Nordic Hydrology 4, 1973, 86–104
Published by Munksgaard, Copenhagen, Denmark

TIME LAG RESPONSE IN BOULDER CLAY WELLS

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Well hydrograph and change in well level map analysis, associated with a small boulder clay catchment, detected a time lag response with the causal factors rainfall and potential evapotranspiration. The main purpose of this investigation was to test whether a suitable statistical method can detect this time lag and therefore translate this mechanism into quantitative terms. The analysis proved to be very successful despite some defects in the original data. The results confirm the general trends indicated in the earlier hydrograph and contour map analyses.

The characteristics of groundwater movement were examined in a small glacial drift catchment – the Catchwater Catchment (15.43 sq. km) – in Holderness, East Yorkshire, England. A detailed description of the hydrogeology, soils and hydrological design considerations were made in earlier work (Bonell 1971, 1972a, b, c). However, it is relevant to state that this is a predominantly boulder clay area, of gentle relief, with associated clay loam soils containing ubiquitous A and B soil horizons. The centre of the B horizon (clay pan) is about 30–90 cm below the surface. The lower, unweathered boulder clay has a coarse prismatic structure and is thought to contain a permanent saturated zone. The catchment is mainly utilised for mixed farming, primarily of cereals.

This groundwater project was achieved on two scales of investigation. The first concerned the whole catchment (well density 2.27/sq. km) and the areas immediately adjacent designated the network (Bonell 1971, 1972c). The second scale, and the primary interest of the present work, concerned two microstudies devised for a more detailed assessment of groundwater movement in boulder clay. It became apparent from an examination of the well hydrographs and change in well level maps associated with both scales of investigation that a time lag existed between the causal factors, rainfall and evapotranspiration, and the corresponding well level responses. The length of delay of this factor was regarded, both directly and indirectly, as an index of the disposition of water within both the saturated and unsaturated zones. Therefore an investigation was undertaken to test whether a suitable statisical method can detect this time lag and translate this mechanism into quantitative terms.

THE MICROSTUDY

The study area was located in the corner of a permanent pasture field incorporating a rectangular strip, the dimensions of which were 91.7 × 45.9 m (see Fig. 1). This site contained 13 perforated tube wells (5.08 cm diameter, 2.9 m depth) of which 7, i.e. 18/4–1 to 18/4–7, were staggered from north to south in the field itself, aligned with the very gentle slope, towards the open drain. The remaining 6 wells, i.e. 18/4–8 to 18/4–13, were located adjacent to the South Drain for the purpose of a bank storage experiment. The texture of the material consisted mainly of clay loams, with the B horizon located at a very shallow depth in most parts, based on particle size analysis (B.S.I., 1967) of disturbed samples taken from wells 18/4–1, 18/–5 and 18/4–13 (Bonell 1971). General indications were that the centre of clay accumulation was at a depth of approximately 30 cm, but results for 18/4–1 suggested that it may be marginally deeper in this part of the microstudy. A large sand, silt and gravel lens was also detected below 1.52 and 2.14 m, respectively, in wells 18/4–5 and 18/4–13, but this is of no consequence in the present discussion.

The period of data collection for this particular experiment was exactly 12 months, i.e. 2.7.68–1.7.69; observations were made at weekly intervals except on one occasion when heavy snowfall impeded accessibility to the site. The Catchment was divided by Pegg (1970) into four Thiessen polygon areas corresponding to four rain gauge sites. Thus, to achieve greater accuracy, the rainfall records utilised in this paper will refer to the particular polygon area (Cowden Magna) incorporating this microstudy. The potential evapotranspiration (P.E.) data were based on potential evapotranspirometer tanks located at the climatological base station (Pegg 1970, Pegg & Ward 1972, Ward 1967). The method of calculating P.E. was achieved on the lines recommended by Green (1959) using a cumulative graphical technique to obviate the effects of storage.

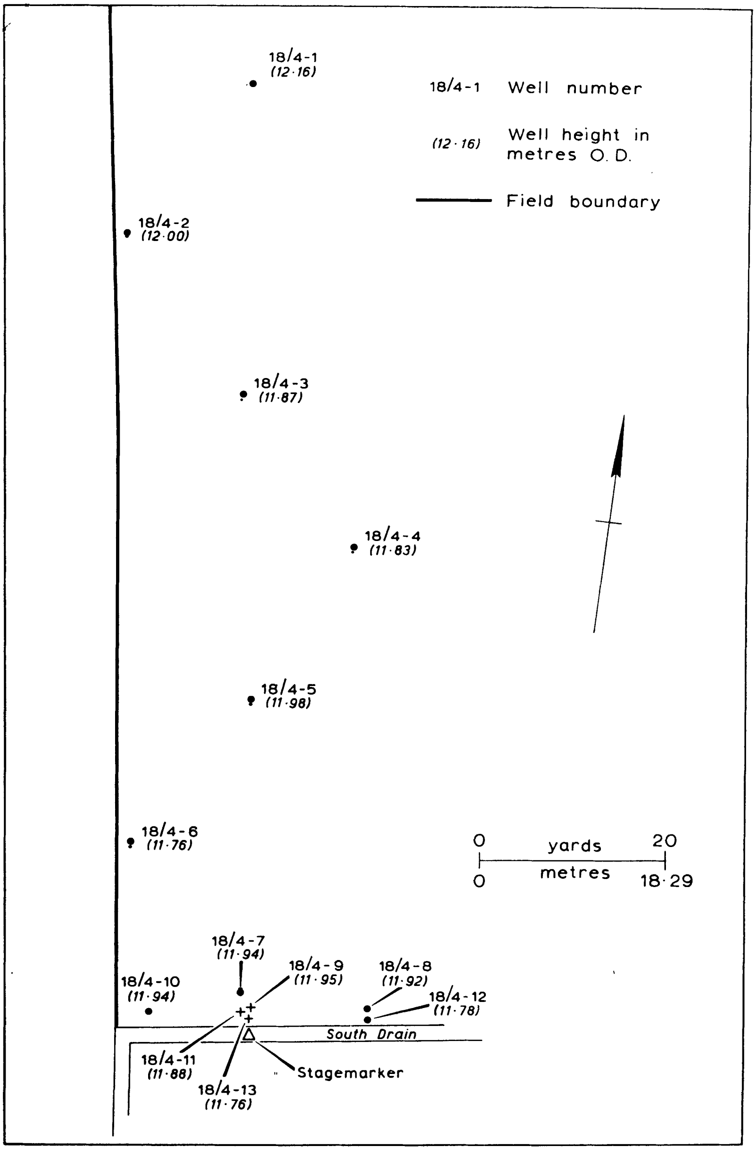


Fig. 1.

The distribution of wells in the Mount Pleasant microstudy (site 18/4). Note that the well heights shown include extensions of the tubes, of varying length, above the ground surface.

The existence of a soil moisture deficit or a water surplus within any 24-hour period was detected through a modification of the water balance procedure devised by Thornthwaite & Mather (1955). This procedure was followed for the period 1.1.68–31.7.69, with the initial starting point allowing the assumption of zero soil moisture deficit to be made, so that calculations could commence. Thus a mid-winter date is favourable because rainfall is far in excess of any accumulated soil moisture deficit.

The well in this microstudy revealed the same characteristics of well fluctuations as the remaining boulder clay wells in the Catchment, that is, a rapid response of well levels to water surplus producing rainfall. This phenomenon was most common in the winter half of the year when the soil moisture deficit was either small or non-existent, and was less common in summer in periods of persistent moderate and heavy rainfall. Lateral inseepage into the well from a newly formed perched water body of some kind, located in the lower regions of the A horizon, was thought to be responsible for this premature response. It was suggested that only after a lapse of several days, at some point on the lower curve of exponential recession, did the well levels detect the true surface of the permanent saturated zone. The implications are that the perched water table and lower permanent saturated zone have had time to readjust and equilibrate to the new hydrological situation. This could be effected by the perched water table being dissipated by lateral seepage in the A horizon; or by gravity movement down the "steeper" boulder clay hillocks, or by the action of distant tile drains. Simultaneously, much slower vertical movement through the B horizon would recharge the permanent saturated zone in the parent till. It is possible that both saturated zones may coalesce for a time, especially if the lower permanent feature was orginally located just below the B horizon. However, it is clear that it is very difficult to assess precisely what hydrological phenomenon the well levels are recording if observations have been made soon after a rainstorm (Bonell 1971, 1972b, c). Other work by Ward (1972) indicated some possible indirect, confirmatory evidence of this hypothesis.

On the other hand, well levels are represented by a gently graded recession in periods of prolonged soil moisture deficit, reflecting the very low saturated hydraulic conductivity (1.2742 cm/day) of the lower unweathered till in conjunction with the small hydraulic gradients of this area (Bonell 1972a). This phenomenon is particularly associated with the late summer period when the soil moisture deficit is sufficiently high to absorb all but the heaviest rainfalls which may occur, thus preventing any recharge to the water table. Further, the well levels observed at this time are probably detecting the true permanent saturated zone surface.

The immediate effect of a water surplus producing rainfall on the well levels

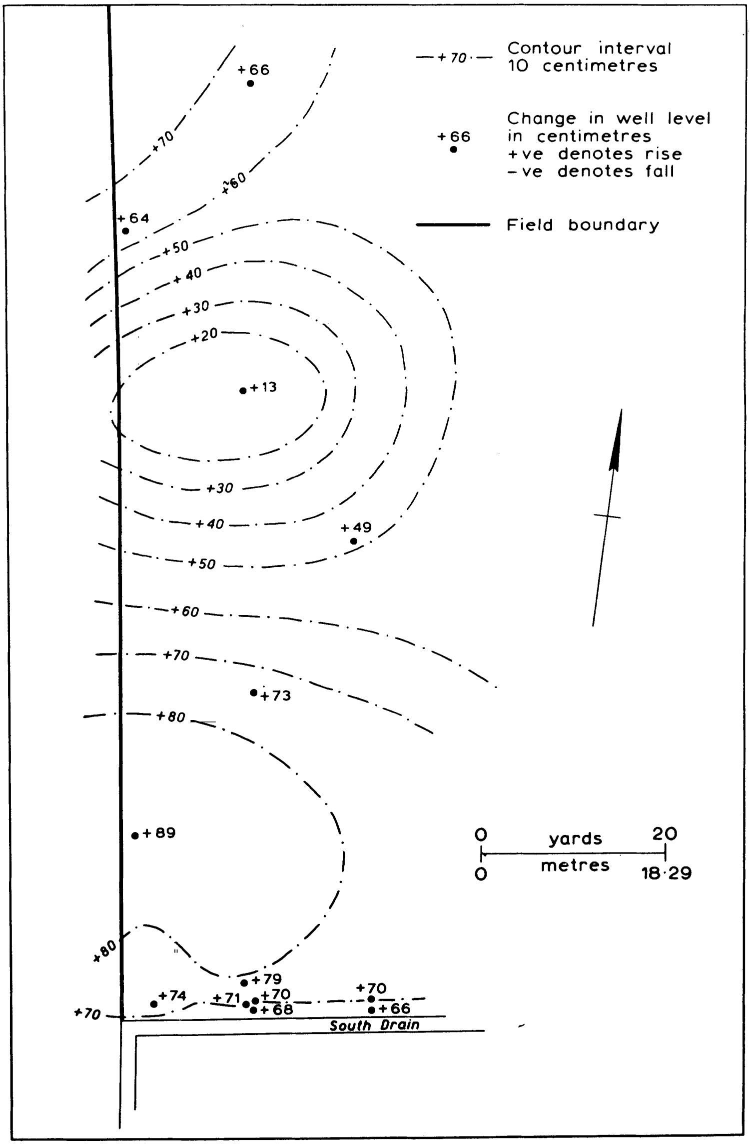


Fig. 2.

The change in well level map for the period 27.5.69–3.6.69 (site 18/4).

Table 1.
The Thornthwaite and Mather (1955) water balance method – Cowden Magna polygon area, 27.5.69–3.6.69.

	May 1969					June 1969		
	27	28	29	30	31	1	2	3
R.	3.81	2.29	3.81	–	2.54	0.25	29.46	0.25
P.E.	2.28	2.28	2.28	2.28	2.28	1.20	1.20	2.07
R.–P.E.	1.53	0.01	1.53	–2.28	0.26	–0.95	28.26	–1.82
ΔSt.	1.53	0.01	1.53	–2.28	0.26	–0.95	8.60	–1.82
Moist. deficit	–	–	–	2.28	–	0.95	–	1.82
Moist. depletion	7.17	7.16	5.63	7.91	7.65	8.60	–	1.82
Moist. surplus	–	–	–	–	–	–	19.66	–

R. – rainfall (mm)
P.E. – potential evapotranspiration (mm)
ΔSt. – change in storage

in this microstudy is shown in Fig. 2, which depicts the change in well levels during the period 27.5.69–3.6.69. Table 1 shows that only small amounts of effective rainfall (R. – P.E.) occurred on 27.5.69, 28.5.69, 29.5.69 and 31.5.69 and, using Thornthwaite & Mather's (1955) water balance technique (also included in this Table), a soil moisture deficit predominated until 2.6.69 when a large effective rainfall (28.26 mm) produced a water surplus of 19.66 mm. It is beyond the scope of the existing discussion to explain the observed contour pattern but, more important, this map emphasises the very short lag response of the well levels to rainfall seeing that the observations were made within 9 hours of the termination of rainfall. This was also confirmed by continuous records of two other boulder clay wells in areas adjacent to this microstudy (Bonell 1971).

THE HYDROLOGICAL AND STATISTICAL PROPERTIES OF THE DATA

The statistical technique selected was originally developed by Pitty (1966) who correlated spring water hardness fluctuations with antecedent climatic data. By noting where the intervals with the highest correlation coefficients (using Pearson's r) were grouped, Pitty hoped to discover when an apparent effect was at a maximum, i.e. time lag between cause and effect.

This method was adapted to the current investigation by replacing Pitty's parameters with well levels and hydrometeorological data, the latter having been developed from Thornthwaite & Mather's water balance procedure. Graphically, the employment of soil moisture deficit and water surplus can be visualised as a continuous trace over time. Sometimes this shows a positive value (water surplus) especially in winter, and at other times it shows a negative value (soil moisture deficit) which predominates during the summer. It is evident that this technique in theoretical terms should relate more to the actual field conditions than does the simple use of rainfall or effective rainfall (R. – P.E.). This proved to be generally correct except for a very limited period during persistent moderate to heavy rainfall in July 1968 and in the initial stages of autumn rainfall in September 1968 (Bonell 1971). On both occasions many of the boulder clay wells showed some recovery before the calculated soil moisture deficit was erased. Two possible factors could be considered to explain this phenomenon.

The first is error in the measurement of rainfall and potential evapotranspiration. Thus Rodda (1970) established a systematic negative error of 6.4 % over a period of 8 years in rainfall measurement on comparison of a conventional M.O.Mk II (used in this work) and a ground level gauge. However, this error should be close to the minimum in view of the seasonal location of these two periods in conjunction with the low wind speeds which occurred at these times (Rodda 1970). A much greater problem is the amount of error presented by the assumption that actual evapotranspiration equals potential evapotranspiration. Pegg & Ward (1972) concluded that the simple evapotranspirometer compared favourably with results obtained from the water balance equation when soil moisture storage was at or near field capacity, i.e. in a wet year, in the Catchwater Catchment. However, it was shown that monthly discrepancies could be quite large, especially in July and August. This was attributed to the greater "roughness" of the catchment vegetation giving a higher potential evapotranspiration than that measured by the short grass surface of the evapotranspirometer. In addition, on maturing in mid-summer the cereal crops will check evaporative losses, especially in dry years. However, the period 2.7.68–1.7.69 was exceptionally wet, with particularly large falls occurring in July 1968. This maintained soil conditions near field capacity during mid-summer of that year. Persistent rainfall until early June 1969 also ensured similar conditions towards the end of the observation period. Thus it was anticipated that, during this period, actual evapotranspiration occurred at or near the potential rate, as measured by the evapotranspirometer. Consequently, the error attributed to this factor was thought to be small. Other sources of discrepancy associated with the practical measurement of potential evapotranspiration, such as the oasis effect, non-uniform grass height, etc. (Thornthwaite 1954, Halstead & Covey 1957, Green 1959, Ward 1963), were kept to a minimum through careful maintenance and precautions.

The second and more likely explanation for the premature recoveries of well levels is the rapid emergence of perched water tables in areas with very shallow clay pans and the resultant inseepage into wells located in these conditions. In these cases the soil moisture deficit has probably been erased in the most shallow layers with the progress of the wetting front being impeded by the lower B horizon. Thus positive pressure heads will develop in time, resulting in a perched water table condition.

It has already been indicated that the observation period coincided with above average rainfall. The mean annual rainfall over Holderness ranges from about 609.6 mm in the south to approximately 660.4 mm in the north and is usually evenly distributed throughout the year (Met. Office 1963). The climatological base station recorded 827.78 mm and of this, 551.69 mm fell during the period 19.9.68–29.4.69. Therefore it was also a period with an exceptionally large number of rainfall (and water surplus) events, which will be a significant factor in the subsequent statistical analysis.

The data will now be examined to investigate how far the assumptions for the use of Pearson's r formula are satisfied. As Riggs (1968) noted, "correlation theory requires that the data be drawn randomly from a bivariate normal distribution". But rainfall and potential evapotranspiration are not random and independent. In fact the probability that rain will fall on a given day is much greater if rain fell on the preceding day than if it did not. This statistical behaviour is termed "persistence", and is characteristic of meteorological events (Brooks & Carruthers 1953). It is obvious that properties of potential evapotranspiration, when considered as part of R.–P.E., will be similar and complementary to those described for rainfall, in addition to the seasonal variation of this parameter. Thus it is evident that Thornthwaite & Mather's water balance procedure will be directly affected by this statistical characteristic and have a persistent distribution, i.e. a time series. In addition, the value for a particular day is dependent on the previous day, which in turn will control the succeeding day's value. This serial correlation effect particularly applies to the large soil moisture deficit accumulated during a dry summer period. Thus both these factors prevent this variable from being random and independent.

In addition, histograms were constructed to investigate the frequency distribution of this parameter utilising the data for the whole observational period. They revealed a bimodal distribution – that is, two concentrations of variates, with the first focused on the higher values of soil moisture deficits whilst the second consisted mainly of water surpluses and a smaller concentration of low deficits. More detailed examination showed that this was a seasonal effect, the former representing summer and the latter winter conditions, respectively. Therefore it was decided that the data should be separated into these two seasons for analysis. This was achieved by including into the winter period all well data observed after the first series of water surpluses had been recorded, an event which marked the termination of the large soil moisture deficit. The average data for the four Thiessen polygon areas was 8.10.68 on a well level sampling date. Similarly, the date marking the beginning of the first sizeable soil moisture deficit, coupled with a reduction in the number of water surpluses, was sought during spring. The overlap into spring of the wet conditions of winter made this delimitation difficult. However, there was evidence that potential evapotranspiration and therefore the soil moisture deficit was beginning to recover by mid-May; hence the sampling date 13.5.69 was selected.

A second criterion influencing the above decisions was an observation of the vegetation. By 8.10.68 plant growth had declined and all the fields had been harvested and most ploughed. More continuous and rapid regeneration of plant growth did not commence until the second week of May 1969, coinciding with a major rise in temperature and sunshine amounts. In addition the sowing of cereal crops was not accomplished until about this time. Therefore all well data taken during the periods 2.7.68–8.10.68 and 14.5.69–1.7.69 were regarded as summer conditions, whilst the intervening period was associated with winter. The frequency distribution of the soil moisture deficit-water surplus data corresponding to these two periods "approximated" normality so that no transformation was considered necessary.

The well data also formed a time series, but the interdependence between successive events is not so prominent because of the larger time interval between the observations. Also no transformation was thought to be necessary for these two sets of seasonal data.

A further requirement of correlation theory is no error in both variables. This aspect of the problem has already been considered regarding the hydrometeorological data and it is clear, in the present context, that this error was unavoidable, however small it was considered to be. A more difficult problem was snow, which in this period of study was characterised by protracted melting at varying rates, rather than by a sudden thaw on a specific day following an interval of sustained freezing. This was particularly associated with a period at the end of December 1968 and the beginning of January 1969, and with practically all of February 1969, but in the latter case there were interim complete thaws between each snowfall. It became evident that no accurate adjustment could be applied to the original records to make allowance for this factor. Thus it was very reluctantly decided to enter snowfall in equivalent rain on the day the event took place, which obviously will introduce some unavoidable error in the analysis. The well level data was more accurately observed with a HWK model AG-2 manual groundwater reading instrument which gave results within approximately ± 1 cm.

The reliability of the correlation results depends on the number of items used, and the evaluation of r is strongly affected by the size of the sample; therefore great caution should be exercised when dealing with correlation coefficients obtained from small samples (Kinsman 1957). This certainly applies to the present work.

A final statistical problem is the restrictive use of the Student's t test in connection with correlation coefficients derived from a time series. Dawdy & Matalas (1964) noted that although a correlation between two non-random time series could be determined, it could not be tested for significance in the same manner as the correlation between two random variables. It was recommended that Bartlett's (1935) method be used, but this technique is very laborious and demands larger sample sizes than were available in the present data. Pitty (1966) applied the Student's t test in his karst water investigation but stressed they gave only "... an *approximate* indication of the significance of the correlation coefficient for the convenience of discussion ...". It was decided therefore to follow Pitty's recommendations.

THE STATISTICAL METHOD

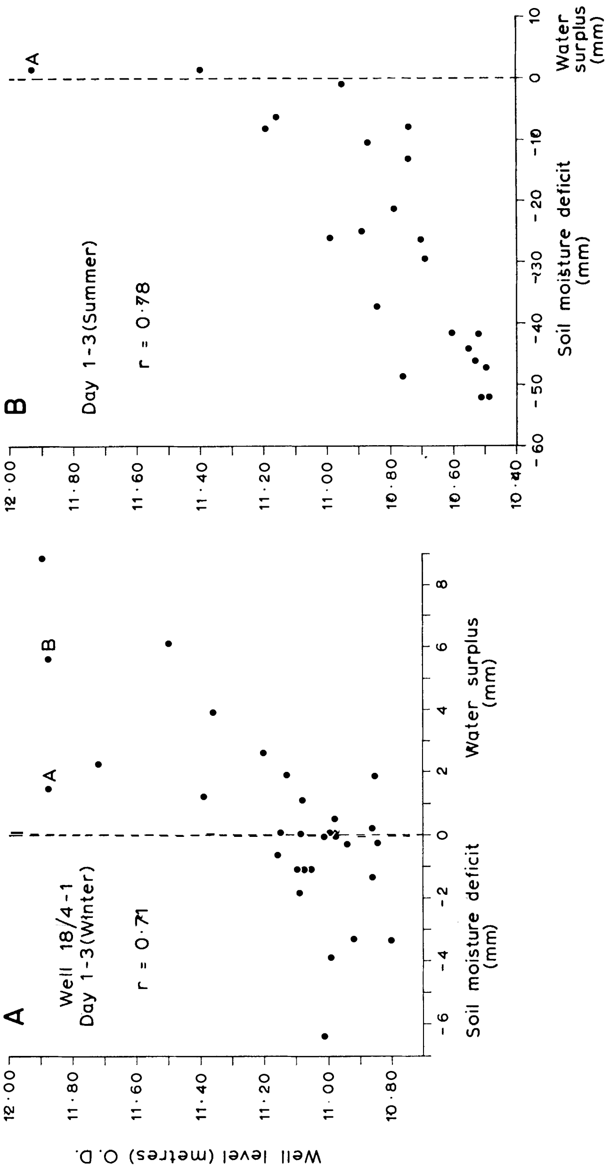
The statistical analysis consisted of the intercorrelation of well levels within the microstudy and the generation of a stream of simple correlations between individual well fluctuations and antecedent 3-day running means of the hydrometeorological data.

The first antecedent day was taken from 0900 G.M.T. on the day of observations to 0900 G.M.T. the previous day because hydrometeorological data collection was made at this time. Unfortunately, the lag response for each well could not be isolated to a single day due to the small sample involved in the analysis. Therefore 3-day running means were adopted which considered overlapping intervals rather than fixed time limits, as used by Pitty (1966), and which enabled effects in the intervening period to be considered. In addition, preliminary trial analysis showed that hydrometeorological data from 21 antecedent days was sufficient for the detection of the lag response.

The time lag response was located from the peak of the group of highest correlation coefficients and then stated in terms of the corresponding antecedent time interval. This may seem rather tentative but Pitty argued that an apparent effect of some kind must exist to produce a group of relatively high correlation coefficients within particular antecedent intervals. In addition, the emphasis was not so much on the precise value of Pearson's r but more on their relative ranking. Statisticians would probably regard this form of analysis as most disturbing in view of the statistical properties of the data. However, it must be appreciated that the latter do not originate from controlled experimental conditions and that furthermore, too much caution towards these difficulties would hinder any possibilities of statistical analysis. Thus, providing that there is an acute awareness of the problem of persistence and serial correlation during the interpretation of the coefficients, the application of this technique should be valid. Obviously the results cannot be regarded as absolutely reliable, but the main aim is to investigate whether they will provide a certain amount of *secondary* evidence in support of the observations made from the change in well level maps and well hydrographs.

A final consideration is the interpretation of the correlation coefficients. The structural composition of the hydrometeorological data showed that not all the winter values represented a water surplus, as about a third showed a deficit. This is very important because it signifies that the calculated lags are not directly comparable with the observations made on the change in well levels as a result of rainfall or R.–P.E. in this season. It can be argued, of course, that with the number of water surpluses being in the majority, they will favour the interpretation that the peak response will be primarily influenced by this factor. But the deficits will also indicate that the soil conditions are favourable for a well level decline. Therefore it would seem that the best interpretation is that the soil moisture condition of the root zone is both a direct and an indirect measure of well fluctuation.

The use of this parameter as an indirect measure is even more significant during the summer. At this time the presence of large soil moisture deficits is overwhelming and is associated more with the local hydraulic gradient and conductivity being allowed to dissipate groundwater, rather than direct withdrawal of water by evapotranspiration. In addition, it is not certain at what critical depth the latter parameter ceases to function.



Figs. 3A and B.
The scatter diagrams of well 18/4-1 for winter and summer, respectively, representing the antecedent day interval 1–3.

Table 2.
The coefficients resulting from the correlation of the 18/4 microstudy well level fluctuations and antecedent 3-day running mean water balance (hydrometeorological) data.

Time interval (days)	Well 18/4–1		Well 18/4–2		Well 18/4–4		Well 18/4–5		Well 18/4–6		Well 18/4–7	
	W r	S r	W r	S r	W r	S r	W r	S r	W r	S r	W r	S r
1– 3	0.71	0.78	0.69	0.62	0.65	0.77	0.56	0.73	0.61	0.67	0.78	0.65
2– 4	0.40	0.72										
3– 5	0.27	0.67										
4– 6	*0.31*	0.64									0.32	
5– 7	0.26	0.50	0.28				0.35		0.34			
6– 8	0.09	0.38										
7– 9	*0.21*	0.30	0.41				0.40		0.46		0.32	
8–10	0.20	0.28			0.30							
9–11	0.16	0.26										
10–12	*–0.17*	0.21										
11–13	*–0.17*	*0.22*	0.09		–0.17						–0.11	
12–14	–0.09	0.20					0.13		0.09			
13–15	–0.04	0.19										
14–16	*0.07*	0.20			0.24						0.21	
15–17	0.05	0.21										
16–18	0.01	*0.22*	0.20			0.20	0.10	0.25	0.16	0.22		0.18
17–19	–0.17	0.20		0.36		0.20				0.22		0.18
18–20	–0.24	0.15		0.36								
19–21	*–0.27*	0.07	–0.12		–0.02		–0.17		–0.15		–0.16	

DISCUSSION OF THE RESULTS

Table 2 shows the peak correlation coefficients and their corresponding antecedent time intervals for each well developed with the use of a computer. Also included are the intermediate values for 18/4–1 to show the basic trends which are representative for this site. The results are based on 30 and 22 observations for the winter and summer season, respectively. (One set of data is missing, due to the fact that the microstudy was inaccessible as a result of an exceptionally heavy snowfall.) It will also be noted that no results are given for well 18/4–3. Surface water was present in the vicinity of this site for a large part of the winter period.

The most distinctive feature of these results is that they all show the peak

Table 2 (cont.)

Time interval (days)	Well 18/4–8		Well 18/4–9		Well 18/4–10		Well 18/4–11		Well 18/4–12		Well 18/4–13	
	W r	S r	W r	S r	W r	S r	W r	S r	W r	S r	W r	S r
1– 3	0.76	0.64	0.78	0.64	0.73	0.69	0.78	0.65	0.75	0.66	0.78	0.64
2– 4												
3– 5												
4– 6	0.30		0.32		0.30		0.32		0.33		0.33	
5– 7												
6– 8												
7– 9	0.37		0.33		0.34		0.33		0.31		0.33	
8–10												
9–11												
10–12												
11–13	–0.04		–0.10		–0.14		–0.11		–0.18		–0.11	
12–14												
13–15												
14–16									0.12			
15–17												
16–18	0.22		0.17	0.14	0.17	0.19	0.17	0.15			0.16	
17–19		0.14		0.14		0.19		0.15		0.15		0.16
18–20												
19–21	–0.15		–0.17		–0.15				–0.19		–0.18	

NOTE: W – running mean winter hydrometeorological data
S – running mean summer hydrometeorological data
r – correlation coefficient.

correlation coefficient (r) within the 1- to 3-day period for both winter and summer. And even more remarkable is the fact that all r values for both seasons are highly significant, i.e. exceeding the 1 % level (Fisher 1930). These results, then, suggest a strong agreement with the characteristic properties of the well observations of this site (Bonell 1971) coupled with the example discussed earlier in connection with Fig. 2. The latter showed that these wells were particularly sensitive to hydrological changes at the surface.

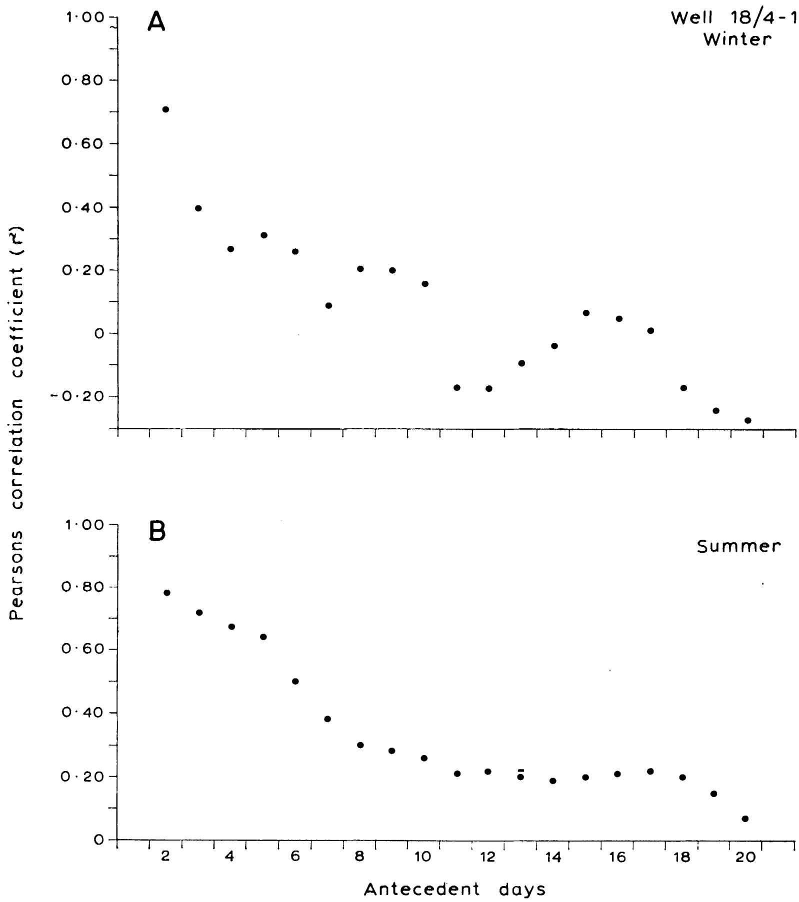
Fig. 3A and B show the respective scatter diagrams for well 18/4–1 for the antecedent day interval 1–3. Using this site as a typical example, the most notable feature is the positive correlation which is to be expected seeing that a winter water surplus or a decline in the summer soil moisture deficit should give a positive rise in well level. More detailed examination of Fig. 3A for the winter period suggests that a curvilinear rather than a simple linear relationship may be a more accurate description of this scatter, despite earlier checks on the frequency distribution of these two variables. If this is the case, then obviously the denoted value of r will not be truly accurate. However, two factors minimise the significance of this issue. Previous analysis using untransformed and transformed rainfall data in correlation with well levels had shown that the same ranking order of r was maintained in spite of a change in their values, i.e. the peak correlation coefficients in the vast majority of cases remained in the same antecedent time interval (Bonell 1971). Other work by Pitty (1972) also detected this characteristic. In addition, it is not the precise value of r which is sought but rather its relative ranking – a fact which had already been emphasised.

A further distortion of the scattering arrangement is illustrated by the two coordinates (1.44, 11.88) and (5.59, 11.88) which are denoted by A and B, respectively, in Fig. 3A. Both points have the same well level but different antecedent conditions. It is immediately clear that in example A a value of 1.44 mm is anomalous in context with the rest of the data. Subsequent investigation revealed that earlier heavy snowfall followed by a slow thaw was the prime factor responsible for this high well level and not the immediate hydrometeorological conditions.

Another explanation for the higher degree of scatter in the winter period could be attributed to the inclusion of the transitional conditions associated with autumn and spring when neither can be accurately categorised as winter or summer.

The summer period (see Fig. 3B) shows a more linear relationship and less scatter with the notable exception of point A representing coordinates (1.34, 11.93) for the well observation 16.7.68. This is an abnormally high well level in view of the antecedent hydrometeorological conditions. However, this was the cumulative effect of persistent moderate–to–heavy rainfall from 10.7.68 which resulted in a premature rise in many well levels; before the formation of the first theoretical water surplus on 14.7.68. Possible explanations were put forward to account for this phenomenon during the assessment of the use of Thornthwaite & Mather's water balance procedure in this analysis.

A more detailed examination of the correlation coefficients of 18/4–1 for both seasons (see Figs. 4A and B) shows that in the winter example the general trend is one of erratic decline until day 6–8. This is followed by non-significant secondary peaks in later intervals. In contrast, the summer period (see Fig. 4B)



Figs. 4A and B.

The 3-day running mean antecedent correlation coefficients of well 18/4-1 for winter and summer, respectively.

shows two "exponential" type recessions, separated by a discontinuity at day 4–6, and then is succeeded by a shallow non-significant secondary peak after day 13–15.

The nature of these two diagrams can possibly be attributed to the properties of the hydrometeorological data. The winter period is more dependent upon relatively short period water surplus producing rainfall which give a series of distinct pulses or rises in well levels. Thus in terms of time their impact is more sudden and easily isolated. However, potential evapotranspiration and the corresponding increase in soil moisture deficit is a more continuous process, especially in protracted summer dry periods. Therefore its effect on well levels cannot be so easily isolated and consequently only a gradual decline in the influence of antecedent conditions on the water table results.

CONCLUSIONS

The use of this simple statistical method to detect a time lag response in boulder clay well levels has been shown to be very successful despite some defects in the original data. The results confirm the general trends indicated in Fig. 2 and previous well hydrograph and change in well level map analysis (Bonell 1971). However, the reliability of this method would seem to hinge very much on the number of observations utilised. A similar analysis on the network wells using about half the sample employed in this work did not show the same degree of success (Bonell 1971). This may be due to the problem of dealing with small samples and the length of time between each observation (in this case once every 2 weeks). Therefore the ability to successfully detect the time lag response by using this technique, without the aid of continuous recorders, would seem to be strongly dependent on the frequency of observations.

ACKNOWLEDGEMENTS

I would like to thank the Natural Environment Research Council of the United Kingdom and the Department of Geography, Hull University for supporting this work and Dr. A. F. Pitty for his interest and valuable suggestions. I would also like to record my grateful appreciation to Mr. B. Fell (local landowner) who released valuable, rent-free agricultural land for the microstudy experiment.

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Received 18 August 1972.