British
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Modelling the impact of climate change on groundwater in the UK

Stage 2 – Using an unsaturated zone transfer function to model groundwater level fluctuations

Groundwater Systems and Water Quality Programme

Internal Report IR/01/59

BRITISH GEOLOGICAL SURVEY

INTERNAL REPORT IR/01/59

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B É Ó Dochartaigh

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Summary

This report describes work carried out as part of the second stage of the joint BGS-CEH project “Modelling the impact of climate change on groundwater in the UK”. The work described in the report involved testing and developing a simple approach to the reproduction of historical groundwater level fluctuations. The technique makes use of an unsaturated zone transfer function to represent delayed recharge. The model was used to replicate long-term groundwater level records from four boreholes in the unconfined Chalk in southern and eastern England. The calibrated model will be used with data derived from climate models to simulate groundwater level fluctuations under potential future climatic conditions.

1 Introduction

This report describes work carried out as part of the joint BGS-CEH Science Budget-funded project "Modelling the impact of climate change on groundwater resources". The project aims to provide a set of techniques for simulating groundwater response to potential future climates. The techniques should be both simple and flexible and use easily available hydrological and hydrogeological data, so that they are easily applicable to a range of hydrogeological conditions.

The first stage of the project involved a review of previous work on groundwater and climate change, the identification of relevant available data, and the selection of four modelling techniques to be tested and developed during the project, and then used with predicted future climatic data. This stage of the project is described in Ó Dochartaigh et al. (2001).

This report describes the application of one of the modelling techniques selected in Stage 1 (Approach 3 in Ó Dochartaigh et al., 2001). This is a simple model using an unsaturated zone transfer function to represent the lagged response of groundwater levels to rainfall patterns at a point. The method allows infiltration at the surface in any month to reach the water table as a pulse distributed over a number of succeeding months, giving rise to incremental water level rises. The model was used to replicate long-term groundwater level records from four boreholes in the unconfined Chalk in southern and eastern England. Historical rainfall data from long raingauge records were provided by the Environment Agency.

2 Background

2.1 CORRELATION BETWEEN RAINFALL AND GROUNDWATER LEVELS

Groundwater level hydrographs often show a delayed response to effective rainfall or calculated surface infiltration patterns. This is assumed to be due to the thickness and nature of unsaturated strata through which infiltrating water flows before reaching the water table (e.g. Figure 1).

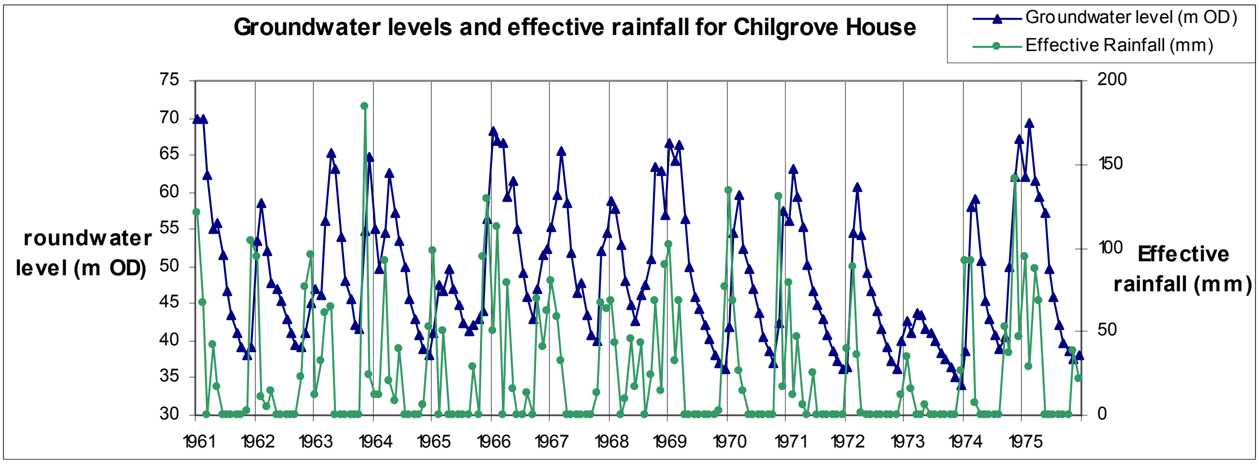


Figure 1 Groundwater level fluctuations often lag behind effective rainfall

The relationship between rainfall and groundwater levels in the unconfined Chalk aquifer was investigated statistically by cross-correlating monthly rainfall and groundwater level series data for each of the four test sites used in this study. The test sites are described in detail in Section 4. The software package Systat 9 was used for the correlation analysis. Cross-correlation is the process of comparing two different time series at various lags to reveal (i) the strength of the relationship between the two series, and (ii) the lag period that maximises the correlation between them. Correlating monthly groundwater levels with monthly rainfall therefore indicates how much of the rainfall ‘signal’ is present in the groundwater level ‘signal’ at various lag periods (months following rainfall signal).

The rainfall and groundwater level data series were first adjusted to remove the seasonal component of the series. There is likely to be significant autocorrelation between groundwater level values from one month to the next, due to the seasonal trends in groundwater level fluctuations; the same effect is likely to be seen in the rainfall series. Seasonal adjustment isolates and removes these seasonal trend effects. The process of seasonal adjustment is described in more detail in Appendix 1.

A cross-correlation function was then performed on the adjusted data, and cross-correlation plots of seasonally adjusted data for each of the four borehole sites are shown in Figure 2. Positive lags indicate a positive correlation between rainfall in month *n* and groundwater level in month *n* (Lag 0) and succeeding months. A statistically significant correlation value is marked on each plot: the probability of a correlation as great as or greater than this significant limit occurring by chance is very small (conventionally taken as a probability of 0.05). The strength and pattern of the cross-correlation relationship between groundwater levels and rainfall is likely to correspond indirectly to the actual process of recharge through the unsaturated zone: months of low rainfall are likely to coincide with months of high evapotranspiration, and therefore low recharge, and vice versa. The cross-correlation plots can therefore be interpreted to provide an indication of the basic unsaturated zone transfer patterns for each site.

At Ashton Farm, the correlation between groundwater levels and rainfall in the first month (Lag 0) is barely significant, and the strongest correlation occurs in the second month following rainfall input (Lag 2). The last significant correlation occurs at Lag 5. This pattern implies that recharge at the Ashton Farm site is both relatively rapid and concentrated in time, with the greatest proportion of surface infiltration in any month reaching the water table some two months later, and virtually all recharge occurring within 5 months. The correlation of the groundwater level and rainfall data for the Chilgrove House site shows a similar pattern, with the strongest correlation one month following rainfall input and the last significant correlation after seven months. There is also a strongly significant correlation in the same month as rainfall input, perhaps implying a rapid recharge mechanism.

The plots for Dalton Holme and Washpit Farm reveal a different pattern, with the strongest correlation between groundwater levels and rainfall occurring later, and a much longer ‘tail’ of significant correlations. This suggests that recharge at these sites is more distributed and therefore occurs over a longer period of time following rainfall input. At Dalton Holme the strongest correlation is reached relatively rapidly, in the third month following rainfall input (Lag 3), but the last significant correlation doesn’t occur until the thirteenth month. At Washpit Farm both the strongest and the last significant correlation are delayed compared to the other sites, occurring in the sixth and fifteenth months respectively.

The results of the cross-correlation exercise were interpreted to obtain the distribution of lagged groundwater response resulting from unit rainfall in month 0, shown in Table 1.

Lag	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Test site															
Ashton Farm	0.03	0.27	**0.3**	0.23	0.12	0.05	0	0	0	0	0	0	0	0	0
Chilgrove House	0.16	**0.24**	0.18	0.14	0.13	0.09	0.04	0.02	0	0	0	0	0	0	0
Dalton Holme	0	0.09	0.14	**0.16**	0.14	0.12	0.1	0.07	0.06	0.04	0.03	0.03	0.02	0	0
Washpit Farm	0	0	0.06	0.09	0.1	0.11	**0.12**	0.11	0.1	0.08	0.07	0.07	0.04	0.03	0.02

Table 1 Transfer (lag) distributions interpreted from cross-correlation of rainfall and groundwater levels. The values represent monthly increments of recharge at the water table resulting from unit rainfall in month 0

2.2 USING AN UNSATURATED ZONE TRANSFER FUNCTION TO REPRODUCE GROUNDWATER LEVEL FLUCTUATIONS

Oakes (1981) and Calver (1997) describe simple methods of approximating unsaturated zone and saturated zone behaviour to model the process of lagged recharge and simulate groundwater level fluctuations. The methods do not take account of the effect of any deposits through which infiltrating water must pass to reach the saturated zone of an aquifer, but approximate all unsaturated zone water transfer by a simple lagged function.

This report describes further investigations into the potential for such a method to reproduce groundwater level fluctuations at a point, i.e. a borehole, with the aim of using it to predict groundwater levels under simulated conditions of future changing climate. The main advantages of the method are the widespread availability of the basic data required for the modelling – groundwater level and rainfall series - and its simplicity and thus the ease with which it can be applied to a wide range of aquifer types and hydrogeological settings. By modelling the groundwater level response at boreholes which are as far as possible representative of local, catchment or even regional hydrogeological conditions, it may be possible to give an overview of the possible magnitude of groundwater level responses to potential future climates.

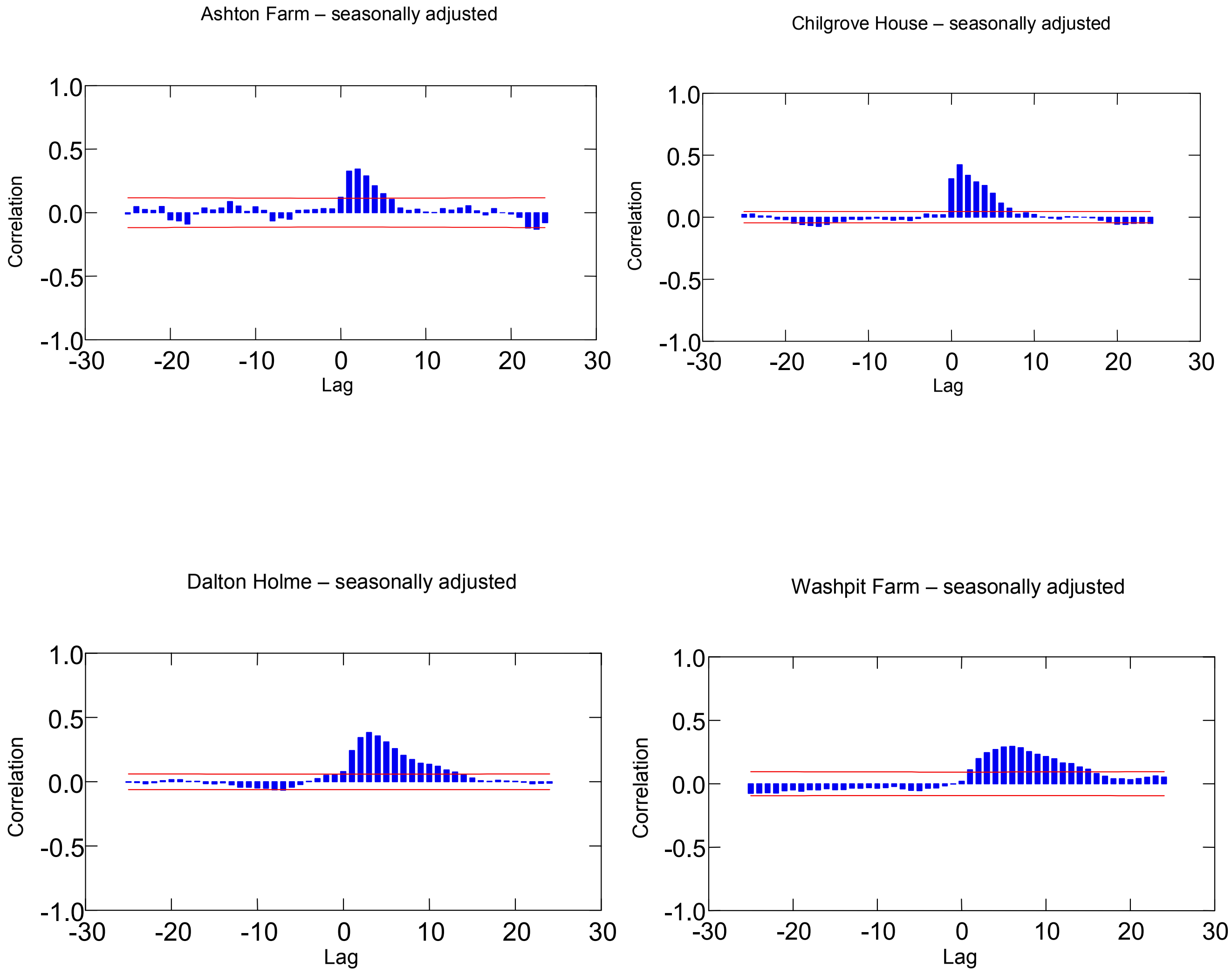


Figure 2 Cross-correlation plots of seasonally adjusted rainfall and groundwater level series for the four boreholes used in the study

3 Modelling Methodology

3.1 BACKGROUND AND INTRODUCTION

The method makes the assumption that infiltration at the ground surface is approximately equal to recharge at the water table; i.e., that lateral water transfer in the unsaturated zone is insignificant compared with (sub)-vertical infiltration (Calver, 1997). The model allows infiltration at the surface in any month to reach the water table as a pulse distributed over a number of succeeding months, giving rise to incremental water level rises. The process of modelling groundwater level fluctuations is done in two parts: one which estimates monthly increments of recharge to the saturated zone (water table), and converts the estimated change in water storage to an increase in water table elevation, and one which estimates the recession of groundwater levels in the absence of recharge as a result of saturated zone outflow.

Both Oakes (1981) and Calver (1997) equate infiltration in any month to a value for effective rainfall - rainfall minus actual evapotranspiration minus any decrease in soil moisture deficit - calculated using soil moisture balance techniques based on the method of Grindley (1969). Oakes calculates effective rainfall on a monthly basis for the period 1970 to 1977. Calver uses monthly hydrologically effective rainfall (HER) from MORECS, also termed excess rainfall, which is available from 1961 to the present (although only available in-house at CEH until 1991).

The current method uses two approaches, equating monthly infiltration at the ground surface to both monthly rainfall and monthly effective rainfall. Monthly timesteps are used, largely because monthly groundwater level records are far more common than daily or even weekly data. The first approach is the simplest possible simulation, where rainfall is directly equated with infiltration, with no account made of evapotranspiration, soil moisture storage, or any surface runoff. Rainfall series data are much more widely available than potential and actual evapotranspiration, which are needed to derive effective rainfall. The aim was therefore to investigate the possibilities of simulating groundwater level fluctuations directly using rainfall data. The second approach equates an effective rainfall series to infiltration. For the purposes of this study, a synthetic series was derived from existing rainfall series using patterns established from the relationship between MORECS rainfall and effective rainfall data. The reason for producing a synthetic effective rainfall dataset was to allow the use of available long rainfall series from individual raingauges, rather than be restricted to the length of the MORECS data series.

The whole of the available overlapping groundwater and rainfall series are used to calibrate the model in each case. This is in order to optimise calibration over periods of different climatic conditions. Such a model is more likely to be able to model groundwater levels with reasonable accuracy under conditions of future climate, which are likely to be more variable than current norms: for example, the 1961-91 period conventionally used to represent current climate patterns. Calibrating the model to a sub-set of the available historical record, and then validating its performance by using it to reproduce the remainder of the record, may allow a more meticulous description of model performance. However, it is more likely to lead to the model being calibrated preferentially to periods of particular climatic conditions, either wet or dry.

A detailed description of the modelling procedure is given in Appendix 2. Section 3.2, below, describes the basic modelling method. Chapter 4 describes the four boreholes used as test sites to develop the model. Chapter 5 describes the data required for the model and its availability. Chapter 6 describes the climatic inputs to each of the two model approaches and the method devised to synthesise effective rainfall series for each of the raingauge series.

3.2 MODELLING RECHARGE ESTIMATION AND GROUNDWATER LEVEL RISE

Total recharge to the saturated zone in month n can be written as:

$$R_n = \sum_{i=1}^{m} I_{n-i+1}\, u_i$$

where I is surface infiltration and u constitutes a delay function, where u_1, u_2 … u_m are monthly increments of recharge at the water table resulting from unit rainfall at the ground surface, and u_1 occurs in the same month as I_1 (and is equivalent to Lag 0). Initial values for u and m, the total number of months by which recharge is lagged behind surface infiltration, were derived from the cross-correlation exercise (Table 1). These were fitted subjectively during calibration by observation of the time series of observed and modelled groundwater levels.

The initial level for the modelled groundwater level series is taken as the observed groundwater level from the preceding month. In order to ensure that the starting level is representative of average groundwater conditions, the initial water level may be taken as the observed groundwater level in the preceding calendar month from any one of the first 5 years of the observed groundwater series. For example, if the first month of the model is January 1950, the initial water level may be taken as the observed groundwater level for December in either 1949, 1950, 1951, 1952 or 1953.

The increase in water storage as a result of recharge at the water table is converted to an increase in water table level by reference to aquifer specific yield (Sy), as follows:

$$\text{Increase in water table} = \frac{\text{recharge (m)}}{\text{Sy}}$$

Where specific yield is small, the addition of a given volume of water will result in a greater rise in water levels than would be the case where the specific yield is larger and the capacity for storage greater. The basic model uses a single value to approximate aquifer specific yield, ignoring any differences over the zone of water level fluctuation, or between the unsaturated zone and saturated zones. The model does however allow different specific yield values to be included if desired.

3.3 MODELLING GROUNDWATER LEVEL RECESSION

It is assumed that over long periods of time the groundwater system is in balance, with no real change in storage: i.e. the start and end groundwater levels for any specified time of year are similar. Therefore, recharge at any location on the water table, e.g. the modelled borehole, is assumed to approximate saturated zone net outflow from that location. Ignoring any recharge lag, and any difference in unsaturated zone storage at the two times, total infiltration over the modelled period was taken to approximate total net saturated zone outflow over the period. This value was divided by twelve to obtain the average monthly saturated zone outflow over the period. This was then weighted on a monthly basis to reflect precedent moisture conditions (assuming that the wetter the previous months, the greater the outflow rate), using the ratio of the previous twelve months rainfall to the average annual rainfall. The final output is an estimated series of net monthly saturated zone outflow at the location of the modelled borehole (Calver, 1997). As before, the decrease in water storage as a result of saturated zone outflow is converted to a decrease in water table level using a value for aquifer specific yield (Sy).

3.4 MODEL CALIBRATION

The initial model conditions were set as follows:

- The choice of initial groundwater level was made from the groundwater level in the same month as the start of the model from the first 5 years of the observed groundwater level record. The starting initial water level was taken as the value closest to the long term mean groundwater level for that month (measured over the period of historical record).
- The initial specific yield value was taken as the high extreme of the range of literature values quoted in Allen et al. (1997) – see Table 3.
- The initial transfer function distribution was taken as the distribution obtained from the cross-correlation exercise (Table 1).

Each model was then calibrated by trial and error by varying the three input parameters (initial groundwater level, specific yield and transfer function distribution) in order to achieve a closer fit between modelled and observed groundwater levels. The goodness of fit was assessed by visual reference to a chart of modelled and observed groundwater levels and by reference to the derived statistics, including mean normalised difference and mean absolute difference between modelled and observed groundwater levels. In general, the specific yield value was adjusted first to achieve a relatively close fit. The initial water level was then varied, if necessary. The distribution of the transfer function was then adjusted to achieve a closer fit between observed and modelled groundwater levels. The first two parameters were then further adjusted, if necessary, in order to optimise the fit.

The nature of the model is such that there may be more than one combination of parameter values which provide similar results. The most reasonable solution was obtained by first obtaining an indication of the probable recharge lag distribution by cross-correlating rainfall and groundwater levels, and further during model calibration by assessing the goodness of fit both visually and by reference to derived statistics.

4 Modelled Boreholes

Four of the index boreholes were used as test sites to develop and test the modelling procedure. The boreholes are all located in the unconfined Chalk aquifer although in different parts of the country (Figure 3). The hydrogeological conditions at each borehole vary, including average unsaturated zone thickness, average annual groundwater level fluctuation, and location with relation to major topographical features. The major characteristics of each borehole are given in Table 2. The groundwater level records for the four boreholes vary from 26 to 164 years in length. During the early parts of the records, groundwater level measurements were generally made on a monthly basis, and although recent measurements are often made more often, all four records have been adjusted to give monthly groundwater level readings. Total monthly rainfall records (derived from raingauges close to each of the four sites) have been obtained for each site, varying from 37 to 165 years in length.

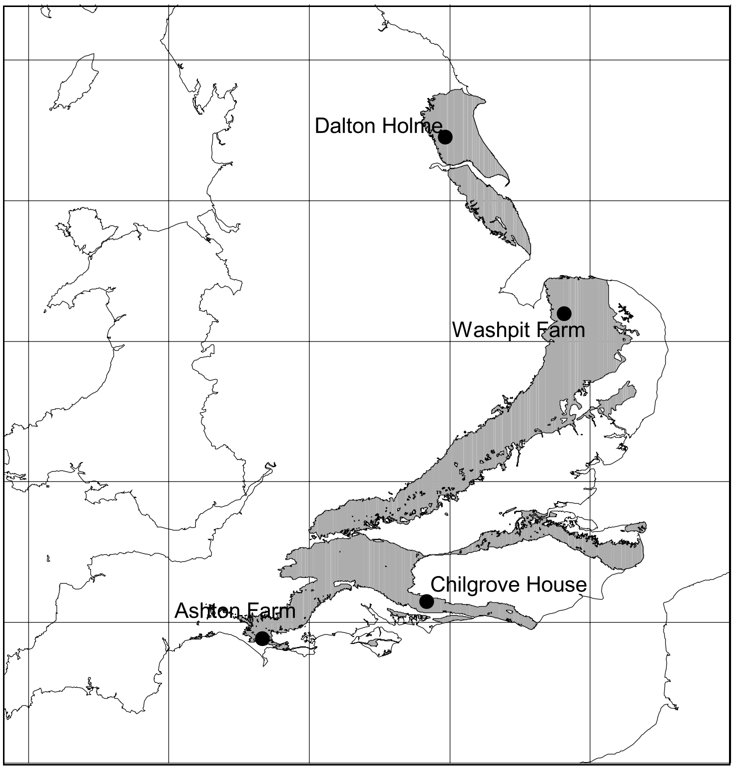


Figure 3 Location of modelled boreholes on Chalk outcrop

Ashton Farm is sited near the top of the Lewes Chalk in the South Downs, equivalent to the lower part of the Upper Chalk in the traditional Chalk subdivisions. The borehole is located slightly higher than the valley floor, with no drift cover (BGS, 2001). It is the shallowest of the four test boreholes, at only 11.7 m deep, and has the shortest groundwater level record, beginning in 1974.

Chilgrove House is sited in the Seaford Chalk Member and the Lewes Nodular Chalk, equivalent to the lower part of the Upper Chalk, and the Middle Chalk of the South Downs. The base of the borehole may reach the Zig Zag Chalk of the Lower Chalk. It is situated in a dry valley connected to the River Lavant. The borehole was originally 41.2 m deep, but has been deepened twice, in 1855 and 1934, to a final depth of 62.0 m. It occasionally overflows, and the bourne very occasionally rises as high up the valley as Chilgrove, such as in 1994 and 2000

(BGS, 2001). Groundwater level records began in 1836, giving Chilgrove the longest groundwater level record of any UK borehole. A local raingauge record dates from 1834. The groundwater level data for the period March 1942 to April 1943 are extrapolated from a borehole at Compton, 6.5 km to the west.

Dalton Holme is sited on thin till over the Burnham Chalk. The original borehole, completed sometime before 1889 when the groundwater level record begins, was 28.5 m deep. It was deepened twice, in 1946 and 1970, to a final depth of 61 m, and in 1990 a replacement borehole was drilled to a depth of 60 m at a distance of 10 m from the original (BGS, 2001). A local raingauge record dates from before the start of the groundwater level record, but there is a break in the rainfall data from 1898 to 1907. The models for Dalton Holme are therefore run from 1907 to 2000, or 93 years of continuous record.

Washpit Farm is sited in the Upper Chalk, with approximately 11 m of drift deposits (till at the surface, possibly overlying glacial sands and gravels) at the surface at the borehole site. The original shaft in 1950, when the groundwater level record begins, was 45.7 m deep, but siltation had decreased this to 40.4 m by January 1965 (BGS, 2001).

Site	National Grid Reference	Stratigraphy	Surface Elevation (m OD)	Depth (m)	Maximum recorded groundwater level (m OD)	Minimum recorded groundwater level (m OD)	Start of record
Ashton Farm	SY 6615 8805	Upper Chalk	72.16	11.7	71.48	63.10	1974
Chilgrove House	SU 8356 1440	Upper and Middle Chalk	77.18	62.0	77.11	33.57	1836
Dalton Holme	SE 9651 4530	Thin drift cover over Upper Chalk	34.5	60	23.52	9.96	1889
Washpit Farm	TF 8138 1960	Drift c. 11 m over Upper Chalk	80.7	40.4	49.9	40.3	1950

Table 2 Major characteristics of the four modelled boreholes

5 Available Data

5.1 GROUNDWATER LEVELS

Groundwater level records are widely available in the UK, although of differing lengths and quality. The National Groundwater Level Archive maintains data on a network of some 175 observation wells across the UK, for periodical assessment of the national groundwater situation. The network includes boreholes in all of the major UK aquifers (Doorgakant, 1995). The longest continuously monitored borehole in the UK is Chilgrove House, where records began in 1836, although the majority of records began in the 1960s and 1970s, giving 20 to 40 years of observations. Most of the observation wells are still measured manually either weekly or monthly, although a number are now equipped with continuous water level recorders. Measurements are normally made to the nearest 10 mm recorders (Marsh and Lees (eds), 1998). Some of the wells are, or have been, seriously affected by pumping, to the point where no useful estimates of natural groundwater level fluctuations can be made (Marsh and Lees, 1998). A subset of 33 boreholes from this observation network are designated as *index wells*. Index wells have a wide geographic spread across each main UK aquifer type, and are believed to be sited in areas which are broadly representative of the hydrogeological characteristics of the aquifer and region. They are further believed to be largely unaffected by pumping, so that measurements of groundwater levels from the boreholes should generally represent natural conditions. However, few of these wells are regularly assessed, and their actual current hydrogeological situations are generally unknown. The longest of these records began in 1836, the shortest in 1981, and the average start date of the records is 1956. Details of the length of the groundwater level records for the four selected boreholes are given in Table 4.

5.2 RAINFALL

Rainfall data records in the UK are available from a number of sources. The MORECS database holds daily average rainfall data for 40 x 40 km grid squares across Britain since 1961. The National Water Archive at CEH Wallingford holds monthly areal rainfall totals since 1986, derived from a 1 km square grid of rainfall values, which are generated from all daily and monthly rainfall data available from the Meteorological Office. Catchment rainfall is calculated by a computer program which averages rainfall values at the grid points lying within digital catchment boundaries. Accuracy depends largely on the adequacy of the network of raingauges used to represent an area (Marsh and Lees (eds), 1998). A large number of individual raingauge records are also maintained by the Environment Agency or water companies, although many (particularly the very old records) were originally maintained by individuals. The individual raingauges often provide the longest records, which are required for the historical simulation of long groundwater records. A complementary project investigating critical period groundwater yields under conditions of climate change used long rainfall records from raingauges close to index wells, provided by the Environment Agency. Because of the valuable opportunity to compare the results from both studies, the same data were used to develop the unsaturated zone transfer model in the current project.

A summary of the length of the available rainfall records for the four modelled sites is given in Table 4, and basic statistics on the data series are presented in Table 5.

5.3 EFFECTIVE RAINFALL

For the purposes of groundwater recharge studies, effective rainfall (or effective precipitation) is generally defined as precipitation (rainfall) minus evapotranspiration (e.g. Robins, 2000; Rushton and Ward, 1979). It is also termed potential recharge (Lerner et al., 1990). Unfortunately, the calculation of evapotranspiration, particularly actual evapotranspiration, which is the most accurate statistic for the estimation of effective rainfall, is complex, and evapotranspiration records are far less widely available than rainfall records. MORECS calculate hydrologically effective precipitation on a monthly basis for 40 x 40 km grid squares across Britain, using a generally accepted modified Penman-Monteith evapotranspiration formulation. However, this is only available in-house at NERC from 1961 to 1991. For the purposes of the current study, a method of deriving a synthetic effective rainfall series from the long-running rainfall series from individual raingauges was tested (described in Section 6.2). A summary of the length of the available effective rainfall records for the four modelled sites is given in Table 4, and basic statistics on the data series are presented in Table 5.

5.4 SPECIFIC YIELD

Specific yield represents the storage coefficient of an unconfined aquifer. It is expressed as the ratio of a measure of the volume of groundwater which can be drained by gravity from pore drainage as water tables fall, to the total volume of rock. A range of estimates of specific yield for the Chalk were obtained from Allen et al. (1997), derived from pumping tests. Allen et al. observe that such values obtained from pumping tests are generally less than those required in groundwater models. It has been recognised that the volumes of water draining from the Chalk in some areas during groundwater recessions are significantly larger than can be explained by gravity drainage (BGS, 1993; Price et al., 2000). This has been accounted for by reference to a delayed yield phenomenon, a slow drainage from the matric porosity in the unsaturated zone which continues even after groundwater level recessions have started, and which is not measured by standard pumping tests (Price et al., 2000).

A description of the range of specific yield values in the Chalk is given in Table 3. The range of values is given according to which stratigraphic division of the Chalk the water table lies in, and the depth from the top of the Chalk (Allen et al., 1997). In all of the modelled boreholes the rest water level lies in the Upper Chalk, and more than 30 m below the top of the Chalk. One of the sites, Dalton Holme, lies in the northern province of the English Chalk; the other three lie in the southern province.

Area	**Specific Yield**		
	<10 m below the top of the Chalk	10 – 30 m below the top of the Chalk	>30 m below the top of the Chalk
Southern Province	0.03 – 0.05	0.0005 – 0.002	0.001 – 0.002
Northern Province	0.005 – 0.02	0.0005 – 0.002	0.001 – 0.002

Table 3 Range of specific yield values in the English Chalk (after Allen et al., 1997)

	Ashton Farm	**Chilgrove House**	**Dalton Holme**	**Washpit Farm**
Groundwater Level	2/1974 – 3/2000	1/1836 – 4/2000	1/1889 – 4/2000	2/1961 – 5/2000
Gauged Rainfall (from raingauges close to borehole sites)	9/1963 – 6/2000	1/1834 – 3/1999	1/1881 – 12/1898 and 1/1907 – 6/2000	1/1961 – 4/2000
Catchment Rainfall	10/1971 – 12/1997	12/1970 – 12/1997	10/1961 – 12/1997	10/1953 – 12/1997
Catchment Runoff	10/1971 – 12/1999	1/1971 – 12/1995	10/1961 – 12/1996	9/1953 – 12/1999
MORECS Rainfall	1/1961 – 12/2000	1/1961 – 12/2000	1/1961 – 12/2000	1/1961 – 12/2000
MORECS Actual Evapotranspiration	1/1961 – 12/2000	1/1961 – 12/2000	1/1961 – 12/2000	1/1961 – 12/2000
MORECS Effective Rainfall	1/1961 – 12/1991	1/1961 – 12/1991	1/1961 – 12/1991	1/1961 – 12/1991

Table 4 **Dates of available climatic and hydrogeological data series**

	Ashton Farm			Chilgrove House			Dalton Holme			Washpit Farm		
	Mean Annual	Min Annual	Max Annual	Mean Annual	Min Annual	Max Annual	Mean Annual	Min Annual	Max Annual	Mean Annual	Min Annual	Max Annual
Gauged Rainfall (mm)	932	553	1197	905	489	1351	709	473	1036	700	442	913
Catchment Rainfall (mm)	1042	680	1342	934	669	1234	693	465	889	677	443	884
MORECS Rainfall (mm)	913	671	1156	839	590	1228	662	453	985	653	479	851
MORECS Effective Rainfall (mm)	376	135	599	304	81	470	125	0	255	127	7	210
Synthetic Effective Rainfall (mm)	414	131	600	341	138	615	151	46	285	156	51	242
MORECS Actual Evapotranspiration (mm)	539	370	613	528	331	594	529	405	615	518	389	609

Table 5 Selected comparative climatic statistics for the four modelled sites

6 Model climatic inputs

6.1 RAINFALL MODEL

The climatic input to the first model is rainfall, derived from single raingauge series located close to the modelled boreholes. The raingauge data series were chosen because of the length of the records, particularly in the case of Chilgrove House and Dalton Holme, and because raingauge series are available close to each of the test boreholes. The rainfall patterns recorded in the raingauge series are therefore likely to closely match those seen at the boreholes. In addition, work carried out during the development of a multilinear regression model to simulate changes in the long term mean and the variability of annual groundwater level minima (Approach 1 in Ó Dochartaigh et al., 2001) suggests that raingauge, rather than catchment, rainfall series provide a better fit when modelling the response of boreholes in Chalk (BGS, 2001). Catchment rainfall series tend to provide a better fit when modelling boreholes in Permo-Triassic sandstone. This is thought to be due to the different recharge and storage characteristics between the two aquifers. The Chalk tends to be more ‘flashy’, with more pronounced responses to local rainfall conditions, recorded by local raingauges, whereas Permo-Trias aquifers tend to show a more distributed response to rainfall input, which is more likely to be reflected by catchment averaged rainfall.

Basic descriptive statistics for rainfall values at each of the modelled sites are given in Table 5. The rainfall is used on a monthly basis and model calculations are also carried out monthly.

6.2 SYNTHETIC EFFECTIVE RAINFALL MODEL

6.2.1 Deriving synthetic effective rainfall series

A synthetic effective rainfall series was derived for each of the single raingauge series used above. It was hypothesised that there is a general relationship between rainfall and effective rainfall, since one of the two variables on which effective rainfall depends is rainfall (the other is actual evapotranspiration). Monthly rainfall and monthly effective rainfall series from the MORECS data base for the period 1961 to 1991, for the MORECS squares in which the 4 modelled boreholes lie, were tested to discover whether such a relationship exists and whether it is strong enough to use to predict monthly effective rainfall from monthly rainfall, without taking account of actual or potential evapotranspiration.

The procedure for deriving the synthetic series for each of the four individual raingauge series was as follows:

(i) Using MORECS rainfall and effective rainfall data for 1961-1990 for the 40 x 40 km square in which the raingauge lies, a simple regression was carried out for each month. The entire effective rainfall data series was first regressed on the rainfall series to give an overall indication of the strength of the relationship between the two series. The effective rainfall series was then regressed on the rainfall series on a monthly basis to derive a regression equation for each month. The monthly regression equations and associated correlation coefficients (r^2 values) derived for each site are presented in Appendix 3, and are discussed in 6.2.2, below.

(ii) The monthly regression equations were applied to the MORECS rainfall series from 1961-1990 to produce a synthetic effective rainfall series. This was compared to the MORECS effective rainfall series to test the correlation, as discussed in 6.2.3 (i), below.

(iii) The monthly regression equations were then applied to the entire raingauge rainfall series to derive a synthetic effective rainfall series from each, for use in the modelling exercise. To check how closely this synthetic series matched with actual effective rainfall data, the synthetic effective rainfall series from 1961 to 1990 for each site was isolated and compared to the MORECS effective rainfall series, as discussed in 6.2.3 (ii), below.

6.2.2 Relationship between MORECS rainfall and effective rainfall series

Details of the regression equations and correlation coefficients (r^2 values) obtained by regressing MORECS effective rainfall on MORECS rainfall series for each test site are given in Appendix 3. Figure 4 illustrates the range in monthly correlation coefficients for each site. As could be expected, the strongest correlations are seen in the winter and early spring, when generally high rainfall and low evapotranspiration result in high effective rainfall, in many cases almost equal to rainfall (see also Figure 7). From late spring to autumn, relatively low rainfall and high evapotranspiration result in low or zero effective rainfall. The difference between rainfall and effective rainfall is therefore greatest in the summer months, producing a poorer correlation.

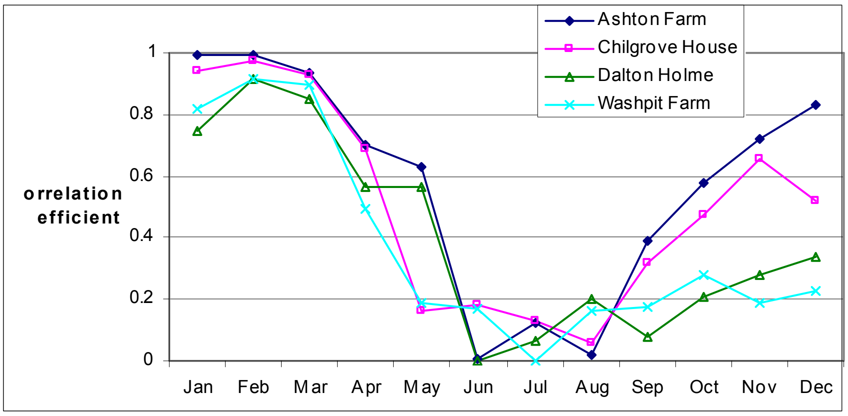


Figure 4 Monthly correlation coefficients for MORECS effective rainfall against MORECS rainfall, for the period 1961-91

6.2.3 Comparison of synthetic and MORECS effective rainfall series

(i) Comparing synthetic effective rainfall series derived from MORECS rainfall with MORECS effective rainfall

A comparison was made of synthetic (derived from MORECS rainfall) and calculated effective rainfall series for the four MORECS squares used. The overall correlation coefficients (r^2 values) are shown in Table 6.

Site	MORECS square	Overall r^2 value	Range of monthly r^2 values
Ashton Farm	180	0.8981	0.0079 – 0.9945
Chilgrove House	183	0.8277	0.0683 – 0.9719
Dalton Holme	94	0.7331	0.0017 – 0.9253
Washpit Farm	130	0.6909	0.0027 – 0.9185

Table 6 Overall correlation coefficients (r^2 values) and ranges in monthly correlation coefficients derived from the regression of synthetic effective rainfall (based on MORECS rainfall) and MORECS effective rainfall, for the period 1961-91

The relatively high overall correlations between synthetic and calculated effective rainfall implies that the regression equations are fairly successful at synthesising effective rainfall series, reproducing 70 to 90 percent of the overall variation in the MORECS effective rainfall series. Figure 5 illustrates the monthly correlation coefficients and reveals some notable relationships.

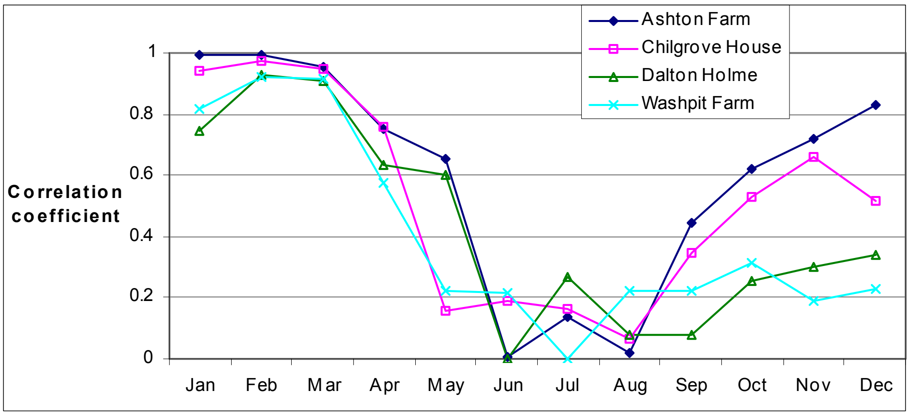


Figure 5 Monthly correlation coefficients (r^2 values) for synthetic effective rainfall (based on MORECS rainfall) against MORECS effective rainfall series, for the period 1961-91

For January to March, the correlation between synthesised and calculated effective rainfall is very high, generally over 0.90; for April and October to December it is intermediate, generally between 0.25 and 0.8; and for May to September it is very low, generally less than 0.2. This relationship is largely due to the characteristics of the regression and correlation analysis techniques, both during the derivation of the regression equations and during the correlation exercise. The correlation function works most effectively if there is a large range of values in the correlated data series, and least effectively where there is a narrow range of values and a large number of zero values. During the winter months, values of monthly rainfall and effective rainfall are both high and vary over relatively large ranges (e.g. 30 to 160 mm). Conversely, in the summer months, although rainfall can vary over almost as great a range as in winter, effective rainfall values are distributed over a much smaller range (e.g. 0 to 30 mm), and are generally very low or zero, because of high evapotranspiration. MORECS effective rainfall is most often zero, and synthetic effective rainfall is generally very low but not zero (a function of the method for estimating the synthetic series). The small range of values and the large number of zero values combine to affect the regression and correlation analysis.

(ii) Comparing synthetic effective rainfall series derived from raingauge rainfall with MORECS effective rainfall

The synthetic effective rainfall series were compared to the relevant MORECS effective rainfall series to assess their reliability. This is not ideal, since the MORECS series is used to both calculate and validate the synthetic series. However, the relatively short length of the available MORECS effective rainfall series (30 years) means that it is preferable to do this than to split the series in two and use half to calculate and half to validate the synthetic series.

Basic statistics describing the synthetic effective rainfall series based on the long-term raingauge records are given in Table 7. Mean annual synthetic effective rainfall is 10 to 20 percent higher than MORECS calculated effective rainfall for all four sites. This is most likely to be because gauged rainfall (from which the synthetic effective rainfall series is calculated) is higher than MORECS rainfall for all four sites.

A comparison was made of the synthetic effective rainfall series derived from raingauge data with the MORECS effective rainfall series for the square in which the raingauge lies. The overall correlation coefficients (r^2 values) and range of monthly correlation coefficients are given in Table 7.

Site	**Overall r^2 value**	**Range of monthly r^2 values**
Ashton Farm	0.831	0.006 – 0.903
Chilgrove House	0.7931	0.0001 – 0.8794
Dalton Holme	0.6219	0.0153 – 0.8249
Washpit Farm	0.6091	0.0017 – 0.8624

Table 7 Overall correlation coefficients (r^2 values) and ranges in monthly correlation coefficients derived from the regression of synthetic effective rainfall (based on raingauge rainfall) and MORECS effective rainfall, for the period 1961-91

The overall correlations between these two series are weaker than those in the previous section. This is unsurprising, since the raingauge rainfall series, on which the synthetic effective rainfall series are based, give higher readings than the MORECS rainfall series (see Table 5). However, the synthetic effective rainfall series still reproduces 60 to 83 percent of the overall variation in the MORECS effective rainfall series.

Plotting the correlation coefficients on a monthly basis (Figure 6) shows a broadly similar pattern to that described in 6.2.2 (i), above. Overall, the relationship between MORECS effective rainfall and synthetic effective rainfall based on raingauge data is strongest in the winter months, particularly in the early parts of the calendar year, and weakest in the summer, when soil moisture deficits are high.

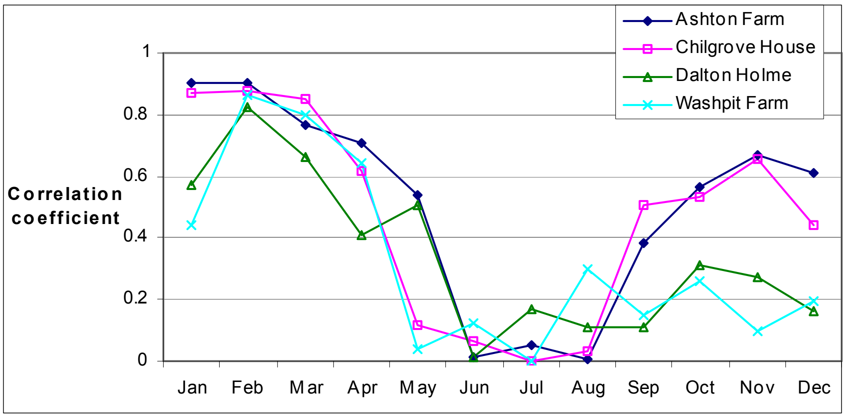


Figure 6 Monthly correlation coefficients (r^2 values) for synthetic effective rainfall (based on raingauge rainfall) against MORECS effective rainfall series, for the period 1961-91

A plot of rainfall against synthetic effective rainfall data, both from raingauge data, for Ashton Farm is shown in Figure 7. This illustrates the overall relationship between rainfall and effective rainfall for all the sites. Synthetic effective rainfall is low or zero during the summer months, and high, approaching total rainfall, during the winter months.

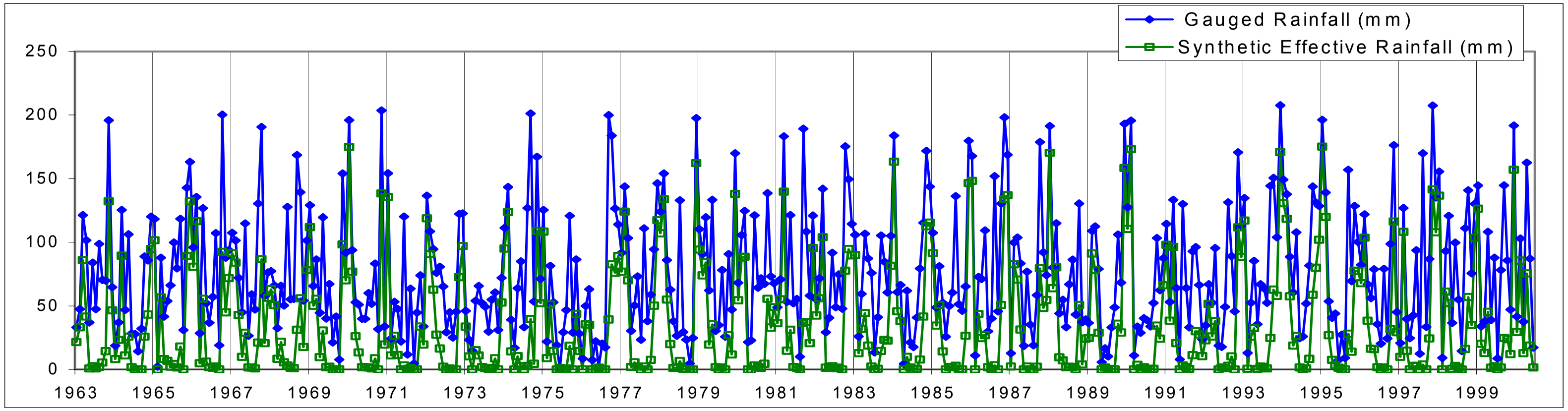


Figure 7 Monthly rainfall and synthetic effective rainfall for Ashton Farm

7 Model Results

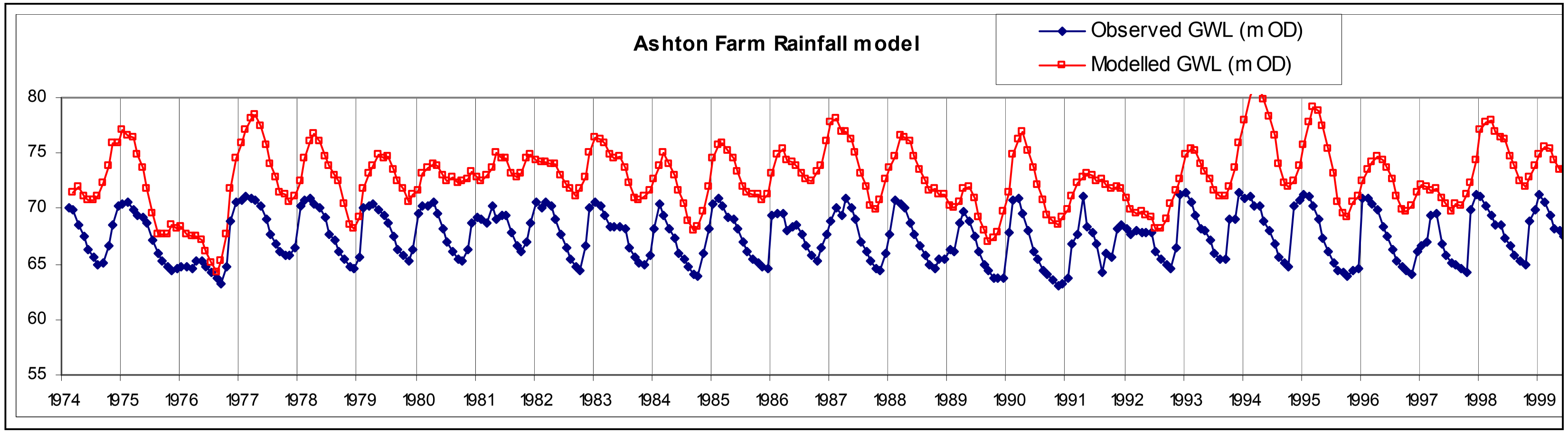
The results of the Rainfall and Synthetic Effective Rainfall models are described below. Graphs of modelled versus observed groundwater levels for each site are presented in Figures 9 to 16. When considering the results it should be noted that a run-in period of at least the maximum lag time (value of *m*) should be allowed at the beginning of the modelled series. Values for the parameters (specific yield and transfer function) derived during modelling are presented.

The performance of the model is dependent on the specific yield value, on how representative the initial water level is of average conditions, and on the distribution of the unsaturated zone transfer function. The specific yield value is of dominant importance in determining the amplitude of groundwater level fluctuations. The initial water level affects the vertical displacement of the modelled groundwater level series relative to the observed. The distribution of the transfer function affects both the timing, shape and amplitude of the modelled fluctuations.

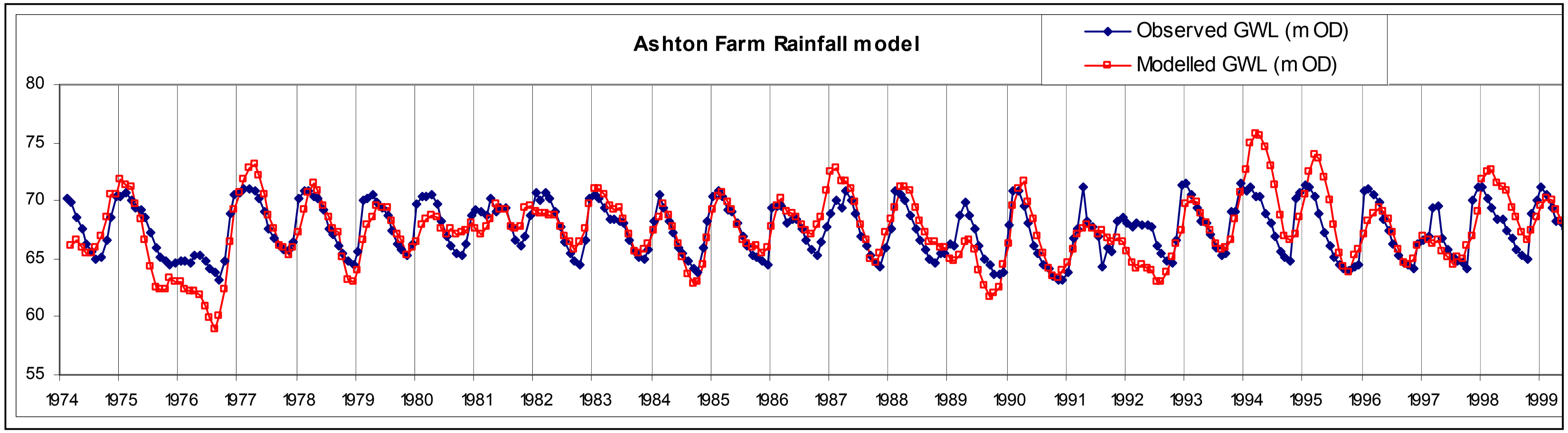
The sensitivity of the model to the three variable input parameters was tested in a non-automated way during the manual trial-and-error calibration of the parameters. The sensitivity analysis was carried out by keeping two parameters stable while varying the third. The number of possible variations in initial groundwater level is small; for specific yield it is relatively high and for the transfer function distribution it is extremely high. Appendix 4 presents a limited example of a sensitivity analysis for the Ashton Farm Rainfall model, showing mean normalised and mean absolute differences between modelled and observed groundwater levels and charts of modelled against observed groundwater levels for selected combinations of input parameter values. In this example, while the transfer function was first set at 1 (i.e. no distributed recharge) and the initial water level was held constant, while the specific yield value was varied. This gave a better indication of the actual specific yield value required to fit the model. The initial water level was also varied once. The specific yield was then held constant at the indicated value while the transfer function distribution was varied. Further analysis allowed ‘fine tuning’ of the specific yield value.

The sensitivity analysis shows that when the specific yield value is less than about 0.05, the model responds strongly to small changes in specific yield (e.g. changes of 0.001). However, when the specific yield value is greater than 0.05, the model responds much less strongly to even relatively large changes in specific yield (e.g. changes of 0.01). There appears to be a relatively small critical range close to ‘expected’ values of specific yield (i.e. in the range values quoted in the literature – see Table 3) in which specific yield is very sensitive to small changes.

Using a different initial water level can significantly shift the overall position of modelled groundwater levels on the vertical axis. For Ashton Farm, the initial water level from the first year of the observed groundwater level record is 70.12 m OD, similar to the long term average water level for that month of 69.70 m OD. However, when the model is run using this initial water level, modelled groundwater levels are consistently too high. This can be seen in Appendix 4 and in the following example (Figure 8): for the final derived specific yield value for the Ashton Farm Rainfall model of 0.0275 and transfer function distribution $u1$ = 0.3, $u2$ = 0.3, $u3$ = 0.4, modelled groundwater levels are of the right magnitude and in the right place on the horizontal axis, but are displaced too high on the vertical axis. Using the initial water level from the third year of the record, 64.84 m OD, modelled water levels fit closely to observed (Figure 8).



Initial groundwater level 70.12 m OD



Initial groundwater level 64.84 m OD

Figure 8 Observed and modelled groundwater levels for Ashton Farm, showing the effects of changing the initial groundwater level (all other parameters remain equal

The main function of the transfer function is to vary the timing of water table response: i.e., the position of the modelled series relative to the observed on the horizontal axis. Model response to changes in the distribution of the transfer function is relatively small, but significant in producing a more accurate fit to the timing of water level response. For example, see the differences in the timing of modelled groundwater fluctuations for Ashton Farm for a specific yield of 0.02 and transfer functions of (i) $u1 = 1$; (ii) $u1 = 0.4$, $u2 = 0.6$; (iii) $u1 = 0.2$, $u2 = 0.2$, $u3 = 0.2$, $u4 = 0.2$, $u5 = 0.2$; and (iv) $u1 = 0$, $u2 = 0$, $u3 = 0$, $u4 = 1$.

The initial groundwater levels and derived specific yield values and unsaturated zone transfer functions are given in Table 8 (Rainfall model) and Table 10 (Synthetic Effective Rainfall model).

The following basic comparative statistics for each of the sites for each of the models have been derived:

- Mean absolute difference between observed and modelled groundwater levels (m)
- Maximum absolute difference between observed and modelled groundwater levels (m)
- Mean normalised difference between observed and modelled groundwater levels
- Maximum normalised difference between observed and modelled groundwater levels
- A confidence level, equal to twice the mean absolute difference between observed and modelled groundwater levels (m)

The normalised difference between observed and modelled groundwater levels was derived by dividing by the range in observed groundwater levels.

The minimum absolute and normalised difference between observed and modelled groundwater levels is always zero.

The derived statistics are given in Table 9 (Rainfall model) and Table 11 (Synthetic Effective Rainfall model), and the mean and maximum normalised differences are shown in graphical form in Figure 9.

A brief overall report of the overall model results is given, followed by a more detailed description of the individual site results.

Overall the modelled groundwater levels fit observed levels relatively well. The model is generally able to reproduce the form and magnitude of historical annual groundwater level fluctuations with relative accuracy.

Specific yield values derived during modelling range from 0.0075 to 0.03, compared with literature values of between 0.0005 to 0.002 for Upper Chalk (Table 3): i.e., an order of magnitude higher than the range of literature values. If this were true for the Rainfall model only, it could be explained by the fact that the infiltration input to the model, rainfall, is larger than actual infiltration would be, because in reality a large proportion of rainfall is lost through evapotranspiration and runoff. Larger than actual values of specific yield are therefore required to 'balance' the model by moderating the groundwater level response to a particular rainfall input. However, it is also true for the Synthetic Effective Rainfall model, for which the same effect should not be seen. This phenomenon fits with the observation that that specific yield values obtained from pumping tests are generally lower than those required in groundwater models (Allen et al., 1997).

The following is a brief description of the modelling results for each borehole.

7.1 RAINFALL MODEL

The charts in Figures 10 – 14 show observed and modelled groundwater levels in the four modelled boreholes, with the optimised parameter (Sy and *u*) values for each model. They also show the moving average (12 monthly running mean) of rainfall. The initial groundwater levels for each model, and derived values for specific yield and the transfer function are given in Table 8. Basic comparative statistics for each of the modelled sites are given in Table 9.

Site	**Sy**	**Initial water level and month (m OD)**	**Long term average water level in relevant month* (m OD)**	***u*1**	***u*2**	***u*3**	***u*4**	***u*5**	***u*6**	***u*7**	***u*8**
Ashton Farm	0.0275	64.84 (February)	69.70	0.3	0.3	0.4					
Chilgrove House	0.0075	50.29 (January)	56.00	0.2	0.5	0.2	0.1				
Dalton Holme	0.0125	20.92 (February)	17.17	0	0.2	0.3	0.4	0.1			
Washpit Farm	0.02	43.79 (February)	44.30	0	0	0.1	0.1	0.2	0.3	0.2	0.1

Table 8 Specific yield (Sy), initial water levels and unsaturated zone transfer delay function (*u*) for the modelled boreholes from the Rainfall model

* average water level in the month of the initial water level, calculated over the modelled period

Site	Mean absolute difference (m)	Maximum absolute difference (m)	Range in observed ground-water levels (m)	Mean normalised difference	Maximum normalised difference	Confidence limit (+/- m)
Ashton Farm	1.45	5.67	8.38	0.17	0.68	2.90
Chilgrove House	5.88	42.91	43.55	0.13	0.99	11.76
Dalton Holme	1.95	7.89	13.57	0.14	0.58	3.90
Washpit Farm	1.39	5.26	9.60	0.14	0.55	2.78

Table 9 Comparative statistics for the Rainfall model for the four modelled sites

Ashton Farm

Ashton Farm shows the worst fit of the four modelled sites. The mean absolute difference between modelled and observed groundwater levels across the 26 year record is 1.45 m; the normalised difference is 0.17.

The graph in Figure 10 shows that the model performs well over much of the record. Modelled groundwater levels seem to be underestimated in years of low maxima (e.g. 1975-76, 1991-92), and groundwater level maxima are occasionally overestimated (e.g. 1977, 1987, 1994, 1995, 1998). Overall, the poorest fits occur in the last 10 years of the record, from 1989 to 2000. There is no obvious relationship between rainfall (represented by the 12 month running mean of monthly rainfall values) and those periods when the model produces a particularly poor fit; i.e., times of poor fit are not confined to times of low or high rainfall.

The fitted transfer function *u* provides a relatively early response to rainfall at the water table, with 60 percent of response within two months of rainfall input, although the largest single – and the final – response (40 percent of the total) occurs in the third month. This is slightly different from the transfer functions indicated by the cross-correlation exercise (see Table 1), in which only 30 percent of the response occurs within 2 months of rainfall input, and the last significant response occurs in the fifth month, although the largest single response (30 percent) also occurs in the third month.

The fitted specific yield value of 0.0275 is at the high end of the range of values for the southern Chalk province given in Allen et al. (1997) (see Table 3).

The initial water level, 64.84 m OD, is significantly lower than the average February water level: 4.86 m lower, compared to a maximum range in groundwater levels over the period of record of 8.38 m.

Chilgrove House

The mean absolute difference between modelled and observed groundwater levels across the 163 year record is 5.88 m; the normalised difference is 0.13.

The graphs in Figures 11 and 12 show that the modelled groundwater levels fits observed values relatively well. Overall, the model reproduces groundwater level minima with relative accuracy, although in years of low groundwater level minima, these tend to be overestimated (i.e. the modelled levels are too low). It is less good at reproducing groundwater level maxima, which tend to be underestimated (i.e. the model produces groundwater level peaks which are too low). From 1979 to 1986 (except 1983-85), modelled groundwater level fluctuations are generally less pronounced and do not fit observed levels. These are years when the 12 month running mean of rainfall shows a subdued pattern, with no marked peaks or troughs. This may cause the model to underestimate groundwater level reactions, possibly because the model doesn't respond sufficiently to cumulative rainfall over time.

The calibrated transfer function *u* indicates that groundwater levels show a relatively rapid response to rainfall, with 70 percent of response occurring in the first two months following rainfall input, and the largest single response (50 percent) occurring in the second month following rainfall. Total groundwater level response occurs within 4 months of rainfall input. The overall distribution is similar to that revealed by the cross-correlation exercise (see Table 1), although the modelled transfer function shows a larger response in early months, and a total response in a shorter time. The lag distribution indicated by cross-correlation shows only 30 percent of groundwater level response occurs in the first two months, although the largest single response (24 percent) also occurs in the second month. Total groundwater response takes eight months.

The specific yield value, 0.0075, is in the middle of the range quoted for the southern Chalk province by Allen et al. (1997) (see Table 3).

The initial water level used by the calibrated model, 50.29 m OD, is some 6 m lower than the long term average January water level of 56.00 m OD, which is a relatively small difference compared to the maximum groundwater level range over the period of record of 43.55 m.

Dalton Holme

The mean absolute difference across the 111 year record is 1.95 m; the normalised difference is 0.14.

The graphs in Figure 13 show that the Rainfall model reproduces observed groundwater levels well, although in a number of instances groundwater level minima and maxima are overestimated (modelled groundwater level minima are too low; maxima are too high): e.g. 1912-13, 1929-30, 1947, 1954-55, 1959-60, 1960-61, 1966, 1974-75. From 1985 to 1989, the running mean of rainfall is relatively constant and subdued (as with Chilgrove House for the years immediately preceding this) and the modelled groundwater level response is similarly subdued.

The maximum water table response as shown by the derived transfer function occurs in the fourth month following rainfall input. The transfer functions for Dalton Holme suggest that water table response to rainfall input occurs over a greater time period than for Chilgrove House and Ashton Farm, with total response occurring over 5 months, and 80 percent of response occurring more than 2 months after rainfall input. The transfer distribution suggested by the cross-correlation exercise (see Table 1) also shows that the largest single groundwater level response occurs in the fourth month following rainfall input. However, as for the models for Ashton Farm and Chilgrove House, the groundwater level response suggested by the cross-correlation results is more distributed than the model indicates, with 99 percent of response occurring more than 2 months after rainfall input, and total response occurring over 13 months.

The derived specific yield value, 0.0125, is towards the high end of the range quoted by Allen et al. (1997) (see Table 3).

The initial groundwater level, 20.92 m OD, is close to the long term average February water level, 17.17 m OD.

Washpit Farm

The mean absolute difference across the 38 year record is 1.39 m, the normalised difference is 0.14.

The graph in Figure 14 shows that the overall fit for the modelled groundwater level series is relatively poor. The model tends to underestimate large groundwater level fluctuations, in years of relatively high groundwater level maxima and relatively low minima. The model fits worst during period of extended groundwater level recession, such as from 1972-74, or more clearly from 1989-1992. The common over-estimation of modelled groundwater levels during periods of low rainfall may be partly caused by dominant physical processes which aren't taken into account by the model, particularly antecedent soil moisture conditions. Large soil moisture deficits in 'drought' years may moderate the groundwater level response, which isn't reflected in the model .

The fitted transfer function shows that Washpit Farm has the longest response time of the four modelled boreholes. The maximum response (30 percent) does not occur until the sixth month following rainfall input, and there is a total response time of 8 months, with 80 percent of response occurring more than 4 months following rainfall input. The transfer distribution suggested by cross-correlation (see Table 1) shows the largest single response occurring in the seventh month following rainfall, and a total response time of 15 months, with 84 percent of response occurring more than 4 months following rainfall.

The fitted specific yield value, 0.02, is near the high end of the range given by Allen et al. (1997) (see Table 3).

The initial water level used in the model, 43.79 m OD, is similar to the long term average February water level, 44.30 m OD.

7.2 SYNTHETIC EFFECTIVE RAINFALL MODEL

The charts in Figures 15 – 19 show observed and modelled groundwater levels in the four modelled boreholes, with the optimised parameter (Sy and *u*) values for each model. They also show the synthetic effective rainfall derived for each site. The initial groundwater levels for each model, and derived values for specific yield and the transfer function are given in Table 10. Basic comparative statistics for each of the modelled sites are given in Table 11.

Overall, the Synthetic Effective Rainfall model performs equally with the Rainfall model. The model generally reproduces the form and magnitude of historical groundwater fluctuations with relative accuracy. The Synthetic Effective Rainfall model produced slightly lower normalised differences for the Chilgrove House and Washpit Farm model, equal differences for the Dalton Holme model, and slightly higher differences for the Ashton Farm model. These differences are not great, however, and neither model can be said to perform better overall. Details of the model results for each borehole are discussed below.

The specific yield values derived during modelling range from 0.0075 to 0.03: almost equal to those derived from the Rainfall model. As discussed above, this range is an order of magnitude higher than the maximum of the range of values quoted by Allen et al. (1997) (see Table 3).

The following is a brief description of the modelling results for each borehole. Basic comparative statistics for each of the borehole results are shown in Table 10.

Site	Sy	Initial water level and month (m OD)	Long term average water level in relevant month* (m OD)	*u*1	*u*2	*u*3	*u*4	*u*5
Ashton Farm	0.03	64.84 (February)	69.70	0.2	0.3	0.4	0.1	
Chilgrove House	0.0075	50.29 (January)	56.00	0.6	0.2	0.2		
Dalton Holme	0.01	17.17 (February average)	17.17	0.2	0.3	0.4	0.1	
Washpit Farm	0.015	43.79 (February)	44.30	0.1	0.2	0.3	0.2	0.2

Table 10 Specific yield (Sy), initial water levels and unsaturated zone transfer delay function (*u*) for the modelled boreholes for the Synthetic Effective Rainfall model

* average water level in the month of the initial water level, calculated over the modelled period

Site	Mean absolute difference (m)	Maximum absolute difference (m)	Range in observed ground-water levels (m)	Mean normalised difference	Maximum normalised difference	Confidence limit (+/- m)
Ashton Farm	1.67	6.94	8.38	0.20	0.83	3.34
Chilgrove House	5.24	25.28	43.55	0.12	0.58	10.48
Dalton Holme	1.96	8.00	13.57	0.14	0.59	3.92
Washpit Farm	1.22	4.57	9.60	0.13	0.48	2.44

Table 11 Comparative statistics for the Synthetic Effective Rainfall model for the four modelled sites

Ashton Farm

The mean absolute difference between modelled and observed groundwater levels across the 26 year record is 1.67 m; the normalised difference is 0.20.

The graph in Figure 15 show that the modelled groundwater levels fit observed values relatively well overall. It appears to fit least well in years with particularly high synthetic effective rainfall during the winter months – e.g. 1988, 1990, 1994 and 1995. However, there were a number of years where the model does not fit very well when synthetic effective rainfall peaks were not particularly high – e.g. 1982 and 1998. During the dry year of 1992, the model underestimates the maximum observed groundwater levels. However, the model is relatively accurate at reproducing groundwater level minima.

The calibrated transfer function *u* is similar to that derived for the Rainfall model, with 50 percent of groundwater level response to rainfall occurring in the first two months following rainfall input, and the largest single response (40 percent) occurring in the third month. The total response time is slightly longer at 4 months, although only 10 percent of response occurs in the fourth month. This is slightly closer to the transfer function indicated by the cross-correlation exercise (see Table 1) than the transfer function derived for the Rainfall model.

The derived specific yield value, 0.03, is at the high end of the range of values for the southern Chalk province given in Allen et al. (1997) (see Table 3).

The initial water level, 64.84 m OD, is the same as that used for the Rainfall model, and is almost 5 m lower than the average February water level, compared to a maximum range in groundwater levels over the period of record of 8.38 m.

Chilgrove House

The mean absolute difference across the 163 year record is 5.24 m; the normalised difference is 0.12.

The graphs in Figures 16 and 17 show that modelled groundwater levels reproduce observed values relatively well. The model is generally good at reproducing groundwater level minima, tending to overestimate rather than underestimate minima where it is wrong. However, of the six years where the model underestimates groundwater level minima (i.e. the modelled values are too high), four occur between 1984 and 1997. This period was hotter and drier overall than much of the previous record, suggesting that the model does not work as well in periods with very different climatic conditions than the historical mean.

The calibrated transfer function *u* shows that groundwater levels respond rapidly to rainfall, with the largest single response (60 percent) occurring in the same month as rainfall input, and total response in only 3 months. This is a slightly faster response than that derived for the Rainfall model, and much faster than the response indicated by the cross-correlation exercise (see Table 1).

The derived specific yield value, 0.0075, is the same as that derived for the Rainfall model, and is in the middle of the range quoted for the southern Chalk province by Allen et al. (1997) (see Table 3).

The initial water level, 50.29 m OD, is some 6 m lower than the long term average January water level of 56.00 m OD. This is the same water level used in the Rainfall model, and is a small difference compared to the maximum groundwater level range over the period of record of 43.55 m.

Dalton Holme

The mean absolute difference across the 111 year record is 1.96 m; the normalised difference is 0.14. These are almost identical to the statistics for the Rainfall model.

The graphs in Figure 18 shows that the overall performance of the model is relatively good. In particular, minimum groundwater levels are generally reproduced well: there are very few cases when modelled groundwater level minima are underestimated (too high relative to observed) – before 1985 there are only two instances, in 1965 and 1976. As for the previous two examples, the model performs worst during the last period of the record, from 1989 to 1997, when modelled groundwater levels in general tend to be higher than observed.

The derived transfer function maximum shows that the maximum water table response (40 percent) occurs in the third month following rainfall input, and total response in four months. This is a more rapid response than suggested by the transfer function derived for the Rainfall model: only 50 percent of the total response occurs more than 2 months after rainfall input, as opposed to 80 percent from the Rainfall model.

The derived specific yield value, 0.01, is towards the high end of the range quoted by Allen et al. (1997) (see Table 3), and similar (slightly lower) than that derived for the Rainfall model.

The initial groundwater level was eventually set as the long term February average, 17.17 m OD, as the February groundwater levels in the first 5 years of the record were either significantly lower (13 to 14 m OD) or higher (20 to 21 m OD) than this, and the model performed better using the long term average.

Washpit Farm

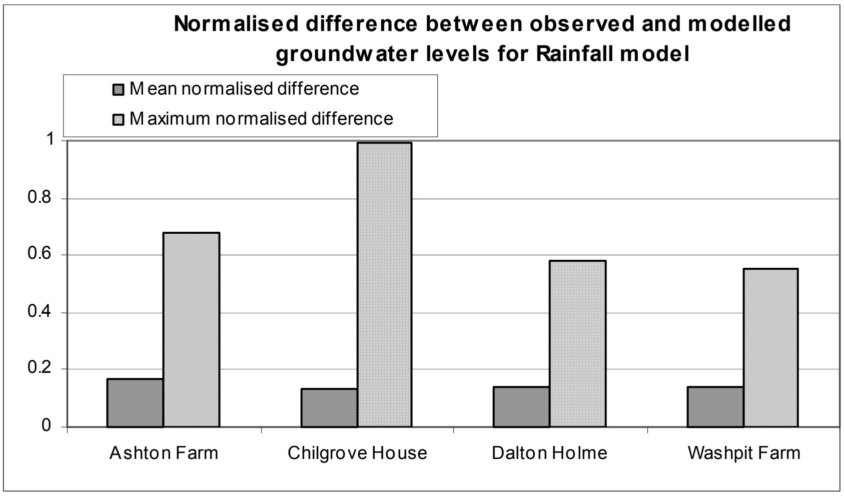
The mean absolute difference across the 38 year record is 1.22 m, the normalised difference is 0.13.

The graph in Figure 19 shows that the overall fit for the modelled groundwater level series is relatively poor. The model performs best during the middle part of the record, from 1972 to 1987, although modelled water levels in 1973 are notably higher than observed. From 1967 to 1971, modelled groundwater levels are lower than observed; from 1990 to 1999, modelled groundwater levels tend to be higher than observed. The worst fits are during periods of extended groundwater level recession, such as from 1972-74, or 1990-1993.

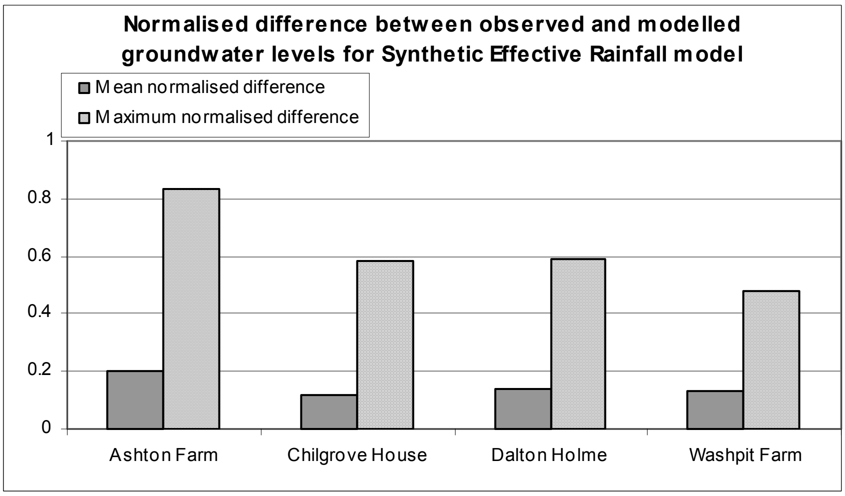
The derived transfer function shows an earlier groundwater response than that for the Rainfall model. Total response occurs over 5 rather than 8 months, with the largest single response (30 percent) occurring in the third month following rainfall input, compared to sixth month in the Rainfall model. Only 20 percent of groundwater response occurs more than 4 months after rainfall input, compared to 80 percent in the Rainfall model.

The fitted specific yield value, 0.015, is near the high end of the range given by Allen et al. (1997) (see Table 3).

The initial water level used in the model, 43.79 m OD, is the same as that used in the Rainfall model, and is only slightly lower than the long term average February water level, 44.30 m OD.

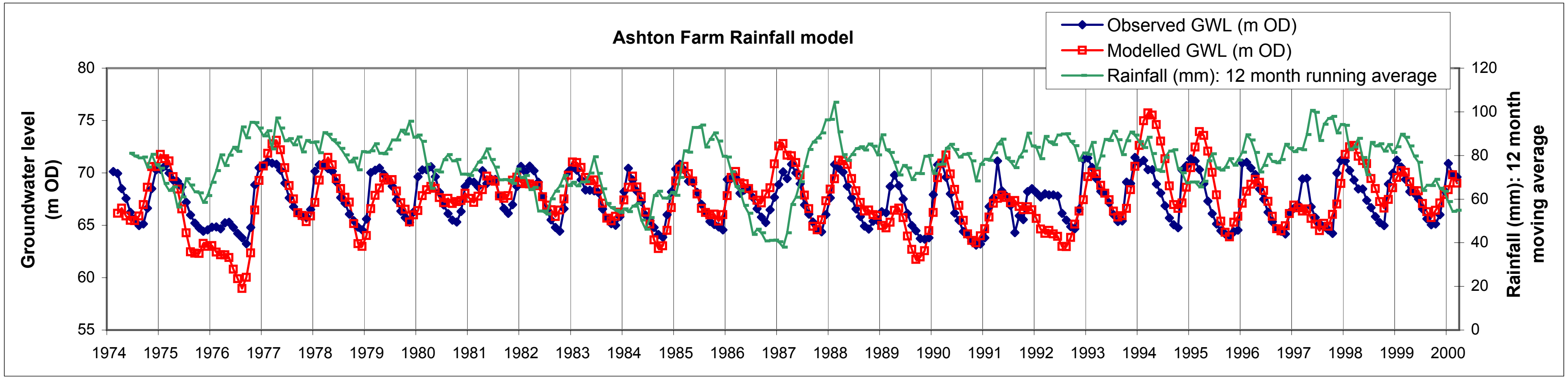


(i)



(ii)

Figure 9 Plots of normalised difference between observed and modelled groundwater levels for (i) Rainfall and (ii) Synthetic Effective Rainfall

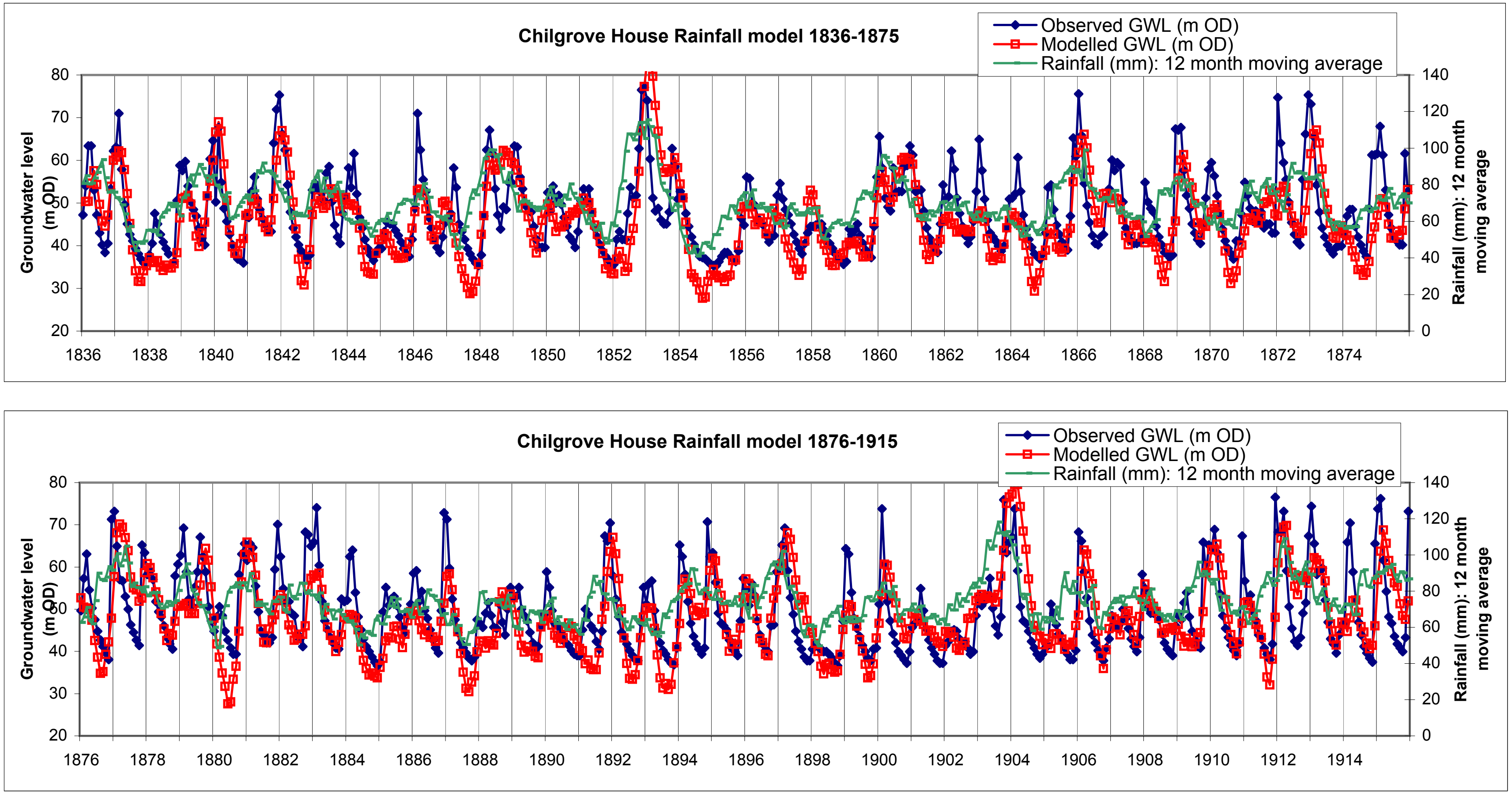


Specific yield

0.0275

u1	*u2*	*u3*	*u4*	*u5*	*u6*	*u7*	*u8*	*u9*	*u10*	*u11*	*u12*	*u13*	*u14*	*u15*
0.3	0.3	0.4	0	0	0	0	0	0	0	0	0	0	0	0

Figure 10 **Observed and modelled groundwater levels and moving average of rainfall for Ashton Farm, Rainfall model**



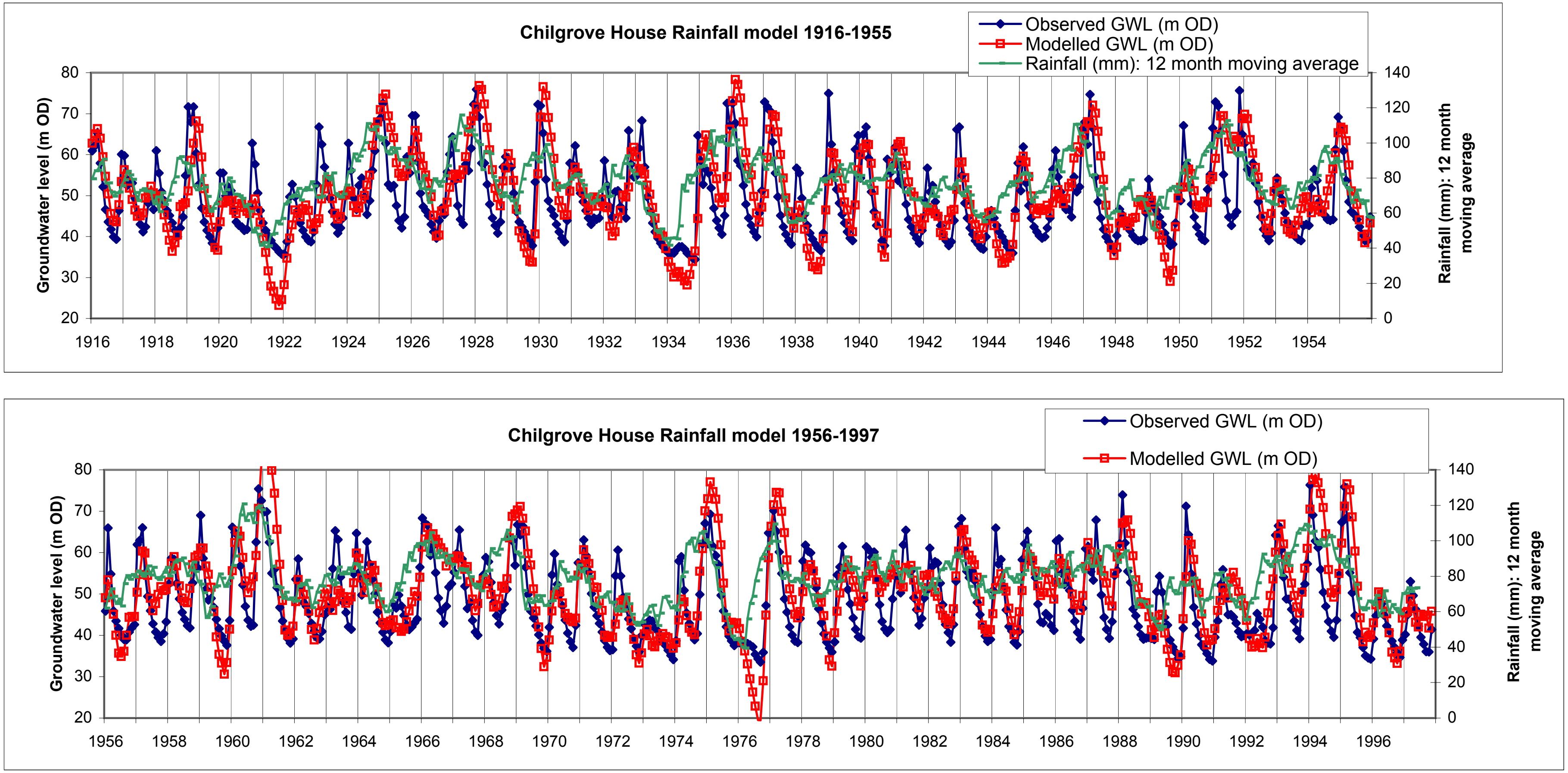
Specific yield

0.0075

u1	u2	u3	u4	u5	u6	u7	u8	u9	u10	u11	u12	u13	u14	u15
0.2	0.5	0.2	0.1	0	0	0	0	0	0	0	0	0	0	0

Figure 11

Observed and modelled groundwater levels and moving average of rainfall for Chilgrove House, Rainfall model, 1836 – 1915


Chilgrove House Rainfall model 1916-1955

Chilgrove House Rainfall model 1956-1997

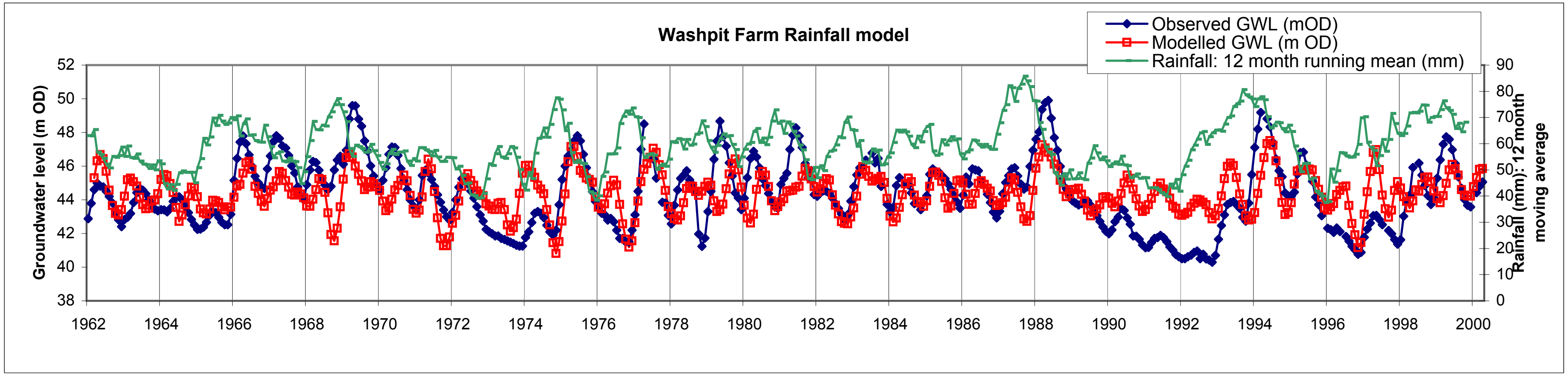
Specific yield

0.0075

u1	u2	u3	u4	u5	u6	u7	u8	u9	u10	u11	u12	u13	u14	u15
0.2	0.5	0.2	0.1	0	0	0	0	0	0	0	0	0	0	0

Figure 12

Observed and modelled groundwater levels and moving average of rainfall for Chilgrove House, Rainfall model, 1915 – 1997

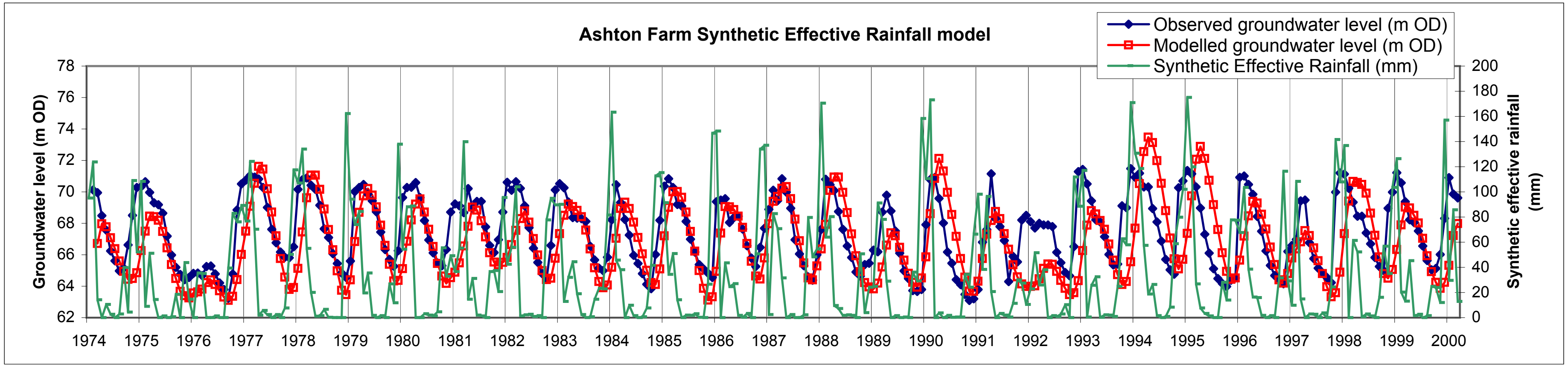


Specific yield

0.02

u1	*u2*	*u3*	*u4*	*u5*	*u6*	*u7*	*u8*	*u9*	*u10*	*u11*	*u12*	*u13*	*u14*	*u15*
0	0	0.1	0.1	0.2	0.3	0.2	0.1	0	0	0	0	0	0	0

Figure 14 **Observed and modelled groundwater levels and moving average of rainfall for Washpit Farm, Rainfall model**

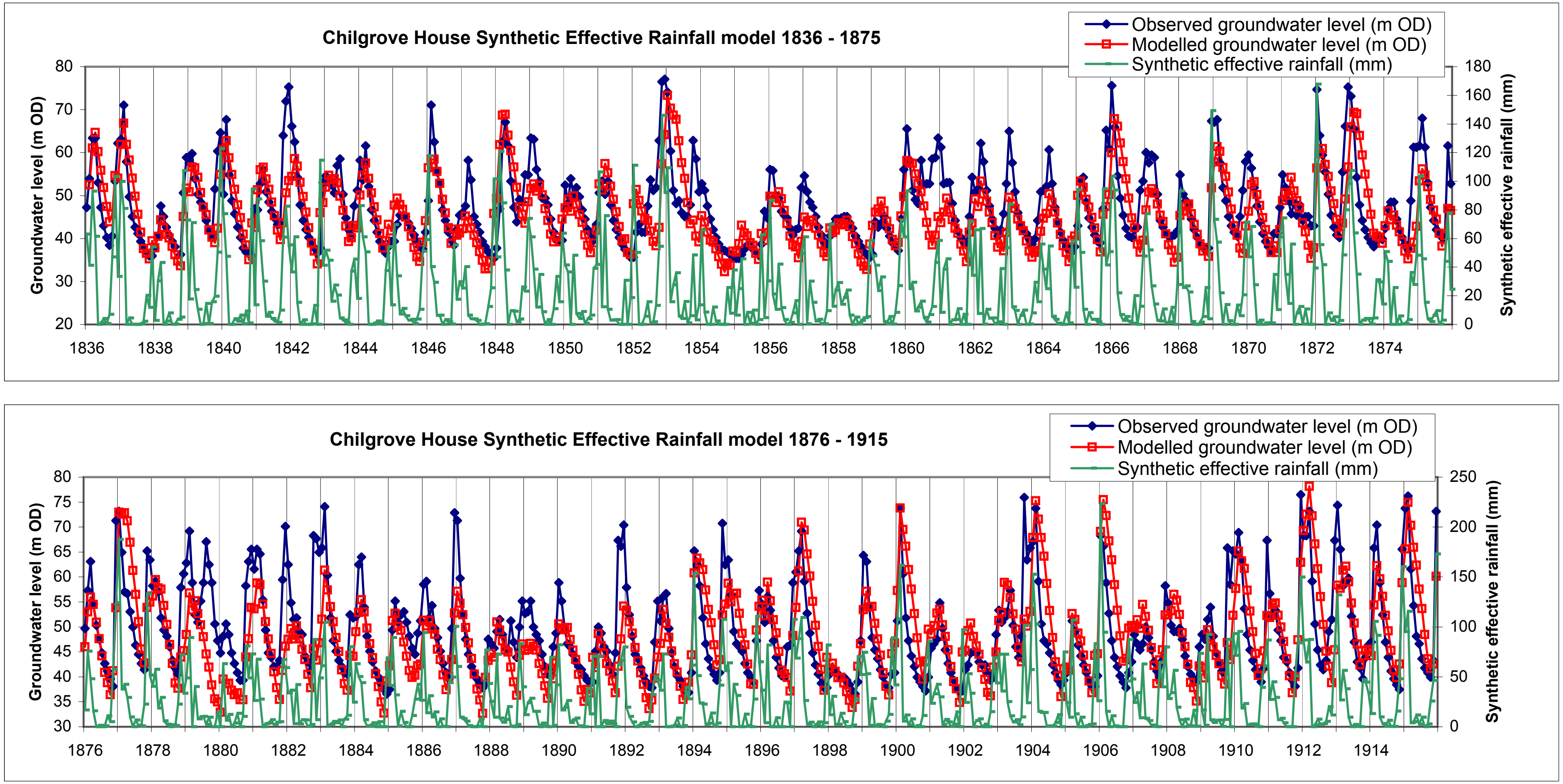


Specific yield

0.03

u1	***u2***	***u3***	***u4***	***u5***	***u6***	***u7***	***u8***	***u9***	***u10***	***u11***	***u12***	***u13***	***u14***	***u15***
0.2	0.3	0.4	0.1	0	0	0	0	0	0	0	0	0	0	0

Figure 15 **Observed and modelled groundwater levels and synthetic effective rainfall for Ashton Farm, Synthetic Effective Rainfall model**

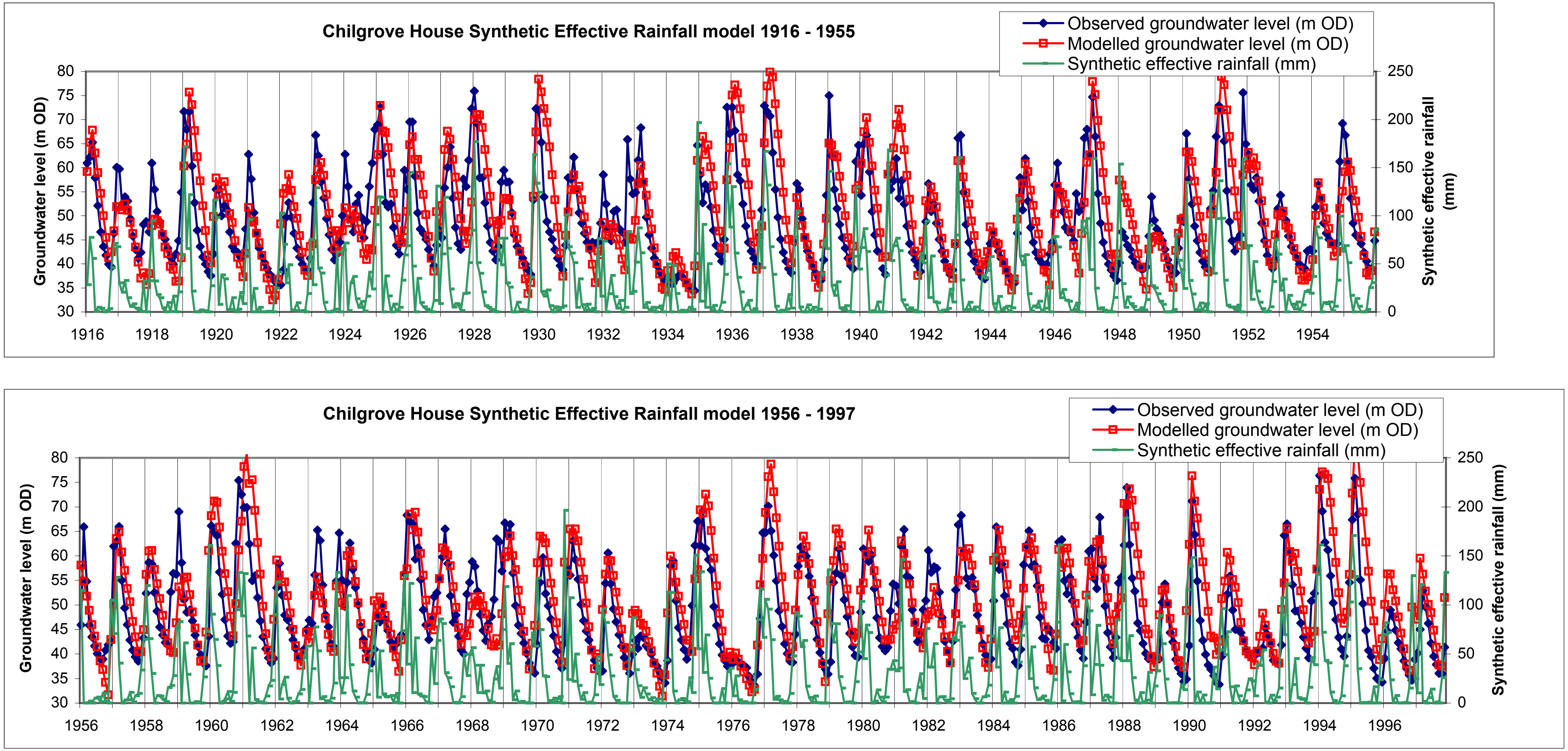


Specific yield

0.0075

u1	*u2*	*u3*	*u4*	*u5*	*u6*	*u7*	*u8*	*u9*	*u10*	*u11*	*u12*	*u13*	*u14*	*u15*
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 16 **Observed and modelled groundwater levels and synthetic effective rainfall for Chilgrove House, Synthetic Effective Rainfall model, 1836 – 1915**

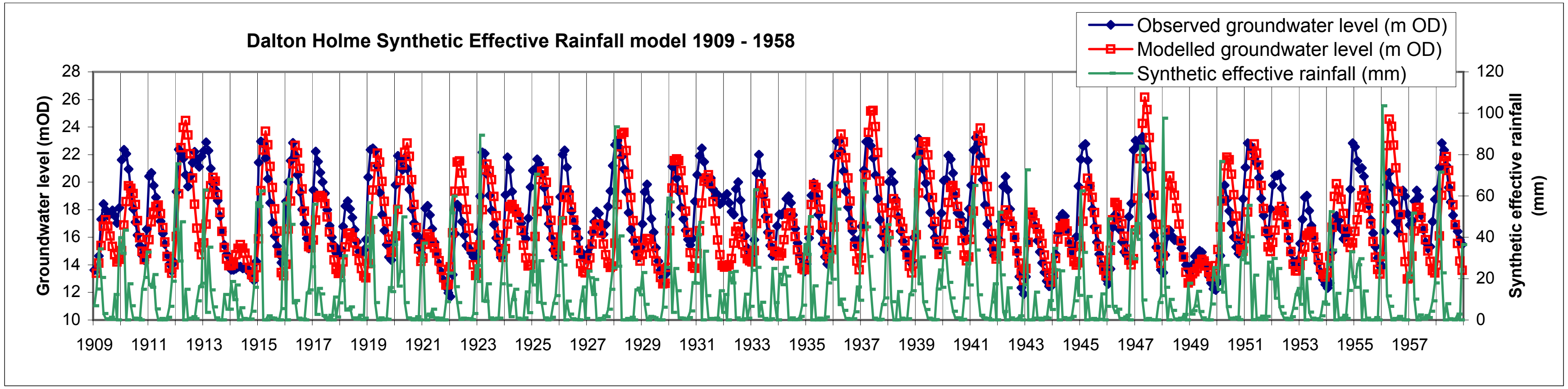


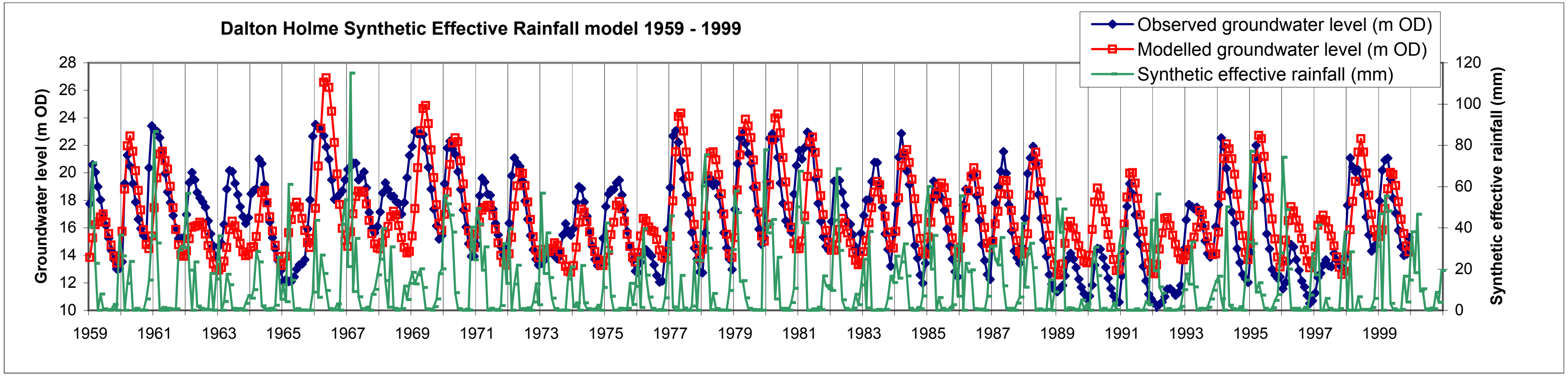
Specific yield

Specific yield
0.0075

u1	*u2*	*u3*	*u4*	*u5*	*u6*	*u7*	*u8*	*u9*	*u10*	*u11*	*u12*	*u13*	*u14*	*u15*
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 17 **Observed and modelled groundwater levels and synthetic effective rainfall for Chilgrove House, Synthetic Effective Rainfall model, 1916 – 1997**



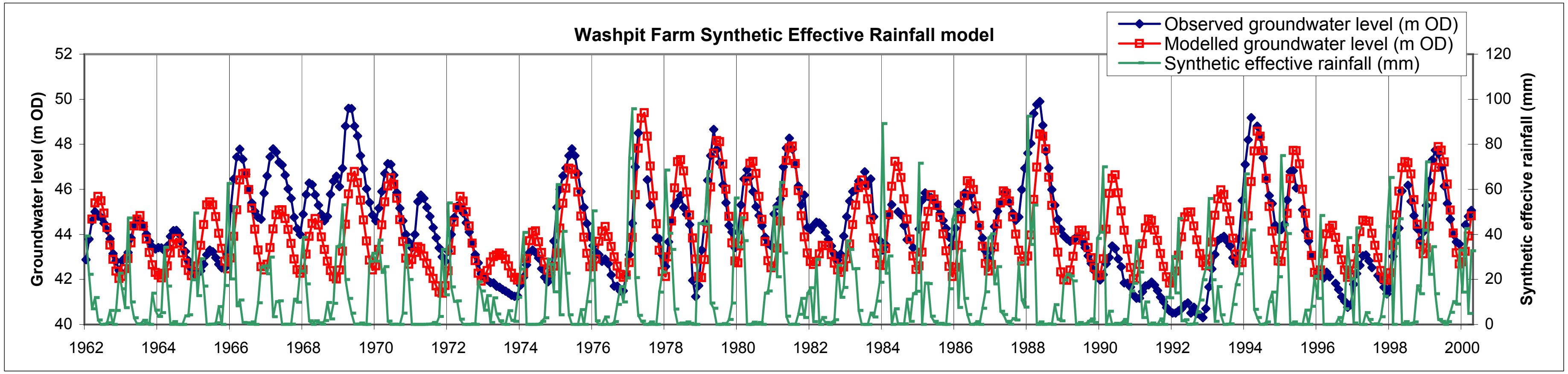


Specific yield

0.01

u1	***u2***	***u3***	***u4***	***u5***	***u6***	***u7***	***u8***	***u9***	***u10***	***u11***	***u12***	***u13***	***u14***	***u15***
0.2	0.3	0.4	0.1	0	0	0	0	0	0	0	0	0	0	0

Figure 18 **Observed and modelled groundwater levels and synthetic effective rainfall for Dalton Holme, Synthetic Effective Rainfall model**



Specific yield

0.015

u1	*u2*	*u3*	*u4*	*u5*	*u6*	*u7*	*u8*	*u9*	*u10*	*u11*	*u12*	*u13*	*u14*	*u15*
0.1	0.2	0.3	0.2	0.2	0	0	0	0	0	0	0	0	0	0

Figure 19 **Observed and modelled groundwater levels and synthetic effective rainfall for Washpit Farm, Synthetic Effective Rainfall model**

8 Discussion and Conclusions

8.1 DISCUSSION OF MODEL RESULTS

The overall fit of the models for the selected sites discussed here is relatively good, with the models generally reproducing 85 to 90 percent of observed groundwater level fluctuation.

Most of the models reproduce groundwater level minima relatively well. Where the models are wrong, they tend to overestimate minima (modelled minima are lower than observed), particularly in years of low overall groundwater levels – such as the notable dry year of 1976. This is encouraging in terms of the application of the technique to predicting groundwater level responses in extremely dry years. For most of the models this applies even for the series of successive dry years in the late 1980s and 1990s, apart for Washpit Farm, where both Rainfall and Synthetic Effective Rainfall models perform worst over this period.

The models of Ashton Farm, which has the shortest modelled data series – 26 years – perform worst overall, reproducing 83 and 80 percent of observed measurements for the Rainfall and Synthetic Effective Rainfall models, respectively. The models of Chilgrove House, with the longest series – 163 years – perform best, reproducing 87 and 88 percent of observed measurements. This suggests that there may be some link between the length of the modelled data series and the reliability of the model. The small subset of only four boreholes makes it difficult to assess whether there is a consistent relationship, particularly as the mean differences for each of the models are similar.

The length of input record to the historical models also has implications for the potential accuracy of modelling future conditions. Groundwater levels do not always response linearly to climatic forcing – e.g., an increase in 50 to 80 percent in rainfall over the winter half-year can treble the recharge to some aquifer units (NERC, 2001). The longer the length of the data series input to the model, the more likely they are to include periods of extreme climate and groundwater level response. A model calibrated on a long data series is therefore more likely to successfully simulate groundwater levels under a wider range of climatic conditions, some of which could be expected under potential future climates. The shorter the input records to the historical model, the more likely the model is to be fitted preferentially to one particular climatic condition, which may reduce its ability to accurately reproduce groundwater levels under different climatic conditions. Calver (1997) notes from her work using unsaturated zone transfer functions that the model is most suitable within the usual range of groundwater level fluctuation: this is likely to result from the same effect.

The most surprising outcome of the modelling described here is that there is no significant difference between the performance of the Rainfall and Synthetic Effective Rainfall models. It might have been expected that using effective rainfall as a proxy for surface infiltration would result in greater accuracy in reproducing observed groundwater levels, since effective rainfall takes into account evapotranspirative losses and is therefore significantly lower than rainfall, so equating more closely than rainfall to the volume of water which recharges at the water table. It might also have been expected that lower values of specific yield would be derived, since artificially high specific yield values would not be needed to ‘balance’ the model by moderating the modelled groundwater level response to rainfall inputs. However, both models perform equally well, and produce similar patterns for the derived transfer functions for each borehole, although the absolute length of lag may differ. The derived specific yield values for each borehole from the two models are also within the same order of magnitude. One explanation of this is that the pattern of seasonal rainfall and effective rainfall distribution is similar, with high values during the winter and lower values during the summer, although the absolute value of each can differ significantly during the summer. Given this fact, it may be that the transfer function makes the model relatively insensitive to extreme (large or small) absolute rainfall or effective rainfall values in any one month or even over a succession of months, and more responsive to the overall distribution of rainfall over a season or longer.

The unsaturated zone transfer functions, particularly those derived from the Rainfall models, reflect the groundwater level response patterns suggested by cross-correlation of rainfall and groundwater levels (see Section 2.1). Ashton Farm and Chilgrove House show the shortest overall response period, while groundwater levels at Dalton Holme and Washpit Farm show extended 'tails' in their response to rainfall, particularly in the Rainfall models.

As well as the parameters used in the model – rainfall, specific yield, delay in water table response – there are other variables which may affect local groundwater level response. The index wells selected for modelling in this study are theoretically free from abstraction influences. However, it is debatable whether any borehole in the major aquifers of the Chalk and Permo-Trias in south, central and eastern England is truly free from artificial influences. The model further assumes that local land use does not change significantly over the modelled period, at least with regard to activities which could affect groundwater recharge. This is likely to be a reasonable assumption. A less justifiable assumption is that groundwater level response in a particular borehole is independent of water table level. In practice, a borehole may intersect zones of higher or lower permeability, and therefore specific yield, in which groundwater level response is considerably different from the 'average' response. Given the same rainfall input volume, water table rise and fall will be more marked in zones of lower permeability, and more subdued in zones of higher permeability. On a larger scale of interest, where natural groundwater drainage (e.g. springs) is rapid, groundwater levels may rise more slowly during recharge periods because large quantities of groundwater are simultaneously being discharged.

8.2 CONCLUSIONS AND FURTHER WORK

The results from this modelling exercise suggest that the unsaturated zone transfer function model reproduces historical groundwater levels with sufficient reliability to justify applying it to scenarios of future climates. The major difficulty in simulating potential future groundwater level conditions is obviously the scale of the unknown. In addition to an imperfect understanding of many relevant current hydrogeological conditions and processes, it is not known whether the relationships between groundwater and climate parameters under changing climatic conditions will be the same as seen in the past. However, simple models, calibrated to good quality historical records, can indicate generic responses to climatic changes, and help to focus attention on key features.

In general, the simulation of changes in rainfall under future climate scenarios is relatively advanced compared to the simulation of evaporative losses. This is largely because rainfall is treated as a single variable in climate models, whereas evaporation must be calculated from a number of simulated parameters including temperature, wind speed and humidity. Simulated future evaporation data is therefore likely to be a less dependable parameter than simulated rainfall data. Using simulated future evaporation data can be avoided by deriving a synthetic effective rainfall series based on the observed relationship between rainfall and effective rainfall over a subset of the historical record, as was done during the development of this modelling approach. However, the historically observed relationship between rainfall and effective rainfall may not remain the same under future climatic conditions, and there is no straightforward method of checking the accuracy of a synthetic effective rainfall series derived from a future rainfall series. The development of the unsaturated zone transfer model has shown that there is little difference in the accuracy of models with rainfall input and those with synthetic effective rainfall input: in general the Rainfall models perform as well as, if not better than the Synthetic Effective Rainfall models. Given this observation and the greater probable reliability of simulated future rainfall data, it seems practical to concentrate on the Rainfall model for simulation of future groundwater level fluctuations.

A number of further applications of the model should be investigated. The most pressing is its application to boreholes in aquifers other than the Chalk, particularly the Permo-Triassic sandstone and the Lincolnshire Limestone aquifers. It would be beneficial to model at least two boreholes in the Permo-Triassic sandstone aquifer and at least two in the Lincolnshire Limestone. Given the observations made above on the performance of the two models developed here, it seems practical to use only the Rainfall model for a reproduction of historical groundwater levels in these aquifers.

A potential modification to the model is the possibility of varying specific yield with depth, instead of using a single, ‘average’ value. Although this may introduce more uncertainty to the reliability of the model results, it also allows the model to take account of heterogeneities within individual boreholes, such as zones of particularly high (e.g. zones of former water table fluctuation) or low transmissivity.

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Appendix 1 Seasonal adjustment procedure for time series data

Moving average. First a moving average is computed for the series, with the moving average window width equal to the length of one season. If the length of the season is even, then the user can choose to use either equal weights for the moving average or unequal weights can be used, where the first and last observation in the moving average window are averaged.

Ratios or differences. In the moving average series, all seasonal (within-season) variability will be eliminated; thus, the differences (in additive models) or ratios (in multiplicative models) of the observed and smoothed series will isolate the seasonal component (plus irregular component). Specifically, the moving average is subtracted from the observed series (for additive models) or the observed series is divided by the moving average values (for multiplicative models).

Seasonal components. The seasonal component is then computed as the average (for additive models) or medial average (for multiplicative models) for each point in the season. (The medial average of a set of values is the mean after the smallest and largest values are excluded). The resulting values represent the (average) seasonal component of the series.

Seasonally adjusted series. The original series can be adjusted by subtracting from it (additive models) or dividing it by (multiplicative models) the seasonal component.

Appendix 2 Modelling procedure

Input parameters:

u – the unsaturated zone unit transfer function, distributed monthly over *m* months and specifying the proportion of infiltration input in a particular month which reaches the water table in each following month, up to *m* months

m – the total number of months over which groundwater level response is lagged behind rainfall/effective rainfall input

rainfall (mm) – either gauged rainfall from a gauge close to the borehole, or synthetic effective rainfall derived from gauged rainfall series

observed groundwater level (m OD) – (i) defines the *initial water level* as the starting groundwater level for the modelled groundwater level series. An equivalent groundwater level (i.e. the same month from each year) from any of the first 5 years of the observed groundwater level record may be used as the initial water level in the model, to give the least overall error in case of unrepresentative groundwater levels in the first few years of the observed record; (ii) used to *calibrate* the modelled groundwater levels, on a trial and error basis

Sy (dimensionless) – constant averaged value representing both saturated zone and unsaturated zone; calibrated by trial and error

Model procedure:

(i) Calculate annual mean rainfall/effective rainfall in mm over the period of record.

(ii) Calculate the total rainfall/effective rainfall over the previous 12 months for each month modelled

(iii) Calculate the ratio of previous 12 months rainfall/effective rainfall to the annual mean rainfall/effective rainfall. If less than 1.0, rainfall/effective rainfall over the previous 12 months was less than the average over the period of record, & *vice versa.*

(iv) Estimate the mean monthly saturated zone outflow, assuming the total outflow over modelled period approximates total rainfall/effective rainfall: i.e. annual mean rainfall divided by 12.

(v) Estimate the monthly net saturated zone outflow by weighting the mean monthly saturated zone outflow by the ratio calculated in (iii) above. If less than 1.0, the saturated zone outflow in this month is less than the average monthly outflow over the period of record.

(vi) Estimate the monthly groundwater level fall (m) due to saturated zone outflow:

[(net saturated zone outflow (mm) / 1000) / Sy]

(vii) Do the recharge calculation for each month, *n*, whereby:

$$\mathbf{R}_n = \textbf{sum (from } i = \textbf{1 to } m\textbf{) of } (\mathbf{I}_{n-i+1} * u_i)$$

where $m = 12$ (maximum); I = rainfall (or effective rainfall); n = current month; $i = 1$ to 12 (maximum) backwards from current month (n)

nb $m = 1$ ($u1$) represents the month in which rainfall input occurs, equal to Lag 0 in the cross-correlation exercise

nb u represents the lag time before potential recharge input at the ground surface reaches the water table, and varies such that the sum of u_n to $\underline{u_{n-i}} = 1.0$

(viii) Calculate the modelled monthly increase in groundwater level (m) due to the estimated monthly recharge input:

(recharge (mm) / 1000) / Sy

(ix) Calculate the groundwater level (m OD) after fall due to estimated saturated zone outflow: start with an initial observed water level from month *n*-1

(x) Calculate the groundwater level (m OD) after rise due to estimated recharge: equal to the water level after net saturated zone outflow in the same month plus the increase in water level due to recharge.

Appendix 3 Regression equations and r^2 values used to derive synthetic effective rainfall series

For each test site, monthly MORECS rainfall and effective rainfall series for the period 1961-1991 were regressed against each other to examine the relationship between them. For each site, a regression equation and r^2 value for each month was obtained. These are given below. A chart illustrating the correlation of the entire data series for each site is also given.

Ashton Farm

All data

Regression Equation	r^2
y = 0.7233x - 23.175	0.5524

Monthly data

Month	Regression Equation	r^2
Jan	y = 0.9411x - 9.6593	0.9937
Feb	y = 0.945x - 11.752	0.9924
Mar	y = 0.8716x - 19.915	0.9348
Apr	y = 0.5569x - 15.017	0.7035
May	y = 0.36x - 12.529	0.6268
Jun	y = 0.0151x + 1.2222	0.0079
Jul	y = 0.0672x - 2.3906	0.1253
Aug	y = 0.025x - 0.4416	0.0177
Sep	y = 0.2627x - 13.172	0.3883
Oct	y = 0.6003x - 27.675	0.576
Nov	y = 0.8077x - 26.136	0.719
Dec	y = 0.8711x - 10.017	0.8304

Chilgrove House

All data

Regression Equation	r^2
y = 0.5893x - 14.97	0.4424

Monthly data

Month	Regression Equation	r^2
Jan	y = 0.9433x - 10.524	0.9414
Feb	y = 0.9059x - 9.5476	0.9719
Mar	y = 0.8176x - 15.658	0.9285
Apr	y = 0.6083x - 17.495	0.6896
May	y = 0.1465x - 2.5812	0.1613
Jun	y = 0.1117x - 2.9996	0.1808
Jul	y = 0.1224x - 4.0892	0.1323
Aug	y = 0.0175x - 0.6233	0.0601
Sep	y = 0.1235x - 5.3084	0.3213
Oct	y = 0.4572x - 20.969	0.4729
Nov	y = 0.8025x - 29.886	0.653
Dec	y = 0.6425x + 2.6908	0.5193

Dalton Holme

All data

Regression Equation	r^2
y = 0.2817x - 4.7018	0.1763

Monthly data

Month	Regression Equation	r^2
Jan	y = 0.9039x - 17.975	0.7454
Feb	y = 0.9267x - 15.218	0.9166
Mar	y = 0.8185x - 21.143	0.8491
Apr	y = 0.5339x - 14.517	0.5669
May	y = 0.2489x - 7.7167	0.5646
Jun	y = -0.0039x + 1.0417	0.0017
Jul	y = 0.0064x - 0.215	0.0636
Aug	y = 0.0192x - 0.9756	0.2011
Sep	y = 0.0188x - 0.5337	0.0782
Oct	y = 0.216x - 7.8476	0.2063
Nov	y = 0.381x - 15.116	0.2783
Dec	y = 0.5099x - 11.638	0.3362

Washpit Farm

All data

Regression Equation	r2
y = 0.2629x - 3.3189	0.1422

Monthly data

Month	Regression Equation	r2
Jan	y = 0.882x - 11.541	0.8181
Feb	y = 0.8497x - 10.796	0.9147
Mar	y = 0.7655x - 17.672	0.8935
Apr	y = 0.4295x - 12.35	0.4918
May	y = 0.1239x - 3.9223	0.1915
Jun	y = 0.0219x - 0.9191	0.1661
Jul	y = 0.0008x + 0.0307	0.0027
Aug	y = 0.0239x - 0.992	0.1599
Sep	y = 0.1093x - 4.2177	0.1765
Oct	y = 0.2322x - 7.8859	0.2796
Nov	y = 0.368x - 14.338	0.1859
Dec	y = 0.4913x - 7.8055	0.2261

Appendix 4 Example of Sensitivity Analysis for Ashton Farm, Rainfall model

The results of the model runs shown in bold type are shown in graphical form on the following pages.

Borehole:		**Ashton Farm**							**Model:**	**Rainfall**
Run No.	**Sy**	***u*1**	***u*2**	***u*3**	***u*4**	***u*5**	***u*6**	***u*7**	**Initial WL (year)**	**Mean Normalised & Mean Absolute Difference**
1	**0.005**	**1**							**70.12**	**1.69 - 14.20**
2	0.006	1							70.12	1.41 - 11.79
3	0.007	1							70.12	1.20 - 10.08
4	**0.008**	**1**							**70.12**	**1.05 - 8.82**
5	0.009	1							70.12	0.94 - 7.86
6	**0.01**	**1**							**70.12**	**0.85 - 7.10**
7	**0.02**	**1**							**70.12**	**0.49 - 4.07**
8	0.03	1							70.12	0.40 - 3.32
9	0.04	1							70.12	0.36 - 3.03
10	**0.05**	**1**							**70.12**	**0.35 - 2.92**
11	0.06	1							70.12	0.34 - 2.86
12	**0.07**	**1**							**70.12**	**0.34 - 2.82**
13	0.08	1							70.12	0.33 - 2.80
14	0.09	1							70.12	0.33 - 2.78
15	0.1	1							70.12	0.33 - 2.76
16	0.2	1							70.12	0.32 - 2.72
17	**0.02**	**1**							**64.84**	**0.37 - 3.07**
18	0.02	0.8	0.2						64.84	0.31 - 2.60
19	0.02	0.6	0.4						64.84	0.27 - 2.27
20	**0.02**	**0.4**	**0.6**						**64.84**	**0.26 - 2.14**
21	0.02	0.2	0.8						64.84	0.27 - 2.24
22	0.02	0.3	0.3	0.3	0.1				64.84	0.25 - 2.13
23	**0.02**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**			**64.84**	**0.25 - 2.12**
24	0.02	0	1						64.84	0.30 - 2.51
25	**0.02**	**0**	**0**	**1**					**64.84**	**0.42 - 3.50**
26	0.02	0	0	0	1				64.84	0.43 - 3.63
27	**0.025**	**0.5**	**0.5**						**64.84**	**0.21 - 1.78**
28	0.025	0.5	0.3	0.2					64.84	0.20 - 1.64
29	**0.025**	**0.5**	**0.2**	**0.2**	**0.1**				**64.84**	**0.19 - 1.58**
30	**0.0275**	**0.5**	**0.2**	**0.2**	**0.1**				**64.84**	**0.18 - 1.51**
31	0.0275	0.4	0.2	0.2	0.2				64.84	0.17 - 1.44
32	0.0275	0.3	0.3	0.3	0.2	0.2			64.84	**0.17 - 1.44**
33	0.0275	0.2	0.4	0.2	0.2				64.84	0.18 - 1.49
34	0.0275	0.1	0.3	0.4	0.2				64.84	0.20 - 1.69
35	**0.0275**	**0.3**	**0.3**	**0.4**					**64.84**	**0.17 - 1.45**
36	0.0275	0	0.3	0.3	0.4				64.84	0.23 - 1.91
37	**0.0275**	**0**	**0**	**0.3**	**0.3**	**0.4**			**64.84**	**0.27 - 2.24**
38	0.0275	0	0.4	0.2	0.2	0.2			64.84	0.20 - 1.72
39	0.0275	0	0	0.4	0.2	0.2	0.2		64.84	0.26 - 2.14