to.

Section 5 provides a brief review of some of the literature referred to by Professor Rushton in his comments.

2. Pumping test and radial flow analysis

2.1 Purpose of Analyses

As part of the investigations into the effects of abstraction on Catfield Fen, a number of pumping tests conducted on various boreholes over the last 30 years were re-assessed and, where appropriate, re-analysed in order to confirm and increase knowledge of aquifer parameters in the area.

The tests for which the best data sets were available were the tests conducted at the AWS Ludham borehole. Monitoring here comprised multi-level observations in the Crag, and this test therefore has the potential to inform knowledge of vertical hydraulic properties as well as lateral. ‘Standard’ pumping test analytical tests are insufficient for such analysis, and so those tests were analysed using a radial flow model purely as a means of improving the type of analysis available via standard pumping test techniques.

The overall aim of these analyses was not to provide parameter values that would be rigorously applied to the regional model, but rather to assess whether the responses to the pumping tests yielded any information on system behaviour that could be incorporated into the regional model

2.2 Professor Rushton’s Questions on the Radial Model

Professor Rushton has raised a number of questions/concerns regarding the use of the radial flow model. The issues are summarised as follows, together with our response.

The suitability of a radial flow model when the hydrogeology, topography and especially the extent of the fens are not radially distributed about the AWS Ludham source.

Professor Rushton notes that a more reliable and informative analysis of this pumping test could be carried out with a three-dimensional model, similar to that used for the NEAC model, with a finer mesh spacing in the vicinity of the pumped borehole, which would avoid the issue of assuming radial symmetry.

We agree that the use of a regional groundwater model with a refined grid around the abstraction boreholes would provide greater confidence in the analysis, but we consider that this would not materially change our findings (see below). Analysis of pumping tests is more typically undertaken using analytical methods (e.g. curve matching) which assume radial symmetry. For the Catfield Fen site, we have used analytical techniques, a layered radial flow model and a regional groundwater flow model with a daily time step. We consider that this represents a robust approach, above the level of analysis normally undertaken for determination of groundwater abstraction licences.

The issue of radial symmetry was understood in undertaking the analysis and is acknowledged in Section 5.3 of the main report, namely:

“It is of course recognised that the real system is not comprised of uniformly flat geological layers possessing radial symmetry, but nevertheless the model provided a useful means of investigating the observed pattern of responses to the test, and is a valuable improvement on standard analytical techniques”.

For this reason the regional model was used to undertake a more detailed analysis of the impacts of abstraction on Catfield Fen. We would also note that the radial flow analysis focussed on the first 7 days of the test (see Figure 5.1 of the main report) and the therefore issues of non radial symmetry are likely to be less significant.

A physically unrealistic assumption at Layer 1 is introduced to reproduce the response of a shallow piezometer

Investigations using the model showed that a near surface low permeability layer was apparently required in order to generate sufficient drawdown at borehole P3 within the upper part of the Crag at distance (450 m away from the pumping borehole). A similar observation was made by Atkins/HSI (2003) who also analysed the test results using a radial flow model. It is possible that this reflects a delayed drainage response (Grout, 1988) that cannot be simulated by this radial model, or it may be an artefact introduced by the need for radial symmetry within the model, and the parameters for model layer 1 should be considered to be not well constrained.

No explanation is provided as to how the results of radial flow modelling has led to refinements of how the Crag aquifer is represented in the NEAC model.

Section 5.4 of the main report notes that "the aquifer parameters derived from the radial flow model, and in particular the information concerning anisotropy, were used to inform the NEAC regional groundwater flow model which is used for predicting the influence of pumping on groundwater levels below Catfield Fen".

The values of Crag transmissivity and horizontal hydraulic conductivity derived from the radial flow model analysis of the pumping test were combined with values from other pumping test analyses to help determine the hydraulic conductivity distribution used in the regional model (see Figures 7.8 and 7.9 of the main report). Anisotropy values are discussed further below.

Definition of a constant head boundary at an outer radius of 10km.

The definition of the model boundary was a simple expedient to ensure that it did not appreciably affect modelled drawdown for the period of analysis.

The vertical hydraulic conductivity of two of the model layers is very low and results in a 'bulk hydraulic anisotropy of 1000'.

This aspect is discussed in more detail in the following section.

In summary, it is important to note that the limitations and approximations involved in 'standard' pumping test analysis techniques, and in radially symmetric flow modelling, are well understood. Nevertheless, these types of analysis do offer some knowledge regarding system behaviour. For this application, the analyses were used to inform the parameters used in the regional model, which is not bound by limitations imposed by radial symmetry. The parameters for layer 1 of the radial model were not used in the regional model, since they are envisaged to be an artefact (see above), however the need for anisotropy was taken forward to the regional model for further assessment, albeit using less severe values than derived from the radial flow analysis. Compared to the radial analysis, the response of the regional model, using daily time steps, in simulating observations is judged to be a much better indicator of whether hydraulic parameters are appropriate.

2.3 Anisotropy

Professor Rushton has suggested that the anisotropy value of 1000 is unrealistic, and has also recommended reference to Cookey, Rathod and Rushton (1987) for further information on anisotropic approximations for layered aquifers. This paper describes the results of experimental work, using a resistance-network analogue and digital radial flow models. The model domain was 100m thick and extended to a radial distance of 10000m. "About 20" mesh intervals were used in both radial and vertical directions. The outer boundary was "assumed to have the condition of zero drawdown". Most of the models described did not allow drawdown of the phreatic surface, although one of the key analyses was the examination of how vertical flow from the phreatic surface varies with distance from the well.

Some of the work concentrates on aspects of well design for water extraction from 'layered' aquifers, and so, for example, models were set up to investigate the effects of partial penetration and of different screen depths, and the results analysed included the approach velocities at the well face. An initial homogeneous isotropic aquifer was used as a baseline, and subsequent models introduced thin discrete horizons of low and high hydraulic conductivity. Unsurprisingly, these models found that, for situations in which low permeability layers were introduced, the influence of abstraction propagated to a greater distance from the well. In particular, the pattern of volume of water drawn from the phreatic surface with distance from the well is similar to the baseline case, but extends to greater distance.

Cookey et al also constructed a homogeneous but anisotropic model that was equivalent to a layered model with zones of high and low permeability. Horizontal hydraulic conductivity was set such that overall transmissivity was the same as the layered model. Vertical hydraulic conductivity was calculated by an appropriate formula, noting that head loss across each layer is inversely proportional to the vertical hydraulic conductivity.

For the parameter values used by Cookey et al, this model had an effective anisotropy of around 20. Comparing results against a layered model, Cookey et al found that the anisotropic model generated flows from the phreatic surface that were quite similar to the layered model, although in the anisotropic case, the greatest flow for the phreatic surface occurred at a slightly smaller distance from the well (one node of their model).

The pattern of approach velocities was significantly different between the anisotropic model and the layered model. This may be important when considering well design, or contaminant transport issues, but is not relevant to the current discussion.

Cookey et al also investigated a homogeneous model with an approximation to a moving phreatic surface: this (probably more realistic) model was found to generate flows from the phreatic surface at greater distance compared to the baseline model.

The formula used by Cookey et al to calculate vertical hydraulic conductivity for the anisotropic model is exactly equivalent to the "thickness weighted harmonic mean" that was used in the NEAC model. Using the values of vertical hydraulic conductivity from the radial flow analysis, the equivalent anisotropy calculated for the upper part of the Crag (i.e. from the top of the uppermost permeable layer to the middle of the central permeable layer, and including the intervening clay layer) is 2434, and for the lower part of the Crag is 1216. Taking the whole of the Crag together, a value of 1819 is calculated.

Recognising that the calculation is most sensitive to the low hydraulic conductivity values, a value of 1000 was chosen for further assessment within the regional model.

Professor Rushton has noted that the clay layers may not be continuous, and that, even if high effective anisotropy values existed in some places, significant spatial variation might be expected. However, the work of Holman (1984) and Holman et al (1999) has identified the presence of at least one laterally extensive, continuous clay horizon within the Crag, extending across and beyond their study area, which was focussed on the Thurne catchment, but also included the lower catchments of the Ant and the Bure. In the Ludham-Catfield area, the top of this clay was estimated to be at around -15 mOD.

The presence of even a thin layer (or several very thin layers) of 'tight' clay could impart significant anisotropy to the Crag. For example, if a total thickness of 0.4m of clay with a vertical hydraulic conductivity of 0.0001 m/d is present within a 40m Crag sequence with a hydraulic conductivity of 10 m/d, this gives a calculated anisotropy of 991.

2.4 Implications for regional model

Results from the radial model were used to inform the regional model. Up until the radial modelling was done, simulations with the regional model had used Crag anisotropy values of 10 or 100, but had not been successful in reproducing some of the observed features of water level responses to abstraction. This applied throughout the area of interest, with signals from abstractions at AWS Ludham, Alston Ludham Road and Alston Plumsgate Road not being well reproduced by the model.

Introduction of the higher anisotropy value (i.e. of 1000) supported by the radial analysis improved the simulation of abstraction signals considerably. Figure 1 illustrates improved responses at the Sharp Street piezometers (affected by AWS Ludham), at boreholes TG32/801 and 805 (affected by Alston Ludham Road), and at the two piezometers at different depths near Plumsgate Road.

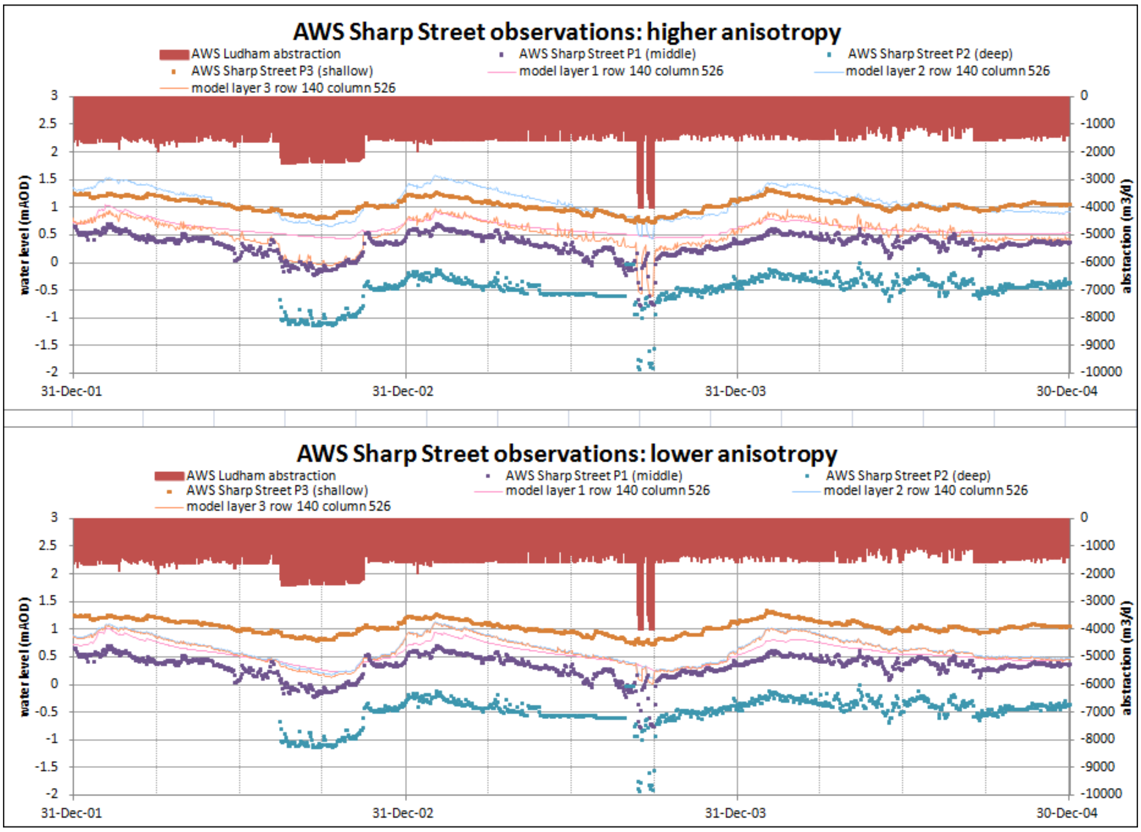

Figure 1. Simulated water levels at AWS Sharp Street

Note the lack of response of the low anisotropy model to the long duration signal test in 2002 and the two short tests in 2003. Absolute levels in the high anisotropy model are a little high, but the simulation of the abstraction signal is much improved. The separation between heads measured in the upper and lower parts of the Crag is also improved.

Figures 2 and 3 show observed and simulated water levels at two locations not far from the Alston Ludham Road abstraction. TG32/805, Figure 2 is very close to the Alston Ludham Road and is believed to respond to changes in the upper part of the Crag; little response to abstraction is seen here, whereas an observation location further away (TG32/801, Figure 3), believed to respond to changes in the middle part of the Crag, shows some subtle response to the abstraction in summer months. This is most clearly seen in May and June 2010, and in May and August 2011. This was difficult to understand until anisotropy was considered. At TG32/805, both the high and low anisotropy simulations show clear responses in the middle part of the Crag (model layer 2) to the seasonal abstraction, but the low anisotropy model shows a response to these abstraction events (albeit small) in the upper part of the Crag as well, i.e. contrary to the observations, whereas the high anisotropy model shows virtually no response. At TG32/801, the low anisotropy model shows virtually no response, which is also contrary to observations, whereas the high anisotropy model simulates the observed signal well. This suggests that the high anisotropy model is applicable.

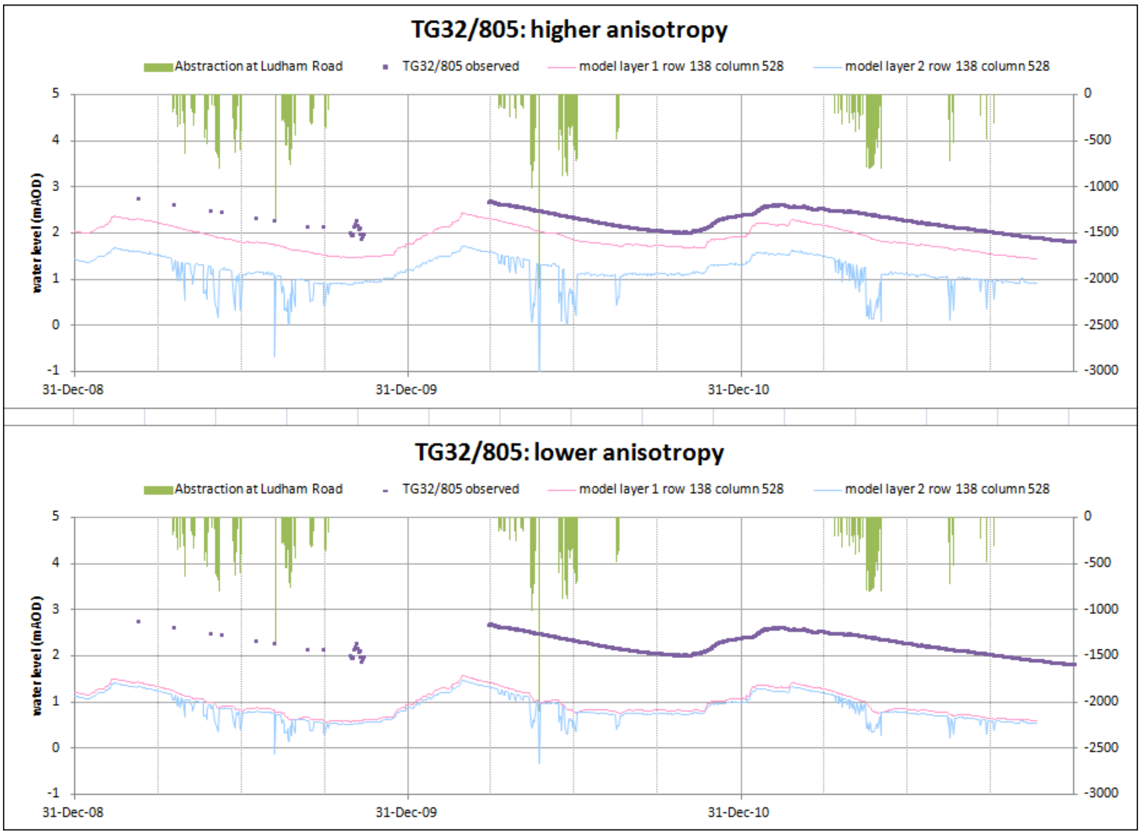

Figure 2. Simulated responses at TG32/805 (near Alston Ludham Road)

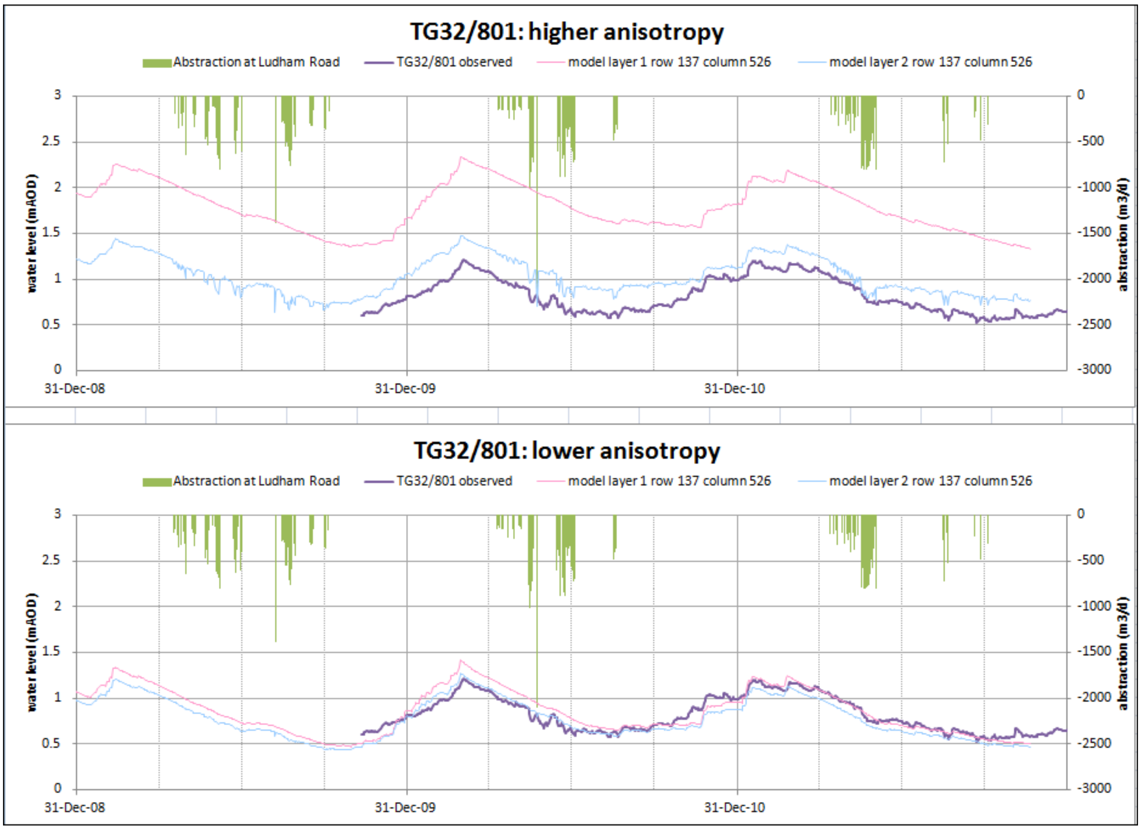

Figure 3. Simulated responses at TG32/801 (between Alston Ludham Road and Catfield Broad)

The model responses at the Plumsgate Road observation locations exhibit less difference between the two simulations. This is partly because the model structure only allows one layer to represent the Crag at this location. Subtle responses to abstraction can be seen in the observed data from the deeper monitoring point (at 15m depth) in summer and autumn 2009. These are well simulated by the strong anisotropy model, but the lower anisotropy model shows a more subdued response. Water levels measured in the shallower borehole are adequately simulated by both models.

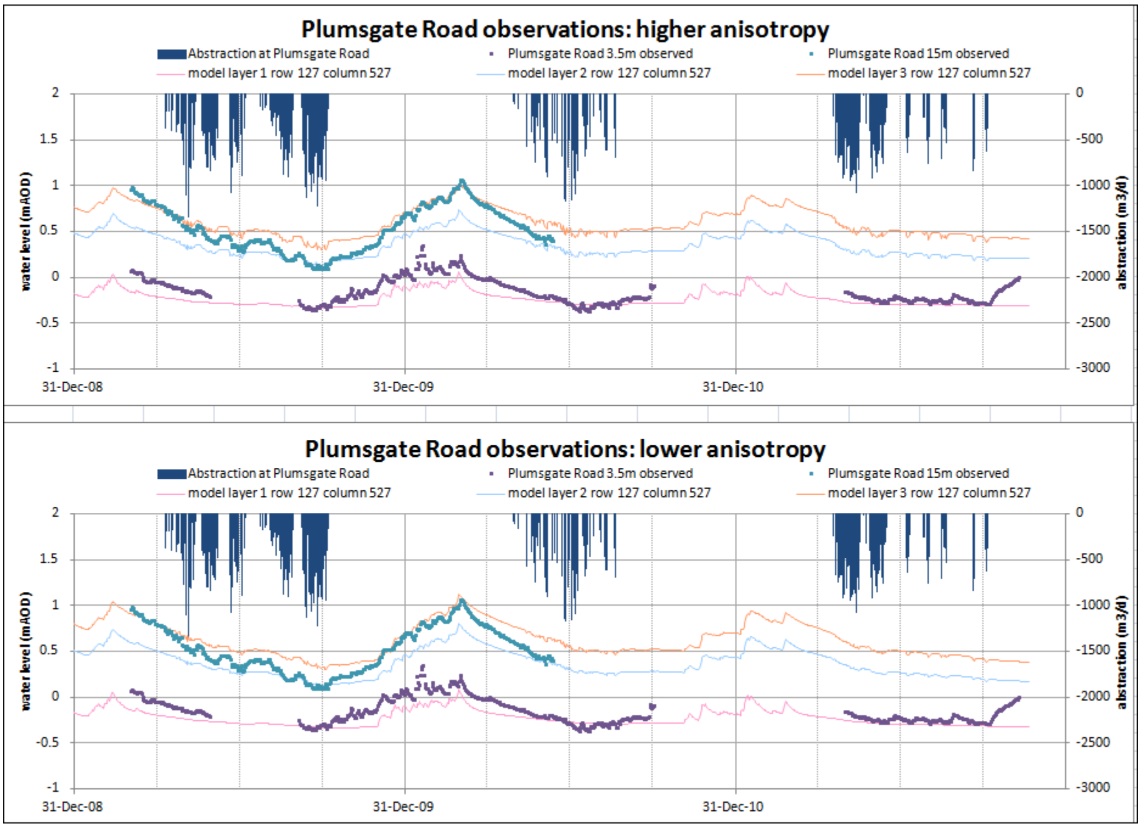

Figure 4. Observed and simulated water levels near Alston Plumsgate Road

The appropriateness of the relatively strong anisotropy value is particularly indicated where multi-level monitoring exists, since it has been beneficial in improving the relative responses at different levels within the Crag. It also improved simulation at the majority of single level installations within the Crag across the whole of the ‘high’ ground in the centre of the area of interest. Note however that these observations are all periodic manual dips, and no abstraction signals can be readily discerned. Two examples are shown below.

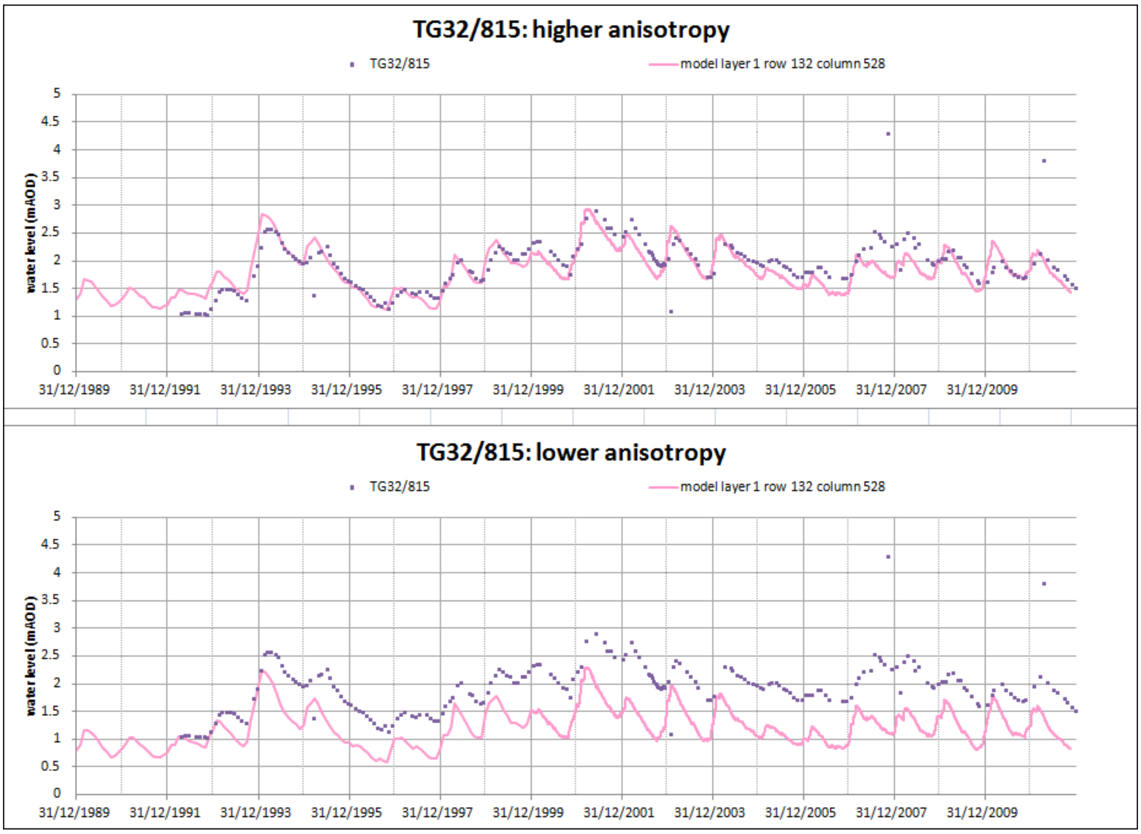

Figure 5. Observed and simulated water levels at TG32/815 (near Catfield Village)

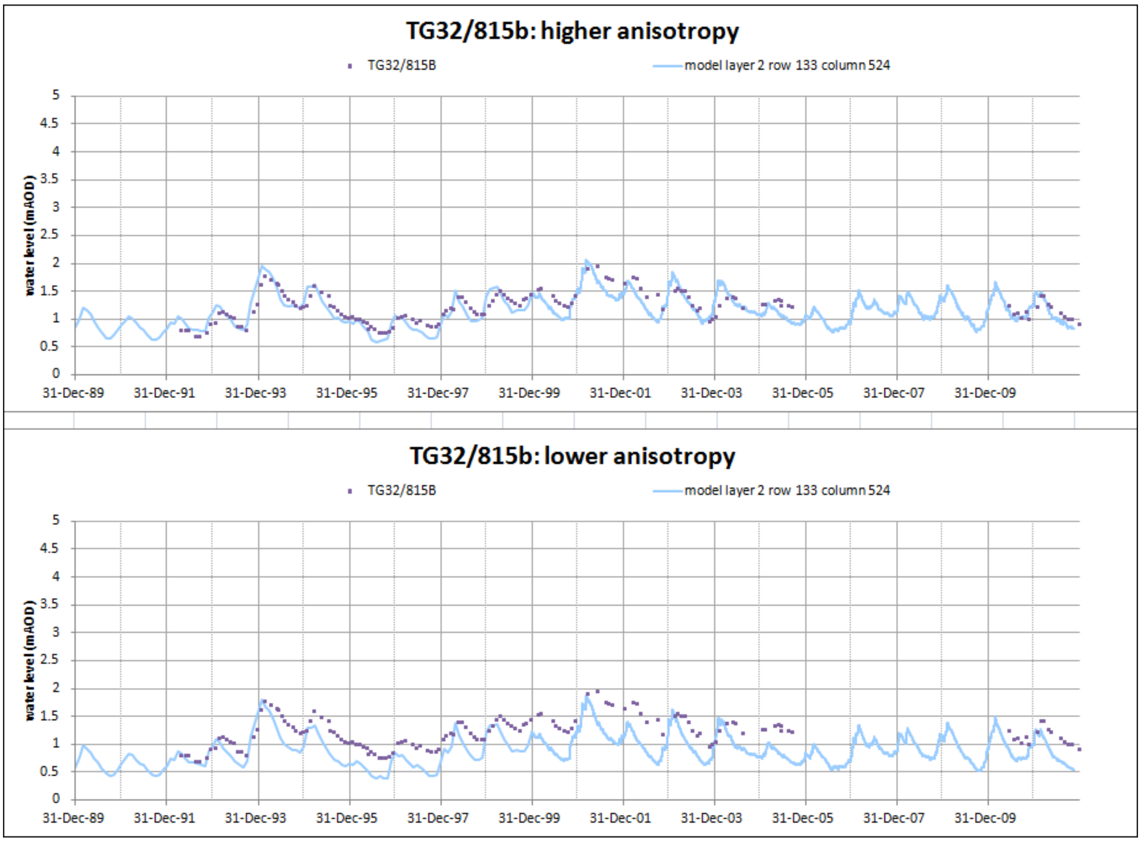

Figure 6. Observed and simulated water levels at TG32/815b (near Catfield Hall)

In summary, evidence from the field and from model behaviour suggests that the Crag aquifer in this vicinity exhibits strong lateral to vertical anisotropy, and models incorporating this value have been used in the assessment of abstraction in the Ludham-Catfield area. However, we acknowledge that it is a higher value than is often found, and given that Professor Rushton has raised concern that the use of a high value of anisotropy will minimise the impact of abstractions at Catfield Fen, we have examined what the effect of a lower value would be. We have therefore compared ‘naturalised’ and ‘historic’ (i.e. including the known history of abstraction) simulations with both low and high anisotropy.

The effect of the differing anisotropy values on calculations of water level change is shown on Figure 7 for the Assessment Cells. On all graphs, the blue line shows the results from the high anisotropy model, and the brown line the results from the low anisotropy model. The same vertical scale is used on all graphs to allow comparison between cells. Figure 7 shows that, when compared to the lower value, the strong anisotropy values used give rise to slightly greater calculated impact at Cells C, E, I and J, and slightly lower calculated impact at Cells G and H.

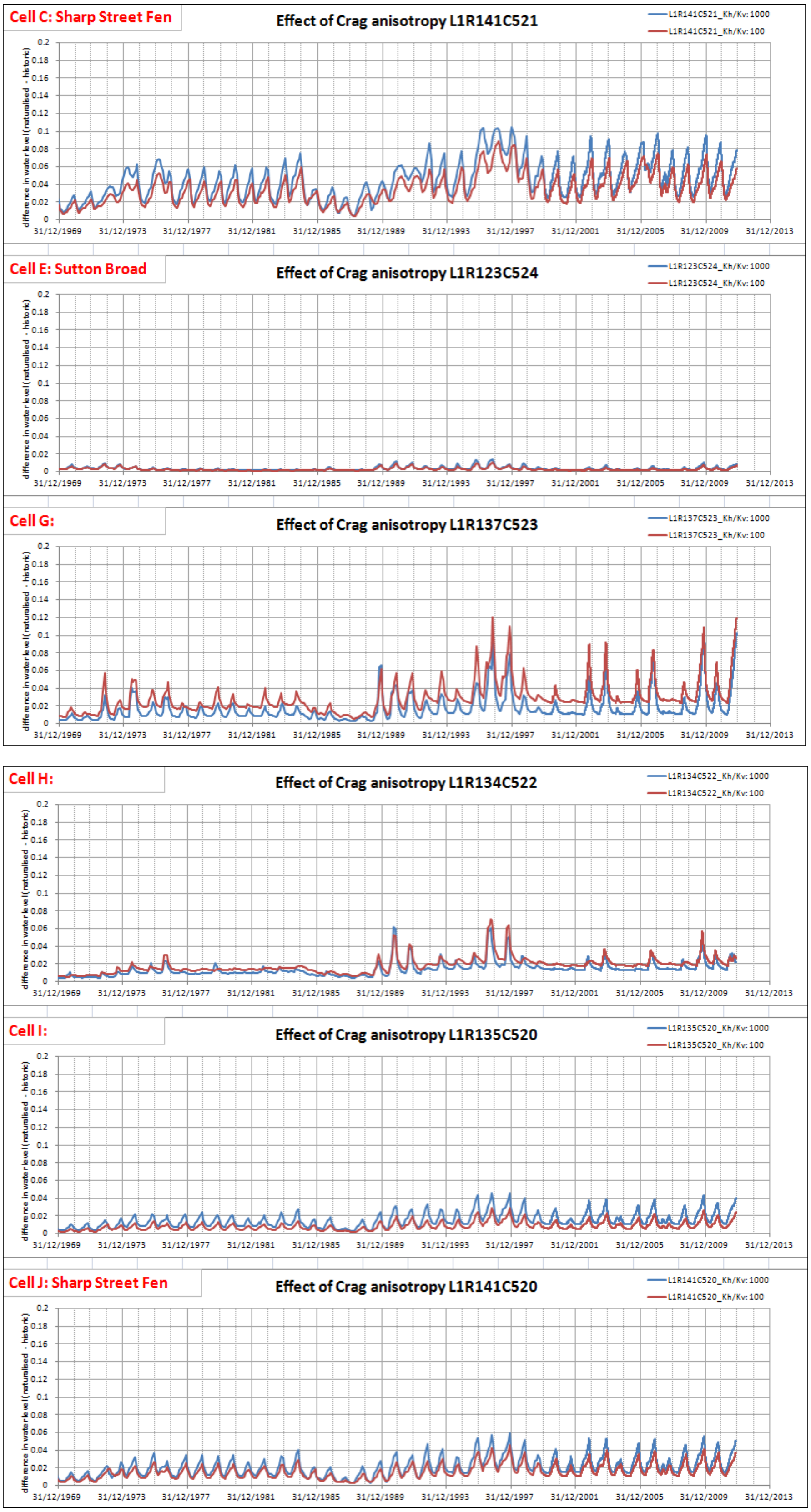

Figure 7. The effect of abstraction on water levels for high and low anisotropy models

These differences vary spatially as shown on Figure 8. Green symbols show where the model used for the assessment calculates a larger maximum effect than an alternative simulation that has lower lateral:vertical anisotropy. Red symbols show where the alternative simulation calculates a larger maximum effect. The label values give the magnitude of the difference in abstraction effect (shown as positive for green symbols, negative for red symbols). Note that this map does not constitute an ‘assessment’ of any kind, since it does not indicate differences in threshold breaches for example, and is provided as indicative information only.

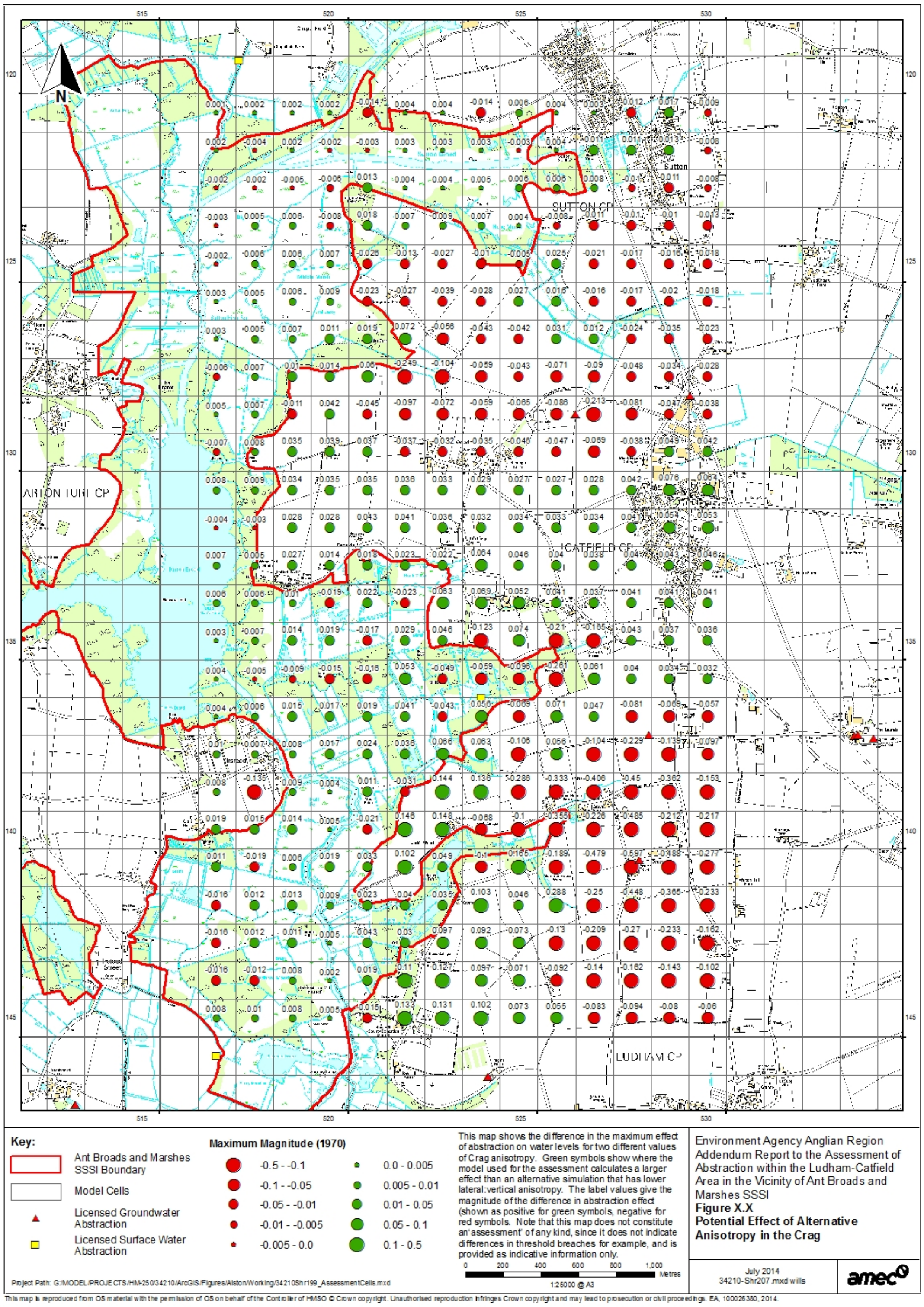

Figure 8. Potential effect of alternative anisotropy on predictions of water level change

Not surprisingly, this shows that the strong anisotropy value estimates smaller maximum changes to water table elevations close to the abstractions, and greater maximum changes further away. Other influences such as the geometry of the geological formations cause some local variations to this overall pattern. Over the majority of Catfield Fen, Sutton Broad and Sharp Street Fen, most differences are of small magnitude, but the strong anisotropy value generally estimates greater impact, the main exceptions being the area around Catfield Broad and at Snipe Marsh. The relative behaviour between these two simulations is consistent with the findings of Cookey et al (1987). This comparison demonstrates that Professor Rushton's concern that the high anisotropy ratio "results in a serious distortion of flows, minimising the impact of pumping on groundwater flows into the fens" is unfounded in the case of Catfield Fen.

The calculated impacts derived from the use of the strong anisotropy value in the assessment may perhaps be considered conservative for most areas of Catfield Fen.

3. Grid size and hydrological functioning

3.1 Grid Size

During the latter stages of development of the regional model, internal consultation within the Agency raised a potential concern that the 200m grid size used may not be capable of representing all the hydrological detail relevant to Catfield Fen, and specifically that it may under-estimate the likely effects of abstraction. This concern was also raised during external consultation.

In response to this concern, the Agency considered the construction of a fine grid model of the area, but this was discounted on the grounds of disproportionate cost weighed against the perceived benefits. In the first instance, a numerical experiment was conducted to assess the potential effect of grid size on model predictions. This comprised building a small model with relatively simple structure but which encapsulated the essential features of the system. The same model structure was spatially discretised at three different resolutions, and the results compared. This work is written up in the 'Grid Size Technical Note' that was distributed to interested parties at the same time as the Agency Summary Report.

Professor Rushton has provided some comments on the "Grid Size" Technical Note. Italicised text within quotes in this section is taken from his comments.

"*Unfortunately the author fails to grasp….*" This is simply not true: we understand the issue. There is no doubt that a finer grid model would allow better placement of features in their geographic context, but it is less clear whether a finer grid would make a real difference to the main aim of this investigation, which is to assess the impacts of abstraction. The mechanism by which abstraction may impact the fens is by reduction of groundwater flow towards and into the fens. This can be adequately achieved by the regional model together with appropriate analysis and post-processing.

"*Since this Technical Note fail to address the questions raised, most of the findings are of little value.*" We disagree with this statement: the exercise was a valid experiment to assess the implications of the coarse grid on modelled impacts, and the potential need to move to a finer grid. Indeed Professor Rushton then continues that "*there is one aspect which provides insights…*", i.e. stream boundary condition configuration. This was in fact one of the main reasons for undertaking this study.

"*In the Technical Note, attempts are described of adjusting aquifer parameters in the fine grid model with the single stream, to reproduce the 200 m by 200 m groundwater heads; this can almost be achieved (run 18.5), but only by increasing the hydraulic conductivity one-hundred fold!*"

This is true, however, we note that the hydraulic conductivity of the peat in the reference model is 0.1, which is a relatively low value, and that the reference model is not especially sensitive to this value (acknowledged to be partly because of the presence of stream boundary conditions across the fen). Although we have not run such a model, a reference model with a peat hydraulic conductivity value of say 1m/d would be expected to produce similar results. The increase of peat hydraulic conductivity to 10m/d would therefore be a ten-fold increase, which is clearly not as extreme.

Letts et al (2000) present a range of hydraulic conductivity values for peat: median values for 'fibric', 'hemic' and 'sapric' peats are 19.4, 0.17 and 0.009 m/d respectively. Dawson (2006) presents sixteen field measurements of peat hydraulic conductivity values for West Sedgemoor: these range from 0.24-3.57 m/d. Dawson also presents mean values from 27 laboratory analyses: these are 1.511 m/d for 'peaty loam', 1.551 m/d for 'humified' peat and 2.296 m/d for 'semi-fibrous' peat. Sadler (1989) presented several values (after Metcalf, 1988) for Catfield Fen: there is one value of 0.0022 m/d, a group of four values between 20-32 m/d and six values between 430-8340 m/d. The high values are attributed to the tests being conducted in "infilled dykes".

Also, we note that Dekker, Barendregts, Bootsma and Schot (2005) describe a simulation of a fen in the Netherlands in which peat rafts are assigned a hydraulic conductivity of 10-100 m/d and "organic muck", likely to be equivalent to the former turbary features found on Catfield, is assigned a value of up to 2000 m/d.

In the context of the above data sources, a value of 10m/d (as postulated in the technical note) does not seem especially high.

Furthermore, we note that the use of widely spaced stream cells results in unrealistically high heads (several metres above ground level). This suggests that, if peat hydraulic conductivity really is as low as 0.1 m/d, then there is an alternative mechanism that removes water from the fen: this could potentially be ponding and subsequent 'overland flow', enhanced evaporation or the presence of additional small ditches/channels. If we had run a simulation with streams spaced at, say 50m, then a lower hydraulic conductivity value would have been required to achieve 'acceptable' results.

If a finer grid model incorporating "all the detail" were to be produced, and gave results that did not correspond to observations, a hydrogeologist/modeller would assess whether the parameter values and boundary conditions were appropriate, and would make suitable adjustments. These might include changing hydraulic conductivity values within credible ranges, and/or introducing modified boundary conditions, perhaps along the lines of those suggested in the preceding paragraph. The end result would be a model which simulated observed water levels to a satisfactory degree. This is normal practice, so we do not understand why Professor Rushton claims that the statement of such in the Grid Size Technical Note is "*misleading and unsafe*". The most important aim of the fine grid model experiment was to assess how different any calculations of 'impact' might be. The two models that were eventually compared in the Grid Size work exhibited groundwater levels that were similar in character, but around 25-30 cm different in the centre of fen compartments: this seems a reasonable reflection of probable water table variability. Abstraction impacts for these two models, derived using the accepted Review of Consents methodology, were shown to be similar.

Professor Rushton's comments on the Grid Size Technical Note conclude by suggesting that a "*methodology for including features of drained fens in regional groundwater models has been developed for an investigation into drain-aquifer interaction in the adjacent Upper Thurne catchment*", and that "*the Upper Thurne study highlights the need to represent individual features of drained fens in groundwater models*."

Drains are represented in the Upper Thurne model in a very similar way to NEAC, i.e., using boundary condition mechanisms available in Modflow (it is not clear whether a 'drain', 'river' or 'stream' condition has been used, although they are all similar), albeit using conductance values derived using methods proposed by Rushton (2007). The only unusual feature of the Upper Thurne model is the presence of a 'connective' layer between the overlying peat and underlying Crag: additional drains (actually incorporated as 'General Head Boundary' conditions) are included throughout the model in this layer to represent under-drainage.

The model of the Upper Thurne does not represent individual features: there are many instances where there is more than one drain in a model cell (see section 5 for more detail on this reference).

3.2 Water levels

One of the concerns over the use of a 200m grid size when considering conditions at Catfield is that there may be variation of water levels within a cell, and that this variation cannot be included in any assessment of 'impact'. It is therefore perhaps worth considering how much variation in water level behaviour is observed over relatively short distances.

In the western part of the Internal System are a line of five dipwells, spaced at approximately 20m intervals with the line perpendicular to two ditches. All are installed to around 1-1.5m depth. The central dipwell is equipped with a datalogger, but manual readings are also taken. Observed water levels in the five dipwells are shown on Figure 9.

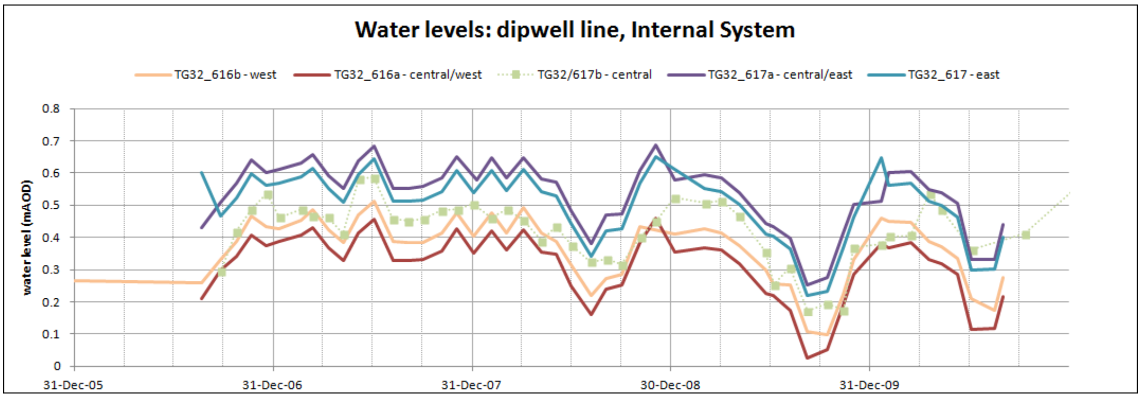

Figure 9. Observed water levels in the line of dip wells in the Internal System

Higher water levels are recorded in the east of the line of dipwells, and lower levels in the west, although the data do not exhibit a simple east-west gradient. Irrespective of location, the pattern of response in all dipwells is very similar, reinforced by examining the change between consecutive readings as shown in Figure 10.

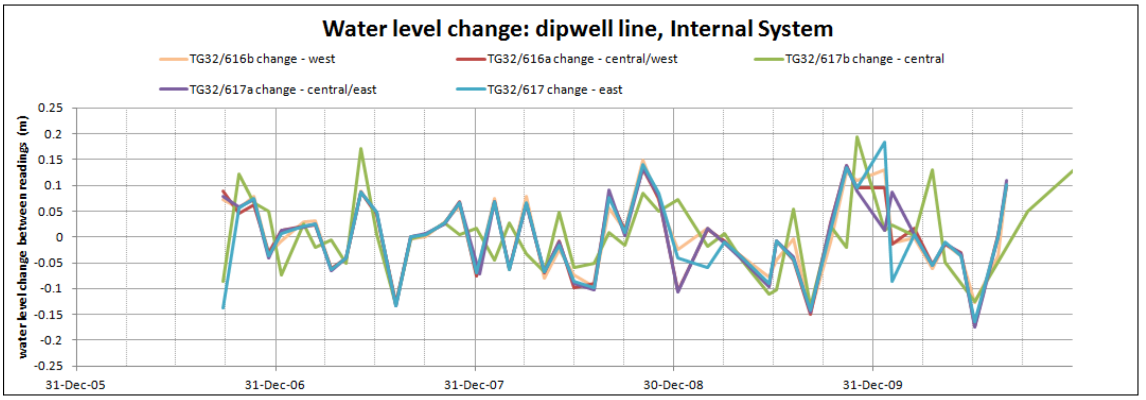

Figure 10. Water level change between consecutive measurements (Internal System)

It is thought that the manual dips from the central dip well may be affected by logger download operations. Removing this dipwell from the graph for clarity confirms that the pattern of water level response is very similar indeed (Figure 11).

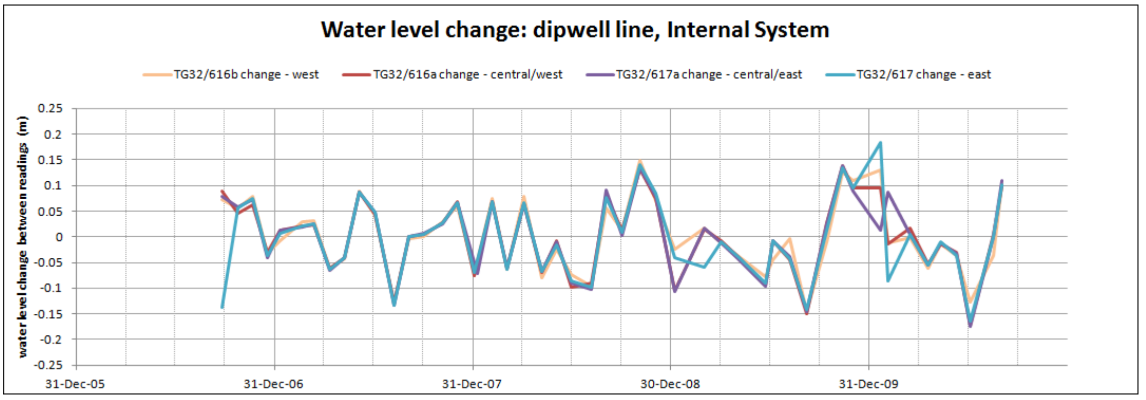

Figure 11. Water level change between consecutive measurements (TG32/617b removed for clarity)

It is also useful to plot the water levels in relation to ground level (Figure 12).

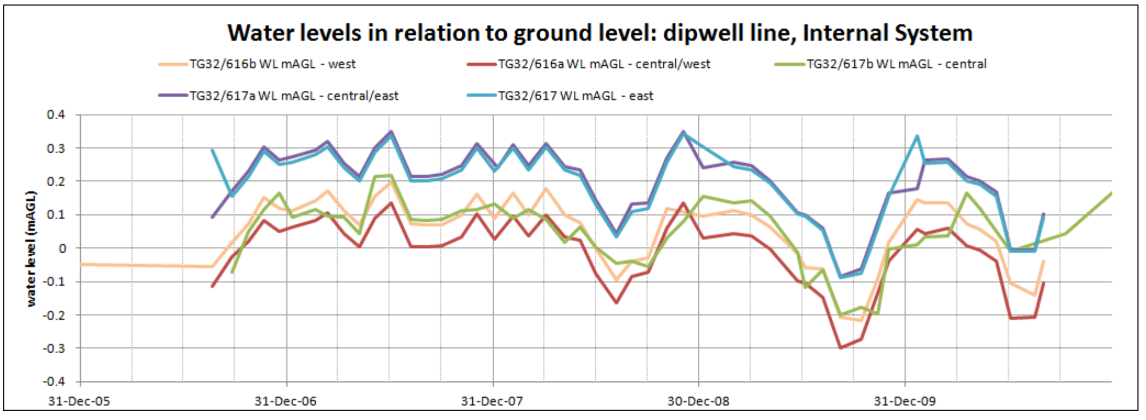

Figure 12. Water levels in relation to ground level (Internal System)

This shows that the pattern of response is almost identical, irrespective of whether water levels are above or below ground level

This is an area of reed bed on which standing water exists for a significant proportion of the time. It is not clear why the dipwells do not record similar values at these times (see Figure 9). It is possible that the dipwells towards the eastern end of the line reflect a true artesian groundwater head, even at quite shallow depth. This would imply the presence of a high vertical gradient in the very top of the peat. This means that the water level recordings from those dipwells are not a true measure of the phreatic surface. Such behaviour has been noted at some other sites, for example Potter and Scarning Fens.

Irrespective of whether or not the higher readings are 'correct', it is clear that the pattern of response in all dipwells is very similar.

These water levels will, in large part, respond to rainfall and evaporation which are essentially uniformly distributed across this area. The uniformity of water level response confirms this. By extension, if the water levels are also influenced by groundwater upflow, then the data show that they are all affected in the same way. If the magnitude of the upflow changes (for example in response to abstraction changes), then these data suggest that any measured water level responses would be the same in all dipwells. Only a single 'measure of change' is needed, suggesting that analysis of upflows from alternative scenarios of the regional model would be acceptable.

A similar picture is seen in the line of dipwells in the External System. Recorded water levels are above ground level for much of the time, but there is some spatial variation in the absolute elevations recorded (Figures 13 and 14).

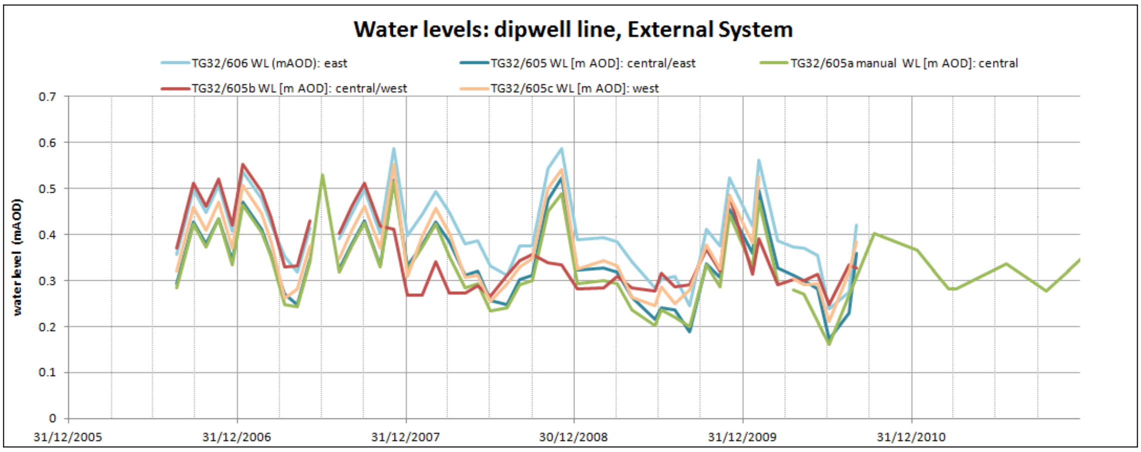

Figure 13. Water levels in the line of dipwells in the External System

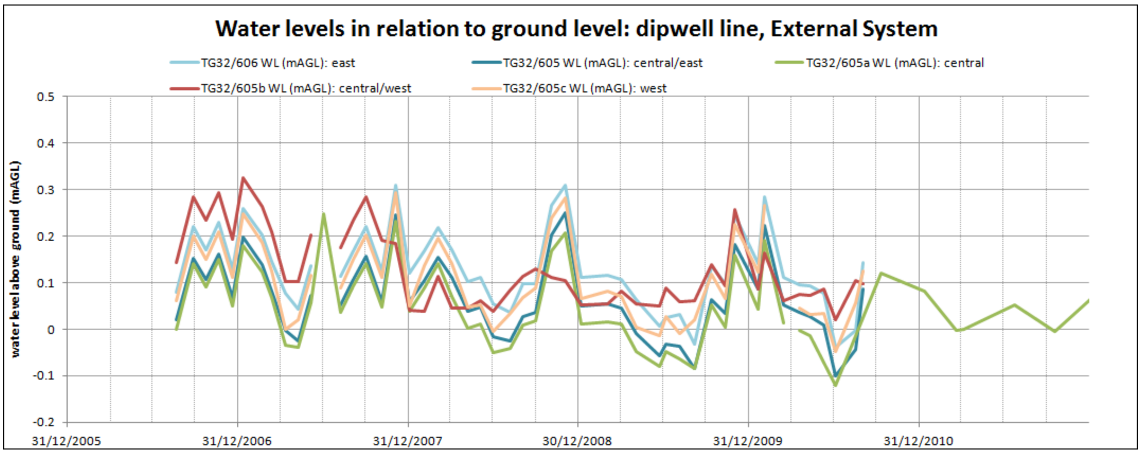

Figure 14. Water levels in relation to ground level (External System)

As in the Internal System, the transient nature of water level change is very similar for all dipwells, as seen below.

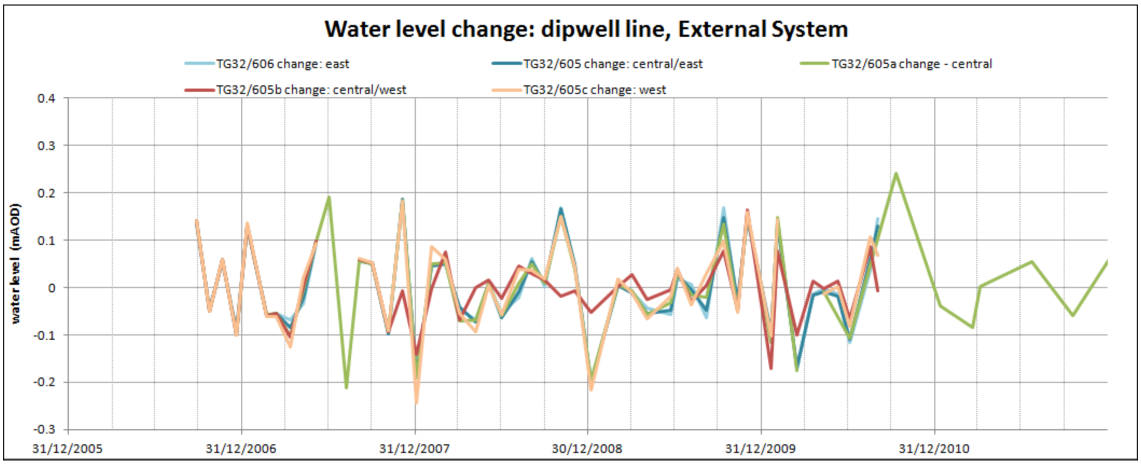

Figure 15. Water level change between consecutive measurements (External System)

As in the Internal System, these water levels will respond to rainfall and evaporation, but they may in addition be influenced more directly by the River Ant. Again, uniformity of water level response is seen.

These observed water level responses, and their similarity, support the use of the regional model as a suitable tool from which to calculate changes in groundwater level due to abstraction.

3.3 Hydrogeological Processes

Professor Rushton has provided comments on the list of 'important processes' included near the end of chapter 6 of the Main Report. Our response to these comments is provided in the appendix to this document.

3.4 Ponding

3.4.1 Background

Professor Rushton states that the current model does not include correct simulation of ponding, and so this is considered here in some detail. The review of the paper by de Silva and Rushton (2008) in section 5 is also relevant. Particular attention is given to location TG32/617b within the Butterfly Conservation land, at which recorded water levels are often above ground level, and which has been specifically mentioned by Professor Rushton.

Ponding of water above surface is not explicitly recognised within 4R/Modflow: ground level does not need to be defined for the uppermost layer of the model, which means that water levels above actual ground level can be simulated, albeit that the model will continue to use the specific yield value for assessing storage change.

Ponding of water is likely to increase the amount of evaporation, and also means that more water is 'retained' on site than may be the case with the current numerical model. However, some of the ponded water could, at times, move away from the location if a 'drainage level' is reached.

The current model configuration provides a good simulation of observed water levels. However, commenting on Figure 7.2 of the Summary Report, Professor Rushton has noted that "*the general form of the fluctuations for field and computational model are roughly similar, but for certain periods there are significant differences with the modelled fluctuations substantially larger than those observed in the field*". Whether the fluctuations are substantially larger is a matter of opinion, but there are some small differences in the character of the time series between observed and modelled. Perhaps the most noticeable is the difference in recession in some years: the model recession happens too early, although the trough is at about the right level. This is not seen in 2007, perhaps related to the wet summer.

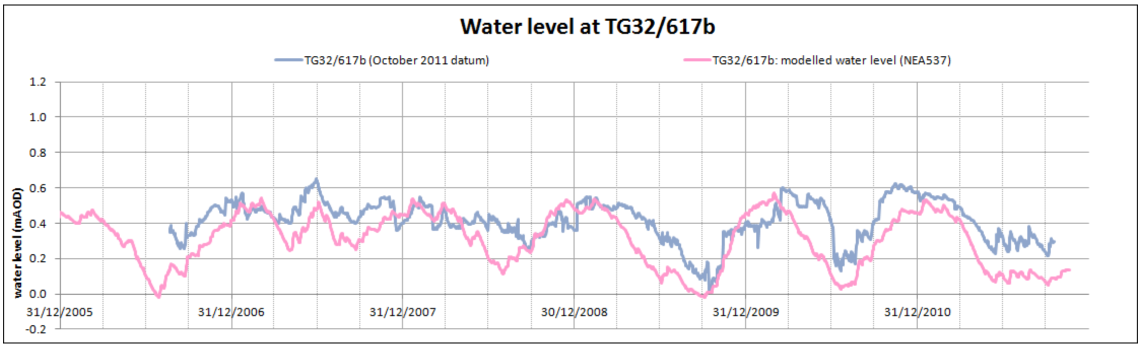

Figure 16. Observed and simulated water levels at TG32/617b

Only data up to early 2010 were used for comparison with simulated levels at the time of model development, and these data were presented in Figure 7.2 of the Summary Report and Figure 7.13b of the Main Report. Figure 16 show additional data covering the full modelled period. The model 'fit' for 2010 and 2011 is similar to the earlier period, i.e. the model recession occurs earlier than observed. The simulated troughs are slightly lower than observed for 2010 and 2011, although the unusual fluctuating 'shape' in mid-2011 is reproduced.

At this location, the elevation of the stream boundary condition is 0.35m. Professor Rushton has noted that "for each stream cell a surface water elevation is imposed, with the result that the groundwater head in Layer 1 cannot be very different from the enforced water elevation". It is clear from the above graph that the modelled water levels are not ‘clamped’ at this elevation, and respond realistically both above and below this elevation.

The table below considers how different a completely ponded system might be compared to the current model configuration:

“Ponded Site” situation	**4R/Modflow**
All rainfall enters the ponded area	4R “removes” some water as runoff and interflow
Effective “specific yield” above ground level is 100%	Ground level does not need to be explicitly defined: water level above actual ground level can be simulated, but continues to use specific yield value
Water may be removed if ponded level reaches certain elevation.	Some water removed to “stream” boundary conditions at most times.
PE (and AE) likely to be enhanced by presence of ponded water at surface, reducing to more ‘normal’ values when water level drops below surface. AE may remain at PE for several 10s of cms below ground level	4R has already taken some evapotranspiration off rainfall. Majority of remaining demand is passed to Modflow. Actual evaporation from groundwater may be less than the demand passed across.
Exchange of water between groundwater (or ponded levels) and ditch/dyke water can occur in both directions. Levels in dykes are variable through time, partly influenced by levels in the River Ant.	Exchange of water can occur in both directions, but the ‘controlling’ surface water elevation is not temporally variable.

3.4.2 Water level calculations

In addition to the regional model calculations of water level in the peat, an alternative check method has been used to assess how the potential differences outlined in the table above might affect the estimation of water levels and the calculation of changes in water levels due to abstraction. This check has allowed for the effects of ponded storage and enhanced PE related to the presence of open water and reed beds.

Using rainfall and evapotranspiration as input, simple mass balance type calculations have been performed to generate a ‘synthetic’ water level time series (i.e. an alternative form of simulation compared to the NEAC model). Ponding is accounted for by assuming a change in storage capacity at ground level. In some of the methods of calculation, factors have been applied to the reference PE data values.

The initial calculation simply used the reference PE values. The blue line on Figure 17 shows that this gave very high calculated water levels. Note that the observed data shown in Figure 17 have been colour coded to differentiate between data flagged as ‘suspect’ (red) and ‘good’ (black) in the Agency database.

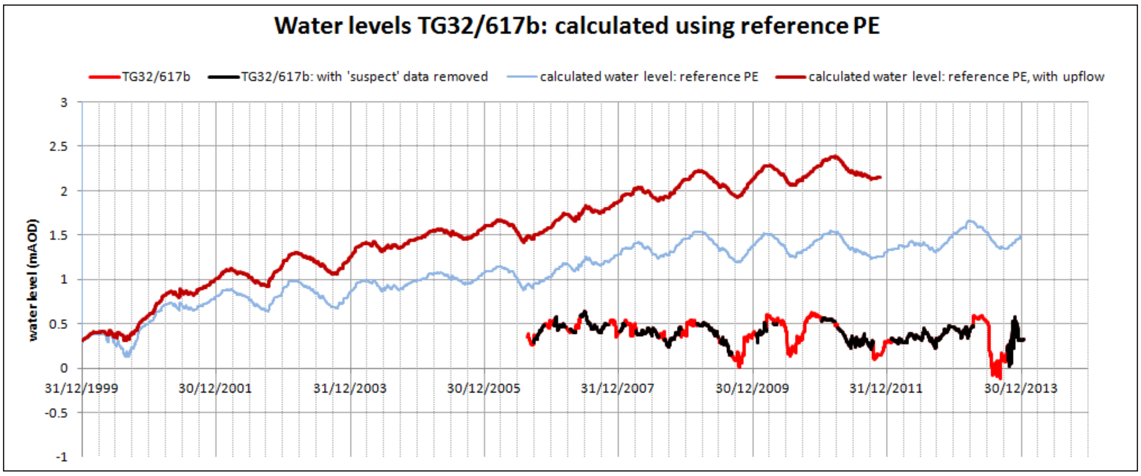

Figure 17. Water levels calculated using reference PE

The blue line shown on Figure 17 has only used rainfall and PE. However, it is believed that there is a component of groundwater upflow to Catfield Fen, and this needs to be taken into account. We can use the upflow from the groundwater model to estimate this, and modify the mass balance calculation accordingly. In this case, this would clearly make the calculated water levels even more unrealistic (the brown line on Figure 17), implying that, if the groundwater upflow is approximately correct then there must be some kind of drainage mechanism that removes water from the site, at least at some times. A drain is postulated at a level of 0.43m, the approximate level of the base of a breach in the southern bund noted during a site visit in April 2012. For the purposes of these calculations, water level dependent outflow to the drain is governed by a conductance value, in this case set to 200. Introducing this to the calculations produces a reasonable representation of the observed data.

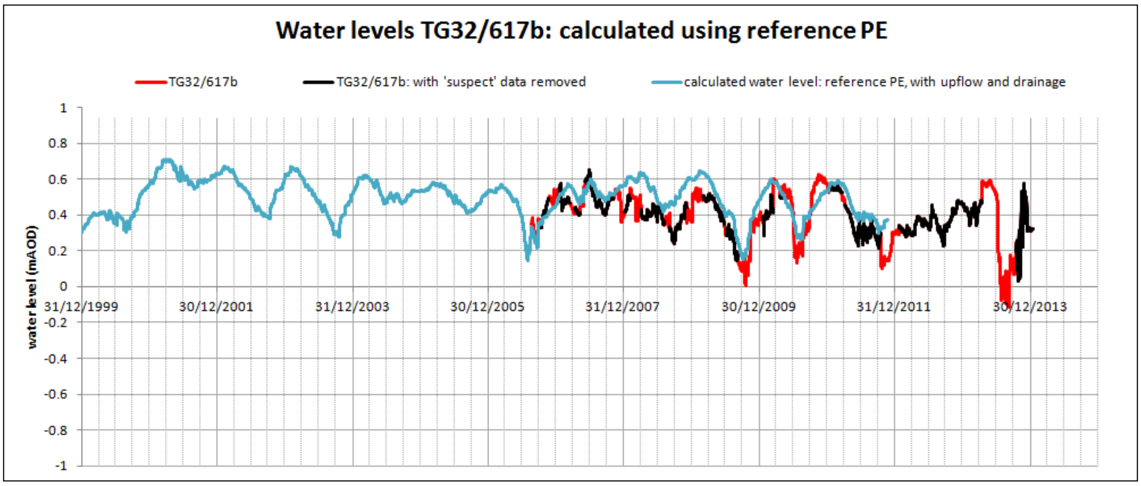

Figure 18. Water levels calculated using reference PE, including a drainage mechanism

It is possible to perform alternative calculations including the naturalised groundwater upflow, and a difference in calculated water level can then be determined.

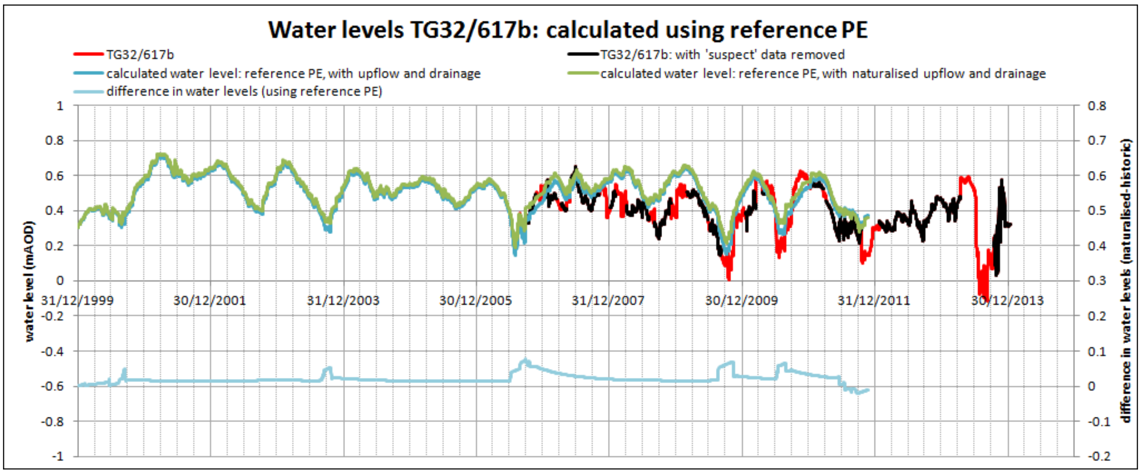

Figure 19. Difference in water levels calculated using reference PE

It has been proposed that PE in ponded reed beds may be greater than the reference values. A number of alternative calculations were performed based on monthly PE factors for 'open water' published in Environment Agency research. The most successful of these modified the published factors to be higher in the period February to June, but also included reduction in PE when calculated water levels dropped below ground level, i.e. ponding was no longer occurring. A uniform PE factor of 0.9 was used in these conditions.

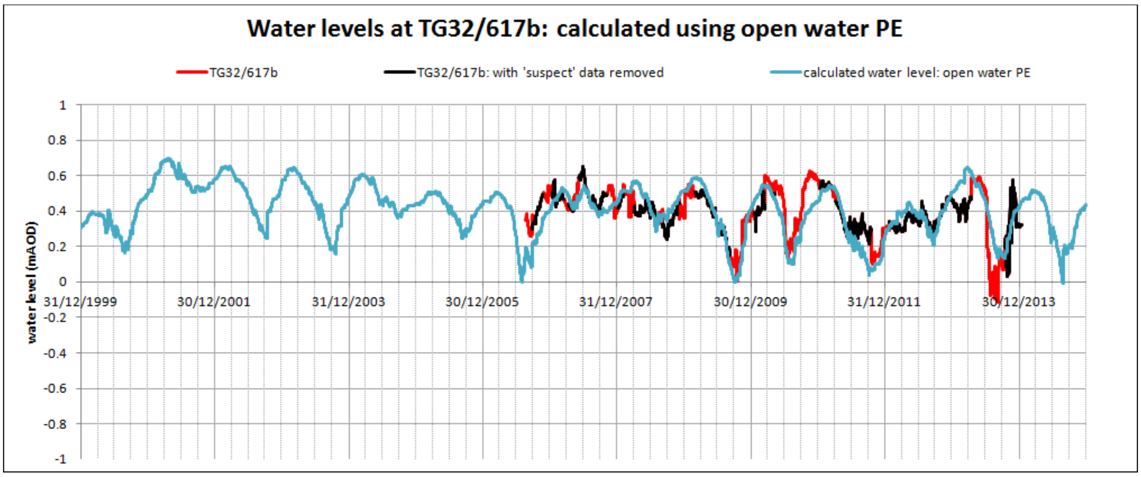

Figure 20. Water levels calculated using open water PE

It is clear from Figure 20 that this type of calculation can simulate much of the character of the observed time series, even without groundwater upflow or drainage, suggesting that the dominant influences are climatic. Of particular interest is the fact that the shape of the recessions in 2008 and 2009 are reproduced well by this calculation, improving on the groundwater model. This suggests that the combination of 'enhanced' PE and ponded storage may be appropriate.

Following the same approach as for the reference PE, calculations including historic and naturalised groundwater upflow were performed. By themselves, these result in calculated water levels that are too high, implying that a drainage mechanism exists. The same mechanism as previously was applied, but this time with a reduced conductance value of 100 (Figure 21).

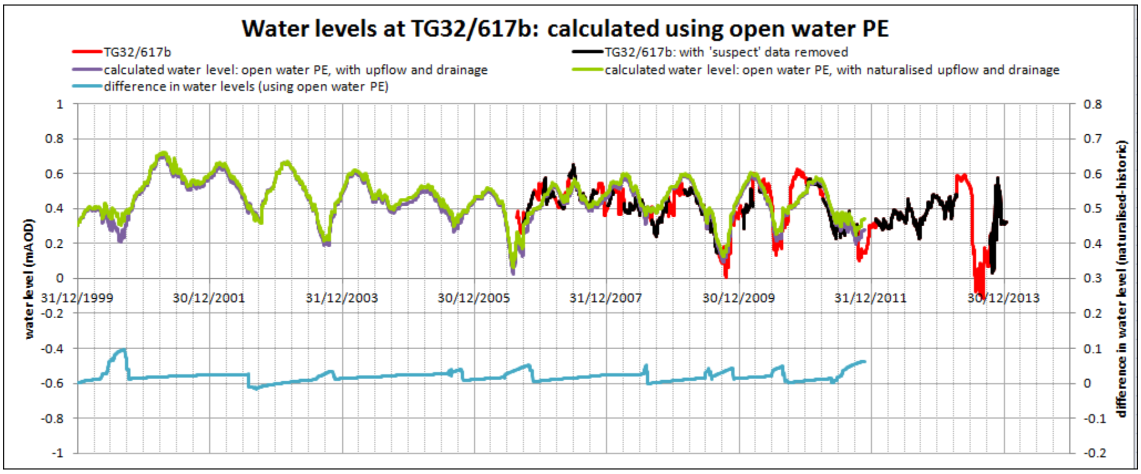

Figure 21. Difference in water level calculated using open water PE

The open water factors recommended in the Agency research document were derived from study of an artificial water body in London, and their applicability is perhaps questionable. Other values from the literature, which may be more suitable for reed beds, were assessed.

Fermor et al (2001) present four sets of factors, based on measurements from constructed reed beds. Acreman et al (2003) in a study on the Somerset Levels found that "evaporative use" of reed beds was around 19% more than the reference PE for a June-October period, and almost three times as great for a short period in October-November. Kelvin (2011) derived values for Wicken Fen for two periods in 2009 (April-December) and 2010 (April-October). Gasca and Ross (2009), in a study of the Pulborough Brooks, applied a methodology in which a uniform (throughout the year) factor of 1.25 was applied, "in line with coefficients proposed by Finch (2003)". The methodology employed by Gasca and Ross also incorporated a reduction in evaporation as water level dropped.

Figure 22 shows the result of calculations using the Gasca and Ross ("G-R") coefficients, and Figure 23 the results using the Wicken coefficients, with a modification to reduce the amount of evaporation taken when the water table drops below ground level. Both methods are capable of reproducing observed water levels well, without any allowance for groundwater upflow or drainage.

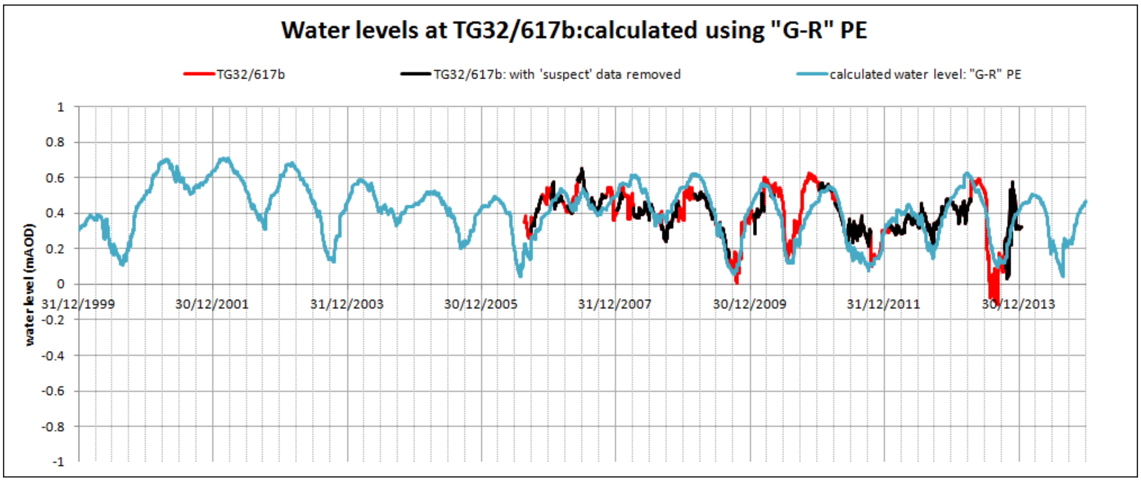

Figure 22. Water levels calculated using the Gasca and Ross PE factors

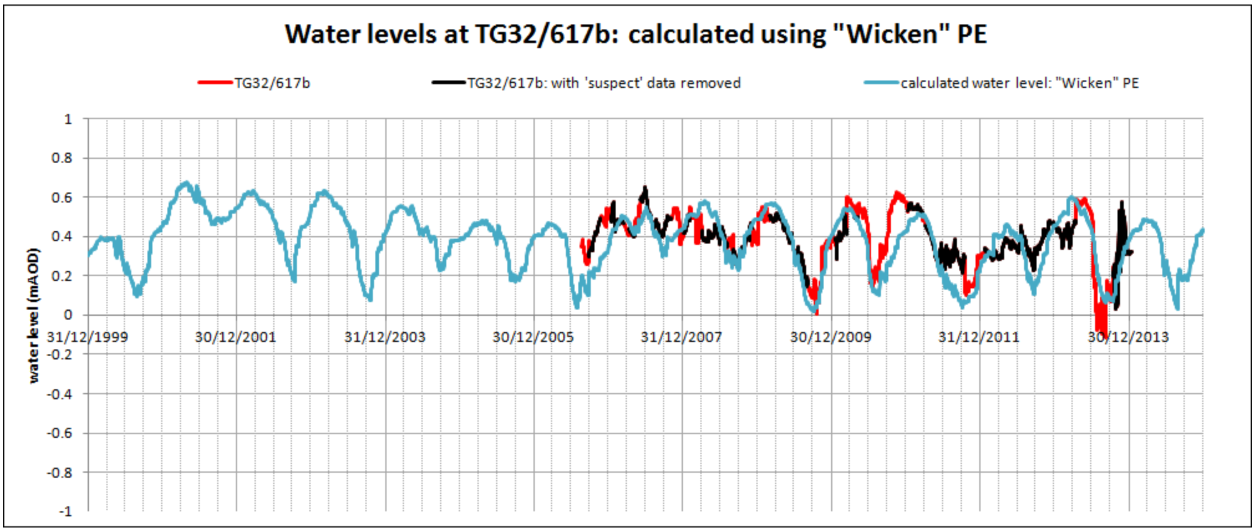

Figure 23. Water levels calculated using the 'Wicken' PE factors

As for the open water PE, calculations have been repeated using historic and naturalised groundwater upflows, together with a drainage mechanism. Figures 24 and 25 shows the results for these two methods.

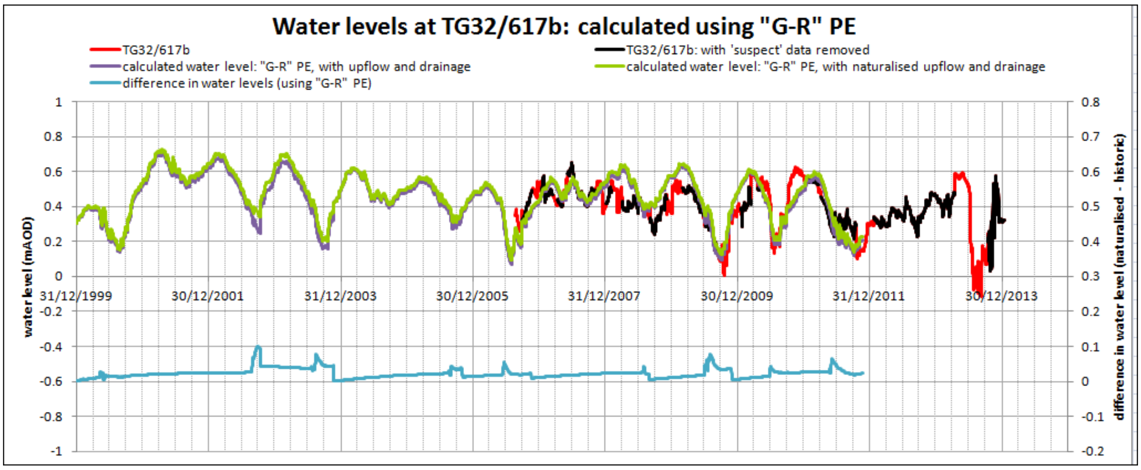

Figure 24. Difference in water level calculated using the Gasca and Ross PE factors

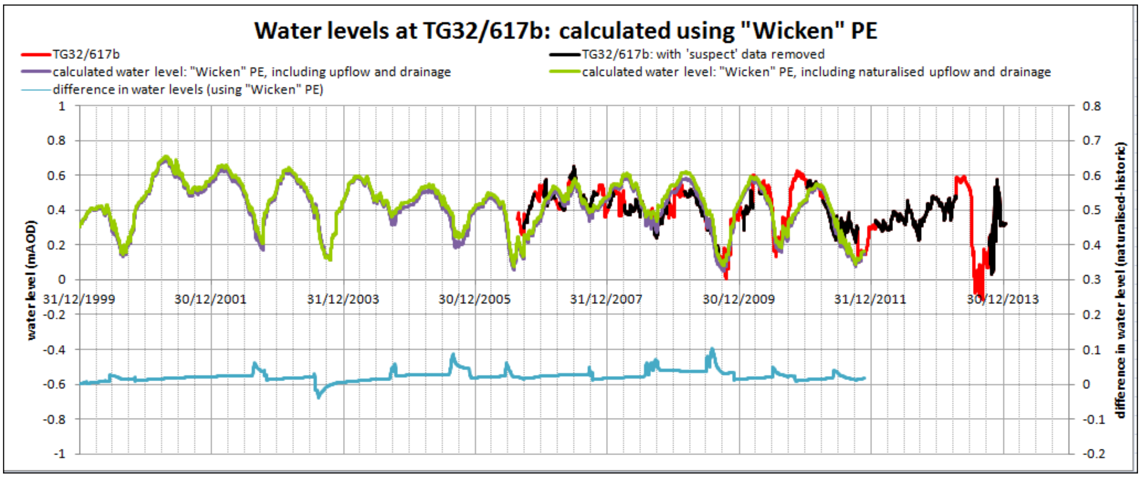

Figure 25. Difference in water level calculated using 'Wicken' PE factors

The water level differences calculated by these methods may be compared to that calculated by the NEAC model (Figure 26).

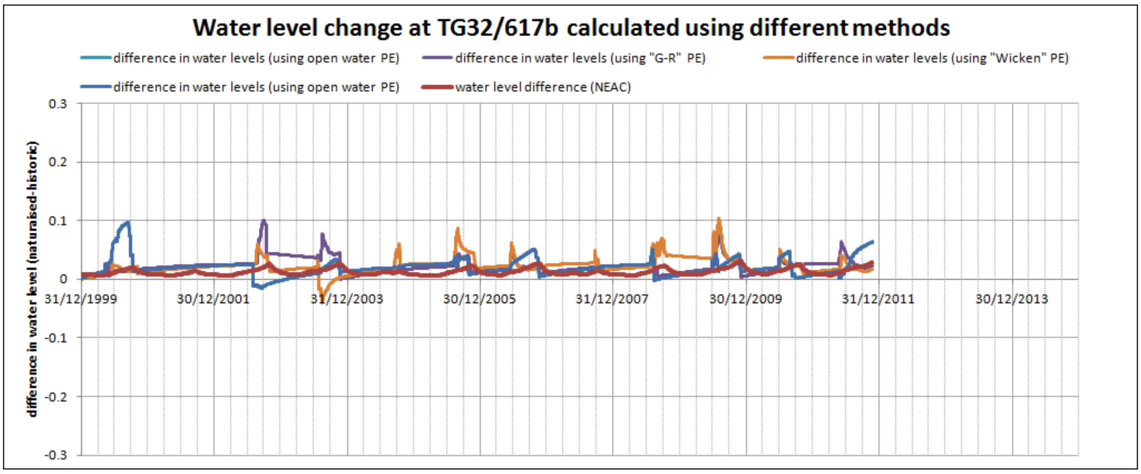

Figure 26. Difference in water levels calculated using various methods

There some differences in the calculations, as might be expected, but overall the magnitude is similar for all calculations. 'Spikes' seen in the calculated differences generally occur when the estimated water level crosses ground level, and are probably not 'real', but reflect the relative simplicity of the calculations.

The above calculations demonstrate that water level variations at this location, including what appear to be quite severe falls in level in some summers, can be almost wholly explained by variations in climatic conditions.

4. Response to Other Comments

This section of the document responds to remaining comments that have not been covered in the discussions above. They relate to Professor Rushton's comments on the Summary Report. We assume that many of Professor Rushton's comments about lack of detail in the summary report have been answered by the main report.

Comment SM
"*However, it is not clear whether the technique can be used when the water table is at or above the ground surface when ponding occurs*."

The method **is** primarily for use when the water table is below the root zone: when the water level is above this, then the method assumes that there is no restriction in the ability of plants to uptake water (up to the potential evapotranspiration), and therefore a situation of full saturation tends to develop. This will include the situation in which the water level is above ground.

"*I cannot understand how, in Fig. 5.7 of the Technical Note (also copied below), the moisture content does not equal 100% for these periods*"

The graph axis is moisture content, not % saturation, consequently the maximum value that can be achieved is the moisture content of the soil at full saturation (in this case around 86%, for peat), the value being taken from the original work by Rijtema).

"*Ponding of water occurs regularly in certain parts of the fen; is it represented in the NEAC model?*"

Ponding is not specifically included in the model (as discussed earlier in this document), although equally there is no restriction on groundwater levels rising above the nominal ground level. Evaporation can be taken directly from groundwater at such times, which may approximate the behaviour of a pond. See further discussion in section 3.4 above.

Reference is made to de Silva and Rushton (2008), in which a negative SMD is used to represent ponding: see section 5 for a review of this paper.

"*…the methodology in this Technical Note fails to represent conditions in fens which often become waterlogged*."

As noted above, the methodology does include representation of ponded conditions.

The soil moisture 'method' is not intended as a complete description of soil physics, rather it is a pragmatic way of estimating changes in moisture content in plant root zones given meteorological and water level information. The method attempts to partition evaporative demand between capillary flux from the water table and changes in soil moisture content. This is an improvement on, for example, simply noting that the water table is at a certain distance below the root zone, since plants can clearly continue to access soil moisture in these conditions. It is assumed that, once the water table elevation is within the root zone, there is no need for capillary flux to the root zone, since the water table is readily 'accessible'. Similarly, in ponded conditions, no capillary flux is taken.

It is accepted that there are assumptions and limitations within the soil moisture method, as is the case with all 'models'. Nevertheless, as an ancillary method of calculation to be considered alongside estimates of water table change and groundwater upflow, it is a useful tool in the assessment of potential effects of abstraction.

5. Review of Selected Literature

In his review of the Summary Report, Professor Rushton mentioned a number of references. Specifically, he noted that "*One standard reference is Ward et al. (1987) where a telescopic mesh refinement technique is introduced*", and that an "*alternative approach is the ZOOM model (Spink et al. 2003). Valuable insights including grid refinement and the representation of wetlands can be found in Gellatly et al. (2012). Information about the representation of fens containing drains can be obtained from a study of the neighbouring Upper Thurne catchment (Simpson et al. 2010, 2011)*".

This section of our response provides a brief review of those papers. We also provide a short review of Rushton (2007), since that is relevant to the Simpson references.

Ward et al (1987)

We have no particular comments to make regarding this reference. It is one of the first, possibly the first, papers to include a description of a Telescopic Mesh Refinement (TMR) approach. In this case, the SWIFT code was used. Three 'scales' of model were used: 'regional', 'local' and 'site', the latter including contaminant transport. It is not immediately clear from the paper, but it is believed that the three models were not iteratively linked, but were run sequentially, with boundary conditions for the local and site models being taken from the next larger model.

Spink et al (2003)

This paper is an introduction to the 'ZOOM' suite of codes developed by the British Geological Survey and the University of Birmingham. ZOOM allows variable mesh spacing, but has not yet had widespread uptake within the modelling community, and remains somewhat difficult to use.

There are no specific Catfield-related comments to make on regarding this reference.

In passing, we note that there are several other 'flexible grid' models, including for example FEFLOW and Modflow-USG, both of which have similar (but more flexible) mesh options when compared to ZOOM.

Gellatly et al (2012)

This describes the modification of an existing regional groundwater model (the Wirral model developed for the Environment Agency) to allow 'better' simulation of a wetland site. The paper describes an interesting case study. Please note that we are not criticising the work presented, but make the following comments.

The original model was developed on a uniform 250m grid, with a single layer essentially representing the sandstone. Drift was not explicitly included, but was "compensated for" on higher ground by modification of recharge calculations, whilst on lower ground (including the wetland of interest) the drift deposits were "effectively treated as a boundary condition"

Two main modifications were made

- Over an area of the model including the wetland the grid was reduced to 50m. The "standard" Modflow code was used, meaning that this grid refinement had to extend to the model boundaries, i.e. there are many cells with dimensions of 250m x 50m;
- In selected areas, two additional layers were introduced, representing drift deposits. On the marshland, drains were introduced into the uppermost layer with widths and elevations "assigned based on land drainage surveys". Details are not given in the paper. Lakes on the marshland were not explicitly modelled, "water levels in the drift aquifer were taken as a surrogate for actual lake levels".

Parameter changes were also made as a consequence of the changes in model geometric structure

Two changes were made to recharge calculations

- Allowance for capillary fringe effects. This was done by preventing the development of a Soil Moisture Deficit in areas with a shallow water table and calculating the required 'capillary flux from groundwater required to meet the evapotranspirative demand. This value was passed to Modflow as 'negative recharge';
- Delayed response to recharge in areas where till exists. The paper says that in the original model a "factor of 0.25 was applied to the calculated recharge in the regional model to account for flow through the drift, but this recharge was assumed to arrive at the water table without any time delay". It is not clear exactly what this means: it is assumed that the remaining 75% would be runoff. In the refined model, a moving average was applied to the "drift-compensated recharge time series". Presumably the runoff is still 75%. Although not clear, this is of no real consequence in the current discussion.

It is worth comparing the processes represented in this model, and simulated results, with those in the NEAC model. The following comments can be made:

- No 'before and after' comparison of groundwater heads or flows is presented, so it is difficult to conclude how much 'better' the refined model is. The paper does state that "the refined model was re-run and found to produce a similar head distribution to the original regional model, with a negligible difference in the area of interest", but there are no figures to illustrate this. In fairness, it is probable that a meaningful comparison of heads cannot be made on the marshland, since this is not explicitly represented in the original model. On this basis, then the refined model must be 'better', however, it is highly probable that the majority of this improvement was brought about by including the two extra drift layers, rather than the introduction of a spatially refined grid per se. Note that the 'drift' is explicitly represented in the NEAC model;
- The prevention of SMD development in shallow water table areas is essentially the same mechanism as is incorporated in the NEAC model. Using 'negative recharge' (as opposed to treating this quantity as potential evaporation from groundwater) in groundwater models can sometimes give rise to problems if the 'aquifer' is of low permeability. This was experienced in early runs of some Anglian models;
- As a result of discussions amongst the NEAC Model Review Group (including external advisors) the method incorporated in the NEAC model optionally allows the development of an SMD in areas with a shallow water table. At Catfield however, as in the refined

Wirral model, a much better representation of near-surface groundwater levels was achieved when the maximum permissible SMD was very low or zero;

- Calibration hydrographs are presented for a number of locations. Whilst we would say that these are acceptable, they are certainly no better than the simulated hydrographs at Catfield, particularly for the high temporal resolution 'pumping test model'. No data are provided from the deeper piezometers drilled as part of the study.

In summary, what might be considered to be the 'novel' features of the refined Wirral model are already present within the NEAC model.

The paper presents impacts as a drawdown graph for various scenarios, although no 'historical' impact (i.e. the estimated difference between the historical model and a naturalised case) is presented. It would be interesting to know how different these estimated impacts would be using the original regional model and a model in which the layering is refined but the grid spacing is not, especially as the nearest abstraction borehole is over a kilometre away from the SSSI.

Rushton (2007)

Note that this isn't referenced directly in Professor Rushton's reviews, but is of relevance to the Simpson papers reviewed below. This paper describes an interesting technical exercise in determining "river coefficients" for a variety of aquifer-river configurations. This is done by comparing results from a vertical slice model with quite fine discretisation, with a more coarsely discretised "one-dimensional Regional Groundwater flow" model (i.e. akin to a slice of a single layer model). Results are expressed as multipliers of aquifer hydraulic conductivity per metre length of river. Most of the multipliers are within 15% of the 'benchmark' of 1.06Kh m^2/d/m, although there are exceptions for very wide river channels, some anisotropic conditions and where low permeability deposits are present in the channel bed.

Rushton reports that the river coefficients are primarily a function of aquifer hydraulic conductivity, and not of river bed characteristics. There is repeated criticism of the "Modflow approach", which is interpreted in such a way that the river coefficients are always a function of stream bed properties only. This is a mis-conception: whilst it is true that the Modflow manuals do describe river coefficients in this way, only a single value is used, and the user is free to choose any value which they deem appropriate. Indeed, what MacDonald and Harbaugh actually say in the Modflow manual (1988) is that the figure that shows the 'river bed' schematic' is "helpful in conceptualising and describing the simulation of stream-aquifer interaction; however, it must be recognised that, in many instances, no discrete low-permeability streambed layer is present. The techniques of simulation developed through the conceptualisation of (the figure) can still be applied to represent these situations, provided the proper interpretation is placed on the various terms and parameters that are used". They go on to say "the task is to formulate a single conductance term, CRIV, which can be used to relate flow between the stream and the depth represented by node i,j,k to the corresponding head difference. This flow is in general a three-dimensional process, and its representation through a single conductance term can never be more than approximate. If reliable field measurements of stream seepage and associated head difference are available, they may be used to calculate an effective conductance. Otherwise, a conductance value must be chosen more or less arbitrarily and adjusted during model calibration. Certain rules can be formulated to guide the initial choice of conductance".

Most modellers are aware that the river coefficients in Modflow must inherently incorporate the effect of convergent/divergent flow as well as what happens at the stream bed. We are not aware of any regional model in the UK in which river coefficients have been rigorously calculated in the way suggested by Rushton's interpretation of "the Modflow approach".

For most situations in which streams are gaining, Rushton reports a nearly linear relation between difference in head (i.e. groundwater and river stage) and flow to the river. An exception to this is where an increase in hydraulic conductivity occurs above river level (presumably analogous to VKD) in which case there is an exponential relationship.

For situations where a river is leaking to groundwater a nearly linear relation applies in some situations, but not others.

One surprising omission from the configurations assessed appears to be the case where the head in an underlying aquifer (Hb) is greater than the river stage, thereby generating upwards flow.

It is also not immediately clear how these results might relate to a regional model that has more than one layer, unless the configuration of an "aquifer with high permeability base" can be used.

Rushton recommends that practitioners should construct specific vertical slice fine-grid models to assess appropriate coefficients for model structures that do not conform to the configurations examined in this paper. It is not clear what the 'limits of application' are for the coefficients and configurations presented.

The potential weakness of the "Modflow approach" (i.e. a single linear relation, nothing to do with the spurious statement that it is based solely on 'stream bed properties') is well known: in summary, the "Rushton approach" is probably 'better' than "the Modflow approach" for many situations in which the streams is losing, but the two methods are very similar for most situations in which streams are gaining. Whether this makes a significant difference to the behaviour of regional models will depend on specific characteristics of the models in question.

Simpson et al (2010, 2011, published in the CIWEM journal and in Hydrological Processes) and Simpson's PhD

The dates of the papers are a bit confusing (different publication dates on line and in print), and will therefore be referred to as **CIWEM** and **HP**).The work presented in the CIWEM paper appears to pre-date that presented in the HP paper, but both build on **Simpson's PhD** (2007) which involved construction of a Modflow model of the Thurne catchment (the text can be downloaded from the Broads Authority website). Unfortunately, Appendix C of the PhD (which may contain important information relating to the configuration of General Head Boundaries) is not included in the downloadable document.

Much of the model construction is not very clearly described in the PhD, but it appears that the model has five layers:

- An 'overlying layer' (peat in marsh areas, Norwich Brickearth or exposed Crag in higher areas;
- A 'connective' layer: "the top of the peat or the clay is the cultivated layer in which the water table is usually controlled by undersoil pipe drains;
- Upper Crag;
- 'clayish' layer;

- Lower Crag.

The model is aligned at 45 degrees to the National Grid (to be aligned with the 'dominant flow direction'), with a uniform mesh spacing of 250/√2, i.e. 176.8m. This peculiar spacing is chosen so that grid intersections occur at regular 250m intervals N-S and E-W.

Derivation of drain coefficients is not very clear, but it appears that a method similar to that proposed in Rushton (2007) is used, i.e. small numerical models are used to derive suitable coefficients which are primarily a function of aquifer hydraulic conductivity (see above). This gives a range of cell conductance values between 3.6 and 1516 m^2/d (erroneously quoted as m^3/d in the PhD). These were simplified into discrete values of 1,5,10,50,100 and 1000 m^2/d. It is not clear whether anything other than the standard Modflow drain (DRN) package was used: assuming that the DRN package was used, then the discharge to the drains does behave in a linear relation to groundwater head, and there will be no scope for the drains to leak to groundwater. If the river (RIV) package was used, then there will be scope for the drains to leak, but only in the linear fashion of 'standard' Modflow, and not according to the modifications suggested by Rushton.

General Head Boundaries (GHBs) are used to simulate the effect of the "under soil pipe drainage system" and are imposed in the "cultivated layer", which appears to be part of layer 1. Again this is not clearly described (more details are apparently in Appendix C, which is not included with the download). It is assumed that these boundary conditions are applied throughout the cultivated marshland. The PhD describes the conductance term (of the GHBs) as being "analogous to representing the resistance to flow between the cultivated layer and the aquifer". There is a figure (6.9) that appears to show that 'layer 2' represents the aquifer, but elsewhere layer 2 is described as 'the connective layer'. It is really not clear how this is implemented. No further details are presented and so it is not possible to assess what may be an important boundary condition within the model.

Note that these GHBs appear to be separate from the 'drains' for which conductance values were calculated as described above.

The model is "time-invariant", although "pseudo-steady-state" results for summer and winter conditions are presented. There are a couple of tables comparing groundwater levels at 12 wells and also comparing 'observed' and simulated (IDB) pumped volumes and water levels. The 'observed' pumped volumes are calculated from electricity records, but modified by a form of hydrograph separation to derive a 'groundwater contribution'. In the 'preliminary' model, most of the pumped volumes are reasonably close to the 'observed' (i.e. calculated), with the exception of one catchment which is considerably over-estimated. The groundwater levels are relatively close, but it is not clear how strong the effect of the GHB boundary conditions is. Without a transient model that replicates the main features of system behaviour, it is difficult to fully assess the credibility of the model.

Attempts were made to improve the over-estimation of pumped volume in the Brograve catchments, essentially by reducing the 'drain coefficients'. This had only limited success. From the PhD text, it is not clear what happens to the water removed from the model by the GHB under-drainage, although some clarification is provided by the HP paper (see below). At the time of the PhD however, it appears that only a groundwater component of IDB pumped volumes was considered, so we imagine that the water entering the drains may possibly have been 'ignored' as being part of the "runoff" component of the pumped volumes.

The **CIWEM paper** focuses on the derivation of drain coefficients. It appears that these have been updated compared to those presented in the PhD, probably using the methods of Rushton (2007). Drain coefficients for model cells now vary between 2.3 and 424 m^2/d. Again, although the drain coefficients appear to have been derived following Rushton's (2007) approach, it seem that the standard Modflow algorithm has been used, i.e. there is a linear relationship between groundwater head and discharge to drains (and probably no scope for leakage from drains). No model results are presented. The model is still described as time-invariant.

In the current context (i.e. Catfield) it is perhaps appropriate to note that "within a single cell there may be two or more drains at different elevations: usually data for the deeper drain are used".

The **HP paper** again focuses on drain coefficients, but this time some transient analyses are presented, with the main emphasis being on simulation of pumped quantities at the Eastfield drainage pump.

Using a single, transient groundwater level series (albeit derived as a composite from two monitoring points), and a uniform drain water level elevation, Simpson et al derive a 'best-fit total drain coefficient' for the catchment to Eastfield.

There is some discussion of "the Modflow approach" to estimating coefficients, which suffers the same mis-conception as Rushton (2007) i.e. that the coefficient must be calculated from stream bed properties alone. As in the CIWEM paper, this paper describes that Rushton's methods have been used to estimate the coefficients, but it is not clear whether any modification to Modflow has been made to allow non-linear relationships between head and discharge/leakage.

The sum of the coefficients derived is compared to the total catchment value derived earlier, and found to be similar. Although this is perhaps comforting, it is not clear whether it is actually meaningful or not, as it is possible that different results would have been achieved if using slightly different "average" heads for example.

This paper clarifies what happens to the GHB flows into the tile drains in the "cultivated layer": they are added to the groundwater discharge to drains (presumably as a post-processing exercise) before comparison with the pumped discharge: this is acceptable. There is a comment however that "cultivated layer flows are sometimes negative" which suggest that, in the model at least, the tile drains leak to groundwater. This doesn't sound realistic, but probably has a small effect on model results.

Comparison of the model simulation with the pumped discharge shows good correspondence. No groundwater head results are presented. Some salinity inferences are made, based on particle tracking and a simple mixing model using inflows derived from the groundwater model.

In the section describing the groundwater balance there is an unclear statement that "groundwater provides about 60% of the total pumped discharge" (implying presumably that runoff provides the remaining 40%), but that "rainfall runoff is unlikely to be high". However this is probably of little consequence.

One of the conclusions is that "land drainage should be given recognition similar to borehole abstraction in the development of conceptual and numerical groundwater models". We agree that consideration of the effects of land drainage on groundwater behaviour is important in low lying areas such as this.

As noted earlier, in section 4.1, drains are represented in the Upper Thurne model in a very similar way to NEAC, i.e., using boundary condition mechanisms available in Modflow, albeit using conductance values derived using methods proposed by Rushton (2007). The only unusual feature of the Upper Thurne model is the presence of the ‘connective’ layer between the overlying peat and underlying Crag: additional drains (actually incorporated as ‘General Head Boundary’ conditions) are included throughout the model in this layer to represent under-drainage.

De Silva and Rushton (2008)

This paper describes a simple soil moisture balance approach for a small ricefield in Sri Lanka, including ponding and bund overflow. Inflow due to runoff from uplands and irrigation from a tank also appear to be included I the calculations.. The area of the ricefield is only a few 100s of m^2

An FAO type approach is used, including two soil ‘stores’. Two stress factors are discussed in the text (i.e. the slopes of the lines for REW-TEW and RAW-TAW), but only a weighted average appears to be used in the algorithm (i.e. similar to the UK implementation of FAO derived by Hulme et al (2001) and used in many UK regional groundwater models including NEAC).

The near surface store is similar in concept to the ‘second soil store’ option in 4R, although the detail of the algorithm is different. Here, the split of water between the two stores is defined by an empirical factor ‘FRACSTOR’. This applies each day, even to water already in the near surface store, thereby introducing a transfer mechanism between the two, rather than having a size limit on the upper store. It is not clear how FRACSTOR is determined, but a value of 0.45 is quoted as appropriate for a sandy loam, whereas more clayey soils might be 0.65 or higher

An interesting feature of the approach is that ‘SMD’ may become negative (i.e. not strictly SMD, but algorithmically the same): once this happens, water may either infiltrate or pond, according to an empirical formula. Ponded water eventually overtops a bund. In the example given, for SMD between 0 and -50mm, percolation is 1.5mm/d, beyond an SMD of -150mm water overtops the bund, and between -50 and -150 1.5mm/d infiltrates and 7% of the ‘excess’ beyond -50mm ponds. FRACSTOR is set to 0.65.

It is not apparent whether any change in evaporative behaviour occurs when ponded conditions apply.

Runoff from uplands is determined by a separate soil moisture balance, factored to reflect relative areas of ricefields and uplands.

The paper notes that this is for a single field, and that different fields may receive different inputs, for example overflow from one field to another. This could be simulated by several concurrent water balances but there is “insufficient field information”.

This appears to be a good, simple approach to the particular problem of estimating water balances in rice fields (and possibly other areas subject to ponding). However, it is a little surprising that none of the results are compared to field observations: it would be imagined for instance that ponding levels might be available. This is even more surprising given that some of the factors are quoted to be “empirical”, suggesting a degree of adjustment to better represent field conditions.

These calculations are not accompanied by any kind of groundwater model, presumably because the main issue is one of surface water. The 'percolating' water presumably contributes to groundwater, but we assume that groundwater flow beneath the site is unimportant.

The method of calculation has many similarities to the 4R soil moisture balance approach, with the exception of the specific representation of ponding. This issue has been discussed in section 3.4 of this document.

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Appendix : Response to Professor Rushton's Comments on 'Hydrogeological Processes'

Wetter periods

	Process	Professor Rushton comment	Response
W1	Significant recharge occurs to the water table resulting in the water table rising to close to, or even above the ground surface.	The 4R model provides a reasonable approximation for recharge to the interfluves but it is not designed for the water balance of the fens and does not represent a water table above the ground surface.	Fen areas are treated as "riparian", which in this context means that only a very small Soil Moisture Deficit can develop, and that any shortfall in evaporative demand can potentially be met directly from groundwater. This demand is passed to the groundwater model which may reduce the actual 'take' from groundwater depending upon simulated water level at the time. This is similar to methods described by Gellatly et al, a paper to which Rushton has referred (see review in Appendix). Ground level elevation is not explicitly included within the groundwater model: simulated water levels in the near surface can continue to rise above nominal ground level, so a water table above ground level is 'represented' (although we accept that there is no change in the definition of 'storage' at this elevation, nor in evaporation). The groundwater model provides a good simulation of observed water levels, including those that are above ground level. (see also W3)
W2	Soil moisture content reaches saturation level.	OK	None required
W3	Ponding of water at surface occurs in some areas: some of this water will later infiltrate, some will evaporate and some may move laterally into the surface drainage system.	Ponding is not represented by either 4R or MODFLOW although there is a correction for additional evaporation from riparian areas; the movement of water into the surface drainage system may occur	As noted above (W1), the model does simulate water levels above ground level, although we accept that the mechanism by which this is controlled is a simplification of the real situation. A more detailed consideration of ponding is given elsewhere, which in summary suggests that the overall

		through the stream cells although the stream cell parameters have not been explicitly designed to represent this process	water balance of such areas is approximately correct. Groundwater outflow to 'streams' is considered in W6 below.
W4	Groundwater gradients can be downwards into the lower parts of the peat and laterally towards water courses within fen compartments, but are also upwards from the deeper Crag aquifer.	The peat appears to be a single layer which means that there cannot be both upwards and downwards flow in an individual cell; flow to water courses can occur as can upwards flows from the Crag.	This will benefit from additional explanation: the peat is represented by a single layer in the model, but we do not mean that there is both downward and upward flow in the same cell (although it is possible within a single 'stack' of cells). The original text is meant to reflect that there must be a small component of downward flow within the peat in order to drive groundwater laterally: this is implicit within the model even though the small vertical head difference is not explicitly simulated.
W5	This results in some mixing with percolating rainfall.	The 4R model recharge, in effect, represents the percolating rainfall.	None required
W6	Groundwater flow takes place from within fen compartments to the watercourses.	As explained above, this occurs through the stream cells although it is a matter of concern that the same stream conductance is used for each cell in the fen	The conductance term is, of necessity, a useful way of representing the interaction of processes that result in groundwater exchange with surface water systems. Although considered uniform across the fen, different values of stream conductance were assessed during model development: the current values gave the best representation of observed conditions. It is accepted that the 'removal' of water by model 'streams' may partially include 'removal' by other processes in some areas. Spatial variation of conductance may be appropriate in some cases, but if set to too low a value then it is highly likely that this would require more explicit detailed incorporation of other physical processes: the net result on simulated water levels would be minimal.
W7	Groundwater flow from the Crag may be able to take place directly up into the peat or directly into watercourses along the eastern margin of Middle	Groundwater flow can occur up into the peat; groundwater flow may also occur into watercourse (catchwater drain) along	As above, the conductance values used lead to good simulation of water levels. Flows in the ditches are not well known. It is true that some of the runoff (and groundwater) that enters

	Marsh.	the eastern margins by means of stream cells but this has not been included specifically in the selection of stream coefficients. Surface runoff which enters the catchwater drain on the eastern margin of Middle Marsh (and elsewhere) can recharge the aquifer but, in practice, it is more likely to become a surface water outflow along the drain.	the drains on the eastern margin can recharge the aquifer, but in practice this quantity is small (see Figure 8.8 of the main report).
W8	Water escapes from the interior system of Catfield Fen generally through the bund and over the bund to the south.	Since the water levels in the stream cells do not vary with time, nor is the bund included in the 4R/MODFLOW model, this process is not represented.	Groundwater flow directly through the bund (Commissioner's Rond) is probably very small. Although the bund is not explicitly represented as a topographic feature in the model, there is a very small simulated groundwater outflow from the Internal System. Likewise, the 'southern bund' elevation is not explicitly included, but, as explained above, the 'removal' of water by the currently modelled boundary conditions gives a plausible representation of water levels and surface outflows from the fen. Temporal variation in dyke water level is not explicitly included in the model: much of this variation mirrors groundwater levels and is heavily influenced by meteorological conditions. It is likely that using a uniform (in time) water level will result in an over-estimate of changes due to groundwater abstraction.
W9	Water flows from the exterior system of Catfield Fen to the River Ant although it may reverse if there is a high tide, and can also flow from the exterior to the interior system, either across the bund to the south or through the sluices if they were opened.	These features are not represented in the model	Temporal variation in water levels in the River Ant is not included in the model, but is unlikely to have any material effect on conclusions drawn from the model. The model does not include inflow of water to the Internal system via the surface water system, which can occur when river levels are high. Groundwater abstraction cannot influence this process to any significant degree. It is considered that the omission of this process from the

			model will, if anything, result in an over-estimate of the impact of groundwater abstraction, and can therefore be considered as conservative. Same comment as above applies for transfer of water between the Internal and External Systems.

Drier periods

	Process	Professor Rushton comment	Response
D1	Evapotranspiration lowers the water table level, although water levels can still rise in response to rainfall.	This is partially represented in the MODFLOW model, the input to MODFLOW is recharge calculated by the 4R model rather than rainfall; nevertheless when combined with EVT, this process is simulated approximately.	A small amount of water is 'removed' by "runoff and interflow" processes within 4R, but otherwise the input to the top surface is the same as rainfall. Evaporation may reduce below the potential rate if groundwater level drops.
D2	Soil moisture content reduces and may reduce below saturation level although this is to some degree offset by the continual upward movement of water by groundwater flow and capillary rise.	Soil moisture is represented in the 4R model, but "the representation of soil moisture conditions above the water table is relatively simplistic" (page 112 of Amec 2014).	The simplistic nature of the representation is not too important in this context. However, acknowledgement of the 'simplistic' nature is one of the reasons why separate soil moisture calculations are conducted as part of the assessment process.
D3	Lateral groundwater gradients within fen compartments may reverse with water drawn in from watercourses to feed the evaporative demand.	MODFLOW can include this but, because the stream levels (watercourse water levels) are held at a constant value throughout the simulation, the process may not be represented adequately.	As noted above (W7), the 'recharge' of the peat from surface water courses in the model is quite small, and may be under-estimated for some time periods. It is likely that this results in calculations which may over-estimate the impact of groundwater abstractions, and therefore this 'omission' could be considered to be conservative.
D4	Vertical groundwater gradients from the Crag aquifer generally remain upwards but may increase compared to the winter	This can be represented by MODFLOW	None required.

	situation.		
D5	Less water escapes from the internal system in response to a falling water level across the bund, although in theory water could still flow from the exterior to the interior system during a high tide, particularly if the sluices were opened.	None of these features are represented in the computational model.	Effectively the same comment as W8 and W9 above.
D6	Capillary flux from the water table tends to draw up Crag groundwater through the peat, contributing to the mixing of these waters with rainfall-derived recharge.	There is a representation of capillary fluxes but, unless the peat is thin, it is unlikely that it will draw up water from the Crag.	This will benefit from further explanation. We did not mean that capillary flux will draw water up directly from a water table in the Crag if the peat is 'dry', rather that 'removal' of water from the water table by capillary flux within the peat will tend to lower the water table and increase the upward vertical gradient thereby potentially leading to enhanced vertical flow from the Crag.