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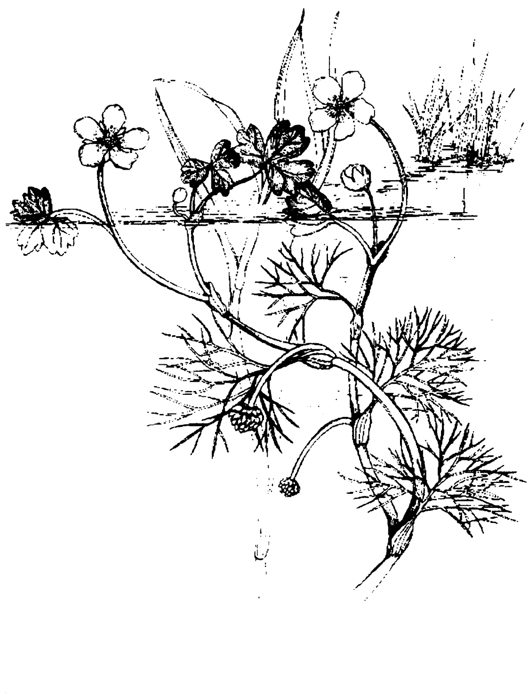
Chippenham Fen NNR

Botanical, Invertebrate and Hydrological Monitoring 1991 - 1995

Appendix 1
Hydrological assessment



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English Nature Research Reports

ENVIRONMENTAL CONSULTANCY
UNIVERSITY OF SHEFFIELD

Chippenham Fen NNR
Monitoring 1991–1995

Appendix 1

Hydrological Assessment

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Summary

1. Chippenham Fen is a National Nature Reserve and SSSI located c. 6 km north of Newmarket in a predominately low lying arable setting. The site is supplied with water by a series of springs and is drained by the Chippenham River and a number of dykes and ditches.
2. Monitoring at the site has been undertaken at a variety of locations and using a number of methods. A total of 15 dipwells have been installed across the site, 9 in 1976 and a further 6 in 1991. Three gaugeboards (GB1–GB3) have been installed at the Principal Spring (where a further piezometer has been installed), and within the site to monitor water levels in the dykes. These have been surveyed to Ordnance Datum and are monitored fortnightly.
3. The dipwell data suggest that there is a distinct separation of trends over the recording period, with three distinct periods:

   a) An initial period of relative stability lasting from the start of recording until c.1989, with winter water table depths stable, but with apparently regular variations in summer water table depths.

   b) A transitional period commencing at the end of period a) and ending c.1991, with summer water table levels markedly lower than those in the previous period and with an apparently lower winter water table depth.

   c) A second period of relative stability, with a suggestion that winter water table depths are initially lower than in period a) but gradually rising over successive winters.
4. Analysis of river discharge data in terms of the periods identified in the dipwell records, where there is a marked change in water table base level, suggest that there is a significant difference in discharge and log-transformed discharge data in the period before and after 1/4/1990 (periods 'a' and 'b' above). In this case readings in the period where dipwell water table depths were much lower (period b) are significantly lower ($p<0.001$) than in the final period, with mean daily discharges of 0.0348 and 0.1007 cumecs respectively.
5. Gaugeboards GB2 and GB3 show a good relationship between each other but show relatively weak relationships with other monitoring data, suggesting that while these gauges are useful in indicating the hydrology of their respective ditches they are less useful as a means of inferring the hydrology of other parts of the fen.
6. The data suggest that there is a significant, positive relationship between observation borehole readings and readings taken at the Principal Spring, although the strength of the relationship between the two variables is not clear.
7. The data illustrate the buffering effect of the fen and its associated extended drainage system, with water entering the system distributed around the fen and 'lost' to the peat mass. It would be expected that in periods where the fen is largely saturated, additional water inputs would be channelled through the fen with minimum loss to storage, while in drier periods the fen would act as a hydrological input to the Chippenham River for as long as water levels in the fen are above those of the River. The extent of the relationship between the fen inputs and the output to the Chippenham River should be examined in more detail in order to assess the validity of these statements.

8. The data would suggest that there is a marginal difference in rainfall totals between specific periods of monitoring, but there are limitations to the statistical tests that make this suggestion suspect. It is also questionable whether the relatively small difference in rainfall between the transitional and final periods mentioned in point three above can be held to be responsible for the relatively large differences in dipwell, borehole and river discharge readings in the periods identified above.
9. The data suggest a relatively constant relationship between inputs to the dyke systems and loss to the fen. However during dry periods it would appear that water levels remain relatively stable in the dykes while water levels in the fen still fall.
10. There is a strong suggestion of a negative relationship between water supply abstraction and discharge in the Chippenham River, although the link may be related to the impact of fluctuations in rainfall on both data-sets rather than causal. The use of pumped storage to compensate for this abstraction has had relatively little impact on fen water table depths and Chippenham River discharge, although the exact magnitude of any effects may be masked by variations in rainfall and evapotranspiration. It is important that the amount of compensation water pumped into the Principal Spring is reassessed.
11. Recommendations for further work and monitoring are provided.

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1. Introduction

The aim of this report has been to review hydrological conditions at Chippenham Fen NNR as monitored by a variety of devices over a five to ten year period. Analysis of available data has been carried out in order to:

1. assess any trends in hydrological conditions over the site during the period of record. This has involved the control of occlusions and impulsive noise within the data so that climatic and management effects may be evaluated;
2. assess, in particular, the impact of local water abstraction on the site;
3. evaluate the application and effectiveness of the supplementary water supply scheme;
4. make recommendations for future adjustments to the supplementary water scheme;
5. make recommendations with regard to a future monitoring strategy.

The data will be discussed in their own right, and in terms of a range of management activities undertaken at the site. The site, the monitoring activities undertaken, and the management activities involved will be described below.

1.1 Site location & description

Chippenham Fen is a National Nature Reserve and SSSI located c. 6 km north of Newmarket in a predominately low-lying arable setting (Map A). The site is supplied with additional water by a series of springs (although their significance is unclear) and is drained by the Chippenham River and a number of large dykes/drains and smaller ditches. The local geology, vegetation and management practices are described below, and are largely adapted from Mason (1990) and DCEUB (1988), which provide more detailed descriptions.

1.1.1 Geology & soils

Geological data suggest that the rocks underlying Chippenham Fen consist of Lower and Middle Chalks, Chalk Marl and Gault Clay dipping gently NW-SE. Chalk Marl outcrops in the Fen as an inlier within the Totternhoe Stone. This latter rock is well jointed and acts as a source of springs within the fen. Pleistocene drift deposits consisting of flint/chalk/clay matrix of variable proportions and size distributions occur across the fen. Overlying this drift (Head) material is a dark brown peat with occasional silt-clay layers. The depth of the peat ranges from between 0.45 m and 2 m.

1.1.2 Site vegetation

Much of the fen is dominated by *Phragmites* and *Cladium* communities, particularly in the site interior, although Northern Meadows area contains *Molinia* and *Juncus* communities. Some scrub and mixed woodland exist at the northern, eastern and southern margins, being connected by wooded corridors through the fen. Some of the sedge fen is harvested periodically for thatch.

1.1.3 Hydrological management

In hydrological terms, the site is not as intensively regulated as some other lowland peat remnants, as its main use has been as a supply of sedge rather than for the peat itself. The fen was drained by 1800 as a result of the cutting of a network of deep dykes and shallower land drains, after which much of the current woodland was planted. It is reported by Mason (1990) in his review of the site's history that this drainage resulted in a lowering of the water table by *c.* 1.5 m, and sluices were installed to prevent drought damage. Many of the shallower drains became silted up by the early 1900s, although a restoration program was undertaken in each of the World Wars.

The larger dykes carrying water around and through the fen are controlled by a number of 'adjustable' dams (known as bund-dams, or collared-dams) installed between 1985 and 1987 to replace old wooden sluices (see Map D). Each dam is culverted by a pipe angled at 90° on the 'upstream' side, so that when the water level in the dyke reaches the top of the pipe, water spills through into the next section. The overspill end is capable of being adjusted by adding or removing additional lengths of pipe, and water levels can be lowered in this way before any site management operations are undertaken.

An additional sluice gate exists on the Chippenham River below the site that can be closed in summer to maintain water levels in the fen.

In addition to hydrological controls on site, external support for water levels in the Chippenham River *via* the fen is supplied by three inflow points in the fen (Map D). The majority of the pumped support is supplied by pipeline to the Principal Spring, with additional supply to points in the boundary dyke at the south-eastern margin of Forty Acre wood. The scheme was implemented in order to ameliorate possible impacts from increased groundwater abstraction in the region.

1.2 Site monitoring history

Monitoring at the site has been undertaken at a variety of locations and using a number of methods, and these are described below.

1.2.1 Dipwell recording

A total of 15 dipwells have been installed across the site, 9 in 1976 and a further 6 in 1991 (see Map B). The dipwells are constructed of heavy gauge drainpipes 5.1 cm in diameter, and have 0.6 cm holes drilled through in the lower 70–80 cm. Readings are taken fortnightly and exist as both relative and absolute values. A Casagrande drive-in piezometer has been installed at the Principal Spring to the depth of the underlying Totternhoe Stone in order to monitor groundwater pressure from the aquifer at one of the main site inflows.

1.2.2 Water level gauging

A total of three gauge boards (GB1–GB3) have been installed at the fen (see Map B). GB1 is next to the Principal Spring piezometer and measures water tables in the pond next to the Principal Spring. GB2 is installed to the west of the centre of the site next to Baxter Ride, while GB3 is further along Baxter Ride and south of the site centre. These have been surveyed to Ordnance Datum and are monitored fortnightly.

1.2.3 Borehole and river discharge monitoring

In addition to measurements within the site, two measures of local conditions are taken outside the fen. River discharge has been monitored using current metering at the fen over a number of years, but the most reliable data consist of readings recorded by a gauging station immediately downstream of the sluice gate. Daily readings from this gauge exist from 1991 to present.

Readings are also available from an automatic logger at the Chippenham Observation Borehole, which records the groundwater levels above Ordnance Datum at 15 minute intervals. These data have been collected since 1991, and have been converted to daily mean values for the purpose of this report.

1.2.4 Rainfall

Rainfall is recorded by three gauges at or near the site: one at Isleham pumping station, and two at Chippenham Fen – an autographic gauge and a tipping bucket raingauge. Monthly summary data for these gauges are given in Table 1.1, and the overall monthly averages illustrated in Figure 1.1. Figures 1.2–1.4 show the entire rainfall record for each gauge. It is interesting to note that despite the relatively close proximity of the gauges (particularly the two Chippenham gauges), there are marked differences in average and total rainfall values.

Table 1.1: Mean monthly rainfall totals (mm) for raingauges at or near Chippenham Fen 1991–1995

Month	Isleham	Chippenham	Chippenham Tipping Bucket	Average
January	13.58	65.15	49.33	**52.91**
February	31.98	33.32	26.70	**32.35**
March	39.66	46.85	22.80	**40.09**
April	42.96	42.60	33.70	**42.89**
May	36.14	43.15	43.20	**35.93**
June	53.60	44.13	54.27	**49.12**
July	47.15	53.00	40.70	**43.02**
August	44.37	51.40	27.05	**35.67**
September	64.67	75.53	67.40	**65.78**
October	64.55	88.10	63.60	**55.40**
November	52.72	51.43	51.30	**52.75**
December	44.02	53.03	52.67	**45.26**
Total	**570.57**	**644.86**	**533.35**	***551.22***
Mean	**47.283**	**53.02**	**45.89**	***45.83***
Standard deviation	**20.16**	**21.81**	**21.86**	***21.40***
Minimum	**6**	**10**	**4.6**	***4.6***
Maximum	**84.3**	**98.8**	**91.4**	***90.33***

2. Monitoring Results

As a result of the variety of monitoring approaches employed at Chippenham Fen a wealth of data has been collected concerning the hydrological behaviour of the fen and its immediate environs. These data can be considered in a number of ways, namely:

a) Examination of the overall behaviour of individual recording instruments

b) Examination of general temporal trends over the whole of the recording period

c) Comparison of specific sets of temporal records within the overall recording period.

The hydrological data collected at and around the site will be examined in terms of a)–c) above, together with an attempt to compare the readings obtained from the different recording methods.

2.1 Dipwell records

The dipwell data can be considered both in terms of the position of the water table relative to the ground surface and in terms of the water table relative to ordnance datum. In terms of ecosystem function the former is probably of greater importance, whereas in terms of hydrological management the former needs to be complemented by the latter. Data relative to the ground surface will be considered first.

2.1.1 Overall dipwell records

Mean data for each of the dipwells monitored over time can be found in Table 2.1, with these data illustrated in Figure 2.1–2.3. Given that for the most part the data presented in the above table and accompanying Figures represents a 10 year average (4 years for dipwells 10 and 12–16), it could reasonably be argued that, in the absence of excessive external influences, this information should give a reasonably reliable indication of the long term average behaviour for each dipwell.

The average value for the whole data-set indicates that overall, the site water table is within that which would be considered reasonable for the continued growth of fen vegetation. There is, however, a degree of variation between dipwells that is to be expected given the areal spread of the dipwells and may mean that some parts of the fen experience water table depths that are less desirable in terms of maintaining fen vegetation. The wettest part of the site on average is that found at dipwell 5, and the driest that near to dipwell 16. The relatively low average for dipwell 16 would seem to be exceptional, with most other locations featuring mean water table depths less than 30 cm from the ground surface.

Table 2.1: Summary data for water table depth above/below ground surface recorded by dipwells at Chippenham Fen

Dipwell Number	Mean (cm)	Median (cm)	Standard Deviation (cm)	Minimum (cm)	Maximum (cm)	Range (cm)
1	–23.5	–16	23.72	–87	2	89
2	–17.049	–12	18.83	–86	7	93
3	–31.73	–16	30.44	–130	4	134
4	–8.81	–3	17.46	–98	8	106
5	4.25	10	23.94	–126	32	158
6	–24.53	–17	25.54	–135	6	141
7	–16.80	–8	22.81	–104	9	113
8	–11.52	1	29.08	–102	18	120
9	–17.73	–12	19.08	–97	3	100
10	–21.40	–6	34.74	–135	12	147
12	–23.91	–15	21.23	–103	–5	98
13	–28.14	–23	14.33	–88	–11	77
14	–18.28	–4	29.65	–119	7	112
15	–27.80	–17	23.65	–91	0	91
16	–45.72	–41	27.06	–107	–2	105
Overall	***–18.99***	***–11***	***26.51***	***–135***	***32***	***105.25***

In addition to the variability between dipwells, the minima, maxima and standard deviation data indicate a high degree of variability for each dipwell, as would be expected from a recording period that encompasses a considerable range of seasonal conditions. The maxima data (Figure 2.2) indicate that all dipwells have experienced some periods of ponding over the period of record, with dipwell 5 having experienced the greatest depth of inundation. Conversely, all dipwells have also experienced some periods where the water table has fallen to levels considerably below the ground surface, and probably well below the maximum depth of any dykes or ditches within the site. Most dipwell minima seem to be within 1 metre of the surface, although some do fall to approximately 1.3 m below the soil surface, a depth that may well exceed the depth of the peat. It is interesting to note that the dipwell with the wettest records overall (dipwell 5) also appears to have experienced one of the lowest water table depths.

While the minima, maxima and means give an indication of the water table average and extreme values that have occurred over a long period, the standard deviations of the data give an indication of the relatively stability of the water table over time. In other words, the smaller the standard deviation the less variation each dipwell experiences about the mean. Table 2.1 suggests that all dipwells have standard deviations close to the mean value, suggesting that as 95% of all readings will be within 2 standard deviations either side of the mean, within the period of record each dipwell has experienced relatively high water table fluctuations. Table 2.1 and Figure 2.3 also suggest that the most stable water table records are to be found at dipwells 2,4,9 and 13, while the least stable would appear to be at dipwells 3, 10 and 14.

The high degree of variability experienced over time indicates that the temporal behaviour of the site is as important a consideration as the behaviour of the dipwells relative to each other. Indeed analysis of variance of the dipwell data suggests that the variability within each dipwell's data is significantly more important than the variability of the data between dipwells. In view of the importance of this temporal variation, the behaviour of the dipwells over time should now be considered.

2.1.2 Dipwell data over time

Two approaches can be made in examining the temporal data available from the dipwell monitoring:

a) an examination of the complete data-set over time

b) Separation of the data into discrete temporal units.

2.1.2.1: Overall temporal behaviour

Whilst a figure illustrating the behaviour of all the dipwells may be useful in showing the general pattern of readings (see Figures 2.4 and 2.5), the resulting plots are confusing and reveal little information other than the broad temporal trends. General inferences about the behaviour of the site as a whole may be made by examining mean data over time for all 15 dipwells. This information is shown in Figure 2.6, along with median data. Median data are presented as, if the range of values are biased towards one end of the data extremes (e.g. most values are around 5, but a few values are over 100), then the mean is not the ideal statistic to use, and the median may be preferable. In this case it is evident from the graph that the mean and median lines are very similar, and while both are presented only the mean will be discussed.

The information presented in Figure 2.6 suggests a number of broad features that categorise the data. There is an obvious cyclical pattern of periods where the water table is relatively stable and close to the ground surface, interspersed with periods where water table levels decline before reaching a minimum value, and then rising again towards the ground surface. It is noticeable that while the periods where water tables are stable and close to the ground surface are approximately equivalent in terms of time, the interval during which water tables are stable at their minimum depth are much shorter – if such stability occurs at all.

Two other patterns can be discerned within this broad context. Firstly, there is an apparent difference between the winter maximum depths in the years 1986–1990 and those after 1991. In the former, water is generally close to or marginally above the ground surface on average, whereas in the latter period water table depths in winter are mostly below the ground surface, suggesting some change in hydrological conditions. However, the winters in 1991–1995 also appear to show that the water table gets progressively higher, perhaps suggesting a re-establishment of equilibrium after some alteration to the fen's hydrological regime.

The second pattern concerns the periods of water table decline and minimum values. These data seem to suggest a cyclical pattern to water table movement in the summer dry period over the 10 years of record. Minimum values in the first summer (1986) recorded reach depths of c.45 cm, whereas in 1987 the figure is c.20 cm. After 1987 the water table depth attained each summer becomes progressively greater, with the minimum water table depth in

1990 reaching c.100 cm below the ground surface. Over the next 3 summers the minimum value reached becomes progressively closer to the ground surface, before falling again in 1994 and 1995. It is possible that this apparent cyclical flux in summer water table levels could be a result of:

a) the normal range of variation that can be expected for the site

b) a response to cyclical trends in rainfall inputs

and/or c) change resulting from long term flux in hydrological inputs independent of the site.

It is difficult to state from the data available which of these (if not all) can be identified as most likely. Winter data tend to be more consistent, as the increase in dipwell depths is limited by removal of water from the site as it reaches the ground surface.

Mean and median data are useful in suggesting general trends, but as illustrated in Figure 2.3 each dipwell has a considerable range of values associated with it, so that Figure 2.6 is less useful for identifying the hydrological activity in any specific part of what is a relatively large and complex site. Figure 2.7 indicates the range of values experienced across the site by showing the maximum and minimum water table depths recorded for each set of dipwell data.

The graph shows that in terms of maximum values, for much of the 10 year record at least one part of the site is under standing water, although the depth of this water rarely exceeds 25 cm. The lowest maximum values are recorded between April 1990 and July 1992, and after 1992 maximum depths are comparable with those before 1990. In terms of minimum values, water table depths are apparently most stable in the winters of 1986–1988. The winter of 1989 shows minimum water table levels comparable with those of the preceding years but a stable level is not achieved. After 1989, water table minima are lower by c.10 cm and for the most part more unstable. In terms of summer minimum values, there is a repeat of the cyclical pattern observed in Figure 2.6.

It is difficult to tell from Figure 2.7 whether there is any overall change in the range of values (i.e. the difference between the minimum and maximum values) changes over the period of record. For this reason the data ranges over time are plotted in Figure 2.8. It is clear from this graph that there is a much greater difference between maximum and minimum values in summer than in winter. It is also possible to note that the range of the data seems to become more variable after 1990, and that the there is an apparent difference between the baselines (the lowest levels generally attained over time) for the periods before and after 1990. This would seem to suggest that while the maximum values remain for the most part relatively constant, the lowest levels to which the water table falls over time extend deeper into the fen peats and perhaps into the underlying drift deposits.

The minimum and maximum data presented above do give an indication of the extreme values experienced over time in any one part of the site. It is possible that these readings represent the values from just two dipwells but this is unlikely given the highly variable nature of the data-set. With this is mind, it is useful to examine the behaviour of individual dipwell readings over time, in order to see whether the trends observable within the overall descriptive statistics are repeated at specific points at Chippenham Fen. The location of each dipwell (see Map B) is discussed below, and Figures 2.9a–o illustrate individual dipwell data over time.

Dipwell 1 *(Figure 2.9a)*: Dipwell 1 is in the south of the site between Jerusalem Wood and Baxter Ride. The data indicate that winter maximum levels are at or very close to the ground surface for 1986–1990, but decline to between 10 and 20 cm below the ground surface thereafter. This apparent difference is at a maximum in 1990 and 1991, with an apparent rising trend in winter maximum readings in the following years. The summer minima appear to follow a cyclical pattern, reaching a low of c.78 cm in 1986, rising to c.30 cm over the next two summers. After 1988 summer levels again fall to a low of c. 80–85 cm for a further two years, after which levels begin to rise again. Summer records for 1995 show a recurrence of the very low water table levels comparable with 1986, 1989 and 1990.

***Dipwell 2** (Figure 2.9b)*: Dipwell 2 is located on Snailwell Poor's Fen to the south-west of the fen, and is in the centre of an area of Saw sedge. Readings for dipwell 2 follow a similar pattern to those for dipwell 1, with the exception that initial winter maxima are slightly above ground level, and the summer minima are generally less than those for dipwell 1. The summer of 1995 shows the greatest decline in water table depth.

***Dipwell 3** (Figure 2.9c)*: This dipwell is in the Northern Meadows section of the site, and is relatively close to one of the main dykes and to a cross drain. A collared dam is relatively close to the dipwell at the junction of the dyke and the Chippenham River. The general pattern observable for dipwells 1 and 2 can also be seen in dipwell 3. Notable exceptions are that the winter maxima in the years 1986–1990 are generally c.8–10 cm below the ground surface, and those in the years 1991–1994 are between c.18–20 cm below the ground surface. The winter readings are apparently more stable than those for dipwells 1 and 2. Summer minima show the same cyclical pattern, although the fall in water table in 1990 is marginally greater than that for 1995 and minimum values overall are greater than for the previous two dipwells.

***Dipwell 4** (Figure 2.9d)*: Dipwell 4 is in an area of reed and saw sedge to the west of the Chippenham River. The dipwell is relatively close to a dyke, and Mason (1990) indicates that the area monitored by this dipwell is subject to surface flow as a result of overspill from this dyke. Dipwell 4 readings show a marked difference in trend to those shown in dipwells 1 to 3. The vast majority of dipwell readings are within c.5–8 cm of the ground surface either in summer or winter. The exceptions to this trend are the readings for the summers of 1989–1992 and 1995. Water table depths in these years fell to between 40–100 cm of the ground surface, with the greatest decline exhibited in 1990 and 1995. Winter water table depths after 1990 are apparently marginally lower than in the period before 1990.

***Dipwell 5** (Figure 2.9e)*: This dipwell is close to a path in an area of reeds and saw sedge known to flood in winter. The data show differences to dipwell records reported above. In this case all winter maxima are well above the ground surface, usually c.20 cm, with the exception of 1990 and 1991 which show a water table c.5–10 cm above the surface. Summer minima tend to stay at or near the ground surface for the first 3 summers recorded, so that water levels remain close to the surface for the most of the 1986–1988 records. From 1989 onwards summer water levels decline further, particularly for 1990, when water table depth reaches c.140 cm below the ground surface. After the 1990 low, summer minima decline in severity but continue to be well below those of the pre-1989 period. The 1995 summer, however, was lower than any of the previous 3 summers and may indicate a continuation of the apparent cyclical trend noted in other dipwells.

***Dipwell 6** (Figure 2.9f)*: Dipwell 6 is relatively close to both a main drain and one of the collared dams in the fen, next to Pigeon Ride in an area of reed and rush with some scrub encroachment. The data exhibit similar trends to those featured by dipwells 1–3, with the initial period showing water tables at or near the ground surface in winter and generally within 40 cm of the ground surface in summer. After the summer 1990, when water table depths fell to c.140 cm below the surface, winter maxima are generally c.15–20 cm below the ground surface. The summers of 1991 and 1995 feature water tables falling to c.120 cm below the surface, but otherwise the winter-summer range of values is comparable to before 1989. It is also noteworthy that winter readings after 1989 seem more variable than those before 1989.

Dipwell 7 *(Figure 2.9g)*: This dipwell can be found near to a main drain near to Baxter Ride in the same part of the fen as dipwell 6. Records for dipwell 7 are similar to dipwell 6, with the exception that maximum and minimum values over the recording period are marginally higher.

Dipwell 8 *(Figure 2.9h)*: Dipwell 8 is close to a main drain near the junction of Baxter Ride and Pigeon Ride in an area covered by reed and rush vegetation. Data for this dipwell show strong similarities with dipwell 5 in that the majority of winter maxima are c.10–20 cm above the ground surface. Only the winters of 1990 and 1991 show lower water table levels, and there are no obvious differences between the periods separated by these two relatively dry winters. The only major difference between dipwell 8 and 5 is that the difference between winter and summer extremes is much larger, with the water table generally reaching depths of greater than 60 cm below the ground surface.

Dipwell 9 *(Figure 2.9i)*: Dipwell 9 is the most westerly dipwell on the fen and is in the same part of the fen as dipwell 8, close to Main Ride and the site boundary. Data for this dipwell show strong similarities in terms of trends and ranges with those shown by dipwell 2.

Data for the following dipwells exist only from 1991 onwards and therefore any comparison with the preceding dipwells must be treated with care given the apparent differences between the first five years of recording and the last five years.

Dipwell 10 *(Figure 2.9j)*: Dipwell 10 is in the centre of compartment 11, between dipwells 8 and 9. Records for this dipwell show initial winter maxima of c.8–10 cm below the ground surface in 1991, rising gradually to c.10 cm above ground level over the next 3 winters. Water table depths in summer vary over the recording period, reaching a low of c.125 cm below the ground surface in 1991, rising to c.35 cm below the ground surface in 1993 and then declining over the next two summers to a low of c.130 cm below the ground surface in 1995.

Dipwell 12 *(Figure 2.9k)*: This dipwell can be found relatively close to dipwell 7, but is further away from the drains adjacent to Baxter Ride. Winter maxima show little variation between winters, with water tables consistently between 5 and 10 cm below the ground surface. Water table depths within each winter period are more variable than those exhibited by dipwell 10, with a range of values of approximately 5–10 cm. Minimum values in summer reach between c.55–100 cm below ground level, with the highest summer water table found in 1993, and the lowest in 1995.

Dipwell 13 *(Figure 2.9l)*: Dipwell 13 is away from the main drain alongside Baxter Ride but is relatively close to a cross-ditch. This part of the fen is covered by saw sedge, although some scrub/woodland species may be found nearby. The trends exhibited by readings from this dipwell bear some similarities to those from dipwells 10 and 12. As with the former, winter water table depths apparently rise gradually between 1991 and 1995. However, the level and range of values of the water table bear closer resemblance to those of dipwell 12, in that readings within any one period of record are more variable than those seen in dipwell 10. Summer minima are consistently c.10 cm nearer the ground surface than those for dipwell 12, while winter maxima are consistently c.10 cm further from the ground surface.

Dipwell 14 *(Figure 2.9m)*: Dipwell 14 is in the same part of the fen as dipwell 5, but is further away from Ash Ride. The majority of readings show that for much of the recording period water levels are relatively stable and within a few centimetres of the ground surface, and between September 1991 and March 1994 occur below 20 cm for relatively short periods. Three summer periods either side of these dates show that there can be considerable falls in water table, with summer minima in 1991, 1994 and 1995 all reaching depths of greater than 100 cm below the ground surface.

Dipwell 15 *(Figure 2.9n)*: This dipwell is in the Northern Meadows very close to dipwell 3, but is further away from the cross drain and closer to the Chippenham River. Data for dipwell 15 closely resemble those for dipwell 12 in terms of the range of values experienced, the relatively high variability during winter periods, and the depths to which the water table declines during summer. One notable difference is that the range of summer minima over 5 years is c.10 cm, compared with c.20 cm for dipwell 12.

Dipwell 16 *(Figure 2.9o)*: Dipwell 16 is in the north of the site, and while it is relatively close to two cross drains it is much further away from any of the main water courses than the other dipwells. The pattern of readings for dipwell 16 indicate a site with a much more variable water table than experienced elsewhere at Chippenham Fen. While winter maxima do approach ground level, the water table can fluctuate as much as 40 cm over periods where other dipwells fluctuate by less than 10 cm. Indeed some of the lower readings in winter can approach some of the higher readings in summer (see readings for December 1992 and June 1993 for example).

2.1.2.2: Dipwell data analysed in temporal units

The broadest temporal unit definable in the overall data-set are the annual means. The data available here commence in April 1986, and therefore the calculation of annual means has used the year running from 1/4 to 31/3. As the data end in August 1995, only 6 months' records are available for the year 1995–96, and this year has been omitted from the discussion below. Annual data are presented in Table 2.2 below.

Table 2.2: Mean annual water table depth (cm above/below ground surface) for dipwells at Chippenham Fen.

Dipwell	April 1986–March 1987	April 1987–March 1988	April 1988–March 1989	April 1989–March 1990	April 1990–March 1991	April 1991–March 1992	April 1992–March 1993	April 1993–March 1994	April 1994–March 1995
1	−23.85	−6.68	−9.16	−28.85	−41.1	−36.58	−26.62	−13.04	−15.35
2	−13.56	−0.84	−5.8	−19.07	−33.4	−27.27	−17.58	−9.08	−15.08
3	−21.89	−11.52	−19.76	−38.4	−53.07	−36	−30.12	−21.69	−31.69
4	−4.15	0.44	−1.72	−9.56	−25.48	−13.85	−7.58	−3.31	−3.96
5	7	19.4	14.56	5.1	−21.37	−5.08	9.35	13.54	8.69
6	−24.3	−12.16	−4.72	−14.89	−46.78	−33.35	−22.08	−20.73	−26.46
7	−17.78	−4.68	−0.08	−7.41	−38.89	−22.77	−14.46	−11.31	−19.27
8	−15.1	8.24	0.44	−12.82	−34.56	−20.73	−7.27	2.96	−9.04
9	−14.67	−3.52	−5.6	−18.49	−33.3	−32.85	−19.38	−8.88	−14.27
10	–	–	–	–	–	−34	−18.35	−1.81	−14.65
12	–	–	–	–	–	−25.5	−18.13	−15.08	−24.46
13	–	–	–	–	–	−34.63	−24.92	−22.27	−24.73
14	–	–	–	–	–	−22.63	−7.12	−6.54	−22.27
15	–	–	–	–	–	−30.08	−24.38	−17.31	−27.54
16	–	–	–	–	–	−50.13	−39.96	−33.54	−46.88
Overall	***−14.26***	***−1.26***	***−3.54***	***−16.04***	***−36.44***	***−28.36***	***−17.91***	***−11.21***	***−19.13***

Graphical presentation of the dipwell data on an annual basis is not entirely helpful, as the large numbers of dipwells and years of record make for confusing graphs that are difficult to interpret. Examination of Table 2.2 does indicate that there is a considerable range of values for each dipwell. The overall average for the site in each year (illustrated in Figure 2.10) indicates more simply the trends identified in the preceding section, with a rise and fall in mean annual water table depths over time. Throughout the recording period the year 1990–91 is apparently the driest, while the wettest years are 1987–88 and 1988–89. Between these extremes mean water table depths for the whole site undergo a gradual change.

As has been indicated in previous sections, water table levels fluctuate not only between years but within years as seasonal variations in rainfall and evapotranspiration have an influence. Mean annual data are therefore unable to adequately represent the range of water table fluctuation experienced at the site in any year. Similarly, the range of variation experienced in any one season is unlikely to be constant. In order to examine the seasonal change in water table at Chippenham Fen, the annual data series have been divided arbitrarily into seasonal components: Spring (March–May), Summer (June–August), Autumn (September–November) and Winter (December–February). While winter values are calculated across the divide between calendar years, for the sake of simplicity only the year for December is included in tables. The resulting breakdown for each dipwell overall can be found in Table 2.3, and is illustrated in Figure 2.11.

Table 2.3: Mean water table depth above/below ground surface for each dipwell, divided into seasonal components.

Dipwell Number	Spring (cm)	Summer (cm)	Autumn (cm)	Winter (cm)
1	–26.19	–47.78	–12.07	–6.28
2	–20.61	–34.38	–7.63	–4.22
3	–39.27	–60.13	–15.12	–10.22
4	–5.50	–23.55	–4.18	–1.17
5	5.40	–19.22	13.86	18.75
6	–25.79	–45.77	–13.58	–11.32
7	–20.19	–33.88	–6.61	–5.18
8	–15.00	–39.83	1.68	9.07
9	–20.65	–35.50	–9.44	–4.10
10	–21.04	–59.07	–9.00	3.68
12	–29.31	–42.31	–13.52	–11.07
13	–29.00	–41.45	–21.70	–20.54
14	–17.54	–46.93	–6.30	–1.93
15	–37.12	–48.72	–14.44	–11.79
16	–60.23	–69.97	–28.89	–25.39
Overall	***–24.14***	***–43.23***	***–9.80***	***–5.45***

Examination of the data presented above suggest that in all cases, as would be expected, water depths below the surface show the sequence: Winter<Autumn<Spring<Summer[1]. Within that general pattern, the seasonal difference seems broadly similar for most dipwells. The exceptions to this general rule appear to be dipwells 10 and 3, where the difference between summer and winter extremes are the largest, and dipwells 2, 4 and 13, where the winter–summer difference is the smallest.

As far as individual 'seasons' are concerned, dipwell 16 shows the lowest mean water table depth in all four seasons, while dipwell 13 shows low water table depths in spring, autumn and winter. Dipwells 3 and 10 show low water table depths in summer only. In terms of maximum water table depths, dipwell 5 shows the highest water tables in all four seasons, and dipwell 8 features a relatively high water table in spring, autumn and winter. Dipwell 10 shows relatively high mean water tables in spring and winter. Dipwell 4 features a relatively low mean water table depth in Summer. These data would again seem to indicate that dipwell 10 data, when considered as an average over longer periods of time, show the largest range overall.

Individual means for specific seasons help to identify general water table patterns for specific parts of the year, but they reveal little concerning the variability between years for these

[1] *Winter*: December–February; *Autumn*: September–November; *Spring*: March–May; *Summer*: June–August.

seasonal components. The annual pattern of individual dipwell response in seasonal terms is available, but as with earlier data the presentation of this data in graphical terms is complex. The level of detail required for considering the differences between dipwells as a function of time will instead be considered in a more detailed analysis in a later section. A simpler approach is to examine the change in seasonal trends over time for the data-set as a whole. This information is considered in Table 2.4 and illustrated in Figure 2.12.

Table 2.4: Mean annual water table depth above/below ground surface for Chippenham Fen, divided into seasonal components

Year	Spring (cm)	Summer (cm)	Autumn (cm)	Winter (cm)
1986	–27.15	–29.00	–0.94	–0.20
1987	–7.18	–7.33	2.37	3.81
1988	–1.13	–16.83	2.00	4.04
1989	–11.49	–41.62	–6.52	1.00
1990	–33.88	–81.00	–15.13	–8.29
1991	–30.13	–57.68	–15.36	–12.05
1992	–26.98	–34.17	–5.38	–6.36
1993	–18.21	–25.41	–4.09	–5.30
1994	–23.94	–39.06	–5.86	–2.35
1995	–28.39	–88.47	–41.93	–
Overall	***–24.14***	***–43.23***	***–9.80***	***–5.45***

These data would appear to suggest that all the seasons show a fluctuation over time and broadly speaking follow the same pattern of gradually rising and falling mean water table depths over time. However, the magnitude of this fluctuation apparently varies with season, with the range between smallest and largest mean values showing the following sequence: Summer>Spring>Autumn>Winter. This would seem to suggest that variability in external conditions have less of an impact in winter months than in the summer.

2.1.3 Dipwell data relative to ordnance datum

Data relative to the ground surface are useful in indicating which parts of a wetland site are experiencing conditions that would be considered sub-optimal in terms of maintaining a wetland ecosystem. In terms of hydrological management they are less helpful, in that they do not reveal the position of individual dipwells relative to each other. It is impossible to tell from the information presented in Section 2.1.1, for example, whether a dipwell experiencing relatively low water table depths does so because of some management factor (e.g. proximity to a drainage system) or as a result of it being located on much higher ground. Data presented in terms of ordnance datum allow such a comparison to be made more effectively.

Each dipwell installed at Chippenham Fen has been surveyed at some point during its lifespan, with this survey data related to ordnance datum. The dipwell data presented in

Section 2.1.1 has been related to the ordnance datum values supplied by English Nature/NRA and will be discussed below. It should be noted at this point that some dipwells have been re-surveyed over time and there are a variety of levels attributed to some dipwells, while others have remained at a 'constant' datum. The information reporting such re-surveys is confusing, and in order to maintain some consistency the original datum given to each dipwell has been assumed to remain constant.

Merely repeating the treatment given to the data relative to the ground surface would reveal little additional information, and so presentation of this data will be restricted to the patterns shown by the overall data-set. Summary statistics are given in Table 2.5, with the data over time given in Figures 2.13a–b.

The most obvious patterns discernible from Figures 2.13a and 2.13b are those concerning the grouping of dipwell readings. In Figure 2.13a there is a clear separation of the 9 dipwells included into three groups. Dipwells 1, 8 and 9 consistently show the highest readings, and dipwells 2–5 consistently the lowest. Dipwells 6 and 7 fall between the two extremes. The remaining dipwells (illustrated in Figure 2.13b) again show a consistent grouping, with dipwells 10 and 12 consistently the highest, 15 and 16 the lowest, and 13 and 14 forming an intermediate group.

Table 2.5: Summary statistics for dipwells at Chippenham Fen relative to ordnance datum

Dipwell Number	Elevation of dipwell at ground surface (m.a.o.d.)	Mean water table elevation (m.a.o.d.)	Median water table elevation (m.a.o.d.)	Standard Deviation	Minimum water table elevation (m.a.o.d.)	Maximum water table elevation (m.a.o.d.)
1	13.061	12.823	12.901	0.2392	12.191	13.081
2	12.176	12.003	12.056	0.1908	11.316	12.246
3	12.374	12.050	12.214	0.3087	11.074	12.414
4	12.307	12.217	12.277	0.1756	11.327	12.387
5	12.204	12.244	12.304	0.2410	10.944	12.524
6	12.838	12.588	12.668	0.2597	11.488	12.898
7	12.815	12.643	12.735	0.2325	11.775	12.905
8	13.049	12.931	13.059	0.2933	12.029	13.229
9	13.064	12.885	12.944	0.1922	12.094	13.094
10	12.924	12.700	12.859	0.3536	11.574	13.044
12	12.869	12.622	12.719	0.2195	11.839	12.819
13	12.770	12.485	12.535	0.1454	11.89	12.66
14	12.582	12.390	12.542	0.3041	11.392	12.652
15	12.396	12.110	12.211	0.2416	11.486	12.396
16	12.903	11.960	12.003	0.2530	11.363	12.393
OVERALL		***12.461***	***12.444***	***0.4111***	***10.944***	***13.229***

The most obvious patterns discernible from Figures 2.13a and 2.13b are those concerning the grouping of dipwell readings. In Figure 2.13a there is a clear separation of the 9 dipwells included into three groups. Dipwells 1, 8 and 9 consistently show the highest readings, and dipwells 2–5 consistently the lowest. Dipwells 6 and 7 fall between the two extremes. The remaining dipwells (illustrated in Figure 2.13b) again show a consistent grouping, with dipwells 10 and 12 consistently the highest, 15 and 16 the lowest, and 13 and 14 forming an intermediate group.

2.1.4 Comparison of specific recording periods

The data above suggest that there is a distinct separation of trends over the recording period, with three zones of concern:

a) An initial period of relative stability lasting from the start of recording until c.1989, with winter water table depths stable, but with apparently regular variations in summer water table depths.

b) A transitional period commencing at the end of period a) and ending *c.* 1992, with winter water table levels apparently markedly lower than those in the previous period.

c) A second period of relative stability, with a suggestion that winter water table depths are initially lower than in period a) but gradually rising over successive winters.

These data would suggest that it may be useful to compare the data from these three periods in order to investigate whether or not there is a real difference them.

The precise marker boundaries between these three time periods are likely to vary from dipwell to dipwell, and so mean data will be used to identify them. The exact point at which to place these boundaries is also open to interpretation. As data recording commenced in April, the commencement of any one year's records has been fixed as that month. For this reason any change in the annual hydrological sequence will be assumed to have commenced in the previous April. Using the mean dipwell data, the three periods have been identified as followed:

Period 1: April 1986 – March 1990

Period 2: April 1990 – March 1992

Period 3: April 1992 – October 1995

Mean data have been calculated for each dipwell for each of these three periods, and these are shown in Table 2.6. The data are illustrated in Figure 2.14.

It is evident from the graph and Figure that there is an apparent difference between the three periods. Overall, the first period exhibits much higher mean water tables than the other two. This pattern is common to all dipwells, as well as to overall mean values. Furthermore, the period exhibiting the lowest water table in any dipwell is the second period, with the final segment of monitoring time showing a slight rise in mean water table depth. This rise does not bring water tables in this latter period to a level comparable with that of the early years of record.

While the above has done no more than confirm initial observations concerning trends discernible within the overall hydrological record of the site, the division of the period of record into three (admittedly arbitrary) sections does allow a more detailed statistical approach: Analysis of variance allows an examination of the difference between the three time periods and between individual dipwells, and the results suggest that there is a significant difference ($p<0.001$) between the three time periods. The analysis also shows that while there is also a significant difference between all the dipwells (i.e. there is a considerable range of values for each dipwell), this is not as important as the difference between the three time periods. While it is known that groundwater abstractions have occurred nearby that may account for this difference, compensation flows have been pumped into the fen. Exact rates of abstraction and the timing of all inflows are not available, and this issue will be discussed later.

Table 2.6: Mean dipwell data for three specific time periods at Chippenham Fen

	Mean water table depth (cm)		
Dipwell Number	**Period 1 (April 1986–March 1990)**	**Period 2 (April 1990–March 1992)**	**Period 3 (April 1993–October 1995)**
1	–17.4	–38.8	–21.3
2	–10.0	–30.4	–17.2
3	–23.1	–44.6	–34.0
4	–3.8	–19.7	–8.0
5	11.3	–13.3	6.5
6	–14.2	–40.1	–27.2
7	–7.6	–30.9	–19.0
8	–5.1	–27.7	–9.2
9	–10.7	–33.0	–16.6
10	–	–34	–17.9
12	–	–25.5	–23.4
13	–	–34.6	–26.3
14	–	–22.6	–17.1
15	–	–30.0	–27.1
16	–	–50.1	–44.5
Mean	***–9.0***	***–30.9***	***–20.2***
Median	***–3***	***–19***	***–13***
Standard deviation	***19.6***	***31.0***	***26.0***
Minimum	***–96***	***–135***	***–135***
Maximum	***32***	***17***	***28***

While the above analysis has generated an interesting result, a number of considerations should be taken into account, namely:

a) Analysis of variance is only applicable where the data are normally distributed. The histogram shown in Figure 2.15 suggests that is the case, but as the values used in the analysis are both mean values and the entire data set, rather than the distribution of individual segments of the data, they may not represent the pattern of the data as used in the analysis.

b) The data within each specific time period consist of a series of repeated cyclical variations in water table, whereas the averages taken from these data effectively describe a straight line.

Any results reported using analysis of variance should therefore be treated with caution.

A further consideration to be made regarding the dipwell behaviour is that of the role of the marl layer separating the upper and lower fen peats. The relative position of this marl layer varies, as does its thickness and its relation to the upper peat. The precise physical properties of the marl are not known, but it is likely to represent an impediment to the vertical movement of water in the fen. Todd (1980), for example, cites typical conductivities for an unspecified peat type (measured vertically through the soil column) of 5.7 $m.day^{-1}$, compared with 0.0002 $m.d^{-1}$ for clay and 0.08 $m.d^{-1}$ for silt. This would imply that those areas with a marl horizon should experience slower rises and falls in water table than those areas where dipwells monitor through fen peat alone.

The question as to whether this marl layer does have an impact can be addressed to some extent by examining the records for dipwells 4 and 5. Dipwells 4 and 5 are located close to auger holes and are on opposite sides of Main Ride. The profile from the former indicates the presence of a marl layer (between c. 30 to 60 cm below ground level), the latter indicates no marl layer (Mason, 1990). Re-examination of Figures 2.9d and 2.9e suggests that the two dipwells do exhibit markedly different patterns of water table behaviour. Dipwell 4 water tables exhibit markedly less fluctuation than occurs at dipwell 5, and water levels rarely descend below the base of the marl layer.

It should be noted, however, that when the water table does fall below the level of the marl, the rate of decline is apparently no different to that exhibited by dipwell 5, and there may be other causes for the difference between the two, for example, hydrological management. Furthermore, it would be unwise to extrapolate these trends to the rest of the fen, given that auger data exist only along the main ride and in isolated parts to the south of the fen, and the soil profiles below the two dipwells examined here may not adequately represent those found elsewhere in the fen.

2.2 Data from other monitoring devices at Chippenham Fen

As mentioned in Section 1.2.2, a variety of other monitoring devices have been employed at the fen for a variety of time periods and serve as useful comparisons with the dipwell data. Three sets of data are available here: data from a piezometer at the Principal Spring, data from three gauge boards around the fen (see Map B), and data from the observation borehole at the fen. As one of the gauge boards is located at the Principal Spring, these data will be considered together.

2.2.1 Principal Spring piezometer data and data from gauge board GB1

Both of these monitoring stations are located to the south of the site and are connected to, but separated from, the main network of drains and fen compartments. Data have been collected at the Principal Spring piezometer (PSP) on a fortnightly basis since February 1993, but infrequent readings are also available as far back as May 1989. GB1 data have been collected since May 1989. These data are presented graphically in Figure 2.16 and are summarised in Table 2.7.

Table 2.7: Summary data for water table elevations taken at the Principal Spring piezometer and gauge board GB1 relative to ordnance datum

	Principal Spring Piezometer (m.a.o.d.)	Gauge board GB1 (m.a.o.d.)
Mean	13.1	12.8
Median	13.1	12.8
Standard deviation	0.18	0.10
Minimum	12.68	12.42
Maximum	13.47	12.96

It is clear from the table that despite the close proximity of the two monitoring devices there is a difference between them, with an average difference of almost 0.3 m. Analysis of the data suggests that this apparent difference is statistically significant ($p<0.001$). Examination of Figure 2.16 suggests that although initial readings (such as they are) correspond reasonably well, when the Principal Spring data are collected on a more regular basis there is a marked difference between them.

GB1 data suggest that there is relatively little variation over time, with only 0.79 cm between the minimum and maximum values recorded over 7 years, but some trends are discernible. The first year's readings show relatively little variation, but after April 1989 the seasonal variation becomes more pronounced and is combined with a declining trend in water table depths until 1991. There is a marked rise in water table depths (c.0.4 m) during August 1991 that persists until October 1991 (when water tables fall by c. 0.3m) that is apparently out of step with the underlying trend but may result from rainfall inputs.

After October 1991 the water table begins to increase gradually until an apparently stable level (with relatively little seasonal variation) is attained after mid-1992. The apparently rapid decline at the end of 1995 can be attributed to both a two month break in readings and the prolonged drought during that break.

PSP data, when considered only after the onset of more frequent monitoring, are too few to suggest any meaningful change in annual trends but it is evident that there is much greater seasonal fluctuation in the data than is seen in GB1 records. Furthermore, close examination of the graph suggests that after the first few months of regular recording, PSP data and GB1 data appear to become asynchronous. The data seem to show that as the water table rises at the PSP, it falls at GB1 and vice-versa. While the two monitoring devices here measure different features of the local table (the PSP measuring water pressure form the aquifer, the latter water levels in the spring pond next to the PSP), it would be expected the two data series would behave in a consistent manner.

This would suggest either that something hydrologically unusual is occurring, or that an error has occurred in the dates attributed to some records. In either event there is clearly a large discrepancy between the two series that may be a result of alterations made to the PSP structure, and/or to changes in recording method over time. Furthermore, if the two sets of data are correlated, then a coefficient of 0.3386 is produced, which suggests that while there is a positive link between the two sets of readings, the relationship is not a significant one.

2.2.2 Data from gauge boards GB2 and GB3

The remaining gauge boards are located in the southern portion of the site NNE (GB2) and NNW (GB3) of the Principal Spring and are located on a drain adjacent to Baxter Ride. Map B suggests that this drain is in two sections with one gaugeboard on each section. Water levels in the drain are maintained by collared dams, shown in Map C. Data have been collected since April 1991 on a fortnightly basis and are illustrated in Figure 2.17 and summarised in Table 2.8.

Table 2.8: Summary water table elevation data for gauge boards GB2 & GB3

	Gauge board GB2 (m.a.o.d.)	Gauge board GB3 (m.a.o.d.)
Mean	12.4	12.3
Median	12.4	12.3
Standard deviation	0.13	0.13
Minimum	12.13	11.94
Maximum	12.79	12.65

The data suggest that there is relatively little fluctuation in the two sets of readings, and the almost horizontal lines presented in the graph suggest very stable water levels in the drains with only isolated changes over time. These fluctuations are relatively small (usually c. 0.1m) in most cases, with the obvious exception of the early records (suggesting a relatively constant rate of input from or loss to the surrounding fen), and the relatively large changes in water levels recorded in late 1993 and 1995. It is also worth noting that the 0.13 m difference in elevation of the water level recorded at the two gauge boards is more or less maintained throughout the recording period. In most cases changes in readings for GB2 are matched by changes in GB3 readings, but there are periods where increases or decreases in GB2 water levels do not find corresponding changes in GB3.

There are inconsistencies in the timings of changes in water levels. For example the decline in water levels at GB2 in late 1991 precedes the decline in GB3, whereas the decline in water levels at GB2 in late 1992 is preceded by a decline in GB3. It is important to note that although these changes occur relatively close together on the graph, the time lag in reality amounts to a number of weeks. It is possible that the nature and timing of the changes in water levels recorded at GB1 and GB2 are related to changes in the overflow levels of nearby dams, and this will be discussed further in Section 4.1.2. Despite the minor inconsistencies in the two series, the correlation coefficient between the two is 0.9472, suggesting that despite the relatively large distance between them (c. 400 m) there is a highly significant relationship between them ($p<0.001$).

2.2.3 Data from the observation borehole

Two sets of data exist for the borehole: a series of monthly readings dating from February 1983 to September 1995 and data recorded by an automatic logger from June 1991 to September 1995. Examination of the monthly data show that they consist of readings taken at monthly intervals, rather than monthly averages, and thus it is possible that short term fluctuations may have been missed before the automatic logger became operational. However, these early records do give an indication of general trends and allow logger data to be 'ground-truthed'.

The monthly records are illustrated in Figure 2.18. The data suggest a similar pattern to those found at the dipwells, i.e. an initially high water table showing a regular seasonal pattern lasting until c.1987, with a marked decline in values between 1989 and 1993. There is an apparent rising trend in readings from 1994 onwards. One interesting feature in the data is that before the water table readings begin to decline, there is an apparent rise in values. However, as this 'rise' only occurs for one year and is based on relatively few data points, it would be unwise to draw any significant conclusions from it.

Annual means have been calculated for the period of record on the same basis as those for the dipwells (i.e. using the year April–March). These figures are shown in Table 2.9 and illustrated in Figure 2.19. The trends identified from Figure 2.18 are more pronounced here, with the years 1990–1993 showing mean levels markedly lower than in the years before and after. In terms of the variability of the data, the standard deviations are relatively similar for all years, indicating that the range of values remains similar, although the value of 0.702 for 1992–93 is markedly higher than those in other years.

Table 2.9: Annual summary data for manual readings of water table elevation relative to ordnance datum taken from the Chippenham Fen observation borehole

	Mean (m.a.o.d.)	Median (m.a.o.d.)	Standard Deviation	Minimum (m.a.o.d.)	Maximum (m.a.o.d.)
1983–84	15.2	15.2	0.42	14.63	15.99
1984–85	15.02	15.1	0.32	14.37	15.43
1985–86	14.85	14.89	0.31	14.4	15.33
1986–87	14.88	14.98	0.35	14.42	15.31
1987–88	15.54	15.35	0.41	15.07	16.4
1988–89	15.21	15.08	0.34	14.91	15.93
1989–90	14.38	14.14	0.48	13.96	15.3
1990–91	14.20	14.15	0.50	13.47	15.11
1991–92	13.56	13.71	0.45	12.86	14.21
1992–93	13.83	13.63	0.70	13.09	15.06
1993–94	15.00	14.96	0.57	14.23	16.15
1994–95	15.12	15.125	0.44	14.59	15.81
Overall	***14.69***	***14.86***	***0.73***	***12.86***	***16.4***

The data from the automatic borehole logger are illustrated in Figure 2.20, with annual and overall summary data presented in Table 2.10.

Table 2.10: Overall and annual summary data for readings of water table elevation above ordnance datum taken by the automatic logger, Chippenham Fen observation borehole

	Mean (m.a.o.d.)	Median (m.a.o.d.)	Standard Deviation	Minimum (m.a.o.d.)	Maximum (m.a.o.d.)
1991–2	13.44	13.37	0.31	13.05	14.04
1992–3	14.22	14.13	0.68	13.12	15.22
1993–4	15.15	15.02	0.55	14.23	16.21
1994–5	15.10	14.93	0.44	14.56	15.89
1995–6	15.06	15.07	0.46	14.24	15.78
Overall	***14.61***	***14.78***	***0.83***	***13.05***	***16.21***

Figure 2.20 suggests that there is a consistent pattern of seasonal variation over time, but there is an apparent change in base level in 1993, when minimum water table readings at the borehole apparently rise to match the maximum values attained in the previous two years. This increase in regional water table elevations may possibly be linked to the apparent rise in fen water tables suggested in Section 2.1.3. However the relatively short period of record here makes precise conclusions concerning this change difficult to achieve.

Although the recording period is much shorter than that for the manual readings, the large number of readings taken each day should ensure that (with the exception of periods during which the logger apparently malfunctioned) the record is a reliable representation of water table depths over this period. If the data from the automatic logger are compared with those taken manually, there is a high degree of consistency between the two sets of overall data. However there are notable differences between the annual series, with only the latter two years (when manual readings were taken much less frequently) showing any correspondence.

It is also interesting to note that while the standard deviations of the two sets of annual data do differ they are by no means markedly different – despite the much greater number of readings available from the automatic logger over the same period. It would be impossible to state with any degree of certainty which of the two data series is the most accurate representation of water table fluctuation at the observation borehole but the reasonable degree of correspondence between the two does allow the inference of a continuous record between them.

The larger number of records taken by the automatic logger allow the creation of seasonal averages on the same basis as those calculated for the dipwell data, as shown in Table 2.11. These data suggest that on average, autumns exhibit the lowest water tables, with winter and spring showing little difference as the wettest parts of the year. It is also evident that water table levels from late 1992 onwards are much higher on average than the preceding seasons.

Table 2.11: Seasonal averages for water table elevation relative to ordnance datum from the automatic logger, Chippenham Fen observation borehole.

Seasonal Mean	Summer (m.a.o.d.)	Autumn (m.a.o.d.)	Winter (m.a.o.d.)	Spring (m.a.o.d.)
1991	13.62	13.13	13.42	14.10
1992	13.63	13.74	15.08	15.05
1993	14.79	14.68	15.83	15.79
1994	14.84	14.71	15.15	15.62
1995	14.73	–	–	–
Overall				
Mean	***14.31***	***14.08***	***15.04***	***15.10***
Median	***14.54***	***14.29***	***15.15***	***15.12***
Standard deviation	***0.61***	***0.73***	***0.81***	***0.66***
Minimum	***13.27***	***13.05***	***13.22***	***14.00***
Maximum	***15.18***	***15.28***	***16.21***	***16.21***

Analysis of borehole data in terms of the periods identified in the dipwell records where there is a marked change in water table base level (see Section 2.1.2) suggest that there is a significant difference in river discharge and log-transformed borehole data in the period before and after 1/4/1990 (periods 2 and 3). In this case, readings in period 2 are significantly lower ($p<0.001$) than in the final period, with mean daily water table elevations of 13.45 and 14.84 m above ordnance datum respectively.

2.3 River flow data at Chippenham Fen

Flow data have been collected from a gauging station on the Chippenham River shortly after it leaves the fen. Initial readings consisted of daily averages, but later data include daily minima and maxima. Summary data from these readings are given in Table 2.12, together with an estimate of average daily river discharge, the amount of day to day change in flow and the difference between minimum and maximum flow. The discrepancies in the table (e.g. the largest daily minimum being considerably lower than the highest average figure) are a product of the different time-spans of the data collection.

Table 2.12: Summary data from the River Chippenham gauging station

	Daily mean flow (cumecs)	Daily minimum flow (cumecs)	Daily maximum flow (cumecs)	Daily change (cumecs)	Total daily discharge (m^3)	Daily range (min.–max.)
Mean	0.093	0.109373	0.120826	2.78E-05	8187.51	0.011
Median	0.06	0.091	0.101	–0.001	5184	0.005
Standard Deviation	0.097	0.094	0.102	0.029	8448.93	0.021
Minimum	0.001	0	0.002	–0.207	86.4	–0.09
Maximum	1.052	0.536	0.598	0.648	90892.8	0.248

The daily averages calculated from the logger data are illustrated in Figure 2.21–22. The former graph uses a normal scale for mean river discharge, the latter uses a logarithmic scale in order to suppress the impact of large events and enable the easier identification of smaller scale fluctuations. Both graphs indicate that there is a distinct pattern to the annual series, namely a markedly higher daily mean discharge in the winter months relative to the summer, a rapid rise in river discharge rates leading to the winter peak and a gradual fall until the lowest flows of the summer are reached.

More detailed examination of the graphs reveals that there is considerable variability between and within years. It is evident from both graphs that river discharges in the first year's data are considerably lower than in any of the years following. Of the three years following, 1994 appears to have the highest discharge throughout the whole of the year and shows the highest peak discharge, with 1993 and 1995 (to September) broadly similar in terms of timing and magnitude of winter and summer flows. The higher discharge rates experienced in 1994 may in part be attributable to the apparent rising trend in dipwell readings in recent years (Section 2.1.3) as regional groundwater levels rise, but the absence of river discharge data for the early part of the dipwell monitoring makes this difficult to confirm.

There are, however, notable variations within years. This is particularly evident in the graph showing a logarithmic scale (Figure 2.22), where the line shows considerable fluctuation around the more obvious trend. It is also evident that there are several well defined and relatively long lived rises in river discharge throughout each winter period, suggesting either relatively long high discharge events associated with accompanying high rainfall, or the release of water from the fen in each year via management activities. The former would seem to be discounted by site records and management sources that suggest a relatively flashy response to rainfall events (i.e. rapid rise and fall in river discharge in high storms) but is not impossible.

Analysis of discharge data in terms of the periods where there is a marked change in dipwell water table base level (see Section 2.1.3) suggest that there is a significant difference in river discharge and log-transformed river discharge data in the period before and after 1/4/1990 (periods 2 and 3). In this case readings in the period where dipwell water table depths were lower (period 2) discharges are significantly lower ($p<0.001$) than in the final period, with mean daily discharges of 0.0348 and 0.1007 cumecs respectively.

2.4 Water supply borehole abstraction data

In addition to information supplied by English Nature and the National Rivers Authority, data have been made available by Anglian Water Services concerning daily abstraction data from boreholes in the Chippenham area. After identifying the location of several boreholes, three were selected for analysis on the basis of proximity to Chippenham and data availability, namely Moulton (NGR TL 700 646, 6.7 km from Chippenham Fen), Longhill (NGR TL 661 642, 5.0 km from Chippenham Fen) and Gazeley (NGR TL 714 644, 8.0 km from Chippenham Fen). Summary data for these boreholes are given in Table 2.13.

Table 2.13: Summary data for three abstraction boreholes near Chippenham Fen.

	Moulton (1991–1995)	Longhill (1992–1995)	Gazeley (1993–1995)	*Overall*
Mean ($Ml.d^{-1}$)	3.167	2.193	1.051	***2.358***
Median ($Ml.d^{-1}$)	3.301	2.141	1.049	***2.33***
Standard deviation ($Ml.d^{-1}$)	0.956	0.793	0.268	***1.118***
Minimum ($Ml.d^{-1}$)	0	0	0	***0***
Maximum ($Ml.d^{-1}$)	8.595	4.467	2.281	***8.595***
Total (Ml)	4724.873	3203.678	775.646	***8704.197***

The data indicate that, of the three, Moulton borehole supplies the most abstracted water and Gazeley the least. All three boreholes apparently have, at some point, had zero abstraction, but it is not clear whether this is as a result of the borehole not operating or an absence of records.

Moulton data over time are illustrated in Figure 2.23a, with a 5 point moving average of this data shown in Figure 2.23b. The graphs suggest that, if the daily variations in abstraction levels are ignored, there is a broad seasonal pattern that apparently changes little over time. As might be expected, abstractions rise in summer and fall in the winter.

Longhill data (Figures 2.24a & b) show a more complex pattern over time. The graphs suggest that the initial months of Longhill's operation were relatively stable, with daily abstractions consistently at levels that are attained only occasionally in the following months. In both the short and longer term, the range of abstraction levels is markedly higher than at Moulton after the initial readings, and there is a considerably less marked seasonal change.

Data for Gazeley are illustrated in Figures 2.25a & b, and suggest that abstraction rates from this borehole are relatively stable, with no marked day-to-day change. There are marked peaks in demand but these tend to appear as isolated examples. Seasonal changes are apparent but these too are relatively minor compared with variations suggested earlier.

Abstraction over time can be examined further using an annual and seasonal breakdown of readings from the three boreholes, shown in Tables 2.14 and 2.15 respectively.

Table 2.14: Annual abstraction data for three abstraction boreholes near Chippenham Fen

	Annual Means ($Ml.d^{-1}$)				Annual totals (Ml)			
	Moulton	Longhill	Gazeley	*Overall*	Moulton	Longhill	Gazeley	*Overall*
1991	3.718	–	–	***3.718***	115.26	–	–	***115.26***
1992	3.085	2.860	–	***2.973***	1129.1	1046.905	–	***2176.005***
1993	3.858	2.106	0.349	***2.954***	1407.994	768.592	2.792	***2179.378***
1994	2.768	1.790	1.014	***1.857***	1010.437	653.224	370.158	***2033.819***
1995	2.910	2.014	1.103	***2.009***	1062.082	734.957	402.696	***2199.735***

Table 2.14 suggests that there is a degree of inter-annual variability for all the boreholes and for the overall data. There is a suggestion that abstractions in the last two years seem to be lower than in the preceding three, and this may have relevance to the change in base level of the dipwell and observation borehole readings suggested in Sections 2.1.3 and 2.2.3. If the same time intervals used for earlier tests (see Section 2.1.4) are used to compare borehole abstraction levels, there are strong statistical differences between the two periods available. Abstraction levels during the transitional period are significantly higher than those for the final period for overall means, Longhill and Gazeley ($p<0.001$) transition period.

There are complications involved, however. The three boreholes come into supply at different dates, and thus as time passes the range of values used to derive the means becomes larger (and incorporates borehole data that is progressively lower) than that at the start of the period of record. This point is particularly important when considering the overall mean, but is less relevant for the significant results found for Longhill and Gazeley.

The presence or absence of any seasonal component in abstraction readings is important given the strong seasonality exhibited by dipwell, river discharge and observation borehole readings. Seasonal data are summarised in Table 2.15.

The overall data suggest that, as would be expected, abstractions tend to be higher in the summer months than in any other period of the year. However, when the data are examined in terms of individual boreholes and years, deviations from this pattern can be seen. Moulton, for example, experienced the largest mean abstraction in the winter of 1992–93 and in the spring of 1993, rather than in the summer of either of those years. Similarly Longhill's mean daily abstraction levels were at a maximum in spring of 1992. It is worth noting that despite the prolonged dry period experienced in the summer and autumn of 1995 there has been no noticeable change in the mean rate of abstraction.

The suggestion has been made above that the differences experienced between specific periods within the overall monitoring time frame in dipwell and other data at Chippenham Fen is matched by a similar change in borehole abstraction rates. The implication from this could be that the apparently lower rates of abstraction in the final two years covered by this report are linked to an increase in water table depths, while the lower water tables experienced over 1992 and 1993 are linked to higher abstraction rates. This relationship may seem reasonable, but the relationships between dipwell data and other readings taken at the Fen should be examined, and other factors (e.g. rainfall) taken into account before a causal link with borehole abstraction could be established.

Table 2.15: Seasonal variations in mean and total abstraction rates for three boreholes near Chippenham Fen

	Seasonal Mean ($Ml.d^{-1}$)				Seasonal Totals (Ml)			
	Moulton	Longhill	Gazeley	*Overall*	Moulton	Longhill	Gazeley	*Overall*
Spring	**3.057**	**2.311**	**1.069**	***2.361***	**1125.158**	**850.498**	**196.722**	***2172.378***
Summer	**3.540**	**2.436**	**1.285**	***2.647***	**1302.595**	**896.267**	**236.475**	***2435.337***
Autumn	**3.166**	**1.991**	**1.005**	***2.264***	**1152.282**	**724.870**	**182.862**	***2060.014***
Winter	**2.907**	**2.078**	**0.813**	***2.197***	**1049.468**	**685.623**	**127.574**	***1862.665***
1991								
Winter	3.077	2.343	–	***2.786***	280.032	140.608	–	***420.64***
1992								
Spring	2.950	3.119	–	***3.034***	271.369	286.966	–	***558.335***
Summer	3.253	3.098	–	***3.176***	299.318	284.992	–	***584.31***
Autumn	3.159	2.863	–	***3.011***	287.461	260.541	–	***548.002***
Winter	3.639	2.057	–	***2.848***	327.486	185.095	–	***512.581***
1993								
Spring	4.441	1.953	–	***3.197***	408.552	179.715	–	***588.267***
Summer	4.133	2.289	–	***3.211***	380.199	210.632	–	***590.831***
Autumn	3.383	2.217	–	***2.800***	307.858	201.768	–	***509.626***
Winter	2.340	1.938	0.522	***1.701***	210.643	174.431	34.962	***420.036***
1994								
Spring	2.081	2.042	1.061	***1.728***	191.412	187.854	97.623	***476.889***
Summer	3.476	2.095	1.281	***2.284***	319.762	192.694	117.892	***630.348***
Autumn	3.141	1.304	1.006	***1.817***	285.873	118.662	91.546	***496.081***
Winter	2.570	2.061	1.029	***1.887***	231.307	185.489	92.612	***509.408***
1995								
Spring	2.759	2.130	1.077	***1.989***	253.825	195.963	99.099	***548.887***
Summer	3.297	2.260	1.289	***2.282***	303.316	207.949	118.583	***629.848***
Autumn	2.979	1.581	1.003	***1.855***	271.090	143.899	91.316	***506.305***

3. Inter-relationships between different data series

The preceding sections have illustrated the behaviour of water table levels and river discharges over time, but it is important to place each of these data-sets into their proper context of the site as whole, rather than treating each set of records independently.

The differing methods of data collection make the above suggestion problematic to undertake, in that while some data have been collected continuously, others have been collected at a more or less regular intervals. These latter data have effectively been treated as a continuous series in order to produce intelligible graphs, but their use against the continuous daily series collected by automatic logger is made difficult by the relative infrequency of their collection. It is possible, however, to draw meaningful comparisons between those variables collected on a daily basis, and to compare all data collected by using monthly means.

3.1 Relationships between water table data series

The monthly averages for data from the dipwell readings, gauge board data and borehole readings are illustrated in Figure 3.1. In order to make the data comparable readings relative to ordnance datum have been used. For the most part it is evident that there is a distinct hierarchy in the data series in terms of the mean height above datum of the water table, and in the relative seasonal variability.

It is unfortunate that the elevation of the gauging station was unavailable, as this would have allowed the elevation of the water surface at the fen outflow to be compared with those within the fen. However the graph does suggest that water levels in the borehole are consistently considerably higher than those in all other locations and exhibits considerably greater seasonal fluctuation than the other monitoring locations. The next highest water levels are those found at the Principal Spring. The gauge board data and dipwell data show the lowest water tables and are roughly comparable, with the exception that fluctuations in monthly mean dipwell readings match those at the principal spring, while gauge board data show relatively little fluctuation.

The magnitude of the fluctuations in readings at the observation borehole tend to mask the fluctuations in other data relating to ordnance datum and thus it is difficult to identify strong relationships between the different measurements taken. When correlation analysis is carried out on the water level monitoring data, the coefficients produced are as seen in Table 3.1.

Table 3.1: Correlation coefficients between monthly means of water table heights relative to ordnance datum from a variety of monitoring devices at Chippenham Fen (relationships significant at $p<0.05$ shown in bold)

	Borehole	Dipwells	Principal Spring Piezometer (PSP)	GB1	GB2
Dipwells	0.13	–	–	–	–
PSP	**0.50**	**0.77**	–	–	–
GB1	0.22	**0.53**	**0.33**	–	–
GB2	**0.60**	0.17	**0.45**	**0.33**	–
GB3	**0.65**	0.09	**0.33**	0.13	**0.94**

The relationships between the three gauge boards and the Principal Spring piezometer have been discussed in Sections 2.2.1–2.2.2 and need not be elaborated upon here. In terms of contributions to the hydrological budget of the fen, the positive correlation between the readings taken at the dipwells and the Principal Spring piezometer is important, and whilst it is not possible to infer a causal relationship (other factors, such as rainfall, need to be taken into account), Figure 3.2 does suggest that a rise in water table elevation at the Principal Spring is strongly matched by a rise in dipwell water table elevation. The relationship between the dipwell data and GB1 is less clear but still significant.

It is interesting to note that although gauge boards GB2 and GB3 show a good relationship between each other, they exhibit relatively weak relationships with other monitoring data. This would suggest that while these gauges are useful in indicating the hydrology of their respective ditches they are less useful as a means of inferring the hydrology of other parts of the fen.

The significant correlations found between the borehole readings and those taken from the Principal Spring and gauge boards (but notably not the dipwell data) are also illuminating. As the borehole gives an indication of the behaviour of regional groundwater tables, the relationship with the Principal Spring is unsurprising. Examination of the data used to calculate this correlation (see Figure 3.3) suggests that there is a reasonable straight-line relationship between the two variables. However, the slope of this line would suggest that the change in borehole water table elevation is disproportionately high compared with that at the Principal Spring, and thus any relationship between the two is likely to be less than clear cut.

This feature can also be suggested from Figure 3.1, where the range of daily values from the borehole over time is considerably greater than those for the Principal Spring and means that the correlation produced here should be treated with caution. It may be that a greater temporal resolution would improve the relationship between these two variables, and more frequent readings at the Principal Spring may provide a clearer explanation of the relationship between these two variables.

Scattergraphs of the relationship between borehole data and the gauge board data (Figures 3.4–3.5) show a similar pattern, in that while there are significant relationships relatively large changes in borehole level are required to produced any noticeable change in gauge board level. In these cases there is more convincing evidence of a straight line relationship between the two series, suggesting that water table levels within the drains may be responding more closely to hydrological inputs from outside the fen, rather than the input from the principal spring. This feature may be confirmed by the absence of a significant relationship between the principal spring and gauge board data.

The relationship between dipwell data and borehole data add a note of contradiction to the suggestions made above. Having established that, while there is a significant relationship between the borehole and Principal Spring the link is suspect, there is a good link between the spring and the dipwells but no relationship between the dipwells and the borehole data. It could be argued that, but for the presence of any artificially manipulated hydrology, such a relationship would exist, hence a reasonable link between principal spring data and the nearby fen, but the relationship between the borehole and the gauge board data suggest that this is not the case. It is also possible that if the ditches are acting as a source of water for the fen, there is a time lag between the arrival of water at the site and its distribution into the peat store. Again the good correlation with the Principal Spring data would seem to refute this, as would the fact that the data used are monthly averages.

It is perhaps safer to conclude from the above that there is a good link between most of the monthly mean data, but the complexities added to the local hydrology by the drainage system and their associated controls make straightforward statements defining simple relationships problematic. It could be argued that the data illustrate the buffering effect of the fen and its associated extended drainage system, with water entering the system distributed around the fen and 'lost' to the peat mass. It would be expected that in periods where the fen is largely saturated, additional water inputs would be channelled through the fen with minimum loss to storage, while in drier periods the fen would act as a hydrological input to the Chippenham River for as long as water levels are above the maximum downward extent of the drainage system. The extent of the relationship between the fen inputs and the output to the Chippenham River should be examined in more detail in order to assess the validity of these statements.

3.2 Relationships between water table elevation and river discharge

The River Chippenham is the destination of water supplied to Chippenham Fen, and thus it would be expected that a strong relationship exists between water levels monitored at the fen and elsewhere and discharge from it. The behaviour over time of the data series are illustrated in Figures 3.6–8, with Figure 3.7 and 3.8 showing the same data series but with discharge data log-transformed in the latter.

Figure 3.6 suggests that there is good correspondence between the three series displayed. It can be noted, however, that the seasonal rise in mean monthly dipwell water tables apparently pre-dates the seasonal rise in discharge, and there is also a suggestion that it pre-dates the rise in principal spring water table. This may be attributable to the fen's potential to act as a large water store after dry summer periods, and thus any increase in water delivery to the fen will enter this store as it passes through en route to the river. Once this store is full, or when sufficient moisture is present to slow the rate of entry of water to the fen, then more of the hydrological input to the fen will leave as river discharge.

The suggestion that the dipwell rise pre-dates the increase at the Principal Spring is less easily explained. It may be that the fen is less reliant on inputs from the Principal Spring than might be expected, given that a number of springs have been observed within the fen, and that the Totternhoe Stone aquifer can be found directly beneath a considerable portion of the fen. The dipwells may therefore be responding to regional changes in groundwater levels before the

Principal Spring. However the distance between the spring and the dipwells is relatively small, and a significant temporal gap in water table change over such small distances would seem unlikely. This feature may therefore simply be a product of the fact that the dipwell mean is composed of a number of dipwells with a large range of values between them. Direct responses to rainfall events also need to be taken into account.

The exact nature of the input from springs on the fen, and their relationship with the underlying geology, is currently unclear, and it may prove useful to install a suite of piezometers of the type installed at the Principal Spring to varying depths in order to assess whether any water is emerging from groundwater stores. If the fen is largely groundwater fed, it may be that dipwells in purely peat horizons are unable to distinguish between hydrological inputs from the surface and underground. As piezometers measure water pressure (rather than the presence of water at a given depth shown by dipwell readings), placing piezometers in such a way that some penetrate only the upper peats, some monitor water pressures within the relatively impermeable marl layers, and others the older peats below these marl layers may indicate whether groundwater or surface water inputs to the fen are more important.

The link between borehole water table elevations and river discharge over time is much less complex, as shown in Figures 3.7 and 3.8. There is a high degree of correspondence between these two series when daily averages are considered, and this is particularly clear when discharge is logarithmically transformed (Figure 3.8). Close examination of these graphs reveals that there is a small difference in timing of rises and falls in the two series. It would appear that seasonal rises and falls in river discharge pre-date similar changes in borehole water elevation by a matter of days. It is possible that the time difference is more apparent than real, and may result from methodological errors, but it is more likely to be a reflection of local groundwater hydrology.

There is nothing to suggest in the information made available that water from the borehole is to support river discharge. However if it is assumed that this is the case, then there is clearly a discrepancy in the fact that river discharge rises before groundwater levels. The fact that the borehole records groundwater levels some 2 km away from the river gauging station may be significant, and it may be that the river is responding to groundwater changes in its immediate environment that manifest themselves at the borehole some time later. Local aquifer hydraulic conductivity rates and groundwater movement is not known in sufficient detail to test the validity of this suggestion, but Mason (1990) does give contour maps of groundwater levels in 1976 and 1989 that suggests a water table sloping ESE–WNW, with higher elevations to the ESE, and lower elevations towards the river. This would suggest that if anything rises in water table level at the borehole should pre-date changes in the river, rather than the reverse.

The relationships discussed above can be examined on a more quantitative basis. Correlation coefficients have been produced in order to examine whether this is indeed the case, and the results can be seen in Table 3.2. As the river discharge data consist of long series of relatively low readings punctuated by short series of high readings, discharge data have also been logarithmically transformed in order to produce a more normally distributed series. As borehole and river discharge data are available as daily mean values, these two have been examined using these readings rather than the monthly means used elsewhere.

Table 3.2: Correlation coefficients for relationships between monthly mean river discharge (except where indicated) and monthly means for water table elevations.

Variable	Correlation coefficient	Correlation coefficient using log discharge
Dipwells	***0.42***	***0.48***
Observation borehole	***0.56******	***0.70******
Principal Spring piezometer (PSP)	***0.75***	***0.83***
GB1	0.16	**0.33**
GB2	***0.46***	***0.40***
GB3	***0.42***	***0.34***
log(dipwells)	***0.42***	***0.48***
log(observation borehole)	***0.63******	***0.70******
log(PSP)	***0.75***	***0.83***
log(GB1)	0.16	**0.33**
log(GB2)	***0.46***	***0.40***
log(GB3)	***0.41***	***0.34***

*Daily mean discharges used

NB: Bold figures significant at p<0.05, bold italic figures significant at p<0.01

The data presented in Table 3.2 suggest that, while all of the variables (with the exception of gauge board GB1 data) show significant relationships, the strongest correlations are those between borehole and river discharge data, and between river discharge data and Principal Spring data. It is also evident from the table that while other data either exhibit a marginal improvement in the correlation coefficient or a decrease in the strength of the relationship, both the principal spring and borehole data show increases in the coefficient when either half of the data pair are log-transformed.

The good relationships between discharge and the Principal Spring piezometer and observation borehole data are perhaps an indication of the relative importance of the hydrological inputs of the fen to river discharge. The dipwell data's relatively poor link with river discharge levels is more difficult to explain. Statistically the relatively low correlation may be attributable to the temporal gap in water table rise and fall mentioned above, but the reason for this gap must still be discussed. It might be expected that the link between these series would be much closer, given that much of the input to river discharge from the spring is routed through the fen, rather than direct to the river, and that in recent years a sluice gate is used in summer to help maintain levels within the fen. However as the levels recorded in these two sites reflect movements in general water table levels, rather than the impact on the water table of a managed system, it may be that much of the recorded discharge is provided by groundwater recharge, with only peak flows generated from other sources.

Scattergraphs of the data pairs showing higher correlation coefficients are given in Figures 3.9–3.10 and these can be used to help explain the relationships between the data. In Figure 3.9 it is possible to infer a straight line relationship between borehole levels and river discharge, but there are problems with the data that cast some doubt on the validity of the relationship, and thus on any inferences made from it. For example there is a considerably greater degree of scatter at the lower end of both scales than at the upper end. This could be used to imply that there is a much stronger relationship between borehole levels and river discharge when readings in both are high, as a greater hydraulic gradient between borehole and river would be produced by higher water table elevations, and this could produce higher discharge. It is also likely that the pattern on the graph is a function of the relatively less frequent occurrence of higher discharges, and it is possible that had a greater number of high discharge events been recorded, then the degree of scatter would have been greater and thus the correlation coefficient lower.

It may be useful in future to analyse the relationship between river discharge in different periods (i.e. when dipwell readings are either falling or rising) as this may reveal more useful figures, but at present there are insufficient data to carry out a reliable test.

3.3 Relationships between rainfall data and other data series

Up to present, this report has focused almost entirely on the hydrology of the fen and its associated inputs and outputs at ground level. Any consideration of the hydrological budget of Chippenham Fen must also consider the role of rainfall, as the timing and magnitude of precipitation inputs will obviously play a major role in the fluctuations in dipwell and other readings over time.

The overall averages for rainfall recorded at a number of monitoring sites have been given in Section 1.2.4, as has the trend over time and the reader is referred to these sections for more information. What has yet to be discussed is the relationship between these trends over time and the other monitoring data collected at the site.

The rainfall data can be discussed in terms of both daily readings (for comparison with observation borehole and river discharge data) and monthly totals (for comparison with dipwell and principal spring data). As three raingauges have been used to monitor rainfall and, as discussed in Section 1.2.4, these gauges do not entirely correspond with each other in terms of the daily amounts recorded, each gauge will be discussed in terms of daily data. Monthly totals will use the series with the longest record. Given that the gauge board data vary relatively little they will not be considered here.

3.3.1 Rainfall and river discharge

River discharge and rainfall data over time are plotted in Figure 3.11a–c. Close examination of these figures reveals a number of contradictions that suggest that the link between precipitation inputs and river outputs is not straightforward.

There are a number of occasions throughout the monitoring period where equivalent rainfall values produce markedly different discharges. For example rainfall in the late 1993 and late 1994 are apparently no different in terms of magnitude or distribution of events and yet the discharges recorded are markedly different. There are also occasions where large rainfall events apparently fail to produce corresponding increases in discharge, and occasions where discharge rises without any apparently significant rainfall. If the data are correlated to assess the strength of any relationships between rainfall and river discharge, the coefficients produced are as given in Table 3.3.

Table 3.3: Correlation coefficients between daily river discharge and daily rainfall

Raingauge	Discharge	log(Discharge)
Isleham	0.033	0.037
Chippenham	0.087	0.057
Tipping bucket	0.180	0.124
log(Isleham)	–0.01	–0.085
log(Chippenham)	–0.003	–0.014
log(Tipping bucket)	0.14	0.174

From Table 3.3 it is evident that, contrary to what might be expected, there are no significant relationships between the two variables There are a number of possible explanations for this.

Firstly, there may be a time lag between the arrival of rainfall at the site and its translation into a river discharge downstream, hence recorded peaks in rain and discharge will be asynchronous. However, site records indicate that the fen has a very 'flashy' response to storm events, i.e. it responds very quickly and it is very likely that precipitation inputs will appear as discharge within 24 hours. Furthermore, comparison of monthly totals with monthly mean river discharge also fail to produce a significant correlation, with a value of 0.2327, although there is an improvement in the strength of the relationship.

Secondly, the use of log transformation to counteract the skewed distribution of rainfall values is difficult as this process does not recognise zero, thus days without rainfall are eliminated from the analysis. It is possible to transform the data by adding 1 to the initial value, but this fails to increase any of the coefficients and certainly does not make any of the relationships significant. Both of these features combine to render interpretation difficult, and while statistically it must be concluded that river discharge and rainfall are unrelated, intuitively this does not seem reasonable.

It may also be that as suggested earlier, the fen is acting as a medium term store for rainfall inputs. If this were the case it may be possible to reveal more significant relationships between any given day's discharge and the rainfall several days earlier using cross correlation. The results of this analysis are given in Table 3.4, where the discharge data are related to rainfall occurring at various time intervals prior to the recording of the discharge.

It is immediately apparent from the table that there is no improvement in the relationship between discharge and rainfall when previous days' rainfall are considered instead of contemporaneous rainfall-discharge data. That this should be the case is clearly unusual, given known site conditions, but not necessarily unusual given the attempts to retain water on site using the adjustable dam system. It may well be that errors in rainfall data, combined with the hydrological management system could account for the absence of a relationship. Further confusion could result if river discharge responds mainly to rises in regional groundwater levels that are responding to other rainfall events in the much wider catchment of the region.

An alternative approach is to examine not the average river discharge but the change in discharge, as it might be expected that high rainfall values would produce a large change in discharge, low values would generate a small change in discharge, and zero rainfall no change at all. However if rainfall values at Isleham, Chippenham and the tipping bucket are measured against discharge change the correlation coefficients are 0.127, 0.3166 and 0.3457 respectively. The latter two are important as they are significant ($p<0.05$), but should be treated with caution given that at such low values the coefficients explain only 10–12% of the data.

Table 3.4: Cross correlations of river discharge and log(river discharge) with mean rainfall at Chippenham Fen

Rainfall examined *n* days prior to discharge	Discharge	Log (discharge)
1	0.19	0.14
2	0.17	0.13
3	0.17	0.13
4	0.11	0.09
5	0.09	0.08
6	0.08	0.08
7	0.08	0.07
14	0.09	0.06
28	0.08	0.06
56	0.07	0.09
112	0.05	0.08

3.3.2 Rainfall and observation borehole readings

The relationships between the different raingauges and borehole data are similarly unhelpful, as illustrated in Figures 3.12a–c. The data suggest that there is a clear change in base level readings for the borehole (most obvious in Figure 3.12b) but there is no corresponding change in rainfall inputs to account for it. Correlation coefficients (Table 3.5) show that, as with river discharge there is no significant relationship between any of the raingauge data and borehole level, although the time lag between rainfall events and change in borehole level is likely to be larger and thus this might be expected.

The time lag between rainfall inputs and borehole water table levels may allow monthly rainfall totals to be measured against monthly mean borehole readings, but again, as with there is little evidence of a relationship ($r = -0.1189$).

Table 3.5: Correlation coefficients between daily water table elevation above ordnance datum at the observation borehole and daily rainfall

Raingauge	Borehole water table elevation	log(borehole water table elevation)
Isleham	–0.046	–0.046
Chippenham	–0.080	–0.080
Tipping bucket	–0.063	–0.062
log(Isleham)	–0.009	–0.009
log(Chippenham)	–0.033	–0.033
log(Tipping bucket)	–0.005	–0.004

3.3.3 Rainfall and dipwell/Principal Spring piezometer readings

The behaviour over time of dipwell and principal spring readings with rainfall totals are given in Figures 3.13 and 3.14 respectively. It is clear from these graphs that while there are obvious trends in water table elevation data, as discussed above, the relationship between these trends and monthly rainfall data are not apparent. Correlation coefficients for monthly mean dipwell elevations and monthly rainfall totals are given in Table 3.6, where any relationships are quantified.

Table 3.6: Correlation coefficients between monthly rainfall totals and mean monthly water table elevations at the Principal Spring piezometer and Chippenham Fen dipwells

Variable	Rainfall total	log(Rainfall total)
Dipwell mean	0.28	0.38
Principal Spring mean	0.20	0.28
log(Dipwell mean)	0.28	0.39
log(Principal Spring mean)	0.20	0.28

As with previously examined data, there is a lack of significance in the relationships found, although the coefficients are generally higher than those found using borehole and river discharge data.

3.3.4 Variation over time of rainfall data

The preceding sections have identified that while there are obvious differences over time in variables such as river discharge and water table elevations, there is an almost complete absence of any meaningful link with rainfall inputs to the fen. It remains to be established however, whether rainfall levels have undergone a similar change over time. In other words, are the changes in water table and discharge trends over time a product of changes in rainfall inputs? If each year's monthly totals from the three raingauges, as well as the overall average, are subjected to analysis of variance, the results may be used to identify whether there is any significant difference in rainfall between years. The result from this analysis are presented in Table 3.7.

The results indicate that in all cases there is no significant variation between years at any of the gauges (although in the case of the overall average and the tipping bucket gauge the lack of significance is marginal). In other words, although there may be an apparent difference in rainfall totals, there is a sufficiently high degree of overlap between different years to cancel this difference out in the test. For example while the average total for 1995 from all gauges is much lower than any other year (as there are fewer readings), the spread of average monthly totals is extremely high as a result of a very wet early part of the year and a very dry summer.

Table 3.7: Summary data from analysis of variance of monthly rainfall totals comparing different years for three raingauges at Chippenham Fen and theoverall average for these raingauges

	Years	Months used per year	Annual rainfall total (mm)	Average monthly rainfall total (mm)	Variance
Raingauge average (p=0.0689)					
	1991	12	441.3	36.77	347.33
	1992	12	617.37	51.44	389.72
	1993	12	680.25	56.68	448.25
	1994	12	565.53	47.12	238.43
	1995	10	353.63	35.36	730.00
Isleham raingauge (p=0.1521)					
	1991	12	441.3	36.77	347.338
	1992	12	631.2	52.6	394.54
	1993	12	671.1	55.92	385.39
	1994	12	538.7	44.89	287.13
	1995	5	223.7	44.74	730.25
Chippenham raingauge (p=0.4704)					
	1992	12	669.3	55.77	476.10
	1993	12	710.8	59.23	480.67
	1994	12	554.5	46.20	262.98
	1995	5	239.6	47.92	1095.49
Tipping bucket raingauge (p=0.0827)					
	1992	6	300.4	50.06	661.21
	1993	11	591.8	53.8	575.76
	1994	12	603.4	50.28	342.34
	1995	8	220	27.5	573.90

The implication from this is that, if any one year's rainfall is no different from any other year, variability in rainfall is less likely to be responsible for the distinct changes found in trends over time in water table and discharge readings.

In an earlier section the suggestion was made that there are three distinct periods in the trends over time shown by dipwell readings (see Section 2.1.3). As with other sections it may be useful to compare the daily readings from each of these three periods to see whether rainfall differs between them, and thus examine whether change in precipitation inputs is responsible for the change in water table readings. As data exist for these periods for only two of the gauges (Isleham and Chippenham) for only two of the periods in question, analysis is limited to t-testing of these two gauges and the overall average rainfall.

The data from this analysis suggests that rainfall is significantly lower in period 2 than in period 3 for the overall average daily data ($p=0.00572$) and the data from the Isleham raingauge ($p=0.03083$). Period 2 covers the range of data where dipwell means apparently fell, and the lower mean rainfall overall (1.26 $mm.day^{-1}$ compared with 1.68 overall) may help to account for the fall in dipwell water table readings. However, as the rainfall data are not normally distributed the test results should be treated with care, particularly as the same test carried out on log-transformed data transforms the significant result into a (marginally) non-significant one.

In conclusion, the data would suggest that there is a marginal difference in rainfall totals over the monitoring period, but there are technical problems in the statistical tests that make this suggestion suspect. It is also questionable whether the relatively small difference in rainfall between the two periods suggested can be held to be responsible for the relatively large differences in dipwell, borehole and river discharge readings in the periods identified earlier.

The above discussion has focused on absolute rainfall values and it may be argued that these values may be misleading given the potential for interception storage (particularly in wooded areas) and evapotranspiration to reduce the effectiveness of this rainfall in raising water levels. As there is a considerable complex of drainage channels throughout the site, loss of moisture through evaporation may be considerable, in that gauge board data in these ditches suggest a considerable degree of stability even in dry weather, and therefore present a potential for water loss surface for most of the year. When this drainage network is considered in terms of the total surface area of the fen, however, this impact is likely to be relatively low. Furthermore, as deeper water is less prone to evaporation than shallow water, then stable ditch water levels are likely to act as a heat sink.

The transpiration component of the fen's water budget is more difficult to isolate. Vegetation cover would appear to be complete across the site, and much of the fen is dominated by vigorous species, suggesting that transpiration rates in summer may be considerably in excess of water supplied by rainfall. This process is complicated by the harvesting of reeds, which both reduces the amount of vegetation in specific areas of the fen and requires a lowering of local water tables in order to facilitate access. It remains unclear as to the extent to which evapotranspiration is responsible for the decline in water table depths (as opposed to shortfalls in precipitation and the impact of drainage networks), or whether water table depths decline so far in dry periods that evapotranspiration ceases to become a major component in the fen's hydrological budget.

3.4 Spatial distribution of dipwell means

The convention in previous reports covering Chippenham Fen has been to treat individual segments of the site as discrete compartments as defined by specific artificial drainage boundaries (see Map C). This approach was considered to be unhelpful here in that

a) the compartments are not of uniform size or drainage network

b) some compartments are unmonitored (e.g. compartment 7)

c) relatively large compartments may have just one dipwell (e.g. compartment 4), whereas some relatively small compartments may be monitored by three dipwells (e.g. compartment 11).

and d) dipwells are unevenly distributed.

Furthermore, given that the majority of compartments are monitored by one dipwell, a detailed description of each compartment would merely serve to repeat data described elsewhere.

The description of the spatial pattern of water table behaviour is complicated by the unavailability of precise dipwell co-ordinate data that would allow a mapping package to produce simple contour maps of groundwater levels. The following analysis will therefore rely on data from Mason (1990), to describe the spatial distribution of groundwater data.

While it should be borne in mind that the same reservations applied to the compartment data can be made for individual dipwells, given the limited number of dipwells and the uneven spatial distribution of the dipwells, it is apparent that the distribution of mean water table depths over the whole recording period is by no means uniform and is often contradictory. However some apparent patterns can be identified within the limitations of the data available. For example, the lowest mean water table depths are found in the far E/NE part of the site around dipwells 3, 15 and 16. The highest mean water table depths can be found in the eastern central part of the site at dipwells 4 and 5 (some 200 metres away from the dipwells previously mentioned), with dipwell 8 in the western part of the site broadly similar. The remaining dipwells showing intermediate mean water table depths are in the southern portion of the fen but there is no readily identifiable consistency to the data.

If the data are examined in terms of the three periods identified in Section 2.3 then the pattern is broadly similar in each period to that described above, although interpretation is complicated by the absence of dipwells 10 and 12–16 in the initial monitoring period.

If the dipwell data can be reliably extrapolated to those parts of the site without monitoring data, the information presented above can be combined with existing information about surface water movements to make some broad inferences about the hydrological behaviour of the site. Mason (1990) suggests that surface water flows into the site along a number of drains from the north-east and from the south from the principal spring. Flow from either source can pass along the site margins, where water table depths *tend* to be relatively low. Mason also suggests that surface ponding occurs as a result of overspill from the drain along the western edge of the fen in that part of the site identified as having relatively high mean water tables.

It would be reasonable to suggest from the above that those parts of the site that receive less water (e.g. dipwells 3 and 16) as a result of their location away from the main drain system feature the lowest water tables on average, while those parts of the site that receive occasional overspill from the drainage system (e.g. dipwell 4) have the highest mean water table overall.

It is also likely that the passage of flow through the site is likely to have some controlling influence on water table behaviour. Those parts of the site where flow is routed rapidly through are less likely to have sufficient seepage to maintain water tables, whereas those areas where surface ponding occurs or where water is circulated around the site are likely to maintain higher water tables.

The influence of site topography and geology cannot be discounted from the above but is more difficult to isolate given the information available. Certainly the presence of local springs from the Totternhoe stone aquifer are likely to have some influence on local water tables, and data presented in Mason (1990) could be used to infer areas with emergent groundwater in the general area of dipwells 1, 6 and 8. However the overall readings from these dipwells do not suggest a marked difference in water table depth, and observations regarding the occurrence of this resurgence are limited to drainage channels and make no attempt to quantify them.

Topographic information is limited to the height of the dipwell above ordnance datum, but correlation analysis can be used to examine the relationship between this height and mean water table depth below the ground surface. The analysis suggests a correlation of –0.3305, implying that, as might be expected, as the elevation of the ground surface increases the mean depth of the water table below the ground surface increases. However this relationship is not significant and topography cannot be said to be important on the basis of the data available. As the datum given for all dipwells is the elevation of the piezometer top, it is possible that the relationship been ground elevation and water table depth has not been tested reliably (unless an equal amount of dipwell tube has been left exposed at each location and no movement of the ground surface has occurred). Elevation of the ground surface is given for the first 9 dipwells, and if these are tested against mean water table depth a correlation coefficient of –0.227 is produced. This again suggests a negative relationship but again the relationship is not a significant one.

While no relationship has been detected between topography, geology and groundwater levels it should not be implied that they are not important contributing factors. It is more likely, however, given the presence of a network of drainage channels around and through the fen, that artificial hydrology is more important. Testing the proposition that those dipwells in close proximity to the drainage networks exhibit different hydrological characteristics to those further away is difficult, in that most of those installed are reasonably close to large drains, and those placed further away from main drains are in close proximity to minor ones. Of the fifteen dipwells, only numbers 1, 2, and 14 could be said to be any great distance from any artificial drainage channel.

It is possible to compare readings from these dipwells with those placed in closer proximity to drains to determine if there is any difference between them, however a t-test fails to reveal any significant difference between them. Given the wide degree of variation already discussed across the site this finding is not surprising and it would perhaps be more useful to examine a number of dipwells in close proximity to each other to determine the influence of the drainage channels.

Of those dipwells available, two sets appear to be suitable for comparison. Dipwells 5 and 14 occur within a single block surrounded by drains, with dipwell 5 relatively close to a boundary drain and dipwell 14 more central. The second set consists of the block containing dipwells 6, 7 and 12 and is also monitored by gauge board GB2. As dipwell 6 is separated from the others by a central drain within the block, dipwells 7, 12 and gauge board GB2 will be compared.

The behaviour of dipwells 5 and 14 over time are illustrated in Figure 3.15, and here there is a distinct separation between the two sets of readings. Of the two dipwells, number 5 clearly has the higher water table. On unrestored bogs (i.e. a drained bog where no attempt has been made to modify the movement of water off the site by blocking drains), dipwells close to drainage networks usually exhibit markedly lower water table depths than those further away. In this case however there is good control of water movement around the site using the collared dam systems described in Section 1.1.3.

It has been suggested that because of this control the drains act as a source of water for each fen compartment, with standing water seeping from the drain margins into the compartment. The difference between the two sets of readings would suggest that this is the case but if the readings are plotted using ordnance datum the situation is reversed, illustrating the importance of local topographic variations.

The behaviour of the second set of readings provide contradictions to the above, as illustrated in Figure 3.16. Using the suggestions made above, GB2 should have the highest water level, followed by dipwell 7 and then 12. As readings are only available for GB2 related to ordnance datum, the data are presented in this format. In this case it is clear that the gauge board readings are generally considerably lower than those for the site interior, where both dipwells show markedly similar levels. This would seem to suggest some form of error in the data, as the difference in elevation ought to produce a hydraulic gradient that would encourage the movement of water from the fen to the ditch, and yet this apparently is not the case, as water levels at GB2 remain relatively stable.

It might be expected that, if water levels at GB2 are maintained by inputs from the fen in winter, when fen water tables are likely to be high, then GB2 should exhibit a rise in water levels corresponding with those in the fen. Even if the dyke on which GB2 is located responded to such an increase in water input from the fen by increasing discharge rates, a stable, higher water level at GB2 should still be the result. For most of the period of record this does not appear to be the case.

The two exceptions to the above description seem to be in the summer of 1994 and 1995. In these two years summer water table levels in the fen fall considerably below those recorded by GB2, and it may be that in these instances water is able to seep into the fen. If this is the case it would appear that evapotranspiration losses from the fen interior are greater than any amounts supplied from the dyke, as the water table falls to levels lower than in the previous two summers. The relatively stable water levels at GB2 suggest that inflows to the fen are sufficient to maintain water levels in the dykes at this point, but are not enough to maintain seepage rates into the fen that would compensate for evapotranspiration rates. The only comparable decline in fen water tables occurred in the first summer of monitoring referred to in Figure 3.16, when a decline in dipwell water table readings is matched by a fall in water levels at GB2.

It would seem from the above that while *prima facie* evidence suggests that water levels decline with distance from the drainage network, when the data are taken in absolute terms (i.e. relative to ordnance datum) the levels in ditches are lower. This would imply that the drainage system still acts as a sink for local water tables, rather than a source, despite the considerable degree of control that can be exercised over water movement within the drains. Recent exceptions to this case may suggest the opposite, but definitive conclusions are difficult to arrive at without more information on hydraulic conductivity. Whatever the reasons for the pattern of results found here, they are certainly more complex than that suggested by Mason (1990).

3.5 Relationships between Chippenham Fen data and abstraction borehole data

The preceding sections have tended to focus on the water table variations in its local context, even when observation borehole data are considered. There are, however, hydrological management activities that occur at a wider scale that may have a bearing on the hydrology of Chippenham Fen, namely abstraction from nearby boreholes for agricultural or domestic water supply. The possibility of a link between abstraction and water table levels at the fen has been mentioned previously, and will now be discussed further.

Data over time for each of the abstraction boreholes are compared with river discharge over time in Figures 3.17–3.19. The high degree of daily variation at Longhill made initial graphs difficult to interpret, and hence for this borehole a 5 point moving average is used as a substitute. The graphs produced provide some suggestion of a link between river discharge and the level of abstraction, but there are a number of contradictions. Moulton data (Figure 3.17) suggest that the seasonal rise and fall in abstraction rates throughout 1993 are matched by corresponding falls and rises in discharge levels. Similarly a marked drop in abstraction in the spring of 1994 is matched by a marginal increase in discharge, while in 1995 marginal rises in abstraction are apparently matched by falling river discharge levels. In contrast, however, abstraction rates are apparently lower in 1992 than in other years, as are discharge readings.

Data for Longhill and Gazeley are similarly contradictory. At Longhill (Figure 3.18) abstraction rate increases in 1992 and is matched by relatively low river discharges, and lower abstraction in 1993 apparently corresponds with increased discharge levels but other relationships are obscured by the high degree of variability over time in abstraction rates. At Gazeley (Figure 3.19), while abstraction rates are considerably lower than the other two boreholes discussed and the day-to-day change is relatively low, but there does appear to be a degree of correspondence between changes in discharge rates over 1994 and the level of groundwater abstraction.

Borehole data suggest similar confusion. Comparison of Moulton abstraction data with water table elevations at the Chippenham observation borehole (Figure 3.20) suggests that any links between abstraction and water table depth are unclear. The peak in water table elevation in 1994 apparently pre-dates the decrease in abstraction rates, and a rise in abstraction over late 1992-early 1993 is apparently matched by an increase in water table elevation. However, the pattern of the two sets of readings over 1995 appear to be more realistic, showing water table elevations rising as abstraction rates fall and vice-versa. Longhill data (Figure 3.21) show similar contradictions, as apparent increases in water table elevation occur before decreases in abstraction, or with water elevation increasing as abstraction increases. Gazeley data (Figure 3.22) show no apparent correspondence between the two series.

The preceding paragraphs have relied on a visual interpretation of the evidence of abstraction, river discharge and observation borehole data. It is possible to examine the presence or absence of any linkages between these data using correlation coefficients, and the results of this application for data recorded on a daily basis are given in Table 3.8. In order to account for the high degree of variability in the data, log transformations have been carried out and correlations undertaken on these transformed data. The number of records used in this analysis effectively means that almost any coefficient produced would have some statistical significance, and so the highest correlation coefficients have been highlighted.

Table 3.8: Correlation coefficients between daily abstraction rates and discharge/borehole water table elevation

	Discharge	Borehole elevation	Log(Discharge)	Log(Borehole elevation)
Moulton	−0.2375	−0.2659	−0.1999	−0.2551
Longhill	−0.2002	−0.3576	−0.3038	−0.3632
Gazeley	<u>−0.6235</u>	−0.4888	<u>−0.5243</u>	−0.4850
Overall mean	−0.3367	<u>−0.542</u>	−0.3635	<u>−0.5376</u>
Moulton 5 point mean	−0.2531	−0.299	−0.219	−0.2866
Longhill 5 point mean	−0.219	−0.4183	−0.3453	−0.4248
Gazeley 5 point mean	<u>−0.6701</u>	−0.5479	<u>−0.5729</u>	−0.5346
Overall 5 point mean	−0.3688	<u>−0.6205</u>	−0.4062	<u>−0.6154</u>
Log(Moulton)	−0.2396	−0.3516	−0.2243	−0.3128
Log(Longhill)	−0.1683	−0.2176	−0.2338	−0.3470
Log(Gazeley)	<u>−0.6533</u>	−0.5431	<u>−0.494</u>	−0.5033
Log(Overall mean)	−0.375	<u>−0.5964</u>	−0.3951	<u>−0.5897</u>
Log(Moulton 5 point mean)	−0.2399	−0.3249	−0.2354	−0.3391
Log(Longhill 5 point mean)	−0.1287	−0.3427	−0.1944	−0.2192
Log(Gazeley 5 point mean)	<u>−0.6595</u>	−0.5085	<u>−0.5082</u>	−0.5377
Log(Overall 5 point mean)	−0.3813	<u>−0.6349</u>	−0.4132	<u>−0.6280</u>

NB: Underlined coefficients are the highest in that group of coefficients

It is evident from Table 3.8 that the highest correlation coefficients are produced when data from Gazeley is considered separately, and when overall mean values are considered. It is also worth observing that all the relationships expressed above are negative, in other words they imply that decreasing abstraction may be linked with increased river discharge and water table elevations and vice-versa. In general, log transformation makes no improvement to the correlations observed (in fact often decreasing them), although the use of 5 point moving averages increases the coefficients in all cases.

The latter point could be taken to imply that the general trend in abstraction data is more important than specific daily rates, and/or that there is a degree of time lag between abstraction to the south and south-west of Chippenham and any change recorded there. This suggestion can be explored further by examining the relationship between monthly mean daily river discharge rates and monthly abstraction rates. In order to make any links clearer, the abstraction data have been converted from value in Megalitres per day to a mean daily abstraction in cubic metres per second (cumecs), so that the two sets of readings use the same base. The result of this comparison can be seen in Figure 3.23, and it is immediately clear that there is a strong degree of correspondence between river discharge and abstraction rate. Not only are the respective rises and falls in data values matched in temporal terms but the magnitude of the respective changes are also similar. It should be noted, however, that the scales of the respective variables differ by an order of magnitude, and thus it is implied that a relatively small change in borehole abstraction is related to a disproportionately large change in discharge in the Chippenham River. In addition, other factors need to be taken into account in order to establish whether there is a causal link between abstraction and discharge (see comments below).

The relatively higher relationships for Gazeley and for overall values may also require some examination. Gazeley has the shortest period of record of the three years, and thus most of the data recorded relate to a year with very low rainfall figures. This may infer that in previous years links between abstraction and discharge or water table elevation have been obscured by greater rainfall. If this is true of other abstraction points then the increased number of readings over a period without the complication of excessive rainfall may contribute much to the high correlations found. The higher number of readings would also help to smooth out some of the extreme readings experienced at Longhill in particular.

The link between rainfall and abstraction may have a more direct influence on the correlations produced, given that higher abstraction rates are more likely to be produced in periods where rainfall has been low and low rainfall is also likely to generate lower discharge and observation borehole readings. Examination of the data available here indicate that there are no significant relationships between rainfall and abstraction but the link between rainfall timing and amount and the demand for groundwater supplies is likely to be too complex for a simple correlation technique to elucidate accurately.

If the relationship between river discharge and abstraction rate is a genuine one, then it might be expected that there would be similar relationships between abstraction and various hydrological measurements taken at Chippenham. As has been noted elsewhere, daily abstraction readings vary considerably, and thus monthly averages of daily abstraction rates, and monthly totals, are used in comparison with monthly dipwell and Principal Spring data: these data have been plotted on Figures 3.24–6. Monthly data from Moulton borehole (Figure 3.24) suggest a reasonable degree of correspondence between dipwell and Principal Spring readings. It is evident that any falls or rises in average abstraction are matched by rises or falls respectively in dipwell and Principal Spring readings. Longhill data (Figure 3.25) exhibit less obvious links, particularly after 1992, when monthly averages show a considerable degree of fluctuation, and given the consistency in dipwell/Principal Spring data compared with those from Longhill it could reasonably be argued that no real link exists. Gazeley data are illustrated in Figure 3.26, and suggest that despite the relatively low abstraction rate and the greater distance from the fen there is a much clearer relationship between the data series. It is evident from the graph that as Gazeley abstraction rates rise, dipwell and Principal Spring water table elevations fall, and there is clearly a much greater degree of consistency in these relationships than is exhibited by Moulton and Longhill data.

As with the daily data, the monthly averages can also be examined to determine the extent of any relationships between variables, and the correlation coefficients produced by this analysis can be found in Table 3.9. As in Table 3.8, it is apparent, despite the relatively low number of data pairs, that the majority of the variables compared with abstraction exhibit statistically significant relationships. Gazeley and overall data provide most of the high correlations, and log transformation of the data gives little or no improvement to the relationships.

The preceding analysis would suggest that there is an apparent link between hydrological variability at Chippenham Fen and the rate of water abstraction from nearby boreholes. However, as with all correlation analyses, conclusive 'proof' of a causal relationship does not necessarily follow from a significant correlation coefficient, and given that Gazeley is 2.3 – 3.0 km further away from Chippenham Fen than Longhill and Moulton boreholes there may be other factors involved. For example, all of the variables measured are likely to have been influenced to some extent by variability in rainfall and evapotranspiration. The extent of that influence varies for different reasons, in that variability in abstraction is dependent on customer demand, but ultimately this demand will be related to the ability of local soils to retain moisture. If the combined effect of soils and drainage systems at points of demand for abstraction are such that water is less effectively retained than at Chippenham Fen, then the demand for water at these sites will be proportionally greater than at Chippenham. This excess demand may then have a secondary effect of lowering the water table at Chippenham at a later date and thus would exaggerate any soil moisture deficits at the Fen.

It is also possible that variables measured at the fen and borehole abstraction data are both responding to climatic variability, rather than a change in one data series producing a change in another. Dry periods at Chippenham Fen will also be experienced at boreholes close to the fen, and as local water demand increases as a result of dry weather, abstraction rates are likely to rise at the same time as fen water table levels fall and Chippenham River discharge declines without there necessarily being any causal relationship. Similarly, increased rainfall is likely to produce rising water tables, increased river discharge and falling demand for abstracted water supply. Any relationship is unlikely to be straightforward, however, given that increased abstraction demand is likely to follow a relatively long period without or with very low rainfall, This is probably reflected in the extremely low correlation coefficients between borehole abstraction and rainfall (Table 3.9 below).

Table 3.9: Correlation coefficients between daily borehole abstraction data and daily rainfall.

Abstraction / Rainfall	Moulton	Longhill	Gazeley	Log (Moulton)	Log (Longhill)	Log (Gazeley)
Isleham	0.016	0.010	–0.016	0.068	0.036	0.016
Chippenham (AR)	0.003	–0.020	–0.019	0.002	0.090	–0.022
Chippenham (TBR)	–0.038	–0.064	–0.060	0.031	–0.027	0.022
Log (Isleham)	0.012	0.011	–0.006	0.047	0.008	0.005
Log (AR)	0.019	0.042	–0.013	–0.001	0.089	–0.013
Log(TBR)	–0.023	–0.041	–0.042	0.041	–0.026	0.041

(AR: autographic gauge; TBR: tipping-bucket raingauge)

Table 3.9 shows that despite what might have been expected, there are no significant links between daily rainfall and daily abstraction rates at the three boreholes considered. As with other relationships discussed above, it is likely that any link with rainfall is more complex than the correlation coefficients suggest. Any rise in demand for abstracted water is likely to follow a prolonged period without rainfall rather than immediately following a single dry day.

It should be noted that the abstraction data considered are derived from boreholes located some 5–8 km from the fen, and thus it is likely that any local impact from abstraction would have been considerably subdued if the effects were to extend as far as Chippenham Fen. Conversely, it is known that other boreholes exist marginally further away than those identified (and others may exist nearby under neighbouring water authority jurisdiction), and therefore any impact from abstraction may be considerably underestimated in the preceding analysis.

3.6 Data monitoring at Chippenham Fen: a summary

The preceding two sections have attempted to discuss a large number of data series collected over a considerable length of time in terms of the behaviour of each series and relationships with other series.

It would appear from this analysis that there have been marked changes in the way in which the different series behave over time, and that there are some relationships between the different variables that help to explain these features. However the relationships between variables are by no means clear cut. Some relationships that were expected have not been found or were less obvious than expected, and this would suggest that some as yet unexplored factor is controlling the hydrological response of the fen and its environments. The fact that the fen is managed hydrologically has been mentioned in previous sections as a possible factor, but the extent of that impact has not yet been fully explored. The next section of this report will attempt to examine the limited information concerning the hydrological management of Chippenham Fen and its surroundings, in order to evaluate their impact.

4. Discussion

The data presented so far have attempted to examine the hydrology of the fen in terms of the behaviour and interactions of a number of parameters. The distinguishing feature of Chippenham Fen, however, is that the movement of water through the site is controlled by a number of devices that are operated by site staff in the normal management of the fen. While significant relationships between some parameters were found the management activities undertaken on site will undoubtedly have an impact on these relationships, and may help to explain the absence of statistically significant results where they were anticipated. Furthermore, there are aspects of the data that themselves may have confounded the analysis undertaken, and these factors will now be examined in order to assess their relative importance.

4.1 Hydrological management at the fen

Hydrological management at the fen falls into three categories, namely the operation of a sluice gate at the Fordham gauging station, raising or lowering of the overspill pipes at dams around the fens, and river support pumping. The locations of these controls are given in Map D. Hydrological management outside the fen in the form of borehole abstractions for water supply must also be considered.

4.1.1 Sluice operation

The sluice gate on the Chippenham River is opened and closed as determined by local conditions, and few data have been made available to determine the exact dates of opening/closing of the gate. However, information is available that shows that the sluice was closed by raising the overflow level by 35 cm between 1/6/92–2/10/92, 5/7/93–23/9/93 and 1/7/94–7/10/94. Figure 4.1a–c illustrate the daily trends over each of these periods, together with river discharge for the month prior to the raising of the sluice gate and the month after it was re-opened.

It is evident from these graphs that while discharge rates fall rapidly immediately after closure, there is a relatively rapid recovery so that within *c.* 24–48 hours river discharges have recovered to a level equivalent to that before closure, or to a level consistent with any pre-existing trends in discharge. It can also be seen that when the sluice is re-opened, there was a rapid rise in river discharge as the dammed water is released, and again within one to two days discharges are equivalent to those before the sluice level was altered. There are occasions on the graph where discharge levels are extremely low, but it is extremely likely that this would have been the case without any changes in the sluice given that its main function is to alter base levels upstream of the sluice rather than alter river discharge.

What is of more concern is the question of whether or not the alteration of upstream base levels affect dipwell levels, and thus it may be useful to examine dipwell behaviour during the periods where the sluice gate has been raised. As dipwell 2 is closest to the sluice gate, it is likely that if there are any changes in dipwell water table depth, they will be exhibited most strongly at this dipwell. Dipwell 3 is further upstream than dipwell 2 and is closer to the path of the Chippenham River through the site, and if the sluice has any extensive spatial impact in other parts of the site then they should be found here. The three years in question are examined in terms of the behaviour of these two dipwells before, during and after the closure of this sluice, and are illustrated in Figure 4.2a–c.

Figure 4.2a suggests that after the closing of the sluice gate at the beginning of June there is little apparent change in water table depth in either dipwell, and levels do not begin to rise until mid-July. It is tempting to attribute this increase to a delayed response to the raising of the sluice, but rainfall data suggest a prolonged dry period in June of that year, and while July was still relatively dry there were a number of small rainfall events in early July, and several storms with recorded precipitation over 10 cm. It is not entirely possible to eliminate this rainfall as the cause of the gradual rise in rainfall levels over this period but the data from dipwell 3 is useful.

If rainfall were solely responsible for the change in water table depth then it would be expected that the rises would be similar. In fact in each case the rise at dipwell 3 is considerably higher than at dipwell 2. While differences in topography may help to explain the difference, it is likely that the proximity of dipwell 3 to the course of the river is responsible, and that the impact of the sluice could have a considerable effect upstream providing that the areas concerned are in close proximity to any river pathways through the fen. However, more exact information would need to be made available from a number of years that would allow the influence of rainfall to be excluded from the analysis.

4.1.2 Operation of adjustable dams

As discussed in Section 1.1.3, water flow around the fen is controlled by a number of adjustable dams. These dams are fitted with a through pipe bent by 90 degrees on the upstream side so that water passes through the dam when it is sufficiently high within the drain to spill over the lip of the pipe. Collars can be added or removed from the upstream end of the pipe in order to raise or lower the water levels within the ditch system. While dams are distributed around the site there are proportionately more in the region of compartment 8 in the eastern part of the fen.

Data are available that show on which dates collars have been added or removed for a few of the 10 years of record, namely 1989, 1993 and 1994. For example in 1989, dams 2–5 had collars raised and lowered at some time, although in most cases these changes were incremental and thus the impact of these changes would be difficult to identify. Furthermore, since 1989 a number of other dipwells have been added that allow more detailed examination of the area around individual dams, and for this reason the only the changes in 1993 and 1994 will be examined.

On 13/1/93, dams 1 to 5 and 12 all had collars removed to allow access for site workers to wet areas, with the decrease in overspill pipe height ranging from between 7.5 cm and 30 cm. The collars were replaced on dams 1 to 4 and 12 on 15/2/93, and on dam 5 on 5/7/93. The collars were then removed again from dams 1–3 and 12 on 18/11/93 and replaced on 11/4/94. In addition dam number 6 was raised by 30 cm on 26/12/94 to winter flood the North Meadows area. The dipwells directly affected by these adjustments are listed in Table 4.1. It should be noted here that the dipwells affected are determined by the flow directions given in Figure 3.1 in Mason (1990), and it has been assumed that dipwells on either side of the dam are considered, rather than just those dipwells in the compartment next to the dam.

Data for these dipwells for the period November 1992 to July 1994 (in order to allow sufficient overlap on either side of the exact dates on which the changes were made) are given in Figure 4.3a. The Principal Spring piezometer data and data for dipwells 5, 14 and 16 are omitted from the graph as preliminary examination suggested that the former was too far from the dam involved to have a noticeable impact, and the latter three will be examined separately.

Table 4.1: Dipwells likely to be directly affected by alterations to overspill pipes on dams at Chippenham Fen

Bold numbers are those dipwells likely to be directly affected by dam level alteration, other numbers indicate dipwells that may also be affected

Dam number	Dipwell(s) monitoring
1	Principal Spring
2	9
3	**7, 12**
4	**6**
5	**6**
6	**16**, 5, 14
12	**13**

Figure 4.3 suggests that the raising and lowering of collars can, as would be expected, alter the water table depth at nearby dipwells. After the first lowering of collars in January 1993 all dipwells show a decrease water level, with an increase following the subsequent raising of collars in February. It is noteworthy that the changes in water table depth are apparently not related to the size of the change implemented, with most dipwells showing a similar rise and fall. The exception to this statement is at dipwell 9 where, although a change is apparent it is less marked than at other locations. This might be explained by the fact that dipwell 9 is considerably further away from the nearest dam, and thus it would appear that the upstream extent of the impact of such changes is limited.

It is also interesting to note that the increase in water table depth exhibited by dipwell 6 in February 1993 occurs at the same time as dipwell 7, despite the fact that the dam nearest to dipwell 6 was effectively raised 1 week later.

The second sequence of lowering and raising of dam collars in (November 1993 and April 1994 respectively) shows a similar sequence. There is a marked decline in dipwell levels following the November lowering of overspill levels, with this fall much greater than that discussed above. The recovery from this water table fall is, however, relatively quick. The raising of overspill pipe levels in April 1994 appears to produce no increase in water table levels, but there is an apparent (if brief) hiatus in the sharp fall in levels experienced before and after the change.

A further data source that would be considered likely to be affected by dam alterations are the readings taken from gaugeboards GB2 and GB3. In Section 2.2.2 it was noted that there were marked fluctuations in water levels recorded at these locations, and it would seem appropriate to re-examine these here. Figure 2.17 has thus been reproduced as Figure 4.3b, with annotations marking the raising and lowering of dam collars. While the annotations should be regarded as having pin-point accuracy in relation to actual dates of alteration, it is readily apparent that where dates of change have been noted there is a considerable fluctuation in gaugeboard readings.

The data in Figure 4.3b suggest a mixed response to dam alteration in 1993. The increase in dyke water levels in January 1993 occurs at around the same time as the removal of collars from dams 2, 3 and 12 (those closest to GB2 and GB3), and would be consistent with the release of water from behind these dams into the ditch sections occupied by the gaugeboards. Similarly, the replacement of these collars is matched by a fall in water levels at GB2, suggesting a reduction in water inputs to this section of dyke.

The pattern is more obvious for the winter of 1993–1994. The removal of collars in late 1993 is clearly matched by a large increase in water levels at both gaugeboards. Similarly, the replacement of dam collars is marked by an equally dramatic, but less pronounced fall in dyke water levels. This latter feature may be explained by the magnitude of the dam alteration: in late 1993 between 15 and 30 cm of collar height was removed from the dams, while the 1994 alteration saw a replacement of only 3.7 to 15 cm of collar. This would suggest that the ditch levels are well managed by the operation of the dams, and that the magnitude of any alteration in water level is proportional to the amount of change in dam height.

The behaviour of the three dipwells associated with dam number 6 can be found in Figure 4.4. Despite the fact that water levels at the dam were raised by 30 cm on 26/12/94, it is evident that the impact of this change can not be found in dipwell readings, with no alteration to the trend lines until two to three weeks after the event. As with dipwell 9, it is likely that the reason for this is the relatively large distance between the dam in question and the dipwell data available.

The information presented above would seem to suggest that, as would be expected, the raising and lowering of water levels in ditches around the fen does produce a corresponding change in water table depths in the fen itself. These changes are, however, relatively localised and are manifested only in readings taken close to the dams involved – i.e. there is apparently no general effect on water levels across the fen.

Any firm conclusions regarding the information presented here must be tempered by the relationship between changes in overspill levels and the dates on which dipwell readings were taken. For example, the dipwells were monitored 12 days before the first lowering of overspill levels in January 1993 and then one day after. When collars were raised again, dipwell readings were not taken until 10 days after the event, with the same gap displayed in the second set of alterations discussed above. It may be that the alterations did produce a more obvious impact than has been identified here, but if this impact was rapid and short lived, then it may have been missed in the time delay between altering the overspill collars and the next dipwell reading. Furthermore the relatively small number of readings taken make any differences found before and after water level changes difficult to quantify statistically, and thus any changes must remain apparent but unproven. More detailed analysis, for example taking into account the possible impact of rainfall events, was outwith the scope of the present project.

4.1.3 Pumping operations

The operation of the drain management system and sluice gate discussed above are effectively localised manipulation of the water table within a relatively short time period.

Of perhaps more significance is the operation of river support pumping into the fen in order to compensate for groundwater abstracted for water supply at nearby boreholes. The extent of this pumping has proved difficult to establish, as records suggest that the amount of pumped supply has suffered operational difficulties, so that actual amounts supplied has not been monitored on all occasions. There are recorded river discharges in 1991, but exact dates are not clear and most are short lived. The largest discharge support episode in this year would encompass only a few dipwell readings and therefore any conclusions drawn would be unreliable. More precise information is available for the years 1992, 1993 and 1995.

4.1.3.1: Pumped support to Chippenham Fen in 1992

Data concerning the exact dates on which pumped support started and finished vary depending on the information source used. In order to ensure that all possible pumping dates are recorded, pumped support has been assumed to commence at the earliest date mentioned (1/7/92) and to end at the latest date (26/11/92).

During this period, support pumping occurred more or less continuously to Chippenham Fen and Chippenham Park Lake, at a rate of between 13.2 and 25.7 $l.s^{-1}$. Mean dipwell data, gauge board data, and discharge data from 1992 for the months before pumping, three months of pumping and three months after cessation of pumping are illustrated in Figures 4.5–4.7. Rainfall over the same period is shown in Figure 4.8. All data illustrated are summarised in Table 4.2. Principal Spring piezometer data are not available for the period in question.

Table 4.2: Mean values before, during and after pumped inflows at Chippenham Fen, 1992

Variable	Before pumping	During pumping	After pumping
Dipwell water table depth (cm)	–37.84	–11.65	–6.37
Discharge (cumecs)	0.0228	0.0466	0.1361
GB1 (m.a.o.d.)	12.845	12.846	12.885
GB2 (m.a.o.d.)	12.476	12.442	12.389
GB3 (m.a.o.d.)	12.311	12.261	12.290
Rainfall total (mm)	113.9	315.0	140.7
Mean daily rainfall (mm)	1.252	2.218	1.481

Mean dipwell data (Figure 4.5) show an obvious and rapid response that may be attributable to the additional influx of water, with a *c.* 35 cm decrease in water table depth shown in early July (although this may also be attributable to the sluice gate operations described in Section 1.1.3). This new level is maintained throughout the pumping period, although small fluctuations may be explained by alteration of the quantities supplied. For example in mid-October the discharge rates decreased from a total of 25.2 $l.s^{-1}$ to 13.2 $l.s^{-1}$, and this apparently coincides with an increase in water table depth. Water tables apparently continue to remain relatively stable after pumping ceased in November. Mean values also show a decrease in water table depth during pumping but in the three months after pumping ceased water table depths decrease further.

Gauge board data (Figure 4.6) on the other hand show minimal change over the three periods. It would be expected that, as the gauge boards monitor water levels in the water distribution network within the fen, they would exhibit greater change, particularly in the case of GB1, which is adjacent to one of the inflow points for pumping at the principal spring. It is possible to identify a decline in readings towards the end of support pumping but its significance is doubtful given that it apparently commences before this support ended. It could be argued that the stability exhibited by gauge board readings is a result of a successful pumping strategy, with inflows maintained at levels sufficient to maintain a stable water level in the drains. If water is seeping from the drains and into the fen, then it is possible that the extra water is arriving at a rate equivalent to the maximum seepage rate of the fen. However, more information on water table depths closer to the drains and on local hydraulic conductivities would be needed to examine this suggestion further.

River discharge data (Figure 4.7) suggest a small increase as pumping commences but flows throughout August and September are extremely low. The increase in discharge in late September pre-dates the cessation of pumping and thus it is difficult to identify the exact impact that pumping may have had. Because discharge over this period has been recorded daily, there are sufficient readings available to test the three periods using analysis of variance. The analysis indicates that there is a significant difference between the periods before during and after support pumping ($p<0.001$), but this may be attributable to the influence of much higher discharges recorded in the third period, rather than to the pumping operations. Given that it is implied above that much of the extra inflow may be lost from the drains, it is possible that most of the water has been lost to storage within the fen. If this is the case then the amounts supplied to the fen by pumping may need to be increased in order to maintain river discharge levels.

4.1.3.2: Pumped support to Chippenham Fen in 1993

Pumped support in 1993 consisted of continuous discharge to Chippenham Park Lake at rates of between 13.5 to 13.7 $l.s^{-1}$ between 2/8/93 and September 1993. It has been assumed for the purposes of the following analysis to mean all of that month. Data over time for the three months before and after this period are displayed in Figures 4.9–4.12, and summary data are given in Table 4.3.

Table 4.3: Mean values before, during and after pumped inflows at Chippenham Fen, 1993

Variable	Before pumping	During pumping	After pumping
Dipwell mean water table depth (cm)	–28.8	–13.65	-3.2
Discharge (cumecs)	0.0534	0.0388	0.2419
GB1 (m.a.o.d.)	12.836	12.887	12.828
GB2 (m.a.o.d.)	12.436	12.393	12.623
GB3 (m.a.o.d.)	12.308	12.229	12.495
Principal Spring (m.a.o.d.)	13.026	13.18	13.37
Rainfall total (mm)	124.0	103.8	129.7
Mean daily rainfall (mm)	1.35	1.70	1.41

As with 1992, there is a considerable rise in mean dipwell water level (Figure 4.9) over the period in question. However, the start of this change in water table depth occurs some time before the supply of water to Chippenham Park Lake and thus it is difficult to establish whether the additional water supplied to a site some distance from the fen has any real influence. The gauge board and Principal Spring piezometer data are shown in Figure 4.10, and for the Principal Spring there is a marked rise in water level immediately after the commencement of support pumping. Gauge board data do exhibit distinct changes at specific dates but these are apparently unrelated to any alterations in support flow. Similarly Chippenham River discharge data (Figure 4.11), while exhibiting marked changes in quantities leaving the fen, show no apparent change as a result of the commencement of pumped support. It would seem reasonable to conclude that while pumped discharges to Chippenham Park Lake may help maintain water levels elsewhere, they do not have a noticeable effect at Chippenham Fen. However as this suggestion is made from a limited amount of data, further research would be needed before stating conclusively that this is the case.

4.1.3.3: Pumped support to Chippenham Fen in 1995

Data for 1995 suggest that pumped support occurred from 26/6/95 until the end of the year, and thus while conditions before and during such support are available, there are no data available to suggest the sequence of events after the cessation of pumping. Records suggest that support was supplied to Chippenham Park Lake throughout this period (progressively rising from 3 hours per day to 9 hours per day), and to the fen directly between 22/8/95 and 21/9/95. Rates of support are not given, although totals are estimated. Water table variables for 'before' and 'during' pumping are illustrated in Figures 4.13–4.16, and summary data are given in Table 4.4.

Table 4.4: Mean values during and after pumped inflows at Chippenham Fen, 1995

Variable	Before pumping	During pumping
Dipwell mean water table depth (cm)	–41.29	–63.51
Discharge (cumecs)	0.0714	0.0177
GB1 (m.a.o.d.)	12.882	12.462
GB2 (m.a.o.d.)	12.627	12.400
GB3 (m.a.o.d.)	12.506	12.400
Principal Spring (m.a.o.d.)	13.022	12.832
Rainfall total (mm)	49.2	116.4
Mean daily rainfall (mm)	0.61	1.57

Examination of dipwell water table depths (suggests that while support is supplied to Chippenham Park Lake there is apparently no improvement in mean water table depth at the fen. However, on the commencement of support discharge to the fen directly (22.8.95) there is a marked improvement in dipwell water table depths (Figure 4.13) and in water table elevations recorded at GB1, while Principal Spring piezometer data suggest a gradual fall over the period in question (Figure 4.14). Discharge data (Figure 4.15) suggest no immediate change in values at the commencement of support pumping to Chippenham Park Lake, but there is a marked discharge peak as pumping commences to Chippenham Fen, after which river discharge continues to rise overall towards the end of the monitoring period. It is interesting to note that the end of the discharge peak in mid to late September coincides with the cessation of pumped discharge support to the fen. Examination of Figure 4.16 does indicate that there was a significant storm event in mid September, and at least some of the features mentioned above may be a response to this event rather than any anthropogenic hydrological activity.

Of the results reported above, the dipwell readings are perhaps the most consistent indicator of any impact on the fen from pumped inflows. However, any of the trends discussed must be seen in the context of variation in rainfall inputs over these periods. Data for 1992, for example (see Figure 4.8) suggest that much of the initial period was relatively dry. August rainfall is more frequent but the amounts recorded are relatively low. In late September there are a number of relatively large storms and from mid-October onwards rainfall is both frequent and greater in magnitude. Analysis of variance suggests that there is a significant difference between the three periods ($p<0.001$) and the data suggest that the rainfall over the period when pumping occurred is higher on average and in total, although the number of records in this middle period is larger.

Similar comments can be made concerning the other two years examined. In both 1993 and 1995 rainfall is low in the period immediately preceding pumped support (hence the need for it) but is marginally higher during it. The role of larger inputs of water from rainfall therefore can not be discounted as being responsible for the decrease in water table depth over the pumped inflow period.

The above discussion would suggest that while there are reasonably strong indications as to the exact impact of pumped support to Chippenham Fen it is not yet possible to state precisely whether the amounts of water delivered to the fen are sufficient to maintain water levels within it. It is possible that it is enough to 'top up' water tables within the fen but it is not certain whether the quantities supplied would be sufficient to prevent serious water loss in severe droughts, such as that experienced in 1995, where mean water table depths were almost 1 metre below the surface and even with the combined impact of pumping and a large storm event water tables remained on average 20 cm from the surface. It may also be desirable to consider commencing pumped support earlier in the year, i.e. before fen water tables and river discharges reach unacceptably low levels. However, the exact criteria for determining when this support should commence would be difficult to establish. It may be possible to select a critical level at which pumped support should commence, but there are obvious limitations to this given the difficulties involved in predicting the duration of any dry periods. If such a policy were to be chosen, more information would be required concerning the exact relationship between inputs to and outputs from the fen.

In terms of stating whether the inflows are adequate to compensate for the effects of water supply abstractions, there are further problems. Data have been made available that give the quantities licensed to be abstracted, and actual abstractions by Anglian Water Services. Data supplied by the NRA suggest that licensed abstractions within 12 km could amount to 74001.33 $m^3.day^{-1}$, equivalent to 0.856 cumecs. Other data supplied by English Nature suggest that mean pumped discharge amounted in 1991 and 1992 to between 0.011 and 0.022 cumecs. Thus, if the maximum possible abstraction levels are achieved, the compensation supply would appear to be inadequate, particularly as the river outflow from the fen has been known to dry to a trickle in prolonged dry periods. It would therefore seem reasonable to suggest that, on the basis of the evidence available, compensation pumping should be increased. However it should be noted that only 1019.39 $m^3.day^{-1}$ (0.0118 cumecs) are licensed within 2 km of the site, 1090.43 $m^3.day^{-1}$ (0.0126 cumecs) within 3 km, and 9054.24 $m^3.day^{-1}$ (0.1048 cumecs) within 4 km of the fen. Even at these levels the potential extraction rate within a few kilometres of the site can exceed discharge rates from the fen and thus threaten flow in the Chippenham River.

The adequacy of supply can be explored further by examining the mean daily pumped inflow in relation to discharge. The data for 1992 give the most comprehensive information concerning pumped support, and by subtracting the support rate per day from daily discharge an estimate of likely discharge without support can be derived. The result of this process can be seen in Figure 4.17, and suggests that without any support the Chippenham River would dry up for considerable periods, as indicated by the line falling below zero discharge. However, this conclusion does rely on a large number of assumptions, for example, that all discharge to the fen is presumed to leave the fen relatively quickly rather than being buffered by fen storage, and that the Principal Spring is the primary contributor to fen outflows. More detailed information concerning water movement in and through the fen, combined with a specific period of pumped support at a known rate, are required before any conclusions concerning the efficacy of the support given to Chippenham Fen can be made with a degree of certainty. However, it would seem reasonable to conclude that pumped discharges directly to the Principal Spring would seem to be effective at raising local water tables and maintaining at least some flow in the Chippenham River. The question as to whether the amounts supplied are adequate requires more detailed data.

It is clear that the exact extent of local contributions to the fen's groundwater and discharge should be ascertained in order to assess with more certainty the impact of these abstractions. It would also be desirable to acquire more information on the maximum loading possible for the drainage system at the fen, both in terms of the maximum drain capacity and rates of flow through the fen.

4.2 Data reliability

The preceding sections have dealt in detail with the temporal and absolute values revealed by a number of hydrological monitoring devices at Chippenham Fen, but while there have been occasional comments on the quality of data collected it is important to have a more thorough examination of this subject. Two areas are of importance in this respect, namely the temporal resolution of the data and the spatial resolution.

4.2.1 Temporal resolution

Most studies of long term trends in data where there is a natural seasonal variability require a reasonable length of record in order to establish the normal pattern of variability. Deviations from this variability can then be identified and hopefully attributed to some known causal factor.

In the case of dipwell readings a ten year length of record is clearly a good base from which to examine medium to long term water table behaviour, and the graphs produced in Section 2 would seem to indicate that the fortnightly recording of dipwell levels is sufficient to produce a reasonable trend line. The difficulty with the dipwell records occurs when there are apparent changes in readings over short timespans, in that the number of readings available for analysis becomes smaller, and thus any differences between specific data subsets need to be larger in order to demonstrate statistical significance. This has not proved to be a problem for much of the analysis carried out here, but the graphs produced for dipwell data that attempt to demonstrate the impact of a particular management activity rely on relatively few points.

A further problem arises concerning the timing of the readings, in that the commencement of some management activity (e.g. dam raising or lowering) may fall between the normal dipwell reading dates. As outlined in the previous section, this may mean that dipwells may not be read until 10–13 days after the change has occurred, and any rapid adjustments to the change may be missed. If the intention behind any dipwell monitoring is to reveal the impact of a specific management activity, it is recommended that dipwell reading should be carried out daily for at least one week before, and as long as necessary after, any such activity. The increase in frequency of readings could be restricted to those dipwells in the immediate vicinity of the area involved and can be recorded as a separate data series from the normal fortnightly pattern.

In terms of the daily readings taken by automatic loggers, these clearly represent a complete record of discharge and borehole water elevation behaviour over time. The only criticisms that can be made against this data relate to the frequency of data collection and the length of record. In the case of the former, borehole data are collected at intervals that make graphing and statistical analysis extremely difficult, and it is recommended that a record is maintained of daily averages, and of averages that are consistent with dipwell data collection dates, in order to facilitate analysis in future.

In terms of the length of record, in normal circumstances 4–5 years of data would normally be considered adequate. However the much longer dipwell data series and the first two years of borehole data indicate that there has been some change in base levels in the years preceding the commencement of borehole records. It would therefore be unwise to draw definite conclusions without further monitoring.

4.2.2 Spatial resolution

The spatial distribution of data records has a number of implications for the results presented in this report, mostly relating to the dipwell data.

In practical terms, the 15 dipwells installed at the site may be sufficient to produce a reliable overall picture of the distribution of water table depths over time at the site. However there are a number of statistical considerations that render analysis difficult. The site consists of a number of compartments within which there are a variety of vegetation types and drainage patterns. If reliable conclusions are to be drawn concerning the impact of different conditions within these compartments then it would be advisable to have at least one dipwell per compartment, with each dipwell placed a standard distance away from any local drains or dams.

At present, some compartments have several dipwells while others have none, and there is no apparent consistency in the placing of these dipwells, some being close to drains, others more central. Ideally, each compartment should have a number of dipwells that can be used to monitor specific factors within each compartment, e.g. some placed immediately adjacent to drains, others centrally. While the practical difficulties associated with what would amount to a doubling or even tripling of dipwell numbers are appreciated, the increase in spatial resolution would allow greater accuracy in the monitoring of water table behaviour under specific conditions, e.g. relative proximity to drainage systems. It may be however, that a compromise of more intensive monitoring of a specific compartment would be sufficient, particularly if dipwells could be located close to a dam, as this would also allow the criticisms made in the preceding section to be addressed.

In terms of other data requiring greater spatial detail, there are two aspects that could be considered, namely the gauge board data and the discharge data. At present, gauge board data are concentrated in the eastern/south-eastern part of the site, and given that limited information about patterns of water movement around the site was available, it may be useful to install one or two others in other parts of the site, possibly more centrally or on the western side to provide more balance.

The discharge data currently monitor water outputs from the fen, but other than the input derived from rainfall little is known about the exact quantities of the inputs. If discharge was monitored at any major inflows to the fen it could be possible to quantify hydrological balances more exactly, rather than rely on modelling, and the extent to which the fen acts as a buffer between inflows and outflows could be determined with greater precision.

4.2.3 Miscellaneous comments concerning data collection and recording

In the light of the above comment concerning flows into the fen, further difficulties in interpreting the dipwell data relating to the direction taken by water through the drainage network can be identified. Mason (1990) identifies common flow directions and gives rates of flow, but it is not clear whether these flows can be universally applied or under what conditions these flow directions apply. For example, does water flow in the same direction under all conditions, and if flow can be reversed what conditions are needed? It would also be useful to identify rates of flow through the fen, both in terms of hydraulic conductivity of the peat and the drainage system. A more detailed study of the movement of water within the fen would again help to improve current understanding of its function in the local environment, and may identify more efficient/desirable routes to either maintain water levels within the fen or maintain desired discharge rates downstream.

The final criticism of the data relates to that information made available concerning pumped inflows and other hydrological management activities. It would have been desirable for all the relevant data to have been available in order to assess the impact of pumping, alteration of collared dams and groundwater abstraction. As it stands, however, this report is based on information for relatively few years considering the length of time the site has been managed and monitored. It may be that, for example, the apparent change in base level for dipwell readings in 1991 and 1992 is easily explained by information already held, but without such information it is impossible to draw firm conclusions about any causal factors in this or any other data. It is to be recommended strongly that all data concerning the site is collated and rationalised so that all relevant information is readily available.

5. Conclusions and recommendations

1. The dipwell data collected in the period 1986–1995 have provided an excellent record of the medium to long term variation in water table depths at Chippenham Fen. Overall data suggest that the water table is –18.99 cm below the ground surface on average. While all areas monitored exhibit surface ponding at some point over the recording period, and for much of the period of record water may be found within 30 cm of the ground surface, each dipwell exhibits a considerable degree of variability. Data from across the site show considerable variation, with some areas clearly much wetter than others, with dipwell 5 showing the highest water tables and dipwell 16 the lowest. The site is clearly prone to drought stress despite the existence of hydrological controls, and water depths may reach in excess of 1 metre in prolonged dry periods.

2. There are two features to dipwell records over time, depending on whether the data are reviewed in terms of their relation to the ground surface or in relation to ordnance datum. Firstly, there is an apparent cyclical trend in the minimum levels attained by the water table in successive summers that is less apparent in winter. This may be attributable to normal medium-term variation in hydrological inputs to the fen, and the lack of a similar cycle in winter maxima can be attributed to the loss of water from the site as surface flow. This loss may then be manifested as higher discharge readings in the Chippenham River. The second trend is an apparent drop in base levels in the early 1990s, where winter and summer readings are obviously (and significantly) lower than in the years before and after. This may again be related to normal climatic variation but it could also be attributable to some as yet undetermined anthropogenic influence on site hydrological regime in these years.

3. Data recorded at the Principal Spring suggest that there has been no general change in water table depth over time, although the period of record is shorter. There is a distinct lack of correspondence between Principal Spring piezometer data and data recorded by gauge board GB1 that could suggest errors in either recording or installation.

4. Data from gauge boards GB2 and GB3 show that water levels in the dykes monitored by them are extremely stable, suggesting a relatively constant relationship between inputs to the dyke and loss to the fen. However, given the rapid fall in water table depths in the fen in dry periods, it could be argued:

(a) that this stability is attributable to the use of water management controls to limit water loss from the dykes to the river, with some inputs from pumped support discharge and localised springs;

(b) that the rapid fall in water table depths in the fen dipwells is a result of net loss of water through evapotranspiration exceeding combined inputs from rainfall and seepage into the fen from the dykes (and springs, if present). It should be noted that during the summer, water levels can fall below the base of the peat, and thus recharge from the dykes into the fen may depend on the permeability of the substratum beneath the peat, rather than the peat itself;

(c) that the fen is a significant contributor to this relatively constant water level in the dykes, so that while water levels in the dykes remain stable, in dry periods they may do so at the expense of fen storage.

The latter seems unlikely, unless there are some inputs from springs directly into the fen (rather than just to the dykes), although there is some evidence that in terms of water table elevation (m.a.o.d.), there is an hydraulic gradient from the fen to the dykes for most of the year, water levels in the fen only rarely falling below those in the dykes. A specific study would be required to elucidate patterns of water movement between the dykes and the peat within the fen compartments, with careful attention paid to measurement of elevations (m.a.o.d.).

5. Records from the observation borehole show a consistent annual range. However there is an apparent change in base level after the first year of recording that is consistent with a rise in water table at the dipwells. It would be unwise to attach too great a significance to this feature, given that interpretation is based on a change after only one year of borehole recording.

6. Discharge data from the Chippenham River suggest that mean daily flow has varied significantly over time in a manner consistent with changes found in borehole and dipwell readings. However correlation analysis suggest that while dipwell readings are significantly related to levels at the Principal Spring, and borehole readings are significantly related to discharge, flow rates show no significant links to dipwell levels. This would suggest that while all three are maintained by regional changes in groundwater levels, the routeing of water supplied to the Principal Spring through the fen reduces the direct relationship between fen and river, particularly as flow to the fen is augmented by pumping through the spring, and flow through the fen is controlled by a series of collared-dams. The unusually low correlations between rainfall and discharge would seem to confirm that direct local inputs to the fen are less important than regional ones except in relatively high magnitude storms.

7. Periods where pumped inflows to the fen have been used to augment water levels suggest relatively little impact as discharges and dipwell readings have fallen to very low levels despite this additional water supply. Detailed examination of the available data suggest that discharge levels in the Chippenham River and water table depths within the fen may respond positively to support pumping, but the effects are frequently masked by variations in rainfall. Extrapolations from existing data suggest that without support discharges directly to the fen, river discharges would effectively cease, although results from this data manipulation should be treated cautiously. It would be reasonable to argue that, given the level of licensed abstraction possible the amount of compensation water pumped into the Principal Spring may need to be re-evaluated.

8. The data available from prolonged dipwell monitoring combines with the availability of discharge, borehole and rainfall records to produce an excellent base for examining the hydrology of the fen and it is recommended that such monitoring activity is continued. The detailed analysis of the data carried out for this report have, however, highlighted a number of areas where the records could be improved and augmented. The implementation of the following recommendations should be regarded as statistically desirable, but the practical and financial constraints are recognised:

8.1 While the elevation relative to ordnance datum of the dipwells and gaugeboards was checked in 1992, it is possible that as ground levels fluctuate over time as soil water stores expand and contract, the assumed elevations of the monitoring equipment have changed, with obvious consequences on data recorded relative to the original datum. This has clear implications for the interpretation of data, for example, the elucidation of patterns of water movement around and through the fen, and it is recommended that elevations relative to ordnance datum are re-surveyed. It would be a useful addition to the dataset if the water level in the

Chippenham River were also recorded to datum, as this would then allow a direct comparison of water levels in the fen with those at its principal outlet.

8.2 While numbers of dipwells and gauges are certainly adequate, the majority of them are concentrated in a particular part of the site. In order to achieve a more spatially representative dataset, additional dipwells and gaugeboards should be installed in the western half of the site. Consideration should also be given to ensuring that dipwells are distributed evenly between locations close to and distant from drains and dykes, and in relation to the dam/collar system controlling flow within the fen.

8.3 It was noted above that in certain parts of the fen during dry periods, the water level can fall below the base of the peat, into the underlying clay or 'head' – any possible recharge into the centre of the fen compartments by water from the dykes in summer may therefore depend on the transmissivity of the underlying substratum, rather than the peat. A specific examination of the implications of this for general data interpretation and assessment of water regimes within the fen was outside the scope of the present study, and it is recommended that this should be looked at in more detail, if possible.

8.4 The data suggest that the operation of the collared dam system and of the sluice at the fen outflow have some impacts on water table depths within the fen, but that the impact of such operations appear to be localised and short lived. More detailed analysis of trends in individual dipwell records in relation to operation of the collared dams, rainfall events and supplementary water supply may provide some useful insights into the hydrological regime (this was outwith the scope of the present report). However, the present location of dipwells in relation to the control devices means that interpretation is problematic and limited. It would be an interesting addition to the body of knowledge in general, and of the fen in particular, if any planned alterations to sluice and/or collared dam levels were to be accompanied by a more intensive monitoring program. This increased level of monitoring would consist of a greater frequency of recording, and ideally would involve a series of dipwells in close proximity to the dam or dams concerned, so that the exact magnitude and extent of any change in water table depth could be more accurately determined. This work could be complemented by monitoring the hydrological impacts on the fen of controlled alterations of collar heights at the dams. The current situation of collar adjustment as required for vegetation or other management purposes is ideal for practical site control but makes analysis of the impact of such adjustment difficult. Ideally, each dam should have several dipwells associated with it at a number of distances, and each collar should then be raised in sequence and the change in water level across the site monitored.

8.5 Additional monitoring of flow rates and directions within the fen would both add to the information provided by Mason (1990) and give more detail about the current state of the fen's hydrological regime. The monitoring of discharge should also apply to any of the fen's major inputs and outputs, and would help to produce a water balance equation for comparison with that discussed in Mason (1990) and DCEUB (1988).

8.6 Water table depths over time have largely been discussed without reference to the control exerted by variations in the clay, marl and peat deposits within the fen, and a number of assumptions have been made regarding the importance of surface water contributions to the fen. There is a possibility that groundwater plays an important role in the fen hydrological regime, but this is difficult to establish given the data available. It is recommended that a suite of Casagrande type piezometers are installed at different depths so that the water pressure in different strata of the fen deposits, and hence the role of groundwater inputs may be assessed. This may help to indicate the effect of the marl layer on fen hydrology and indicate the potential contribution of groundwater inputs to the fen.

8.7 While dipwell and other data suggest that the fen acts as a buffer between hydrological inputs and discharge outputs, the large fall in water table levels experienced in drier years suggests that this fen storage may be short lived and unable to cope with prolonged droughts. This may at least partly result from inadequate control of flow through the fen, and in order to retain water in the fen for longer period it may be necessary to increase the number of adjustable dams, particularly in areas at higher elevations. Alternatively, more complex routeing of flow through the fen would have a similar effect. Both of these options would have obvious consequences for discharge in the Chippenham River, at least in the short term, and thus a more detailed study of the fen hydrological regime using the recommendations made above would be advisable before undertaking them. However, some degree of summer dryness may be natural in a fen system of this type, particularly if spring inputs are not very important, and it is possible that the system of controlled dykes may keep parts of the fen wetter than they would be naturally (see also Appendix 2). Further consideration needs to be given to the possible adequacy of the supplementary water supply under conditions of maximum abstraction, and whether distribution of the water around the fen should (and could) be improved – the current work has highlighted the need for a thorough re-appraisal of the water management of the site.

8.8 Finally, it is recommended that data collection continue, and that where possible data collection dates are rationalised so that consistent data series are available for future analysis. This would include the calculation of daily means for borehole data, and fortnightly means or totals from the daily river discharge, borehole and rainfall data.

6. References

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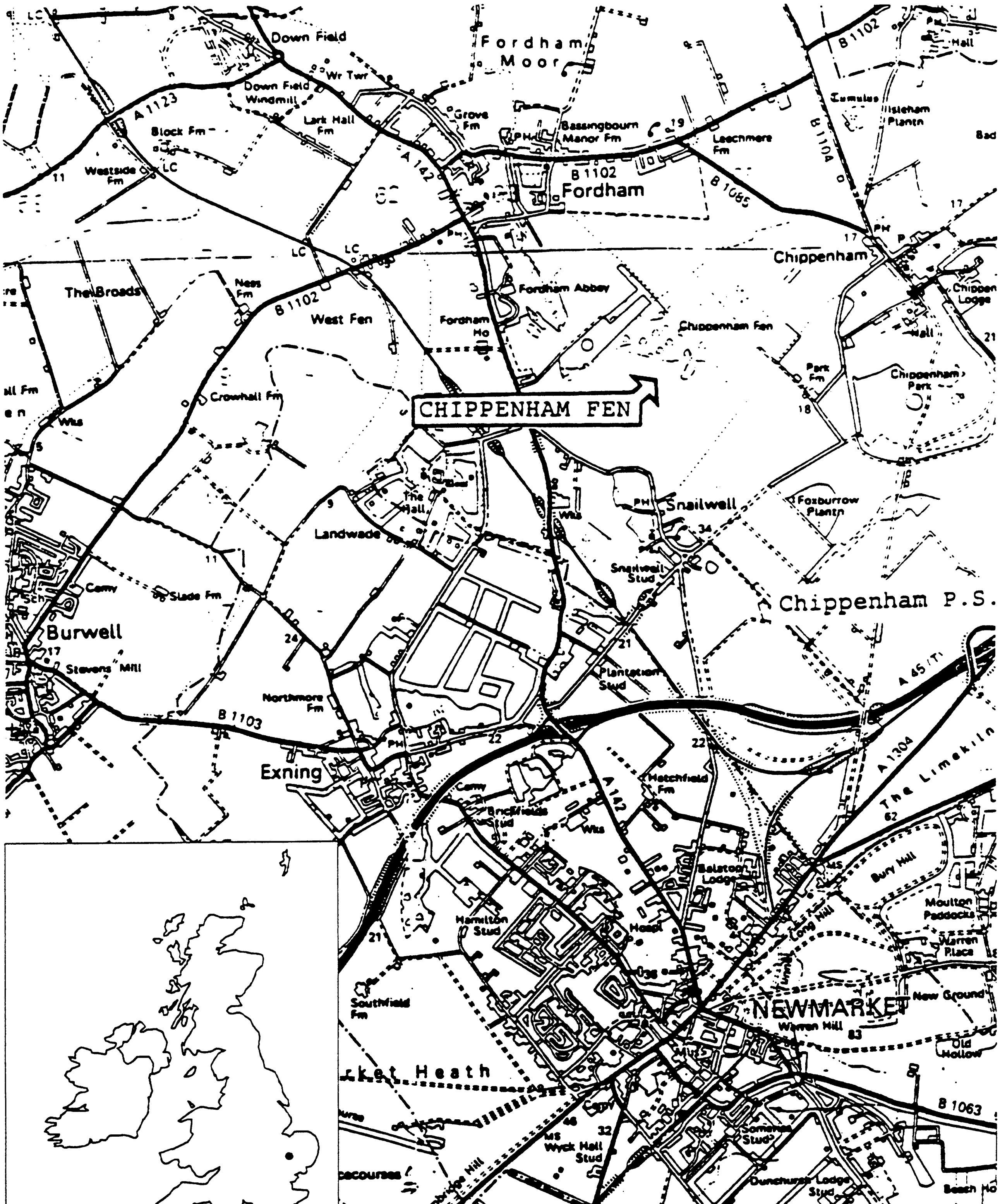
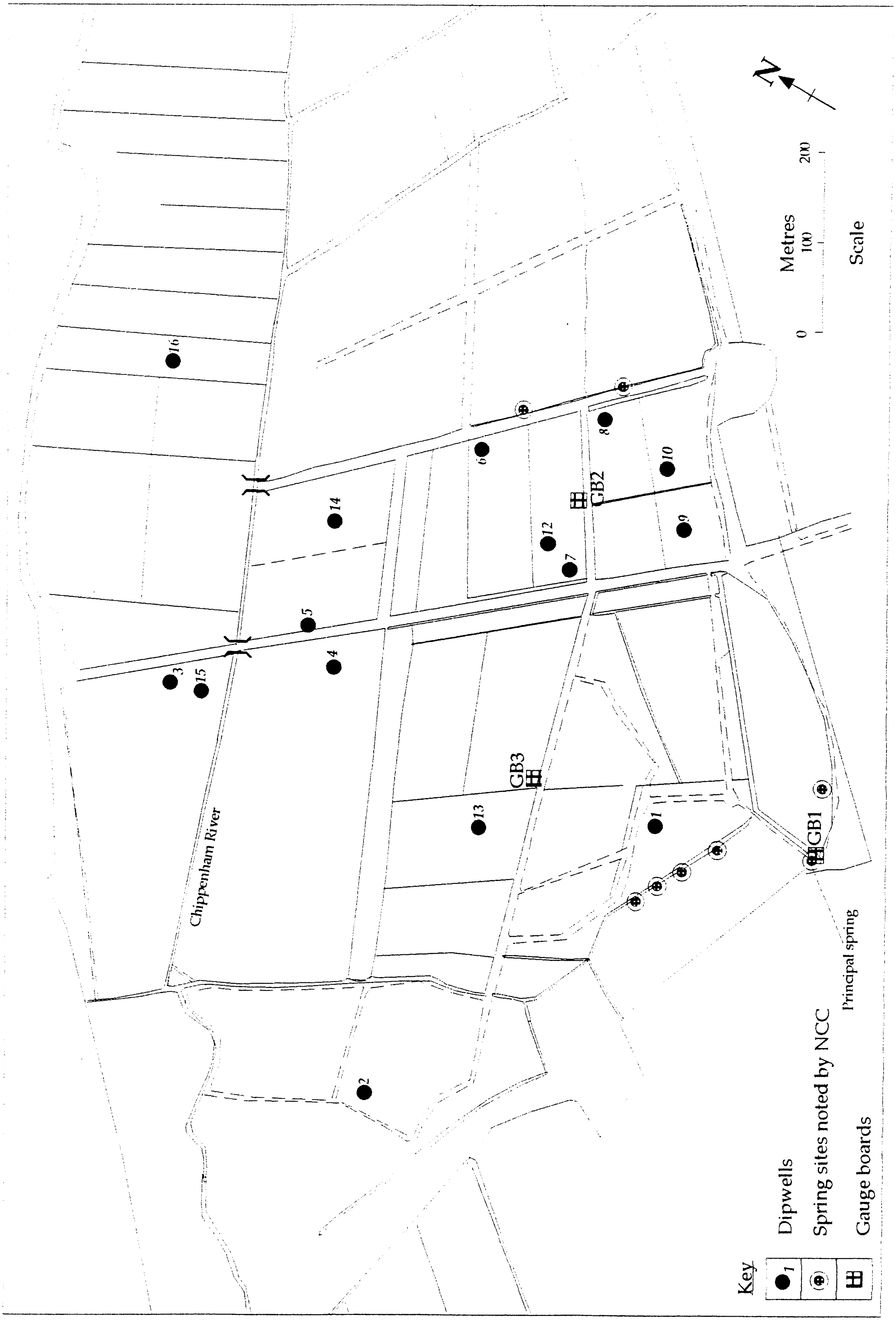
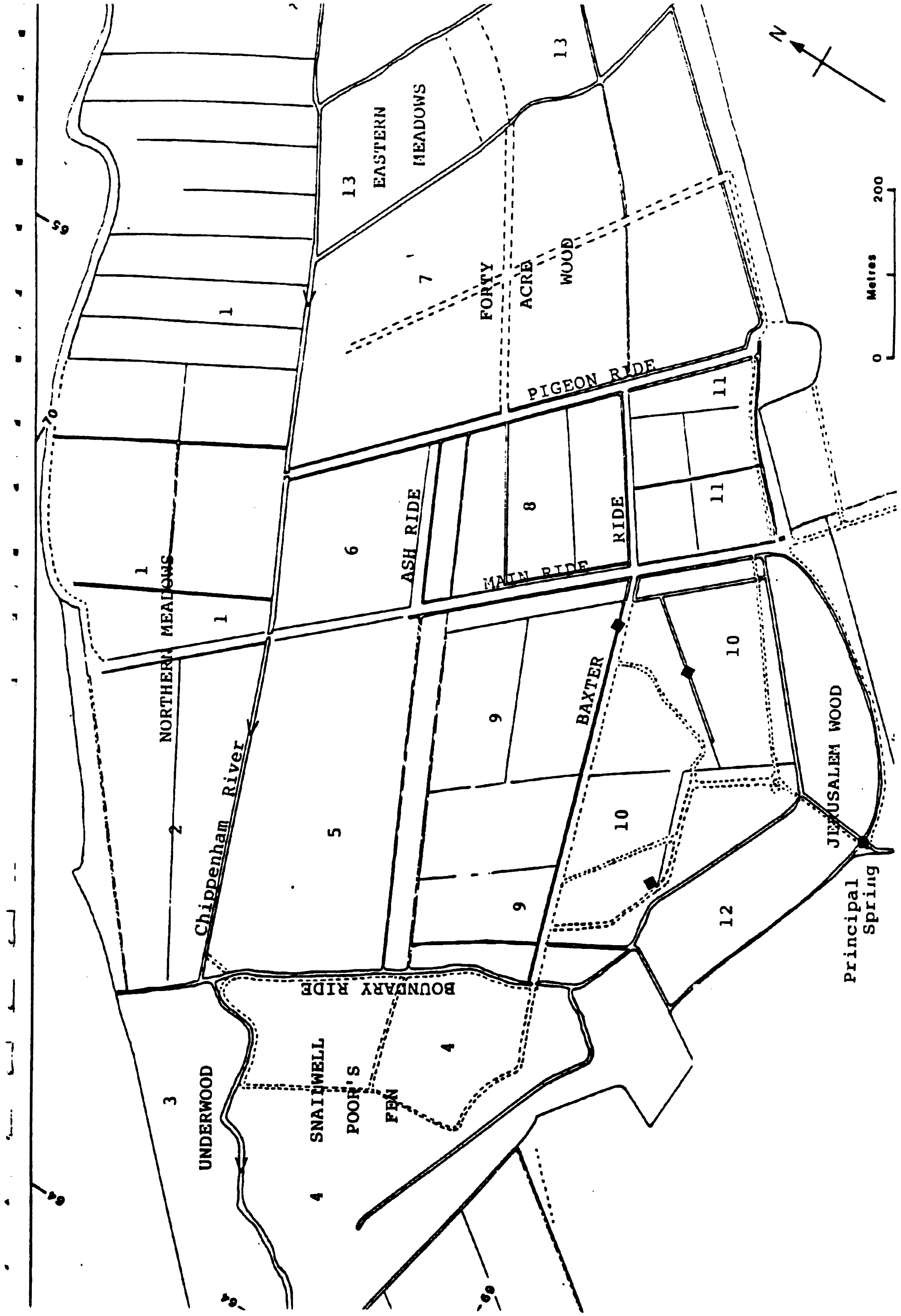


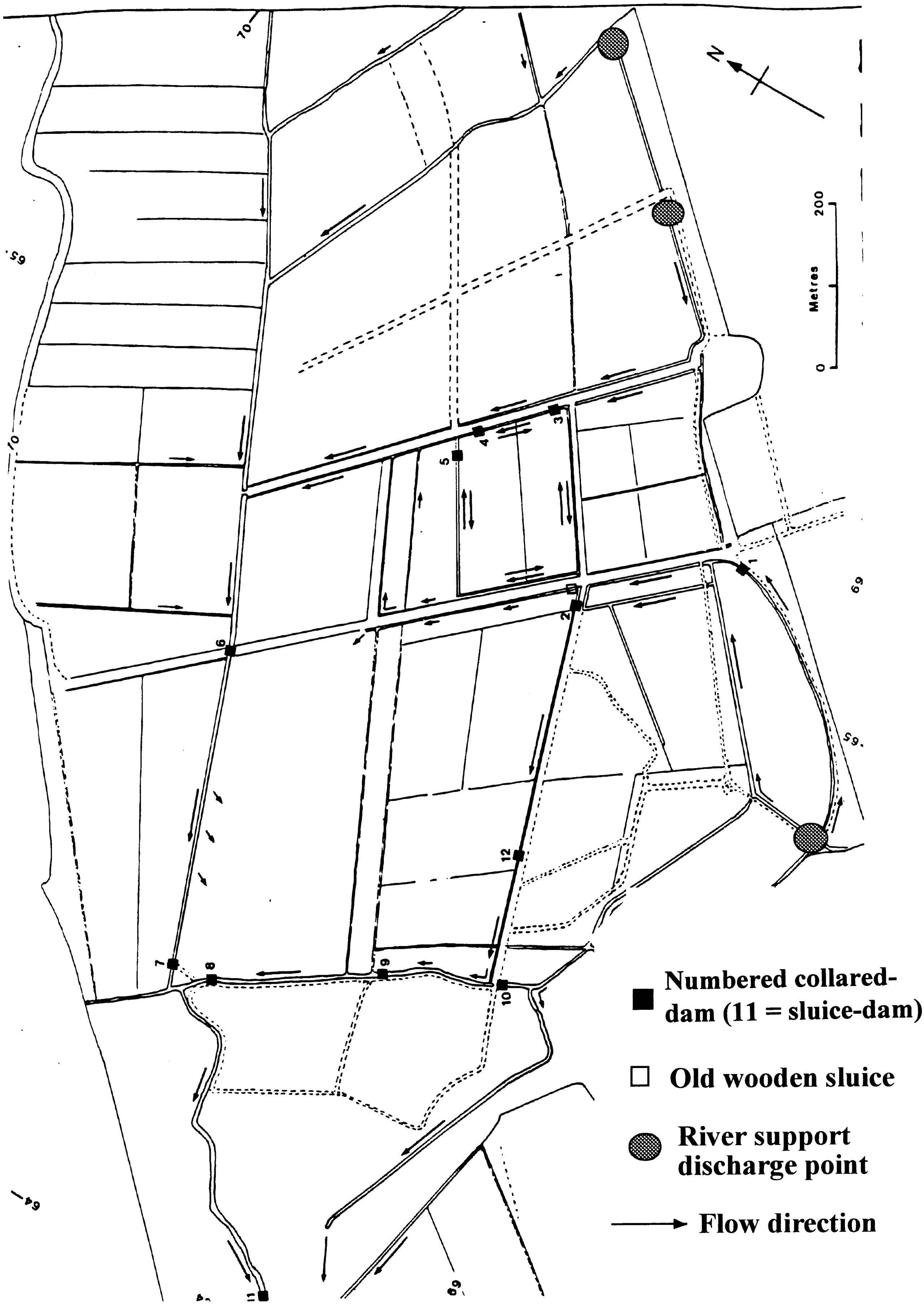
Map A: Location of Chippenham Fen



Map B: Location of dipwells and gaugeboards at Chippenham Fen



Map C: Numbered compartments at Chippenham Fen



Map D: Hydrological control systems at Chippenham Fen

Figure 1.1: Mean monthly rainfall for Chippenham Fen 1991-1995

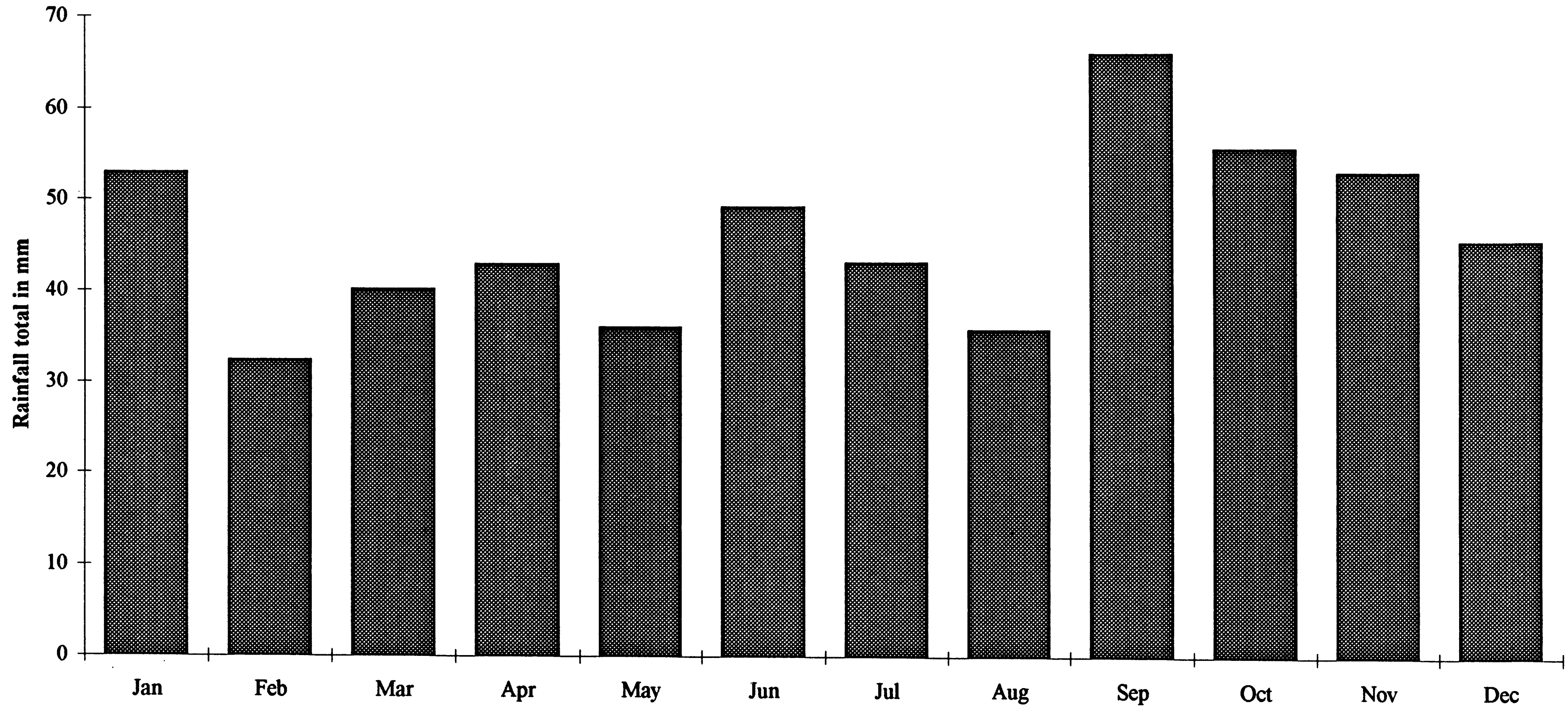


Figure 1.2: Daily rainfall in mm over time recorded at Isleham pumping station 1991-1995

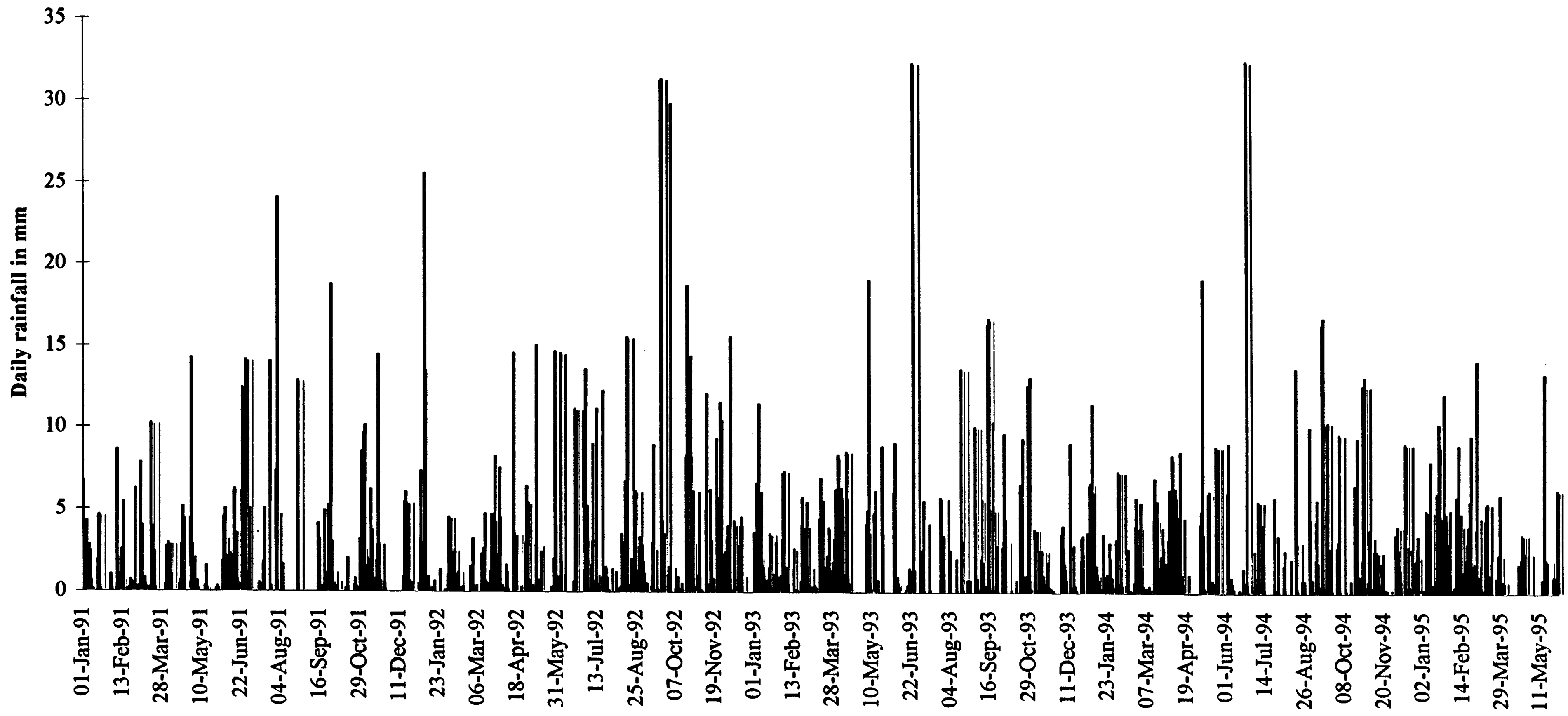


Figure 1.3: Daily rainfall in mm over time recorded at Chippenham Fen 1991-1995

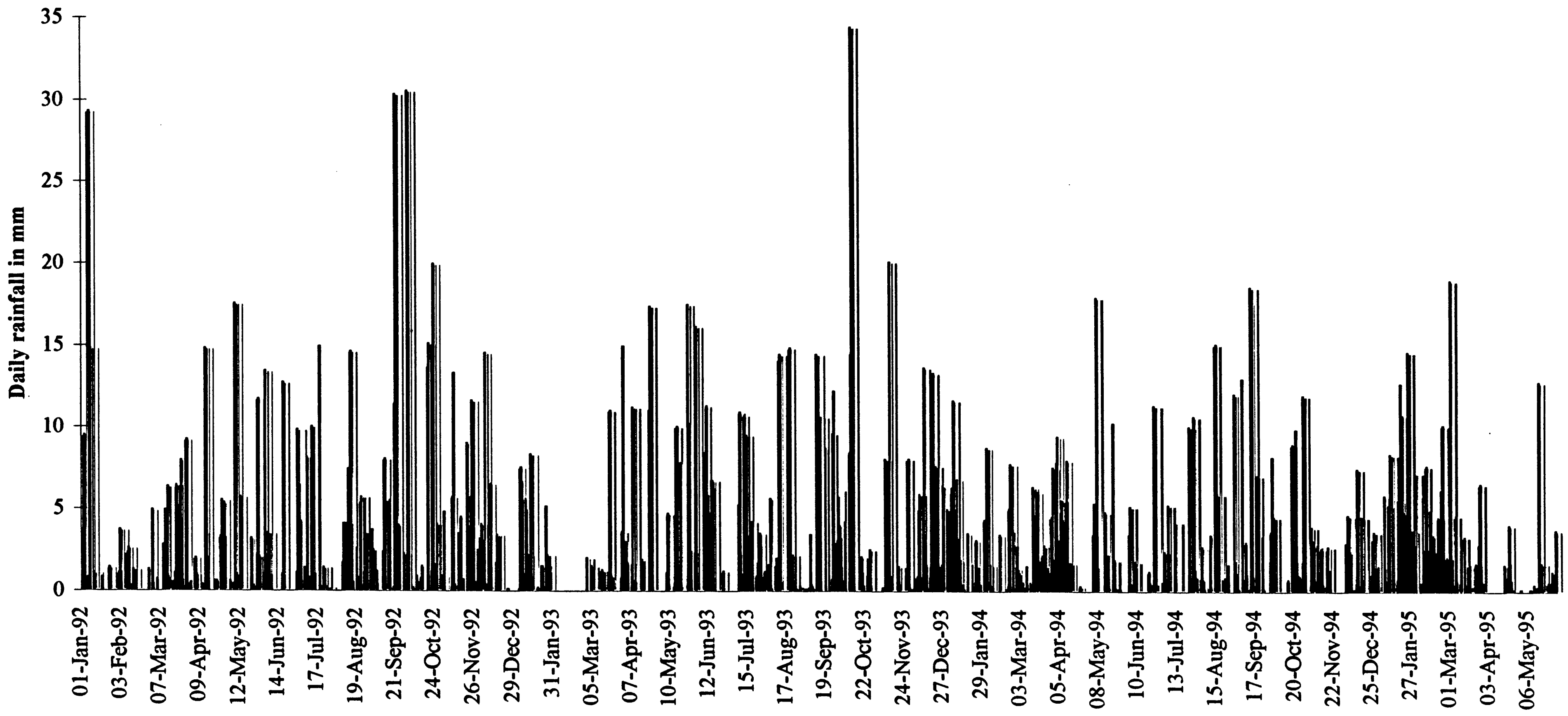


Figure 1.4: Daily rainfall in mm over time recorded by the Chippenham Fen Tipping Bucket Raingauge 1992-1995

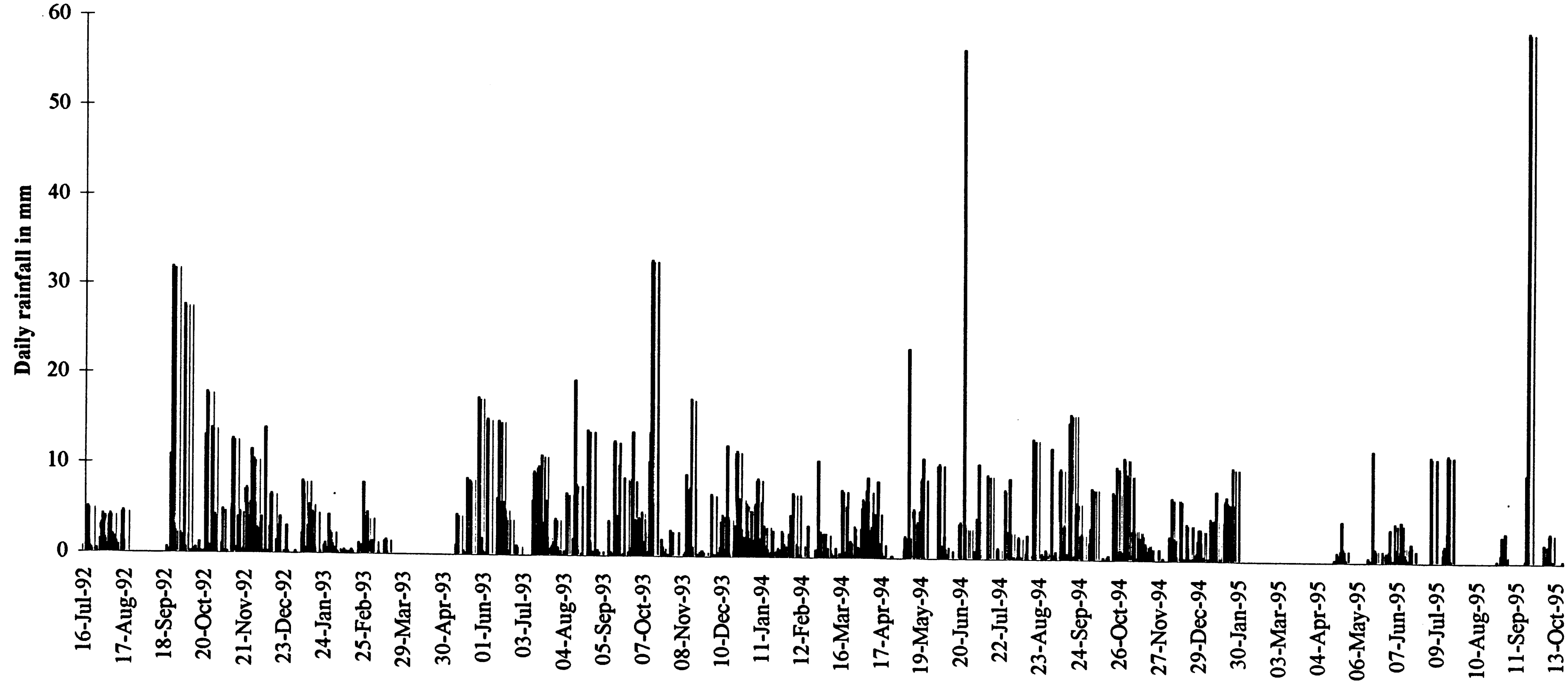


Figure 2.1: Overall mean water table depth for dipwells at Chippenham Fen, 1986-1995

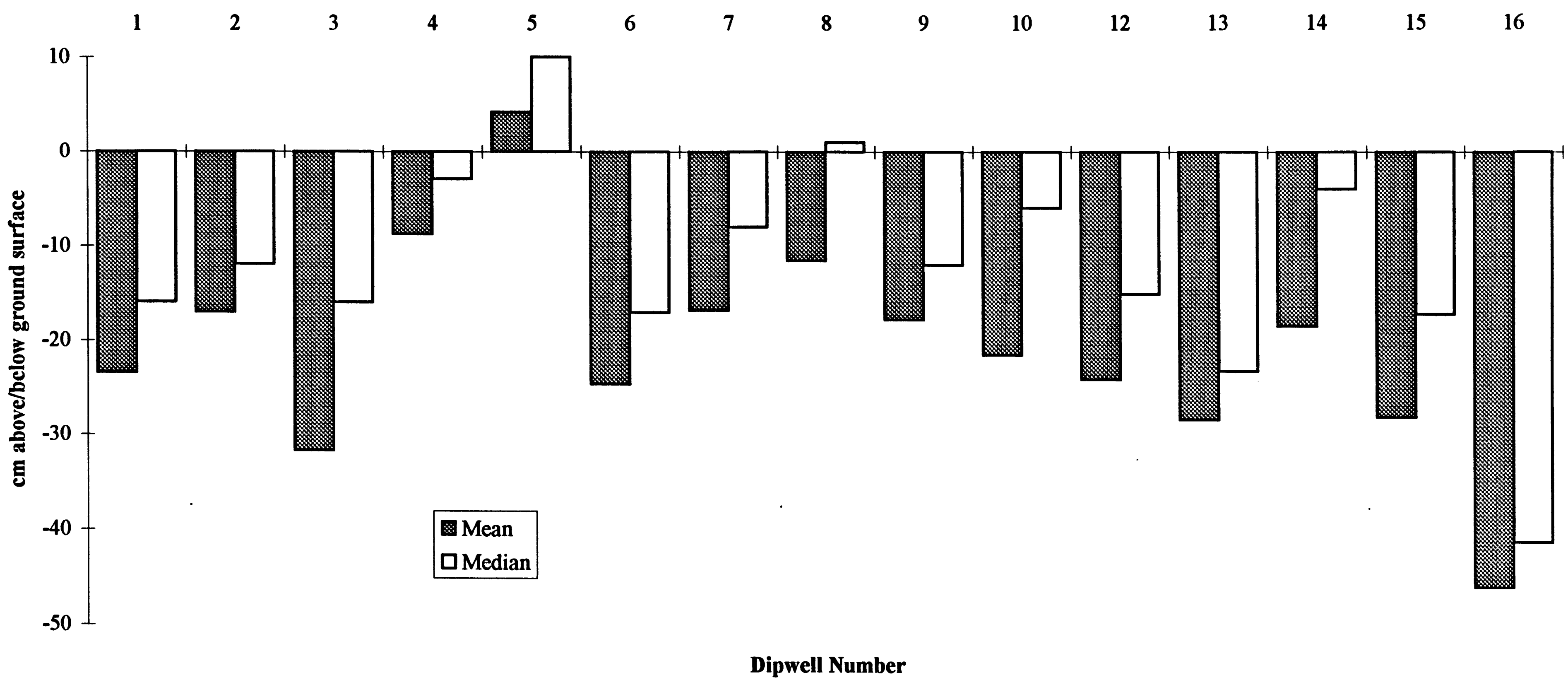


Figure 2.2: Minimum and maximum readings for dipwells at Chippenham Fen 1986-1995

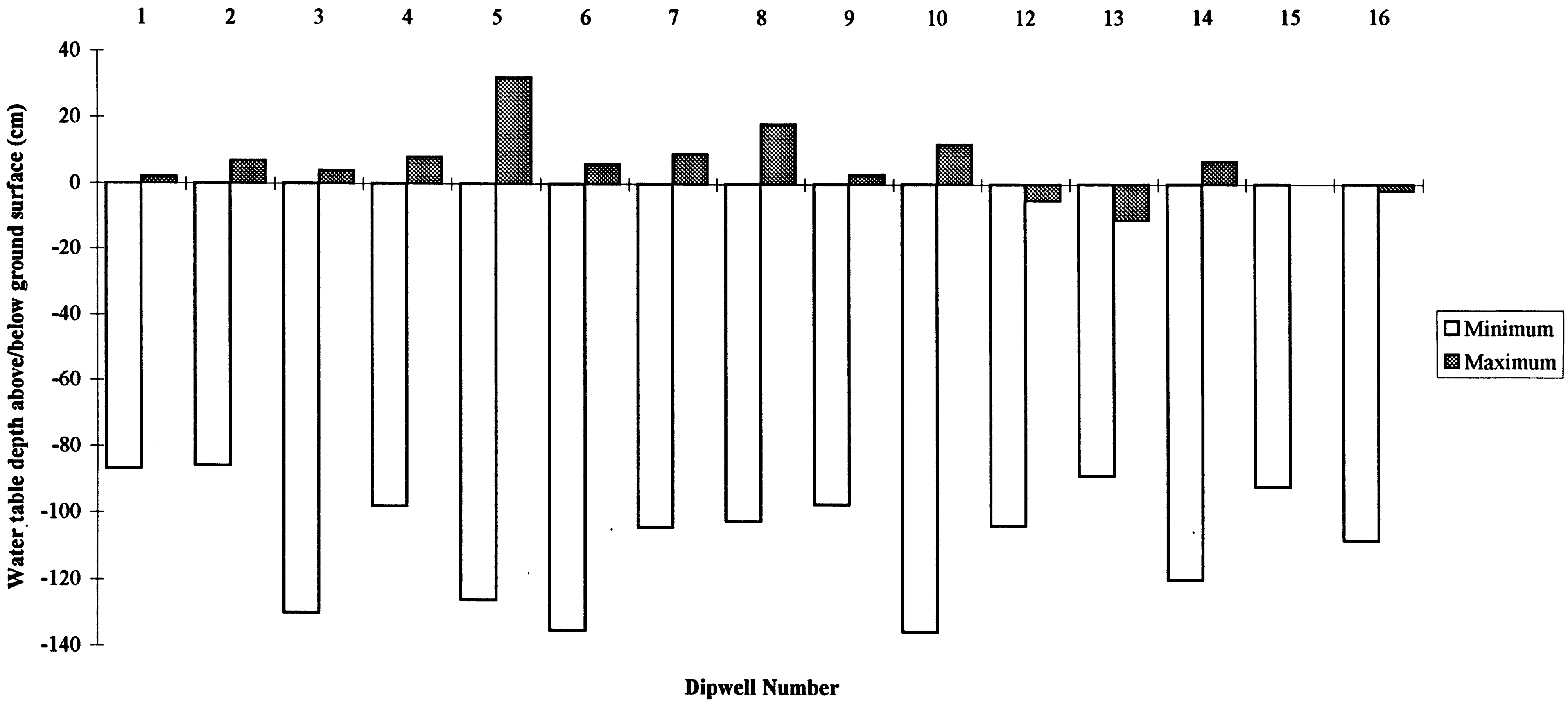


Figure 2.3: Standard deviations of dipwell data at Chippenham Fen, 1986-1995

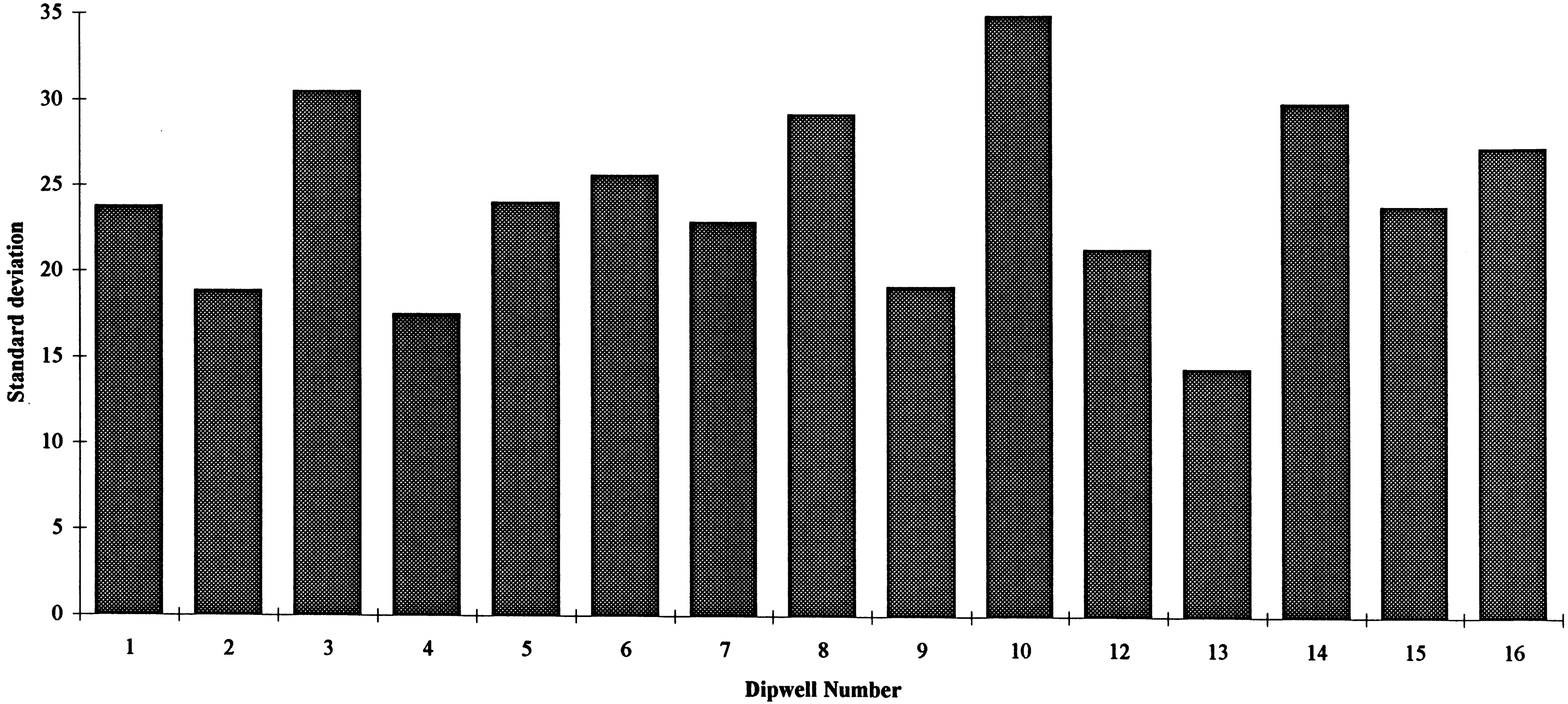


Figure 2.4: Water table depth over time for dipwells 1-9, Chippenham Fen 1986-1995

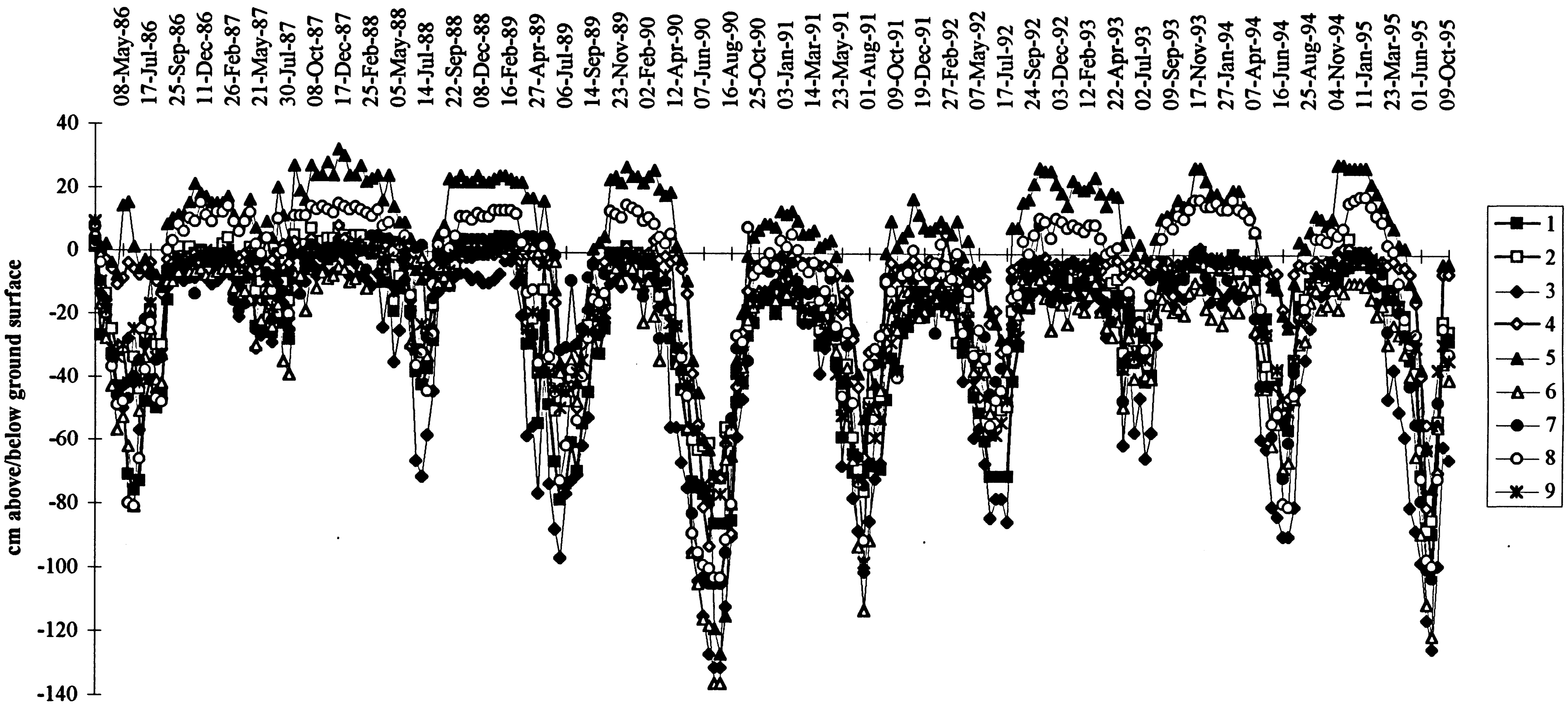


Figure 2.5: Water table depth over time for dipwells 10 & 12-16, Chippenham Fen 1991-1995

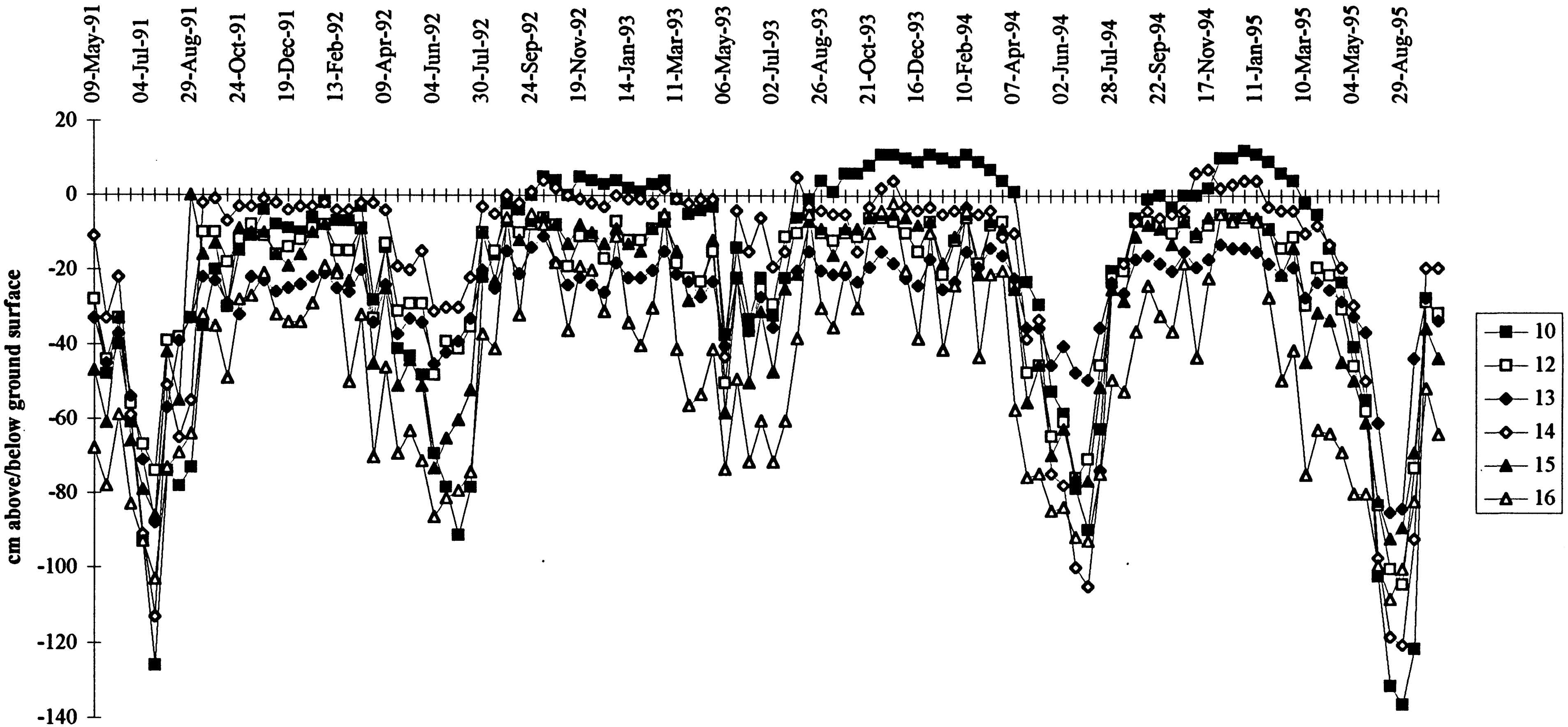


Figure 2.6: Mean & median water table depth over time at Chippenham Fen, 1986-1995

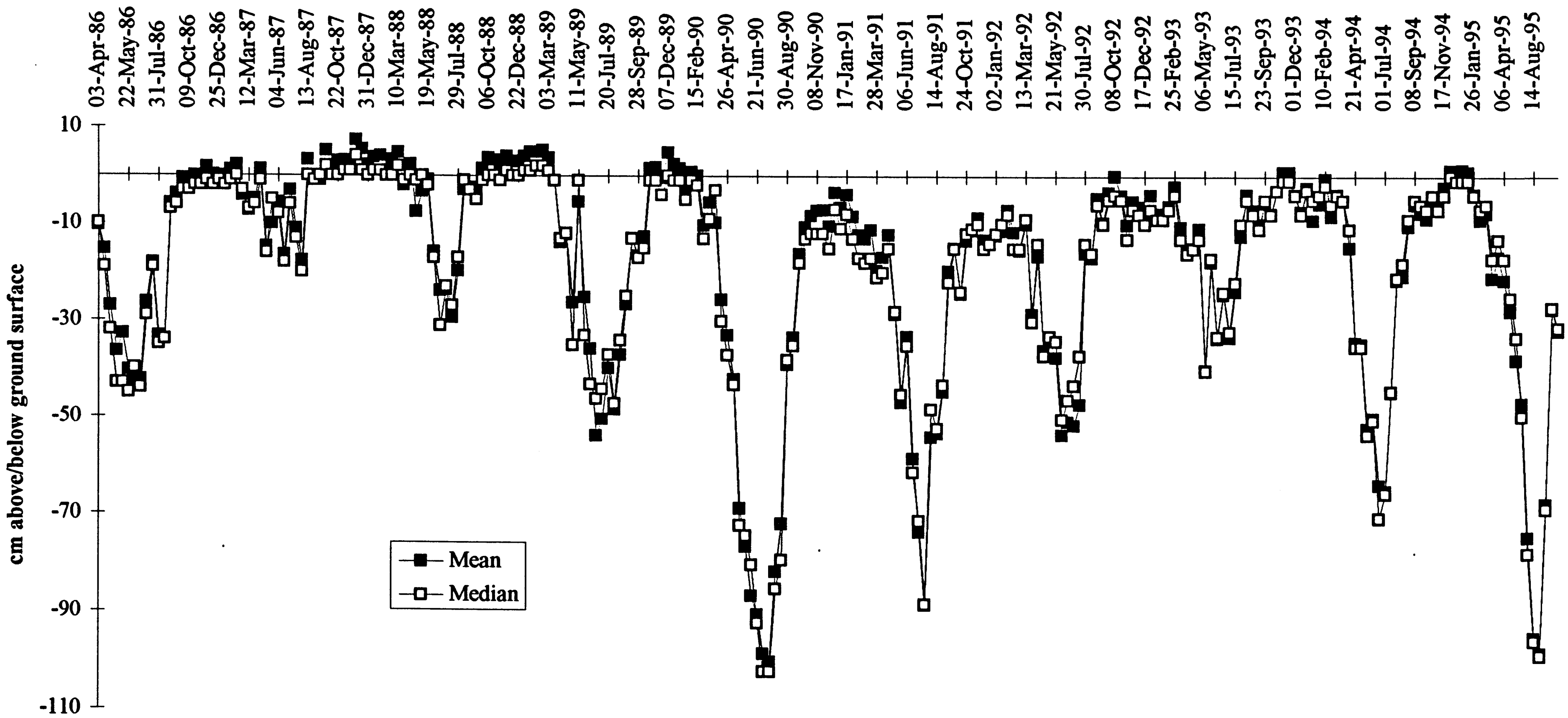


Figure 2.7: Minimum & maximum water table depth over time at Chippenham Fen, 1986-1995

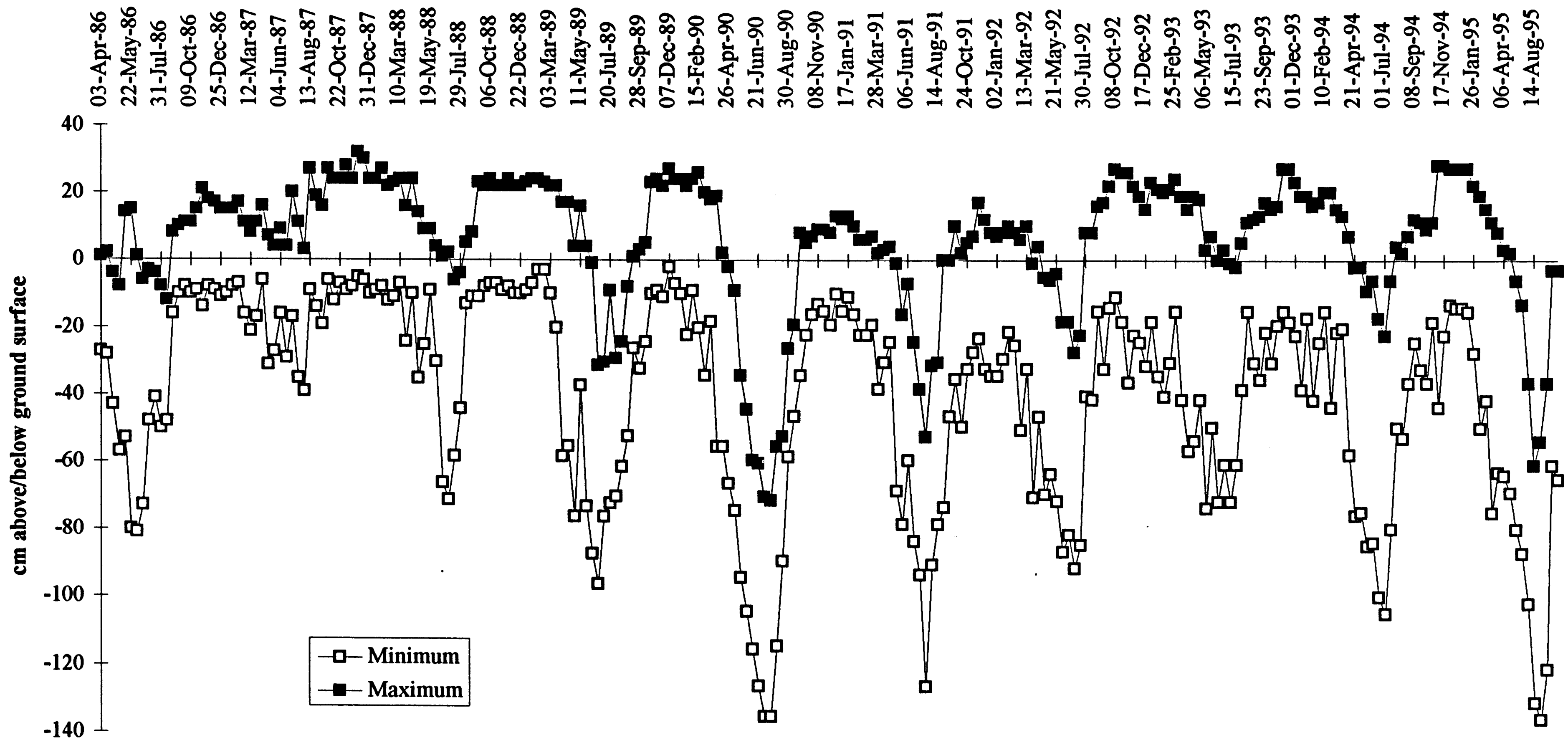


Figure 2.8: Data range over time for all dipwells at Chippenham Fen

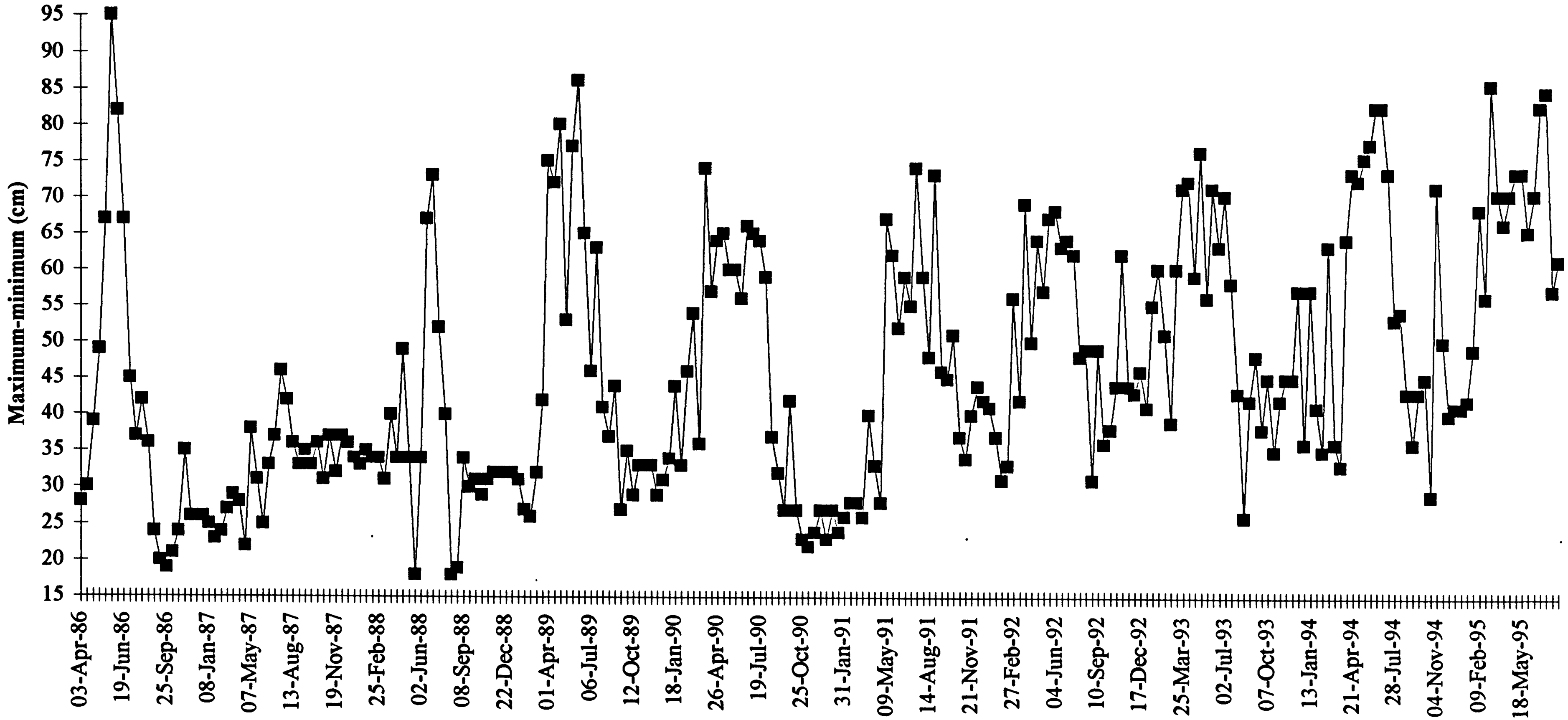


Figure 2.9a: Water table depth over time for Dipwell 1, Chippenham Fen 1986-1995

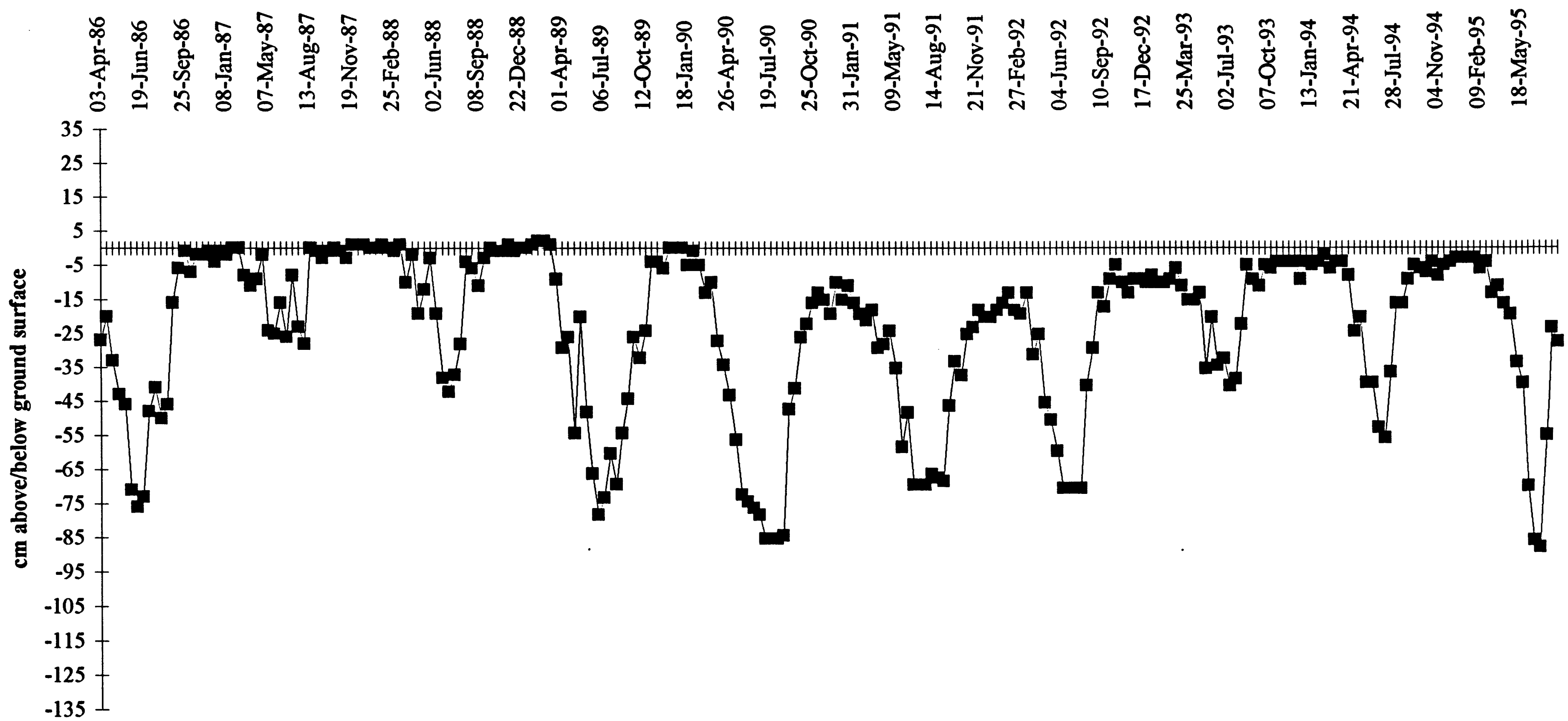


Figure 2.9b: Water table depth over time for Dipwell 2, Chippenham Fen 1986-1995

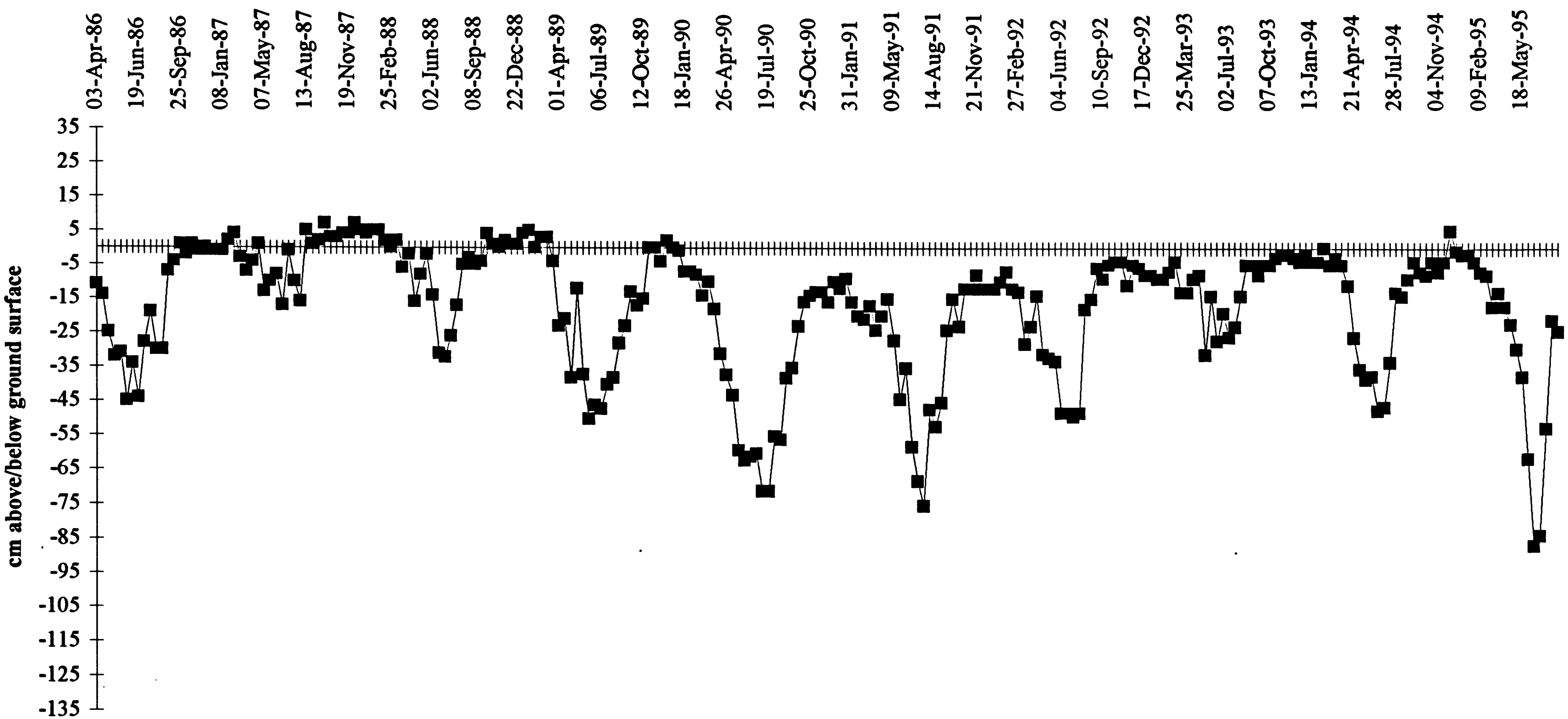


Figure 2.9c: Water table depth over time for Dipwell 3, Chippenham Fen 1986-1995

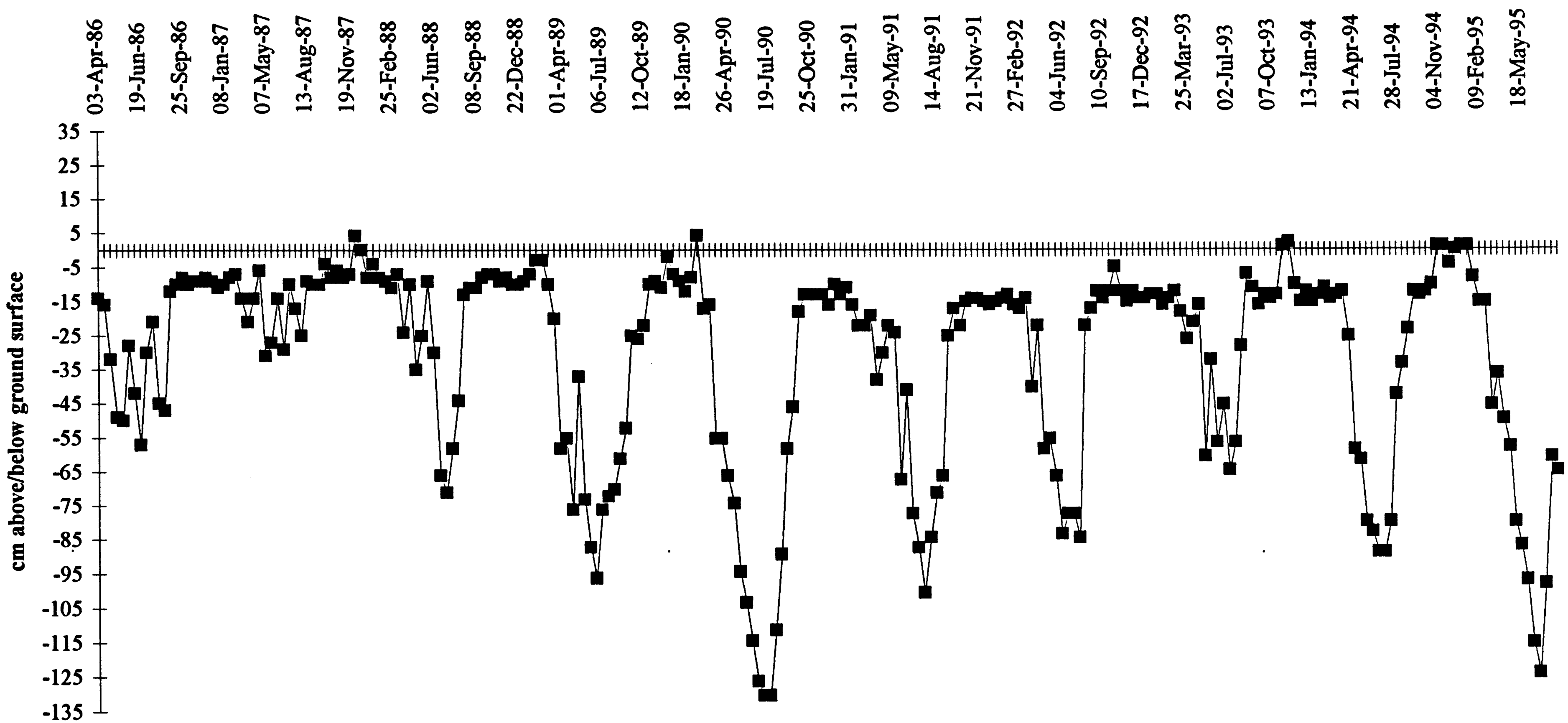


Figure 2.9d: Water table depth over time for Dipwell 4, Chippenham Fen 1986-1995

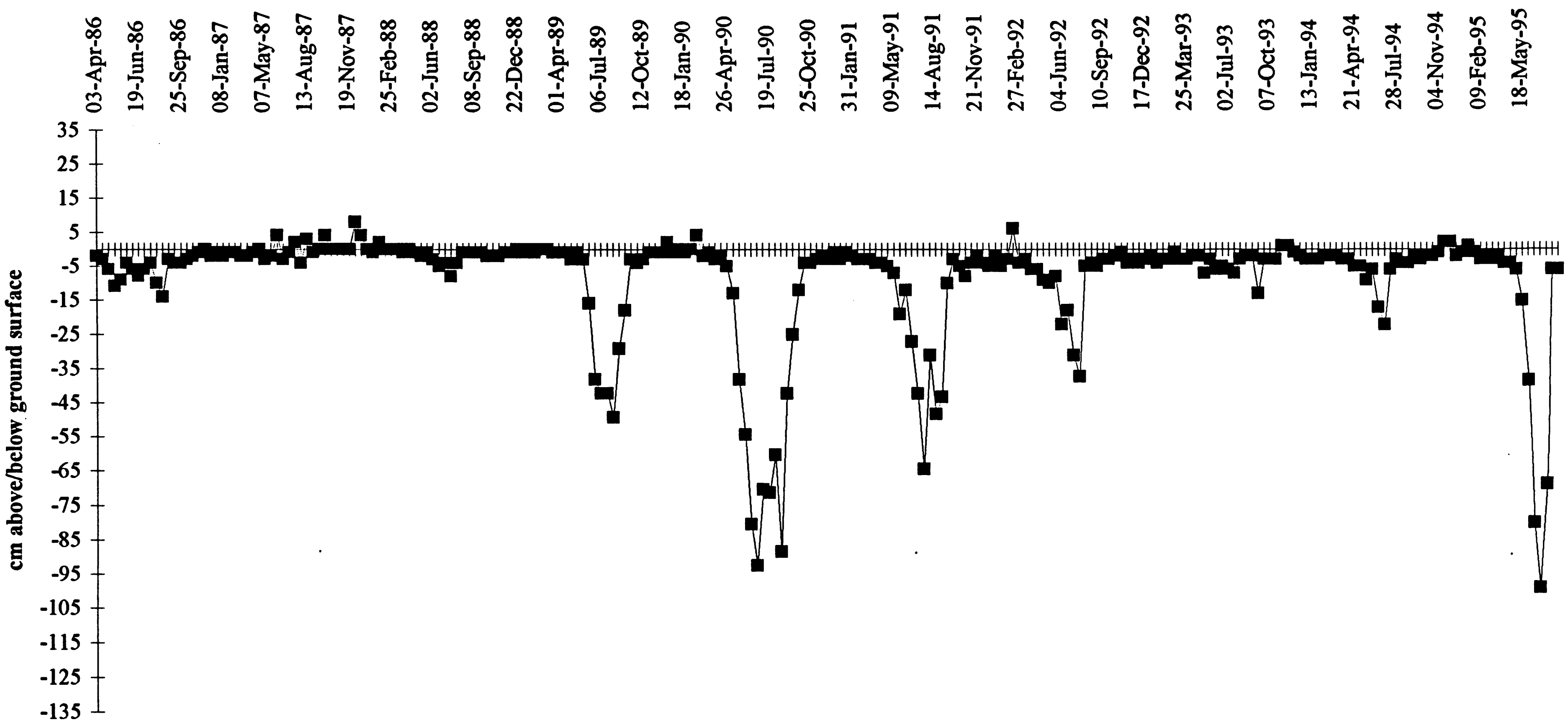


Figure 2.9e: Water table depth over time for Dipwell 5, Chippenham Fen 1986-1995

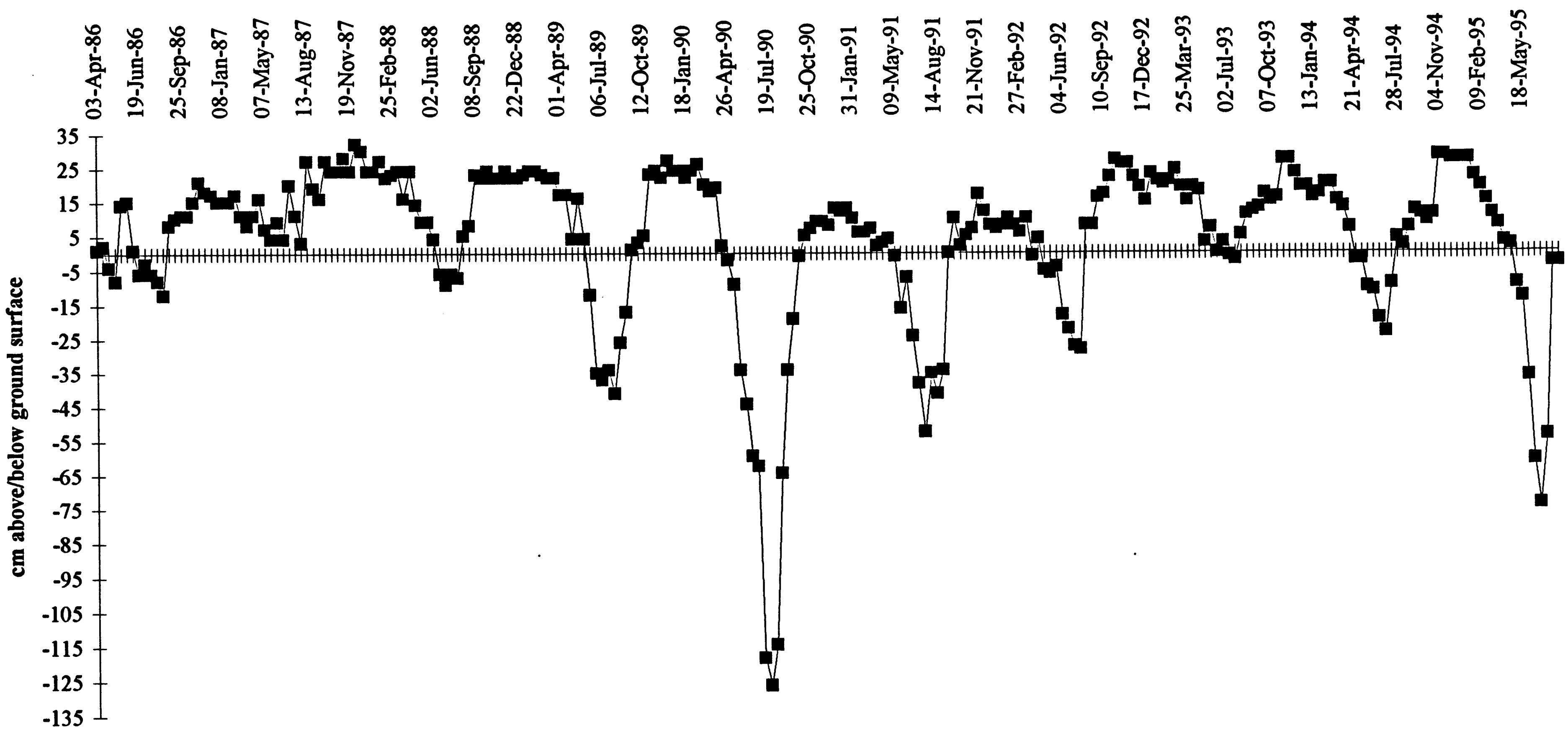


Figure 2.9f: Water table depth over time for Dipwell 6, Chippenham Fen 1986-1995

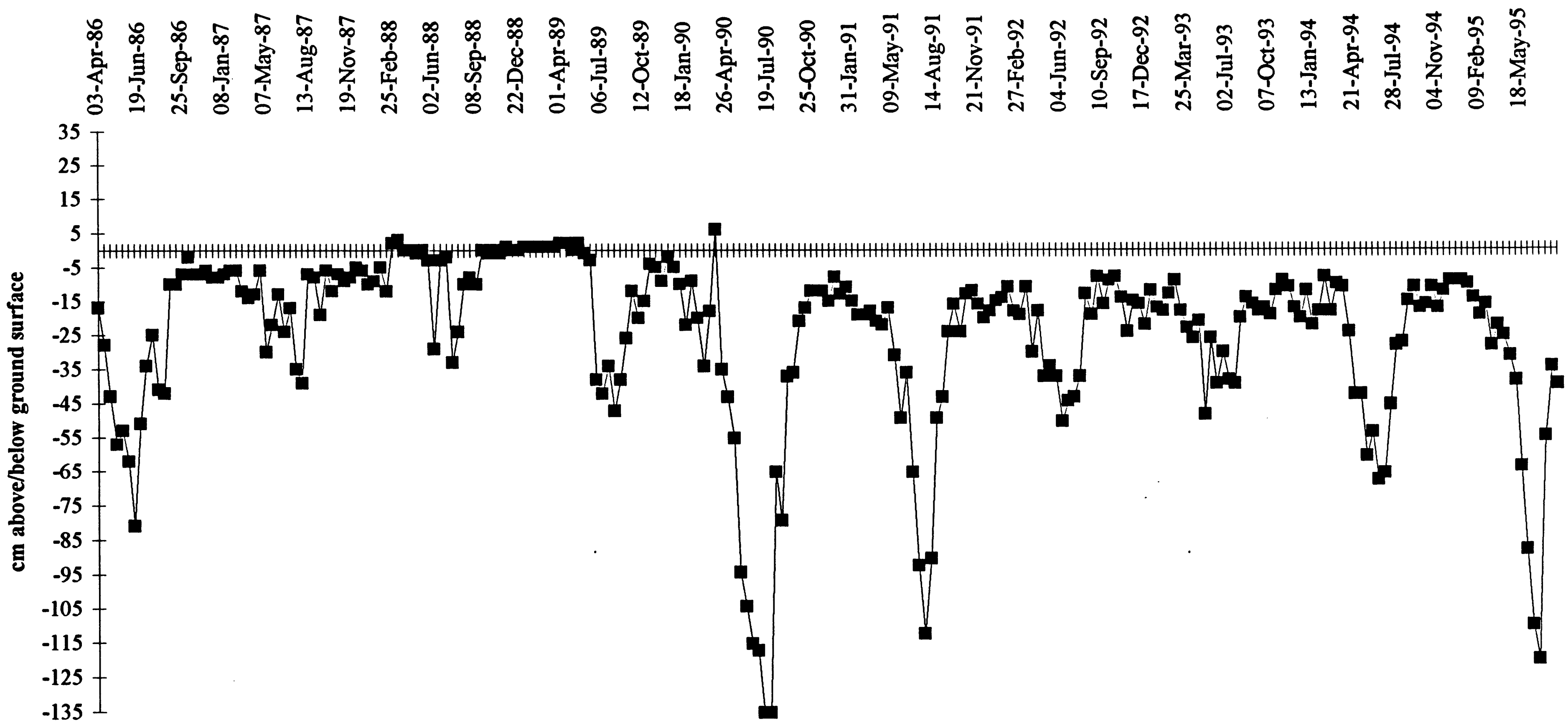


Figure 2.9g: Water table depth over time for Dipwell 7, Chippenham Fen 1986-1995

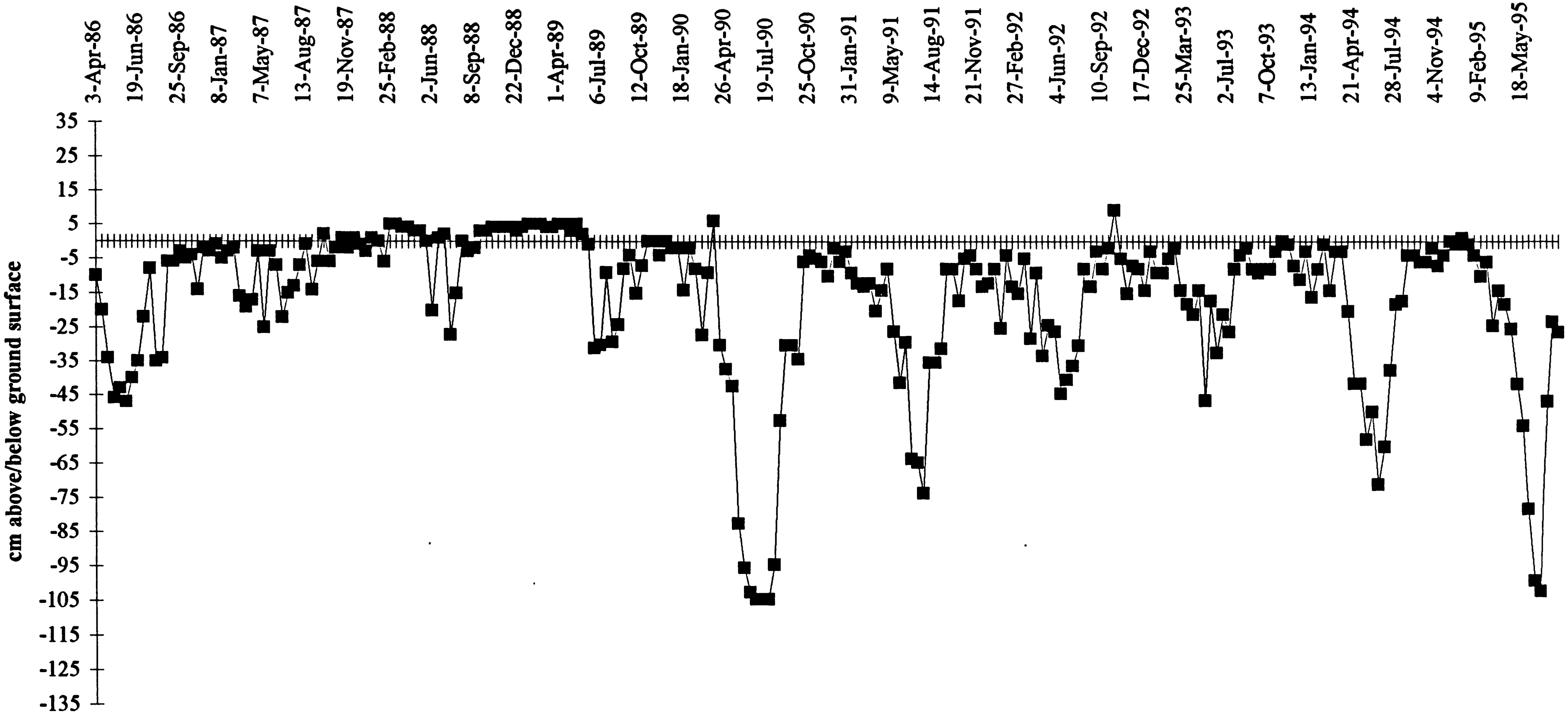


Figure 2.9h: Water table depth over time for Dipwell 8, Chippenham Fen 1986-1995

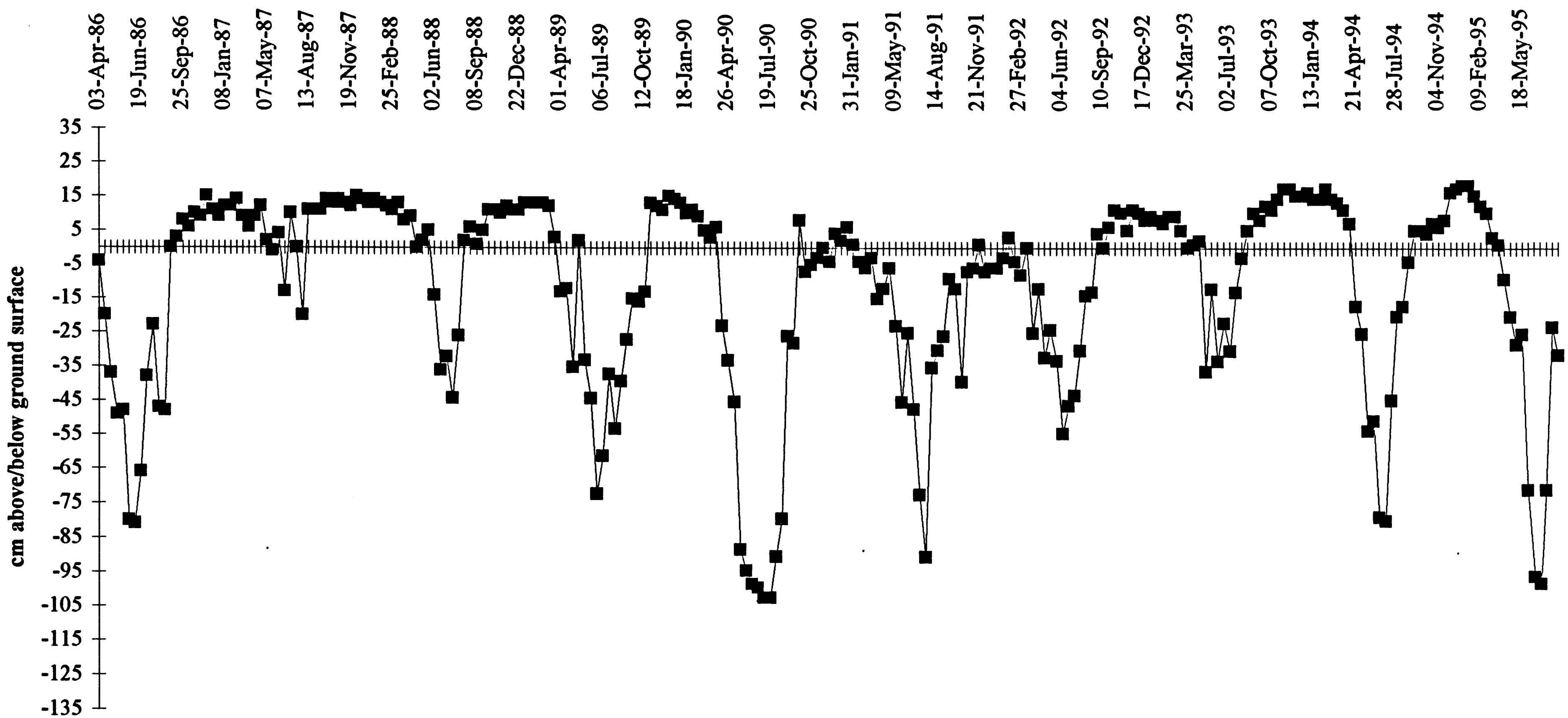


Figure 2.9i: Water table depth over time for Dipwell 9, Chippenham Fen 1986-1995

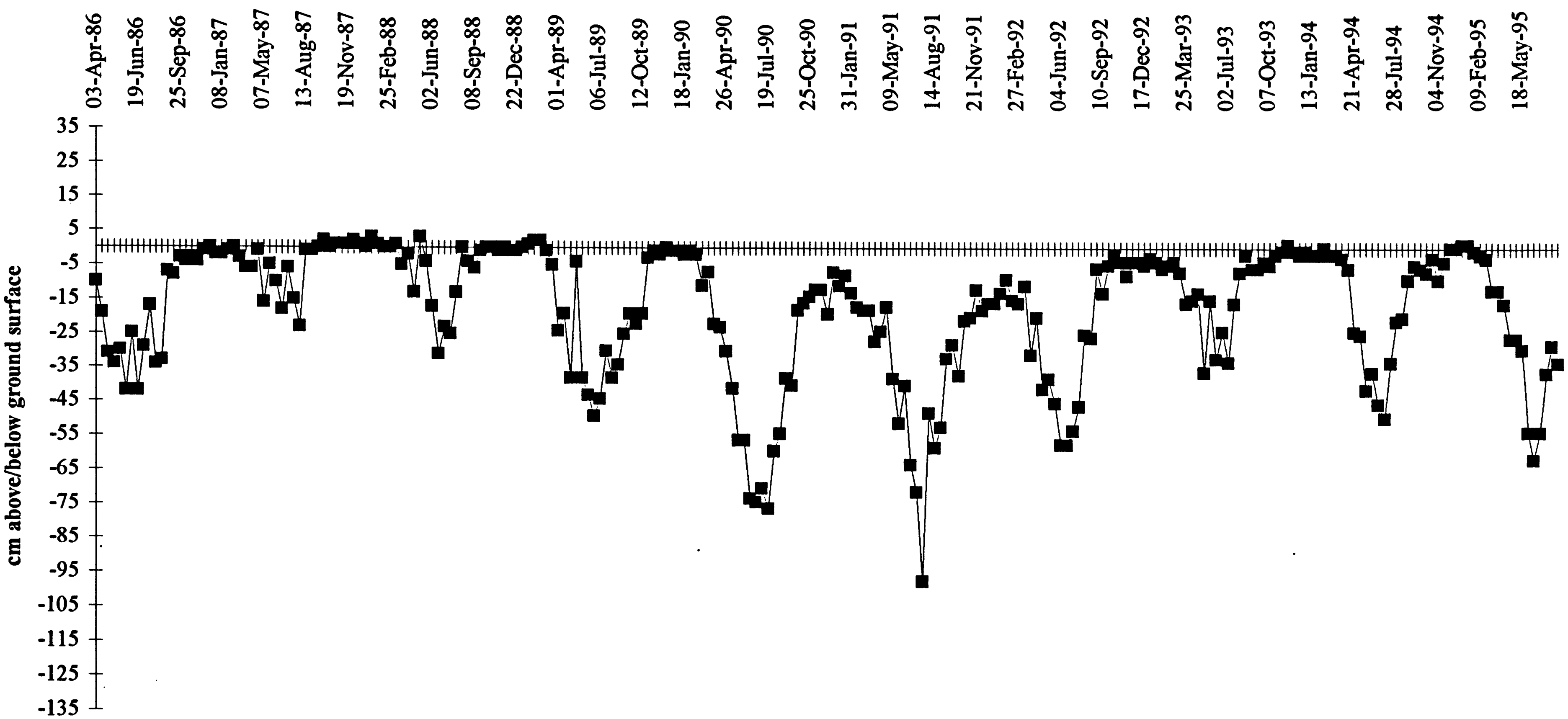


Figure 2.9j: Water table depth over time for Dipwell 10, Chippenham Fen 1991-1995

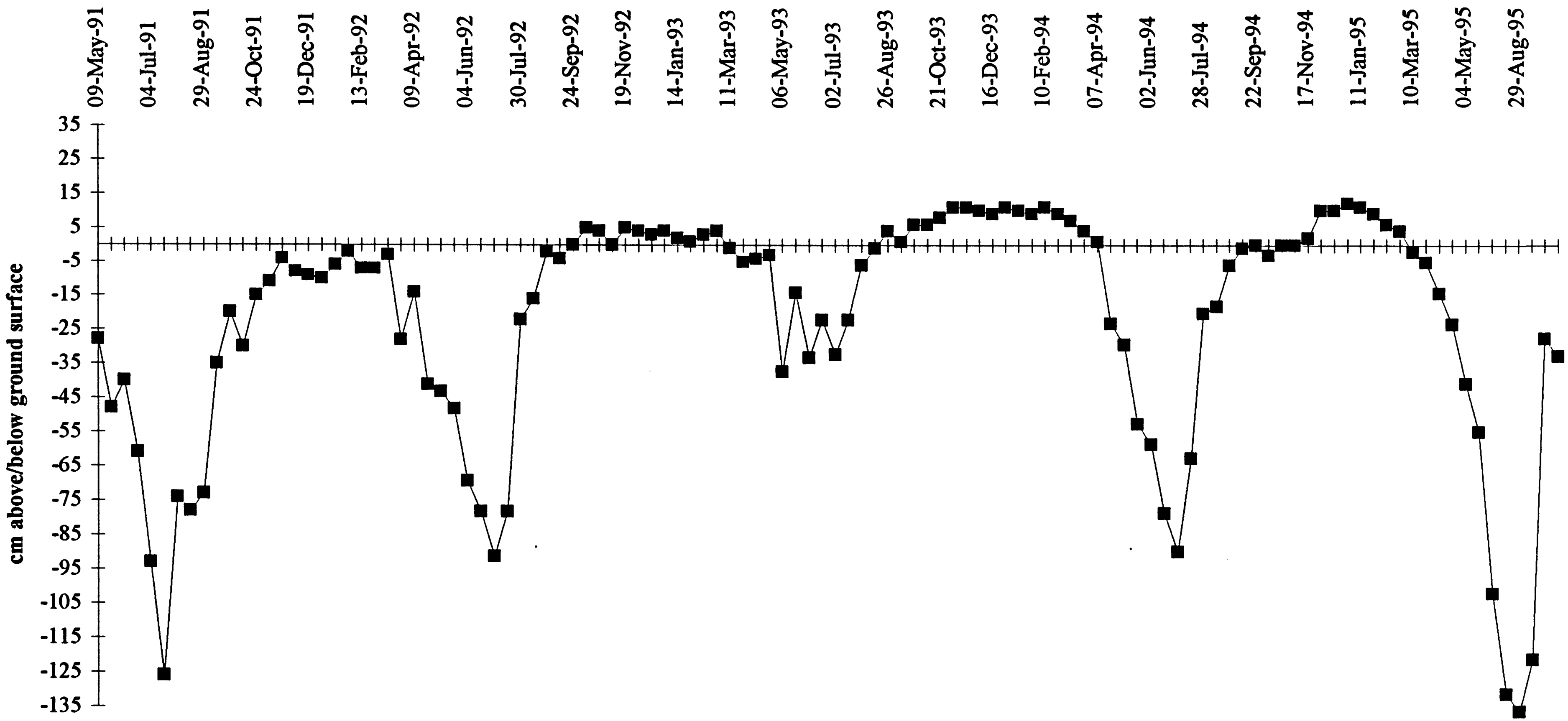


Figure 2.9k: Water table depth over time for Dipwell 12, Chippenham Fen 1991-1995

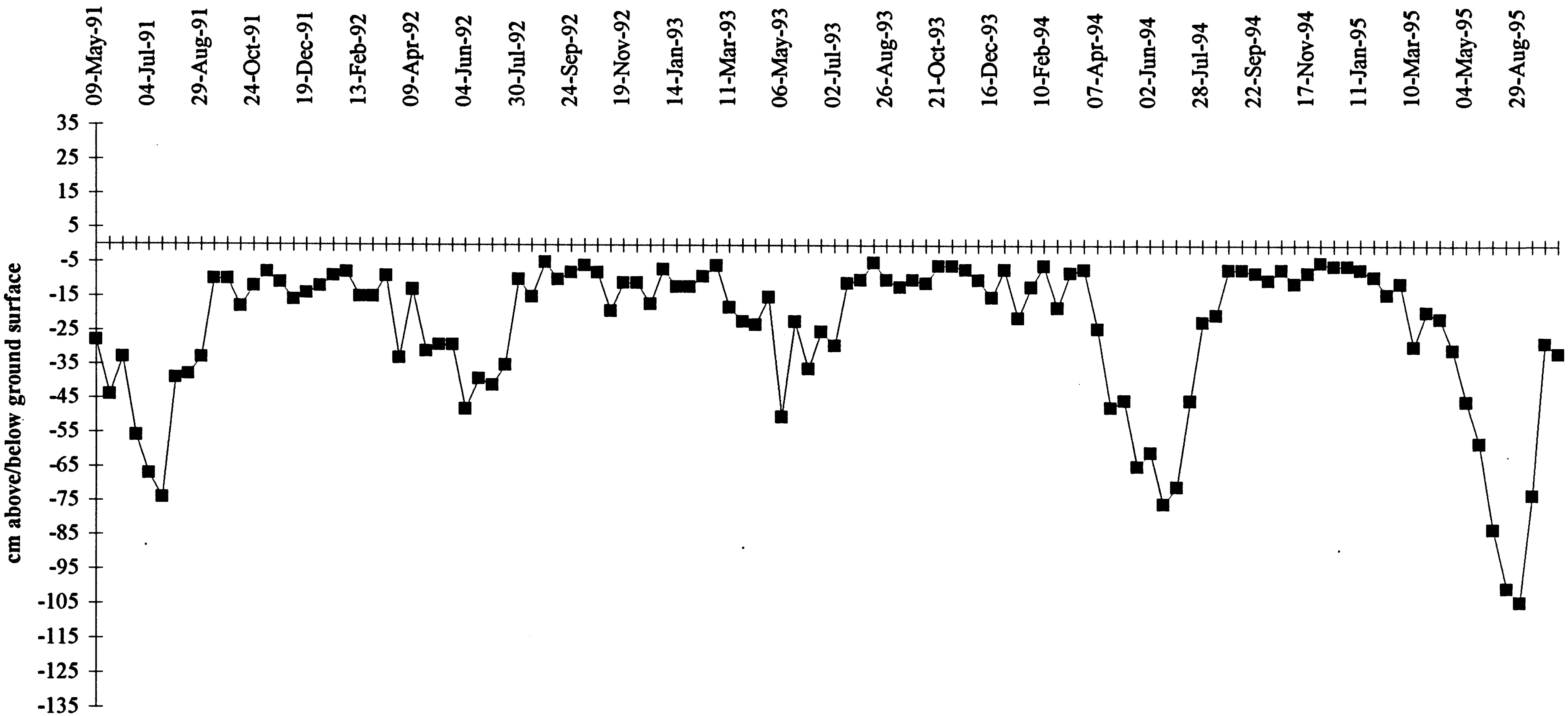


Figure 2.9l: Water table depth over time for Dipwell 13, Chippenham Fen 1991-1995

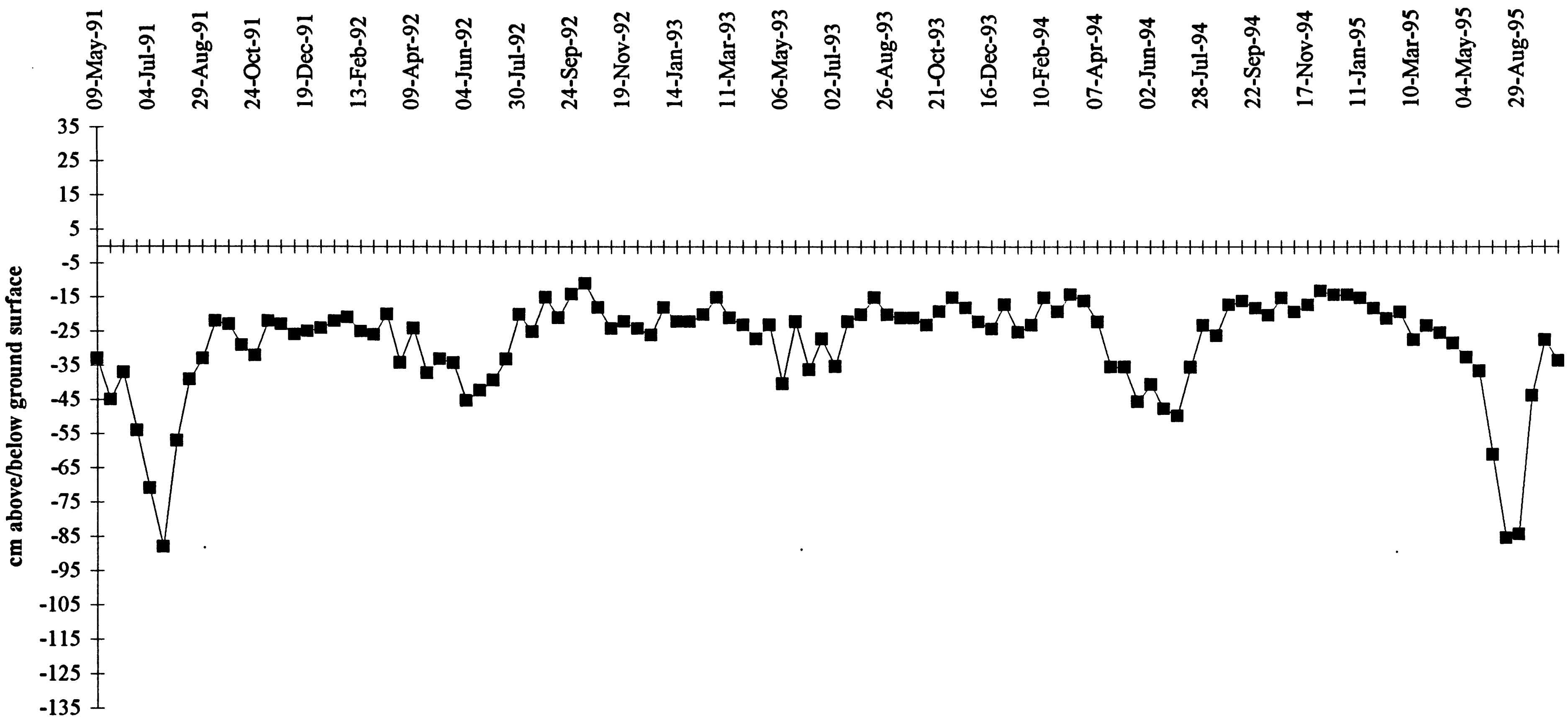


Figure 2.9m: Water table depth over time for Dipwell 14, Chippenham Fen 1991-1995

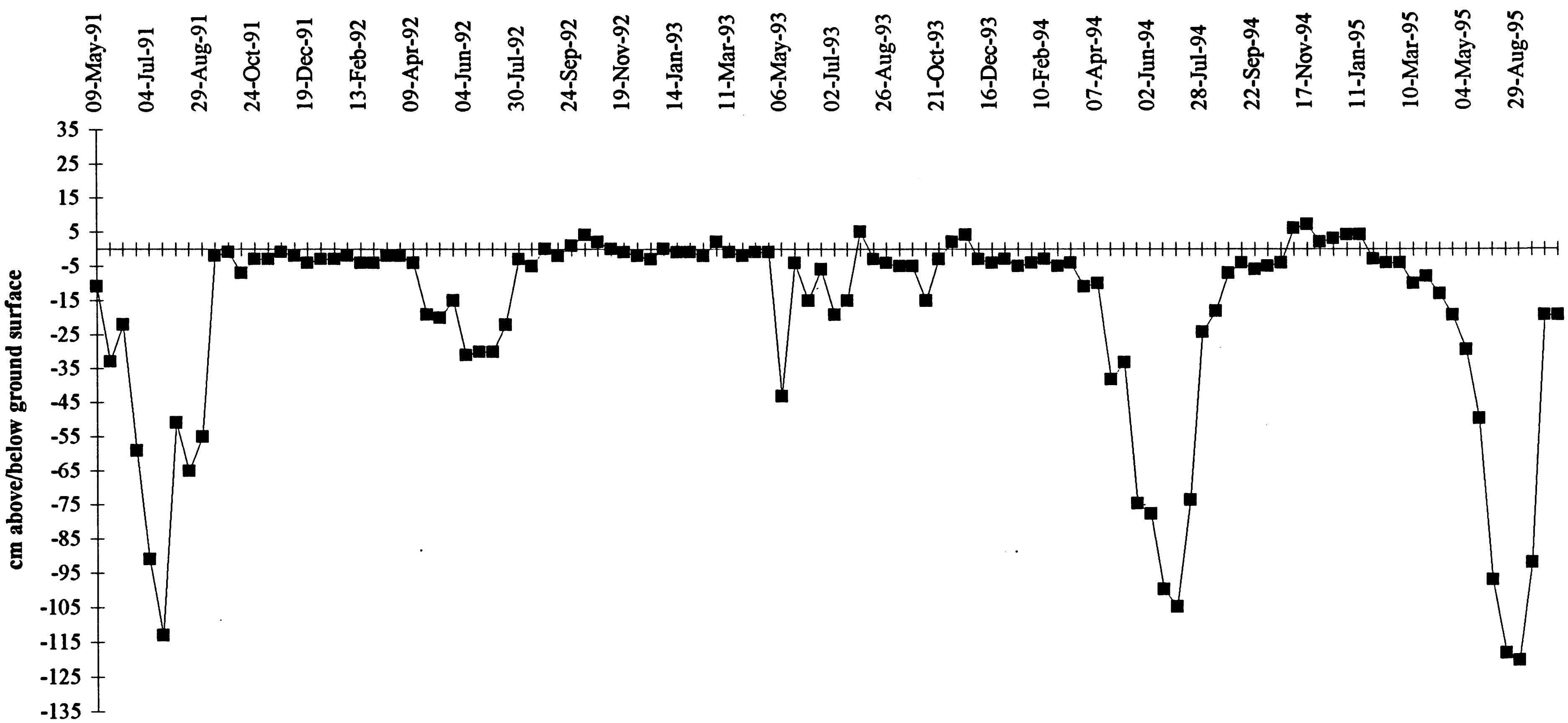


Figure 2.9n: Water table depth over time for Dipwell 15, Chippenham Fen 1991-1995

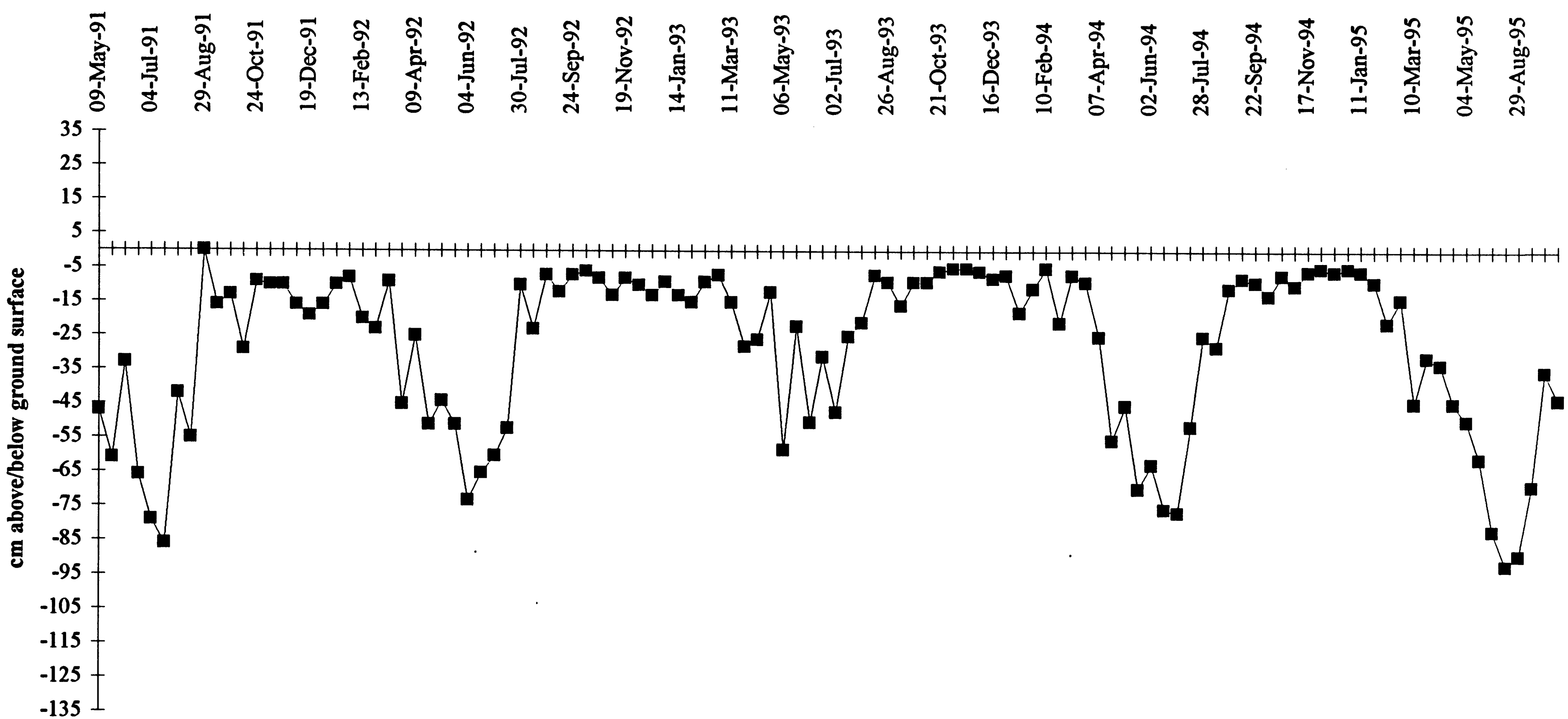


Figure 2.9o: Water table depth over time for Dipwell 16, Chippenham Fen 1991-1995

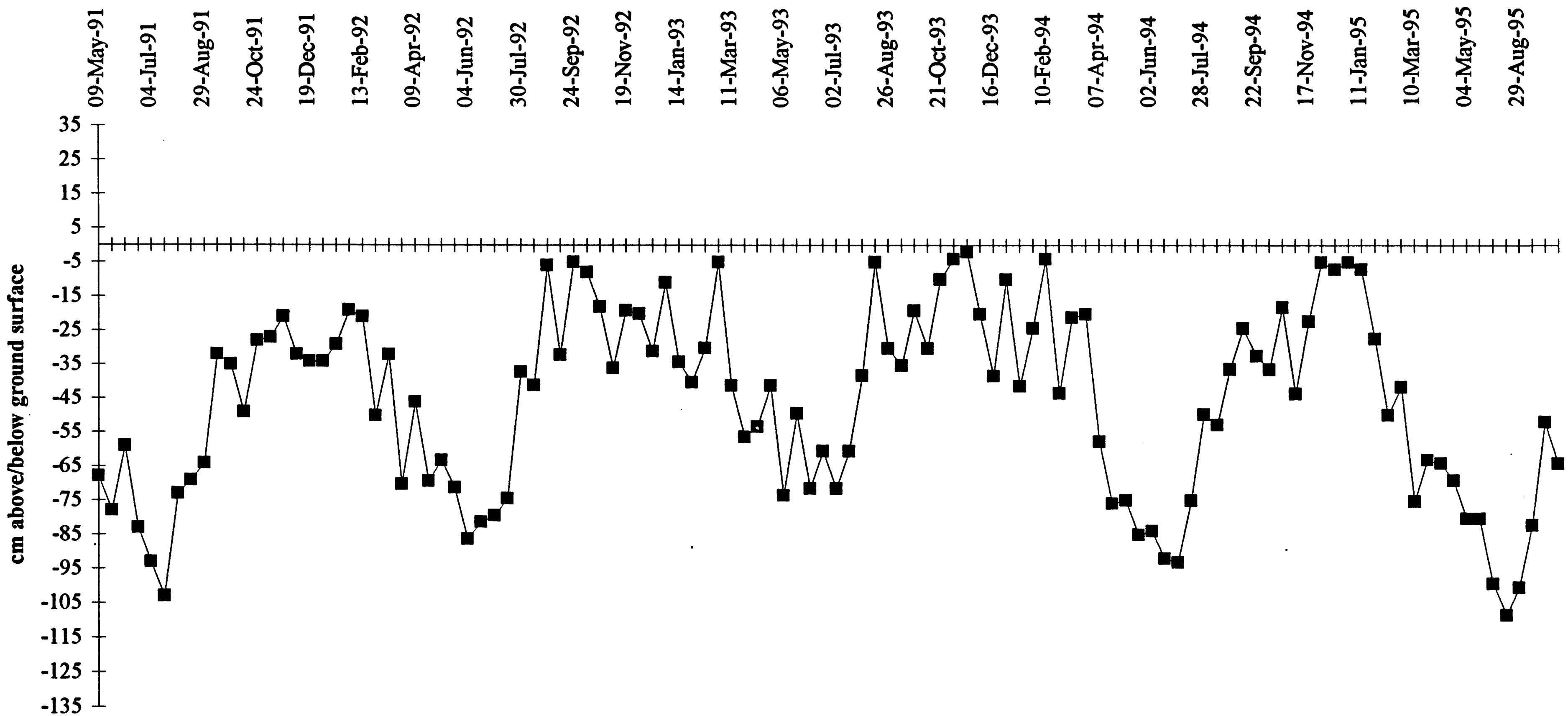


Figure 2.10: Annual site means for dipwells at Chippenham Fen, 1986-1995

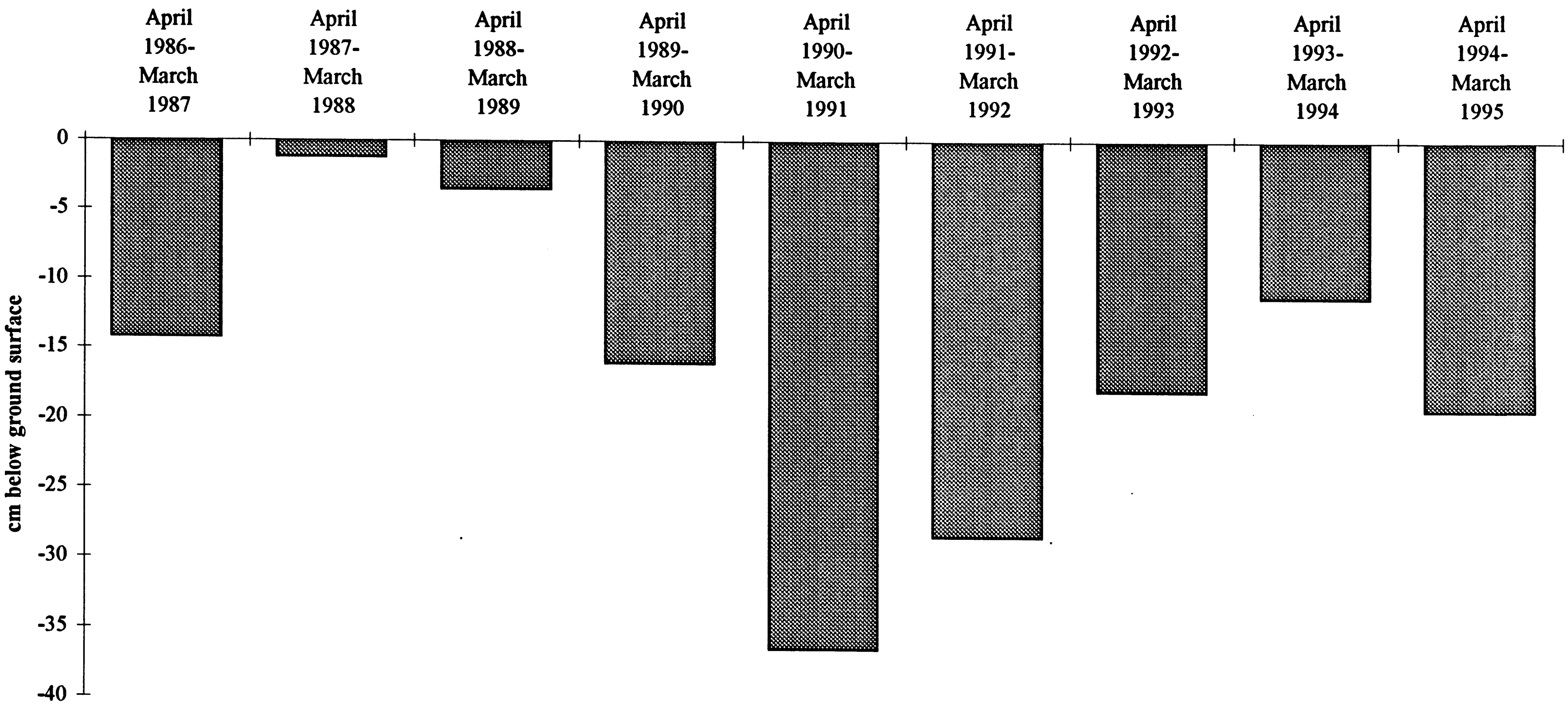


Figure 2.11: Seasonal means for water table depths in dipwells at Chippenham Fen, 1986-1995

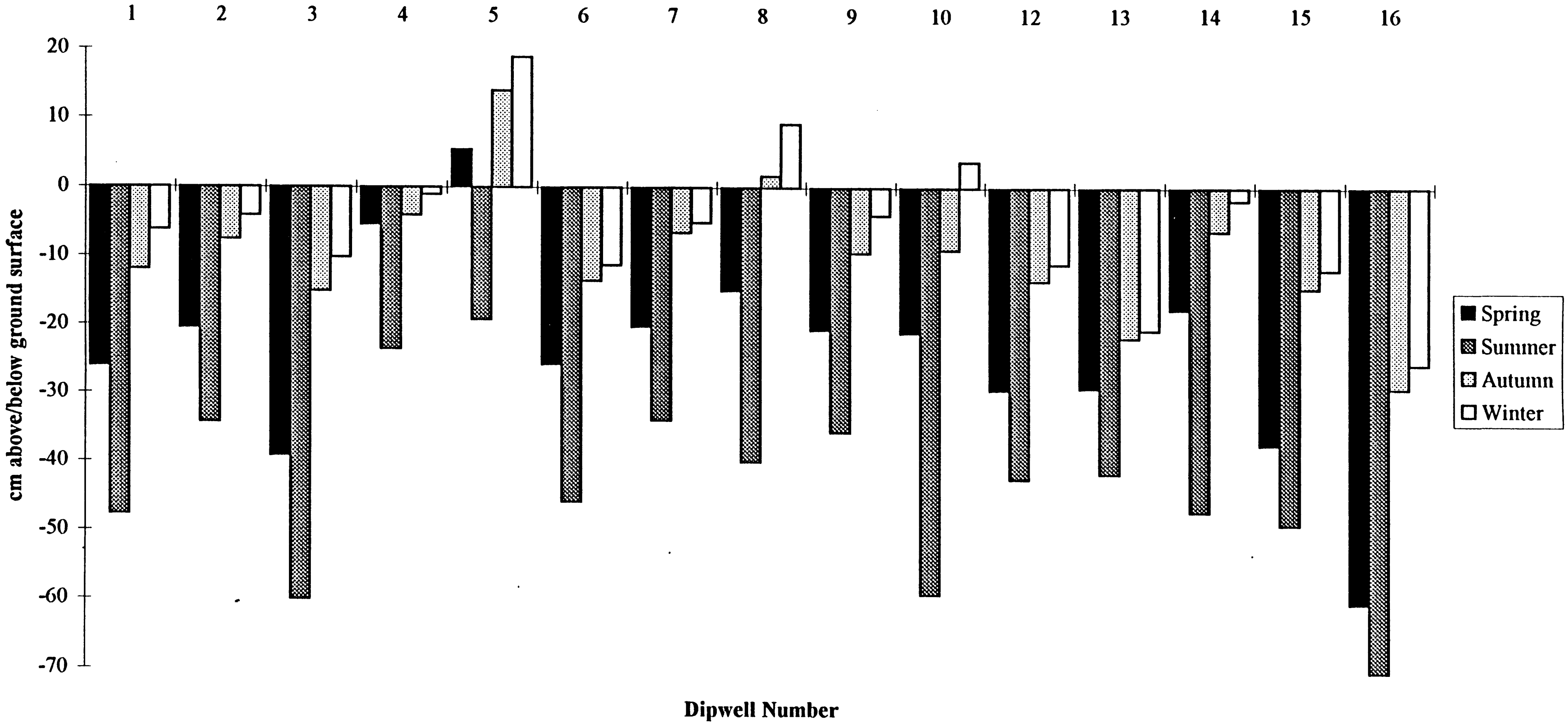


Figure 2.12: Seasonal mean water table depth for all dipwells at Chippenham Fen, 1986-1995

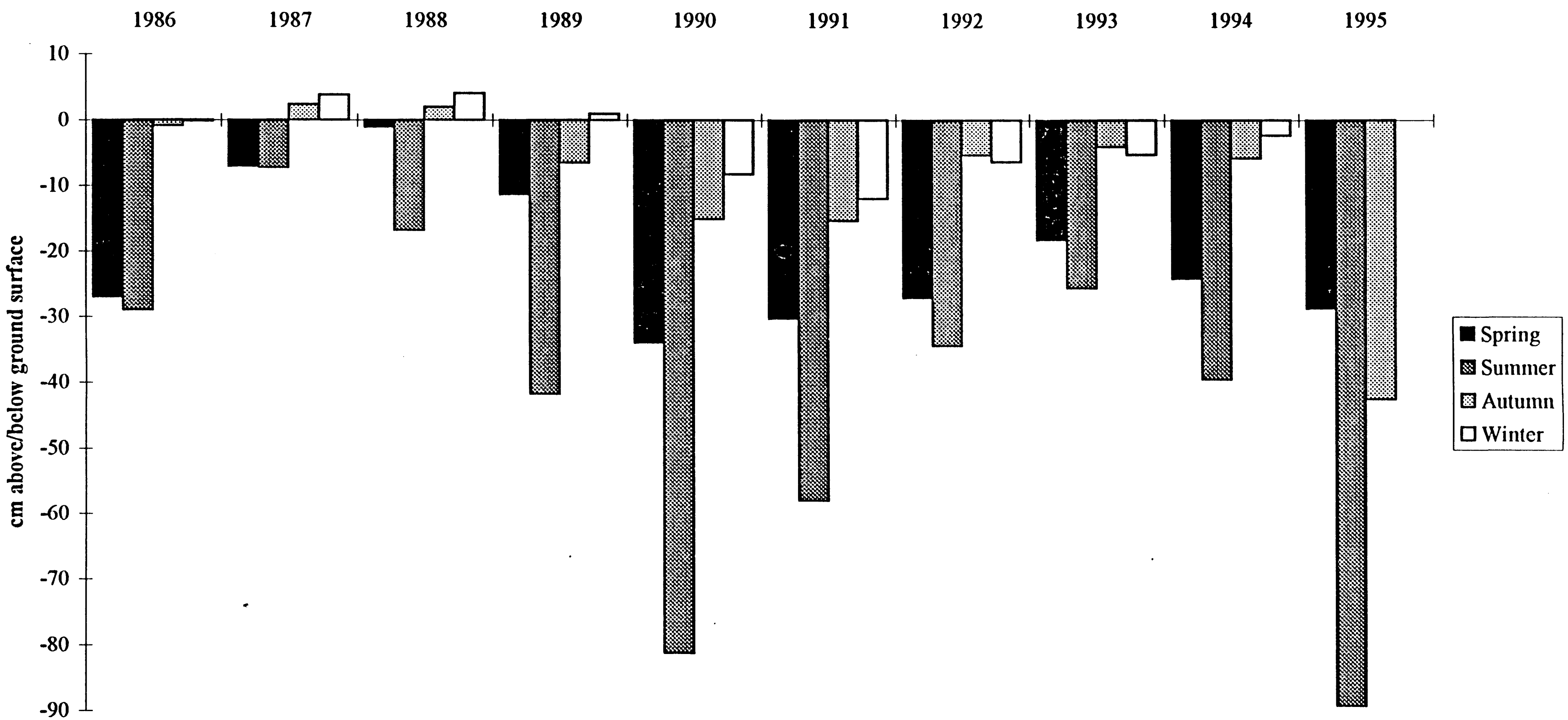


Figure 2.13a: Data over time relative to ordnance datum for dipwells 1-9, Chippenham Fen 1986-1995

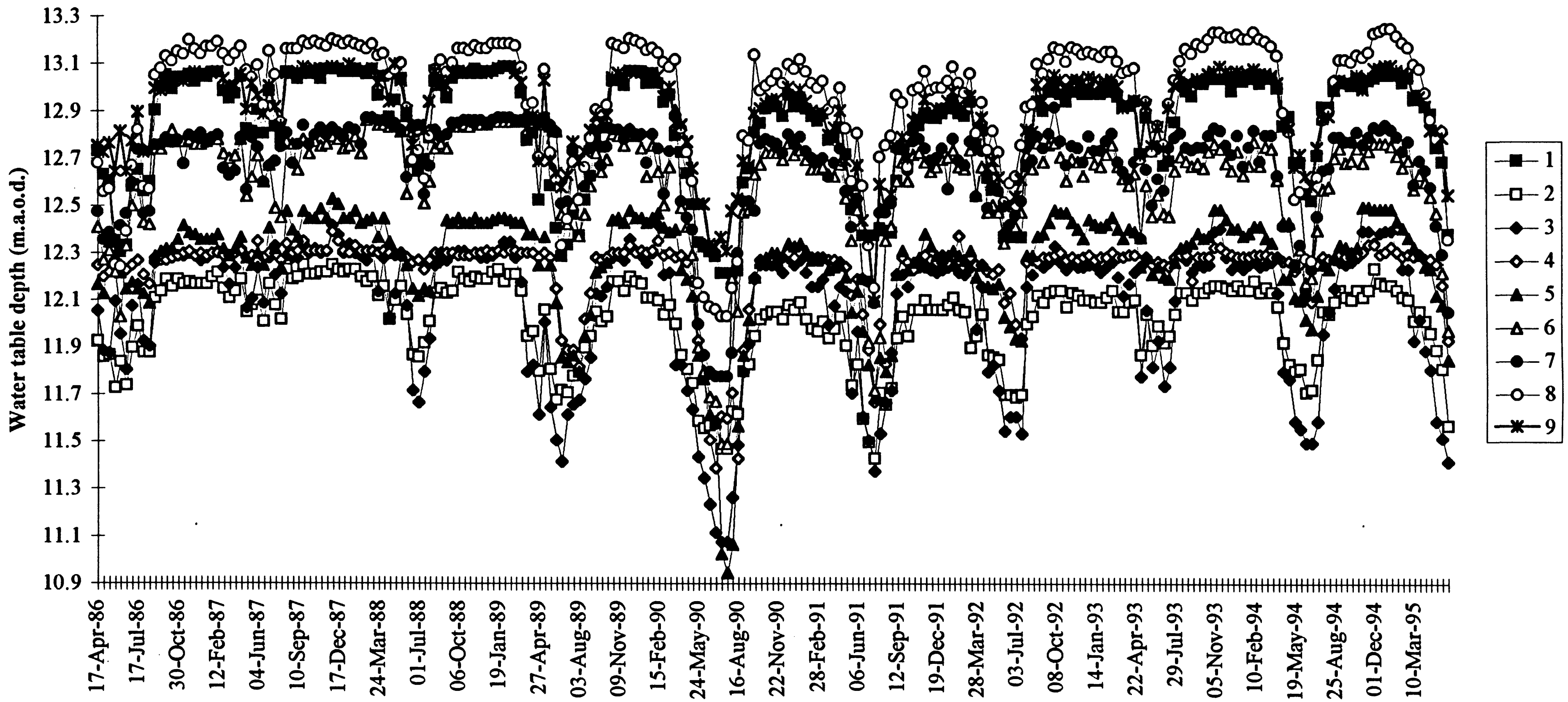


Figure 2.13b: Data over time relative to ordnance datum for dipwells 10 & 12-16, Chippenham Fen 1991-1995

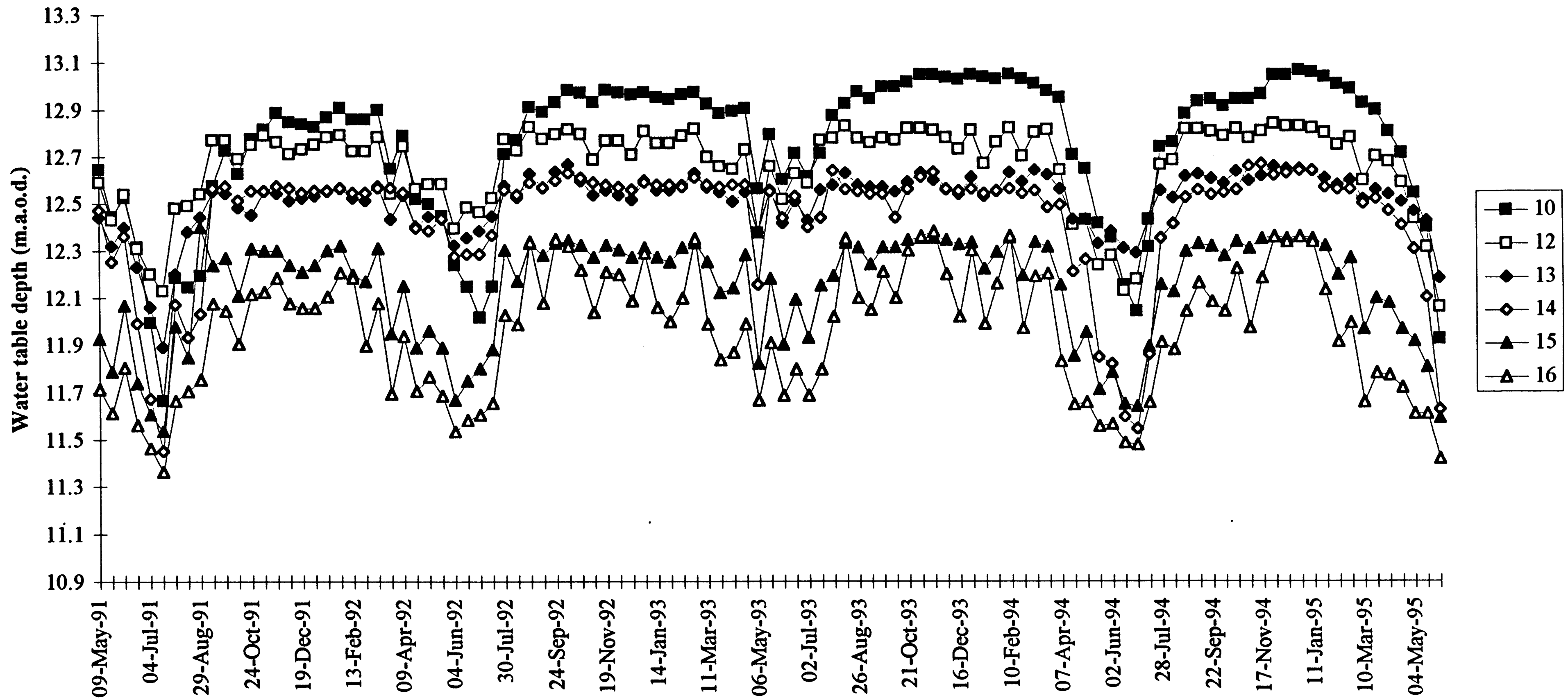


Figure 2.14: Mean water table depth for dipwells at Chippenham Fen for three specific time periods

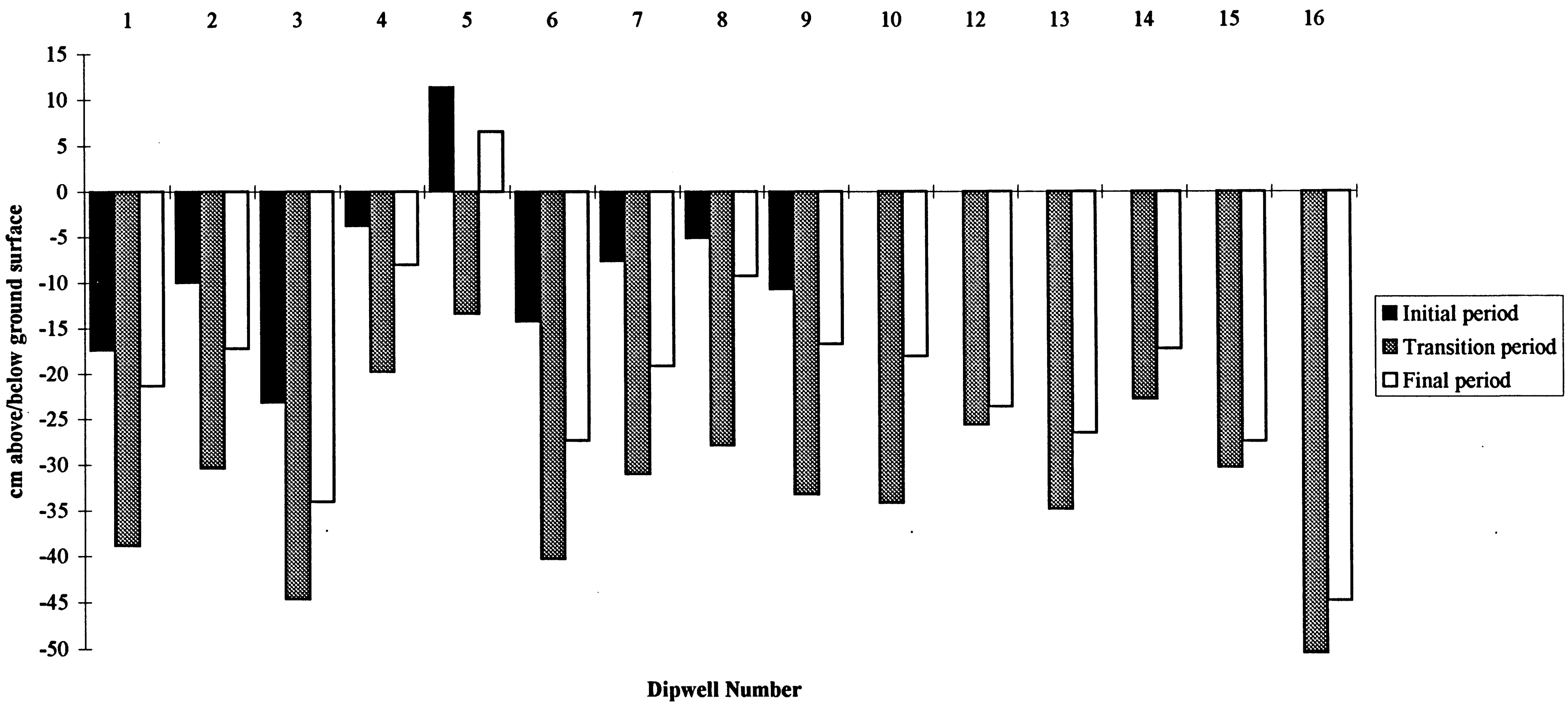


Figure 2.15: Histogram illustrating the distribution of mean values for dipwell readings at Chippenham Fen, 1986-1995

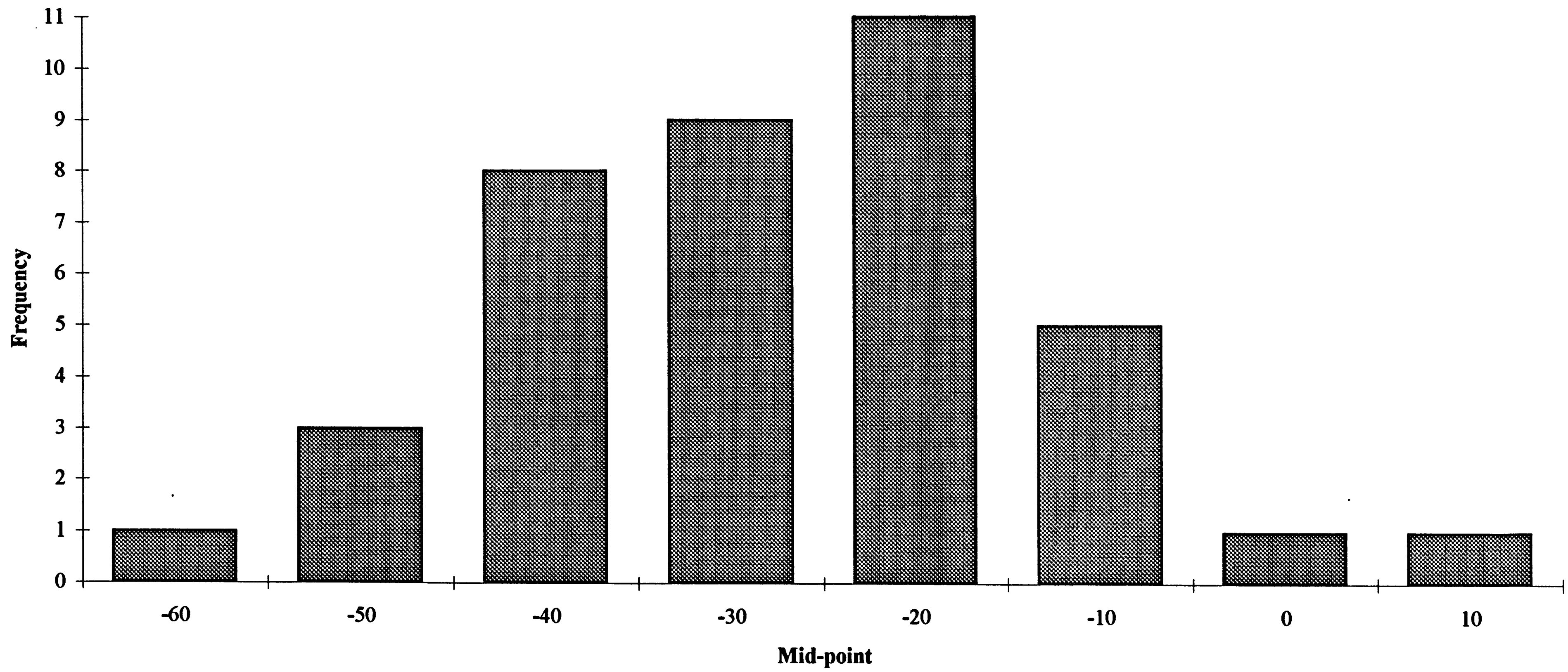


Figure 2.16: Readings from the principal spring piezometer and gauge board GB1 over time, Chippenham Fen

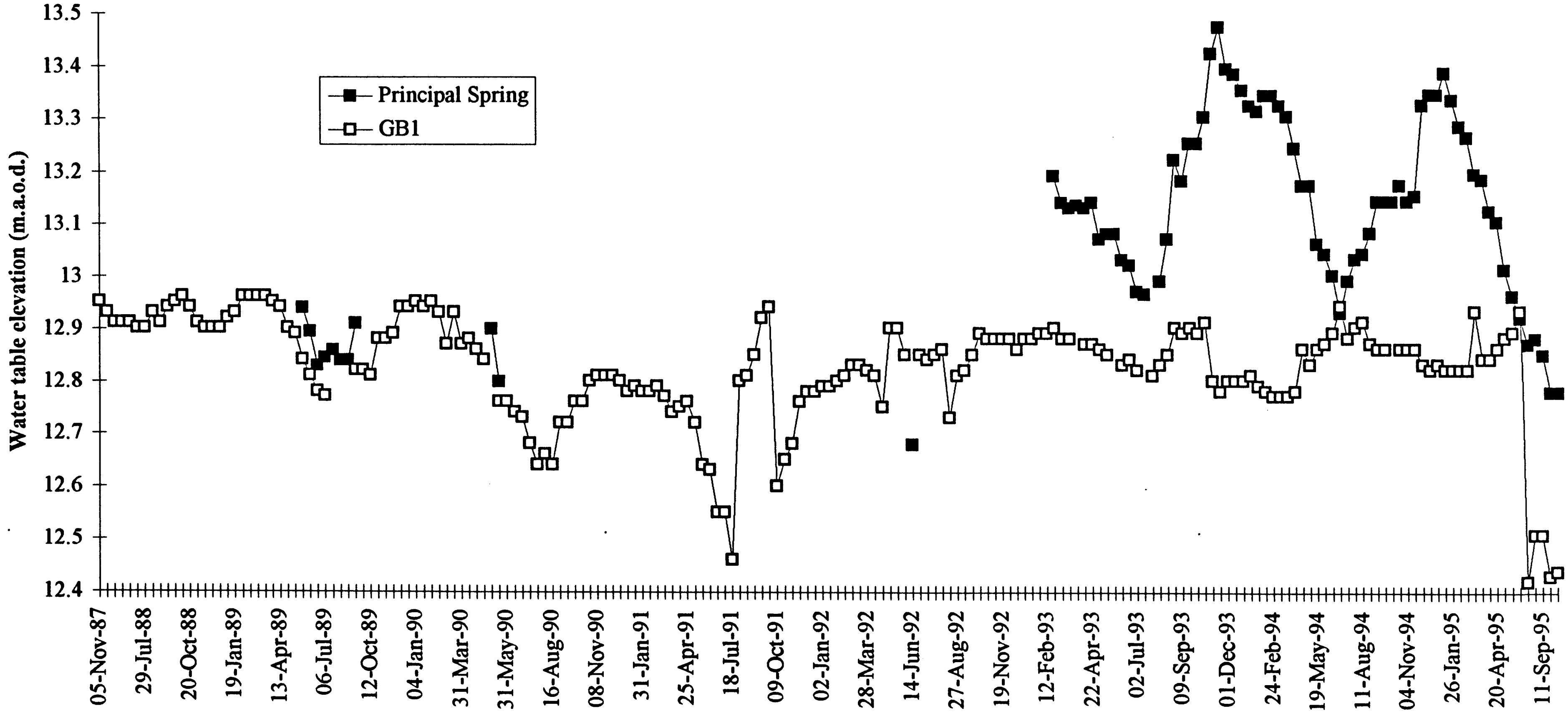


Figure 2.17: Readings over time for gaugeboards GB2 and GB3, Chippenham Fen

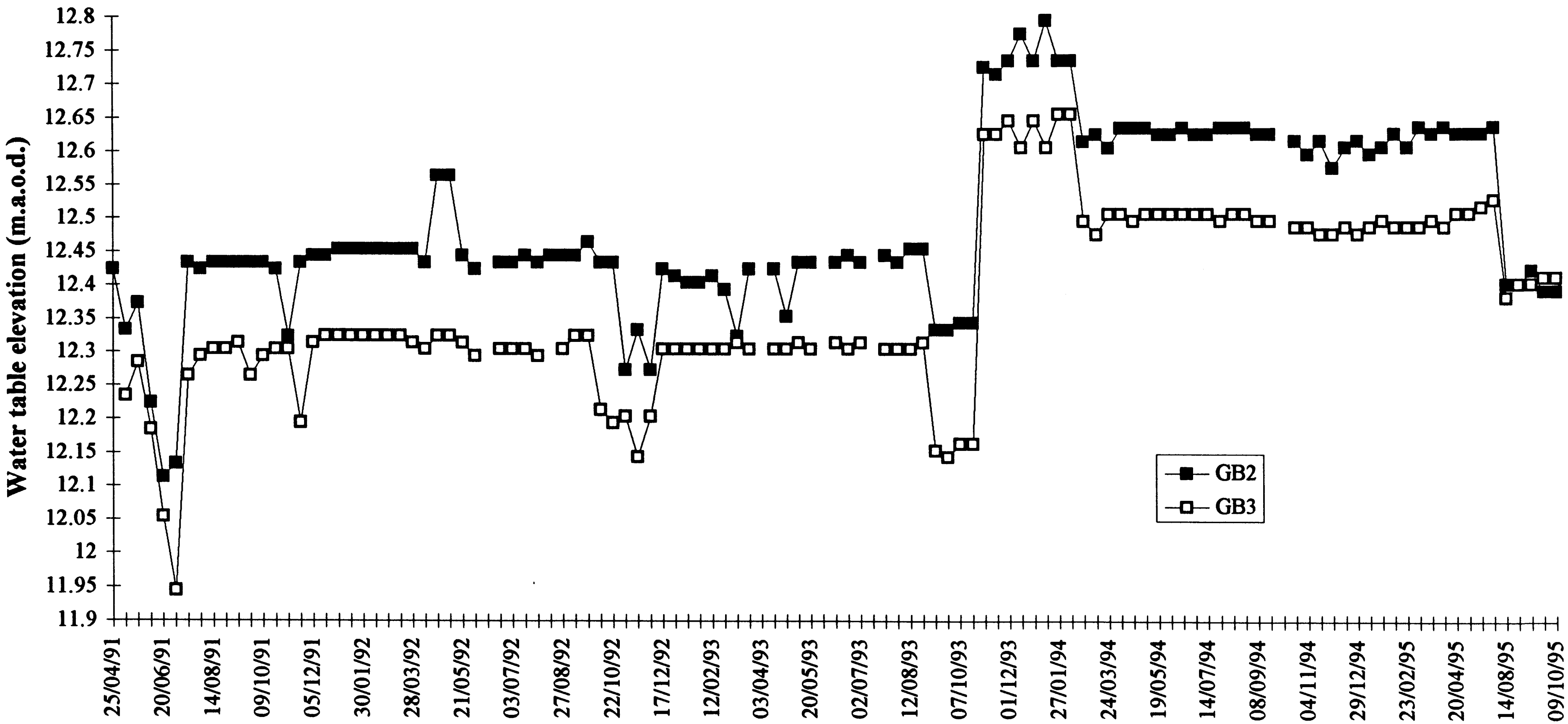


Figure 2.18: Data over time for manual readings at the Chippenham Fen observation borehole

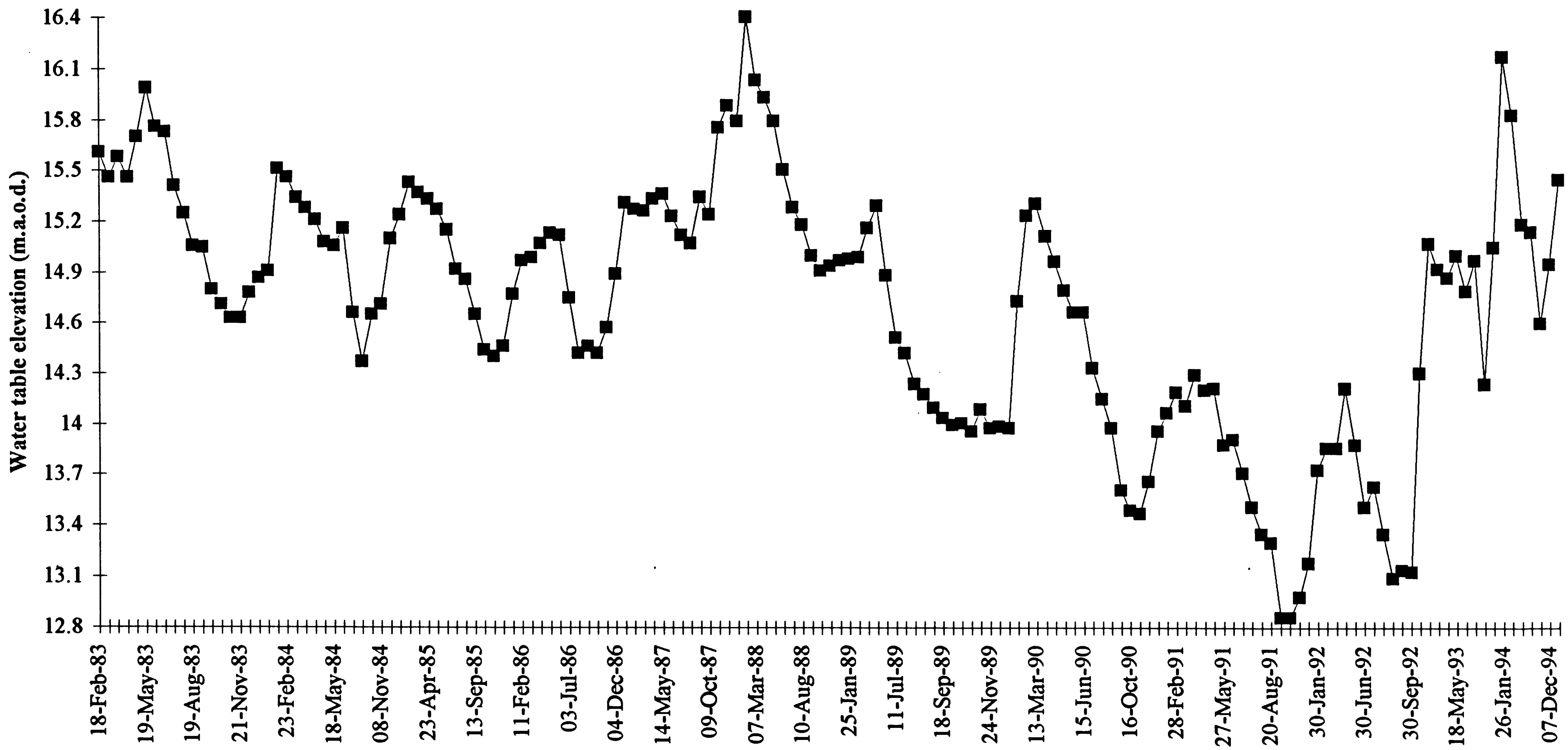


Figure 2.19: Annual means & medians for manual readings taken on at the observation borehole, Chippenham Fen.

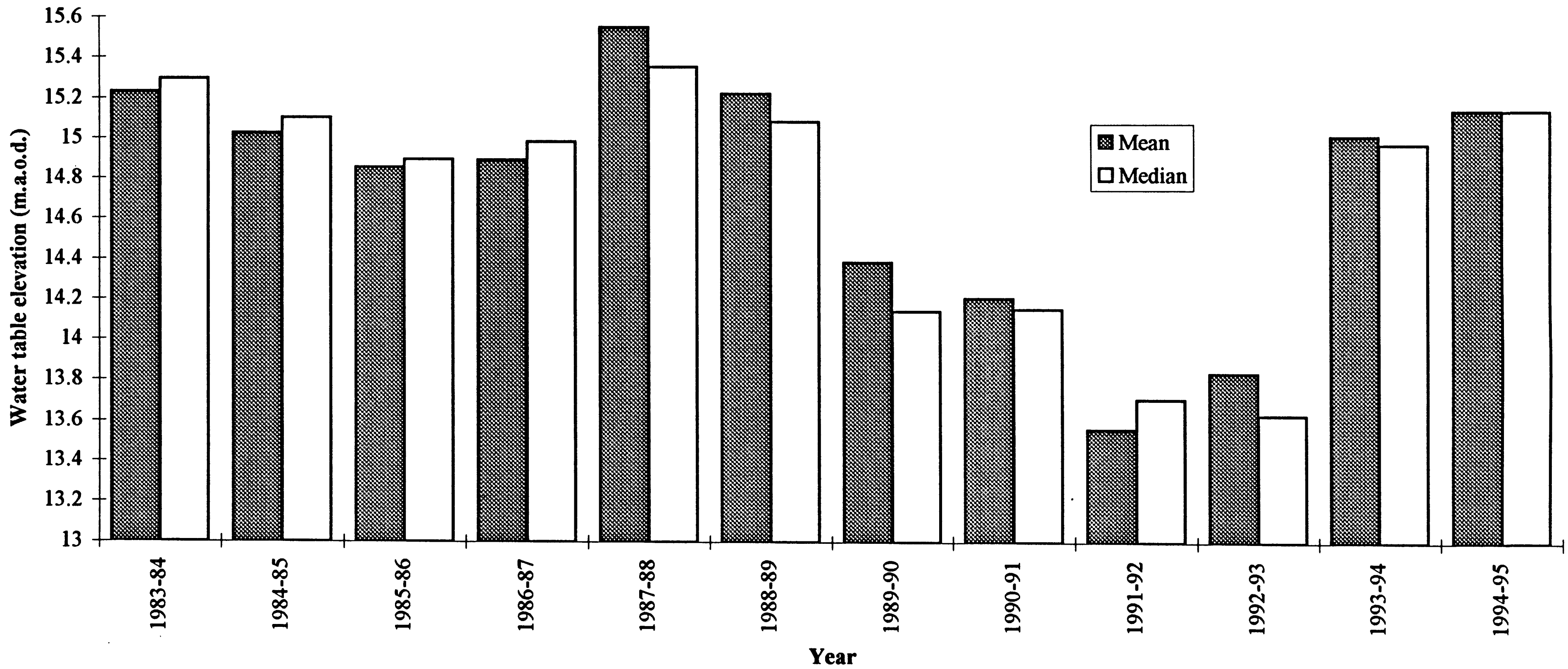


Figure 2.20: Data over time from the Chippenham Fen observation borehole automatic logger

Figure 2.21: Mean daily flow rate over time in the Chippenham River

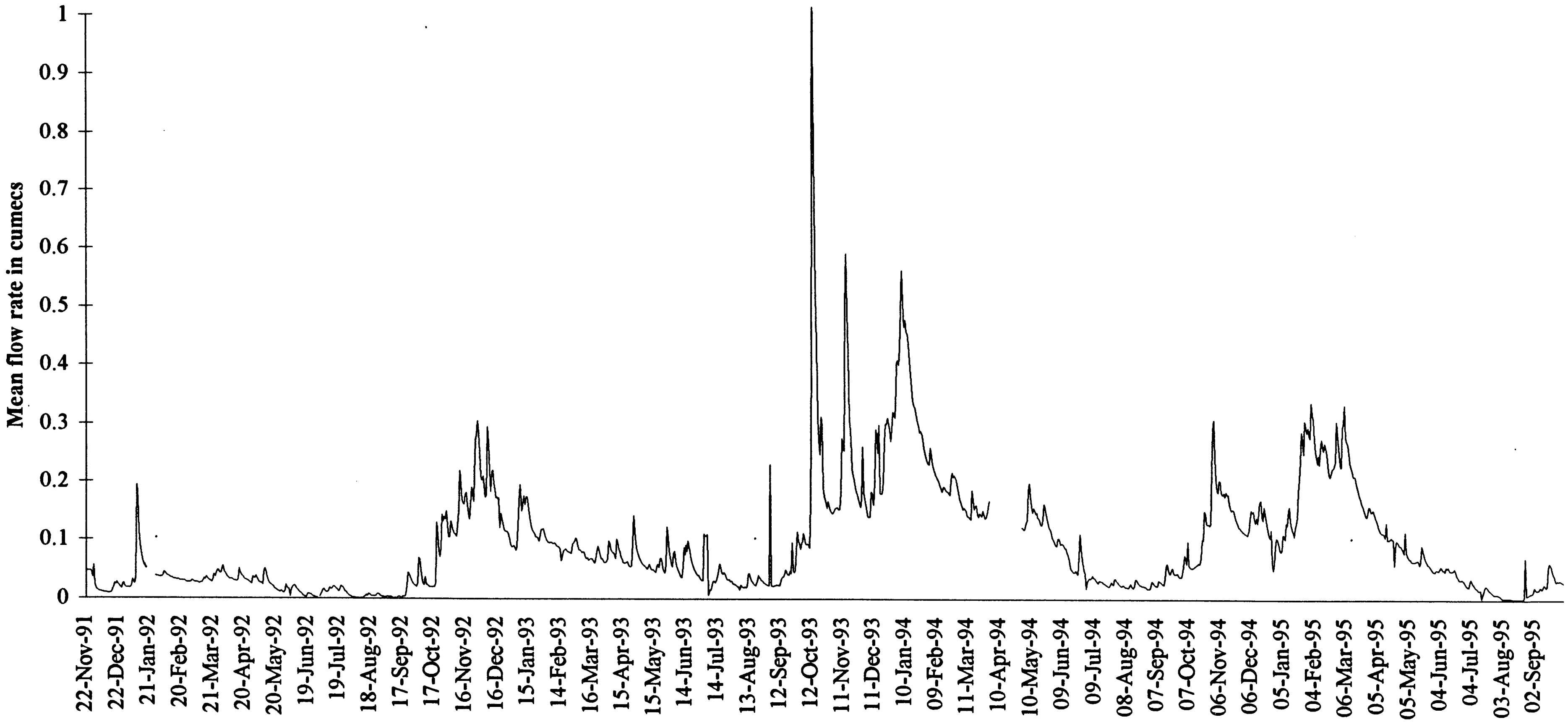


Figure 2.22: Log mean daily flow rate over time in the River Chippenham

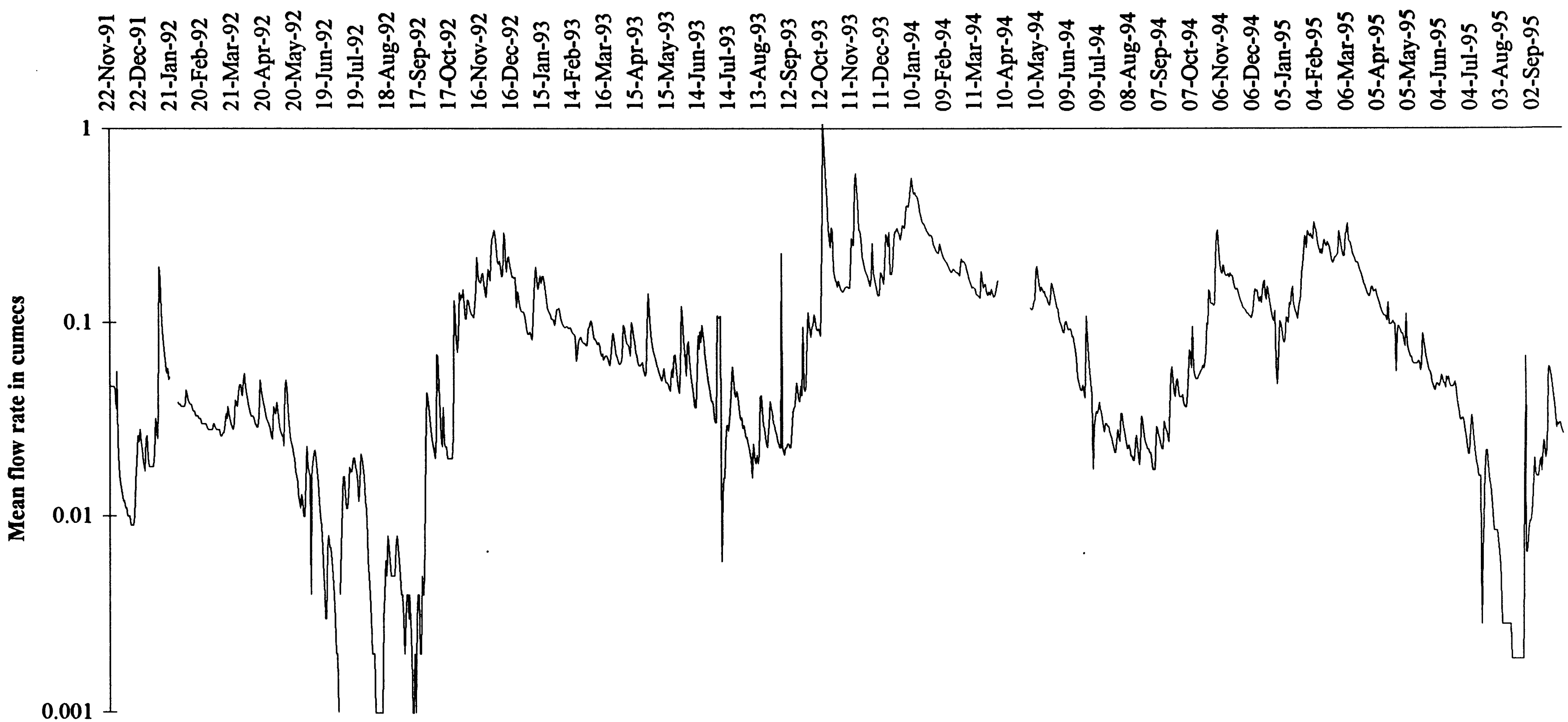


Figure 2.23a: Daily abstraction rates over time from the Moulton Borehole

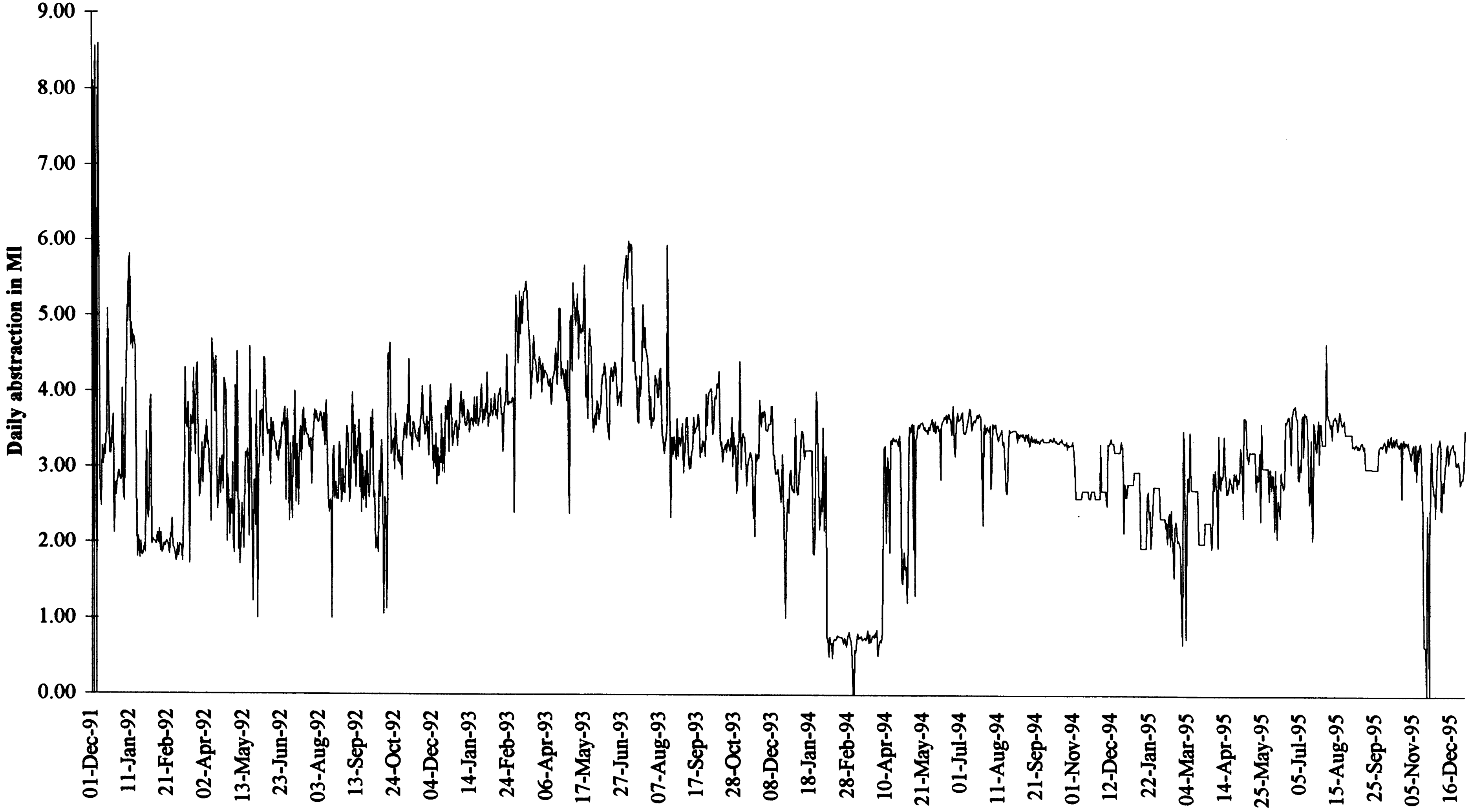


Figure 2.23b: 5 point moving average of daily abstraction from Moulton borehole

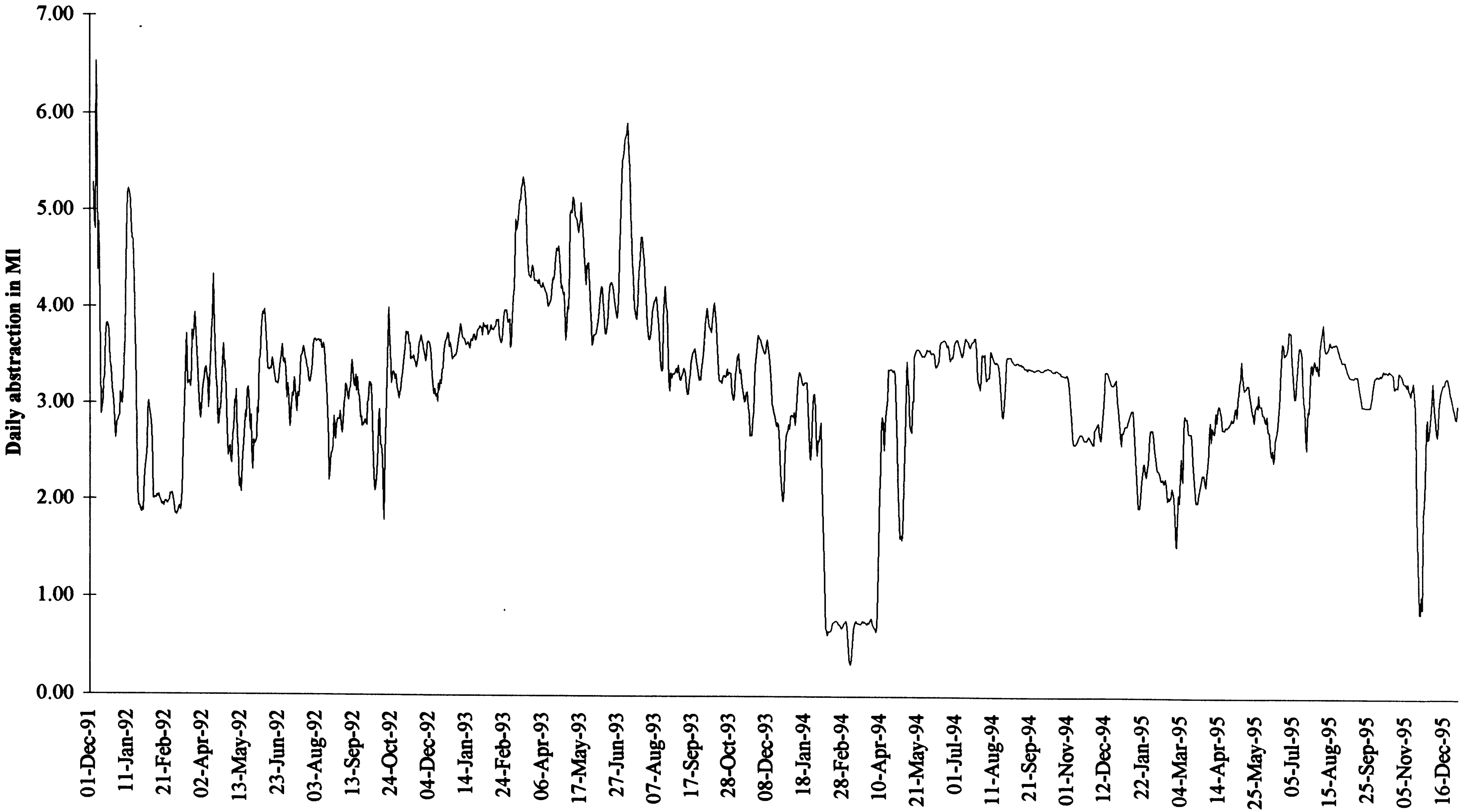


Figure 2.24a: Daily abstraction rates from the Longhill borehole

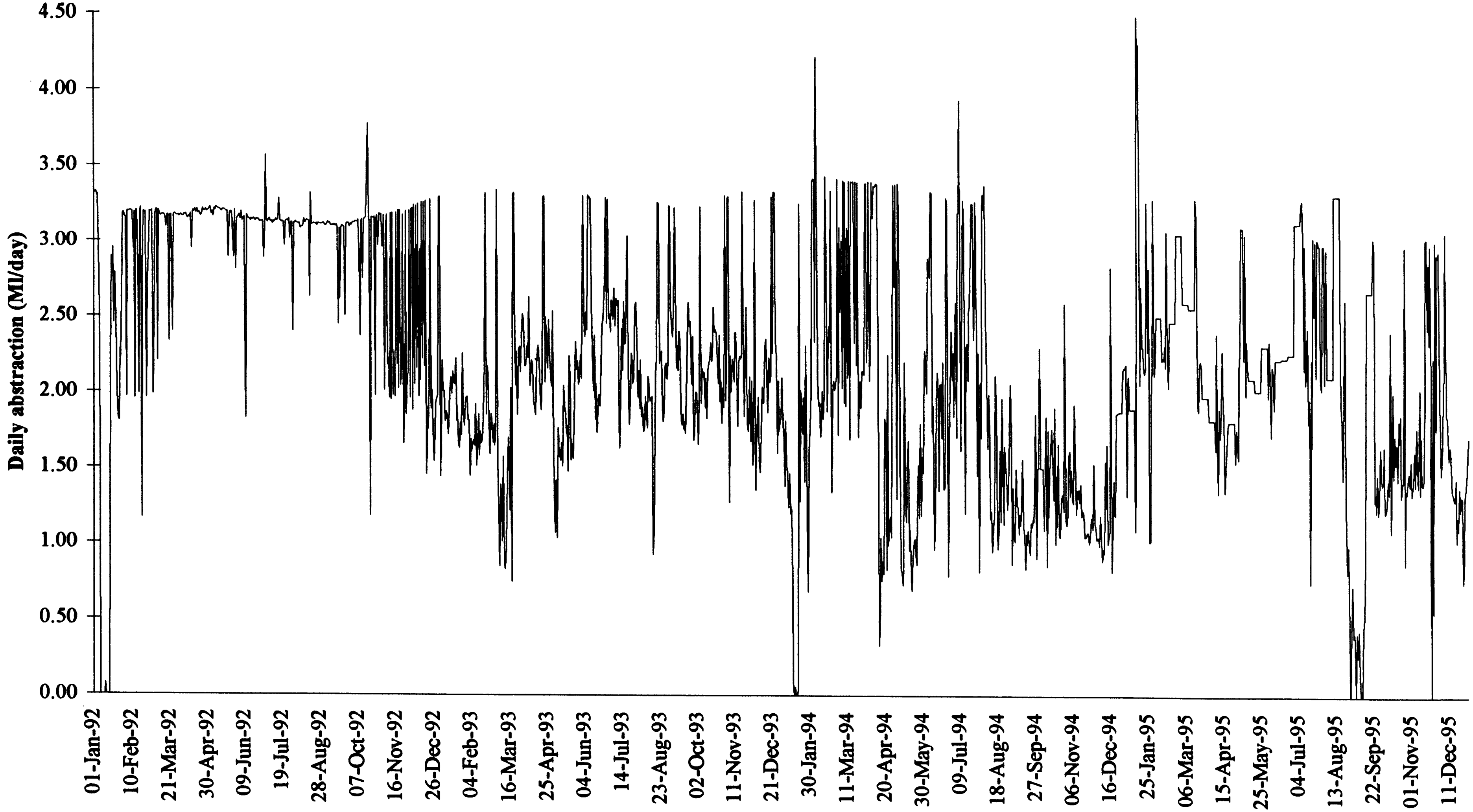


Figure 2.24b: 5 point moving average of daily abstraction from Longhill borehole

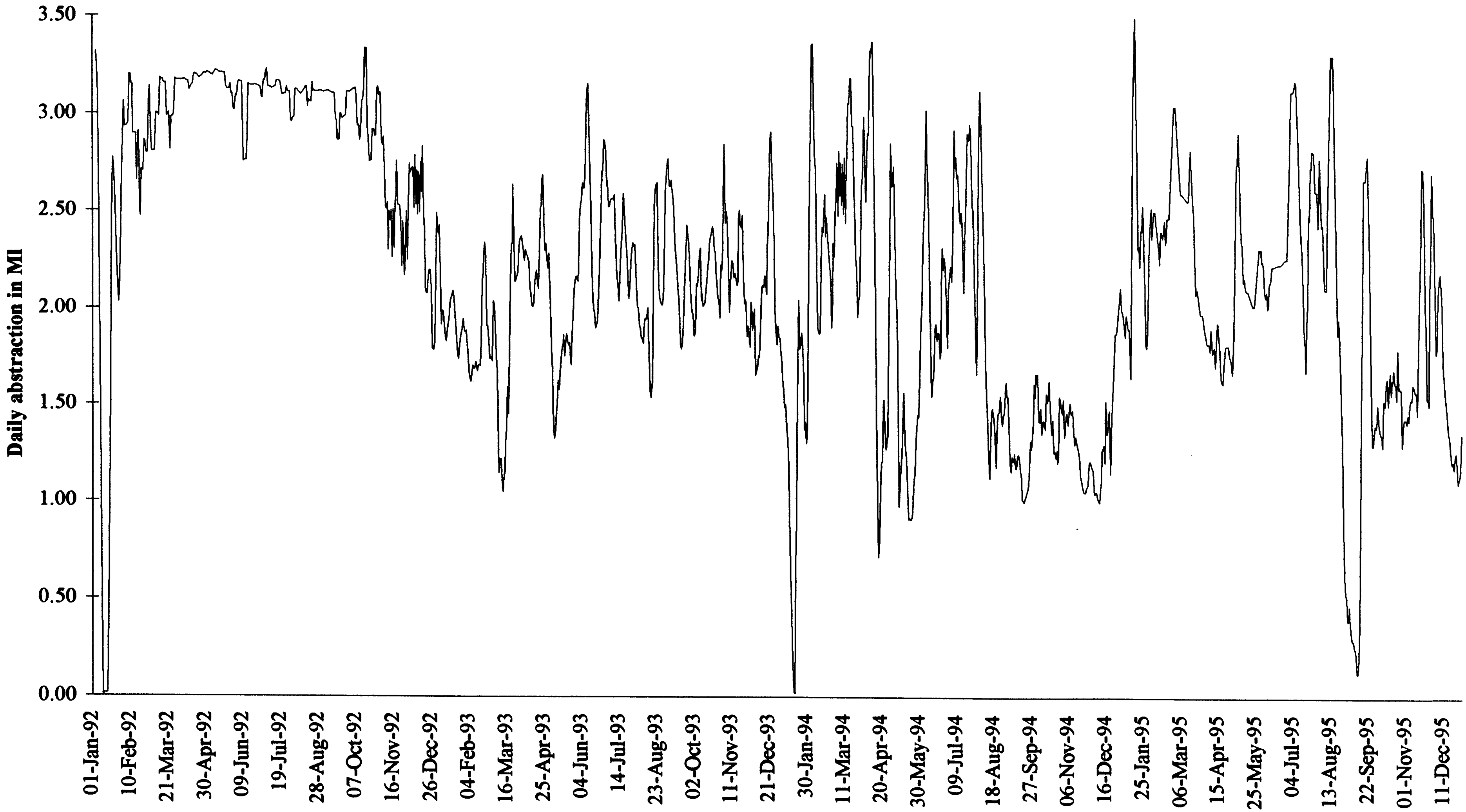


Figure 2.25a: Daily abstraction rates over time from Gazeley borehole

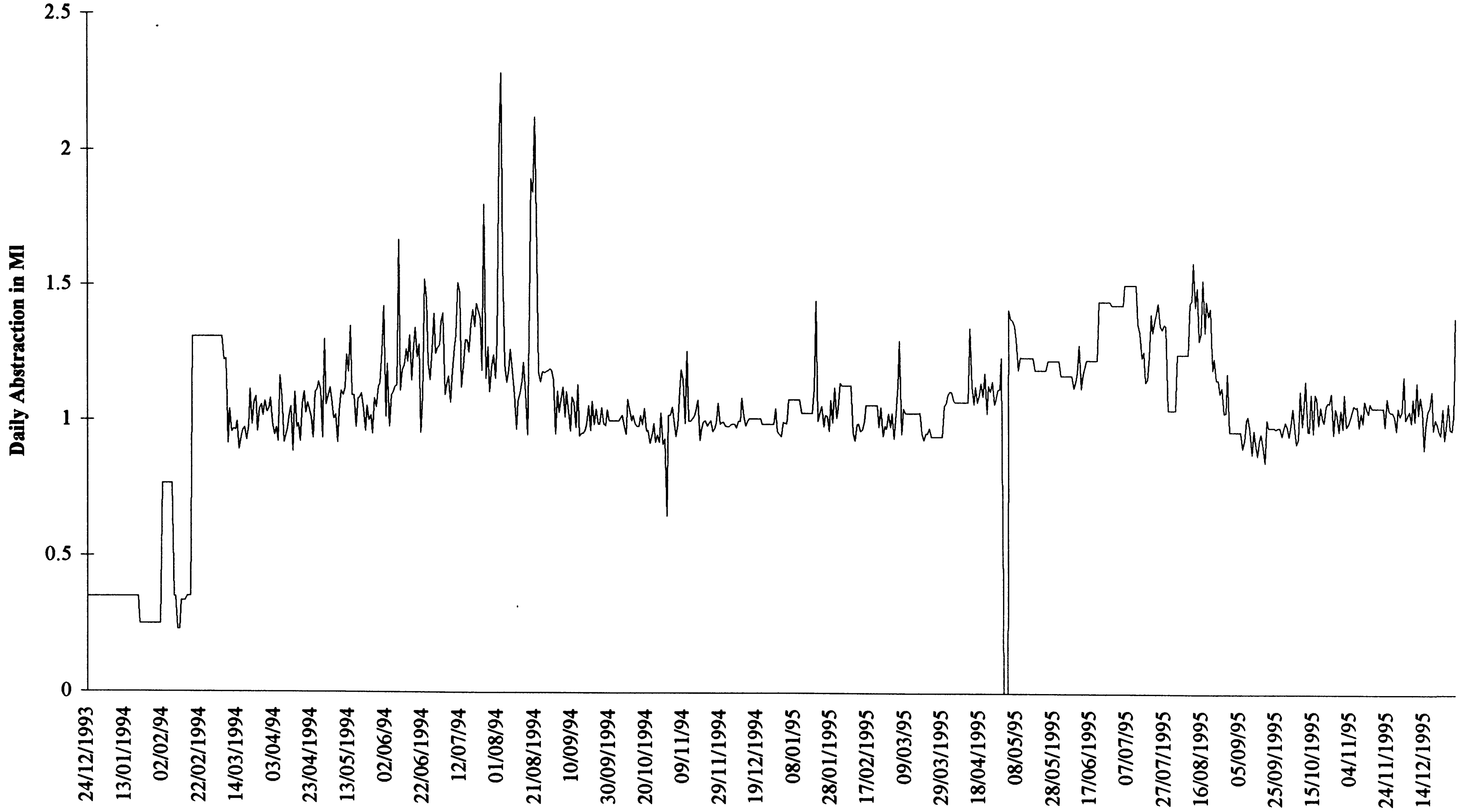


Figure 2.25b: 5 point moving average of daily abstraction rates from Gazeley borehole

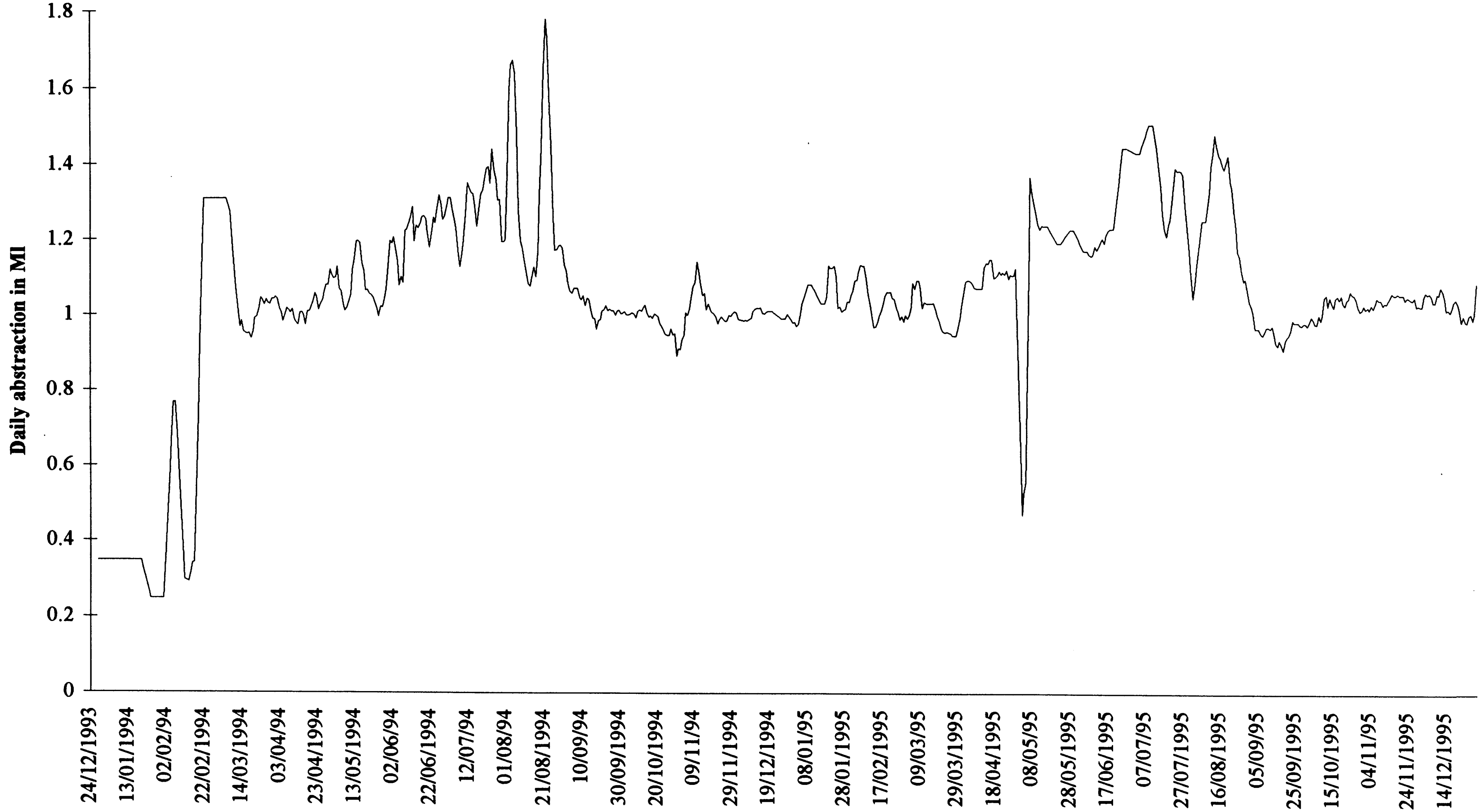


Figure 3.1: Monthly mean data over time for water table level monitoring, Chippenham Fen

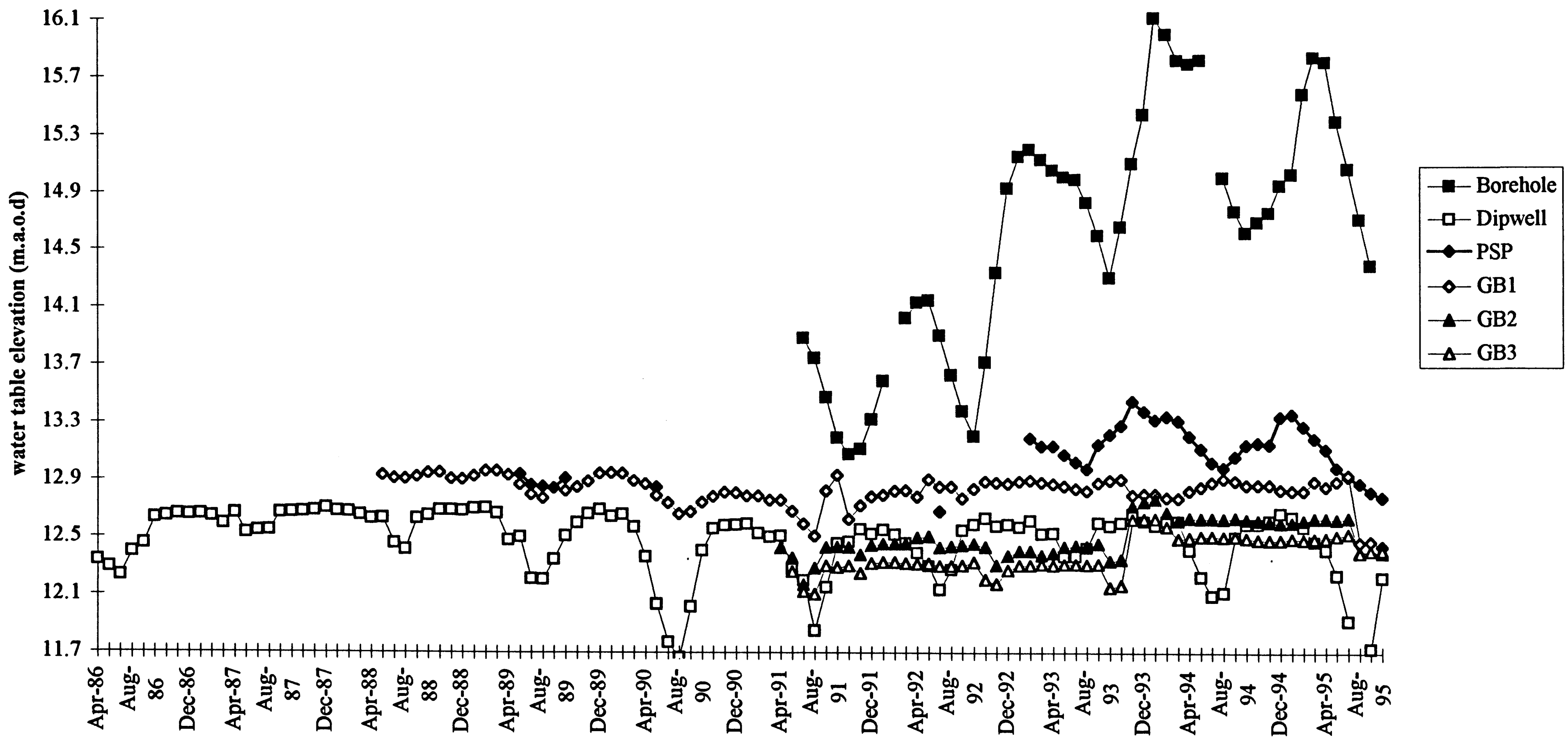


Figure 3.2: Scattergraph illustrating the relationship between mean monthly water table elevations recorded by the principal spring piezometer and the dipwells, Chippenham Fen

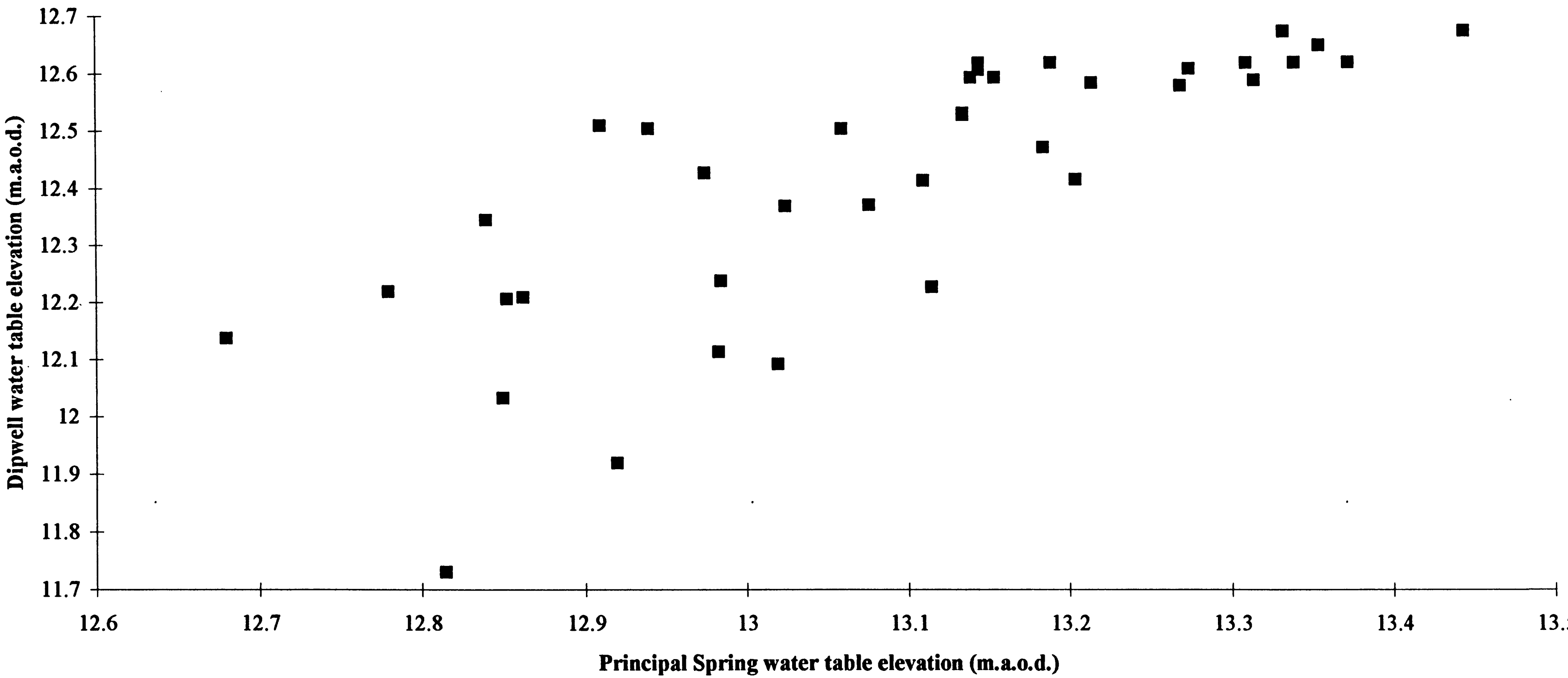


Figure 3.3: Scattergraph illustrating the relationship between mean monthly water table elevations recorded by the Principal Spring piezometer and the observation borehole, Chippenham Fen

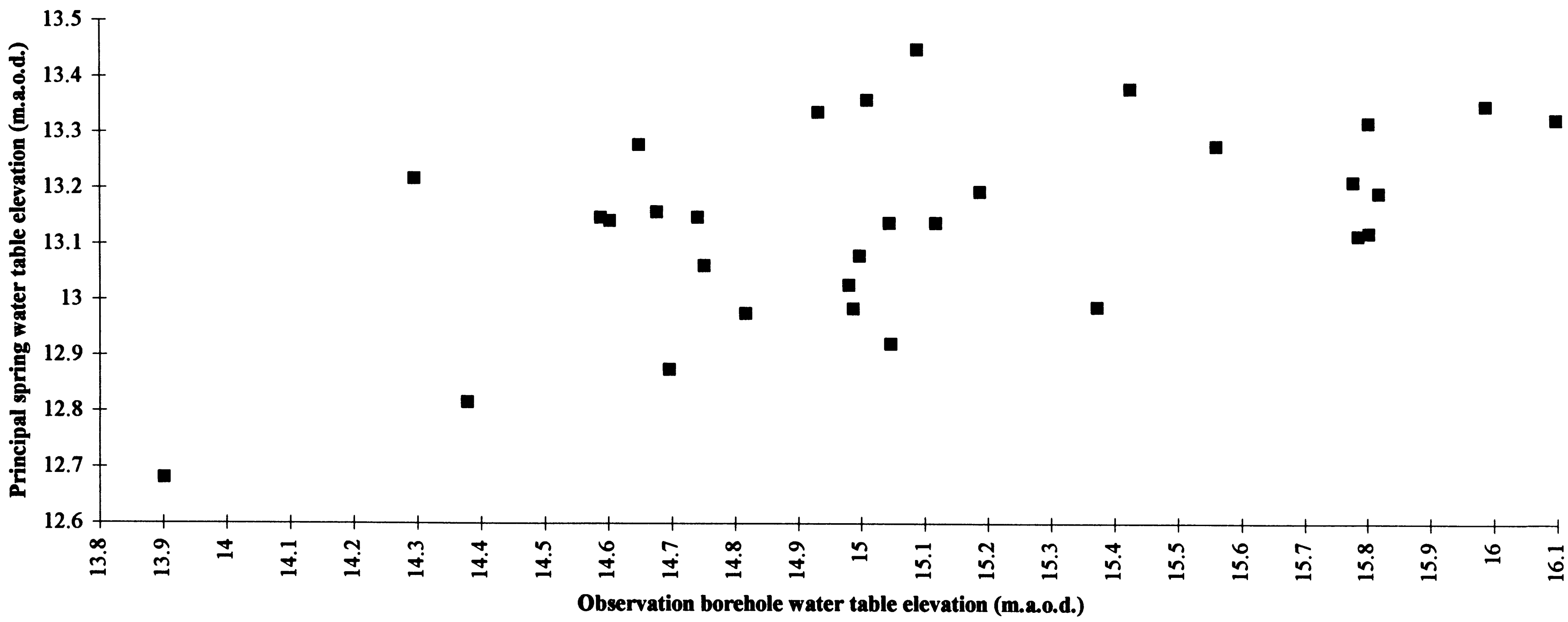


Figure 3.4: Scattergraph illustrating the relationship between mean monthly water table elevations recorded by gaugeboard GB2 and the observation borehole, Chippenham Fen

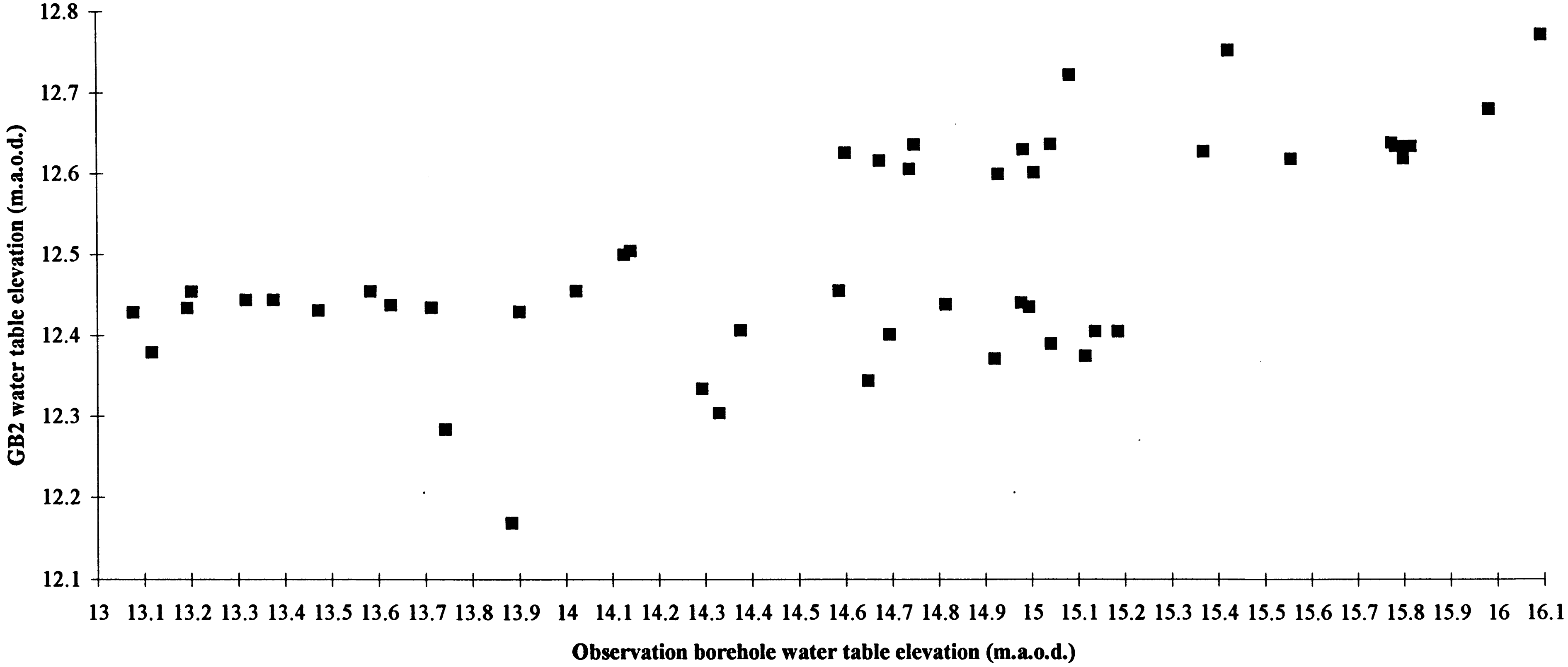


Figure 3.5: Scattergraph illustrating the relationship between mean monthly water table elevations recorded by gaugeboard GB3 and the observation borehole, Chippenham Fen

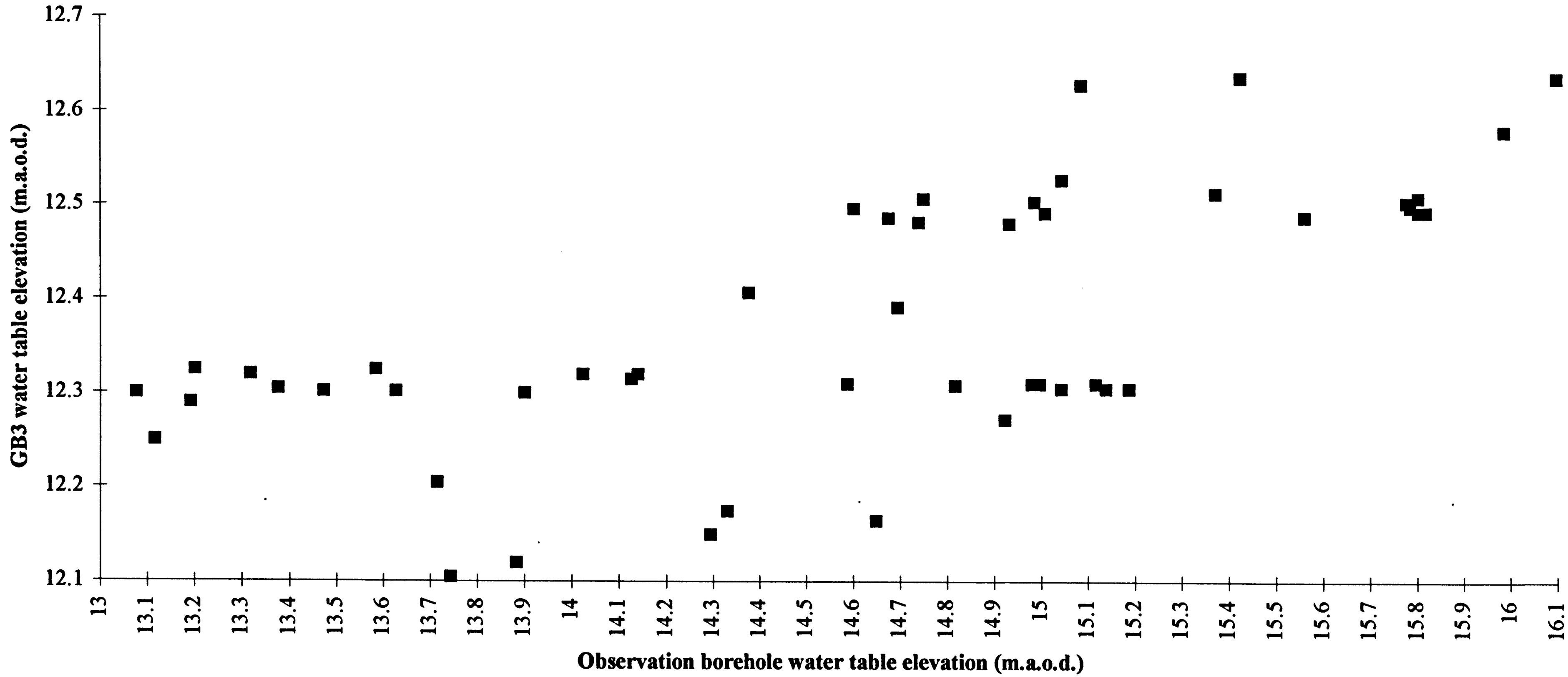


Figure 3.6: Comparison of monthly mean values for water elevation above ordnance datum at the principal spring & dipwells with discharge at the Chippenham river, 1991-1995

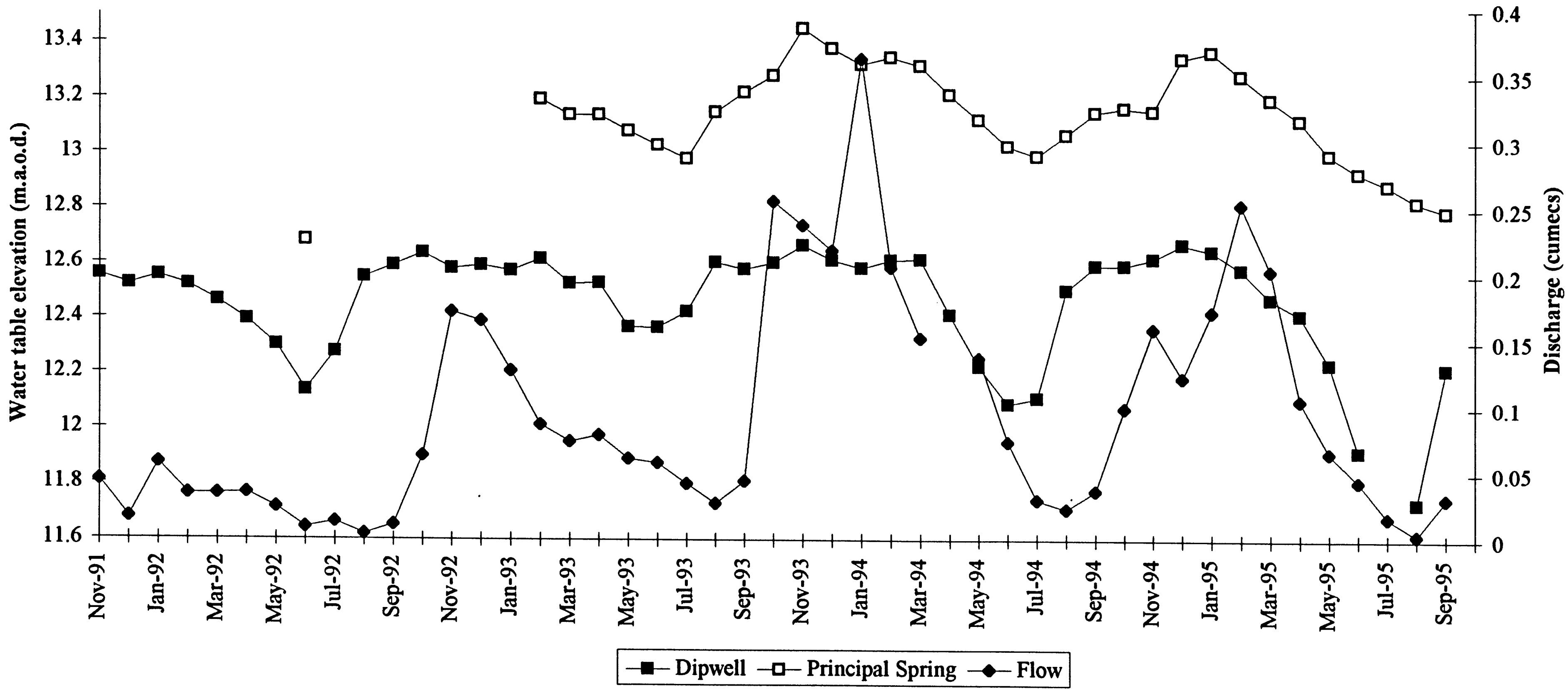


Figure 3.7: Comparison of mean daily flow in the Chippenham river with water table elevation at the observation borehole, 1991-1995

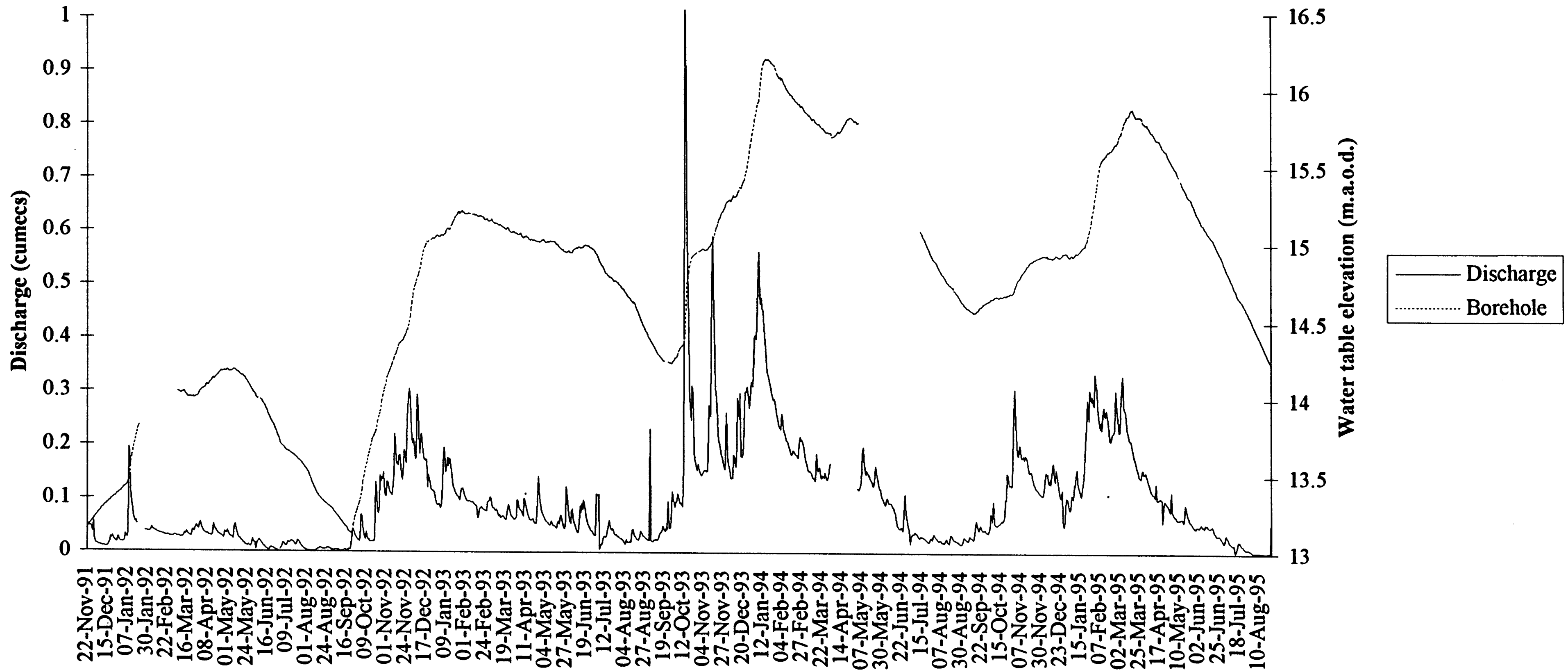


Figure 3.8: Comparison of log transformed daily mean discharge data with daily mean readings at the observation borehole, 1991-1995

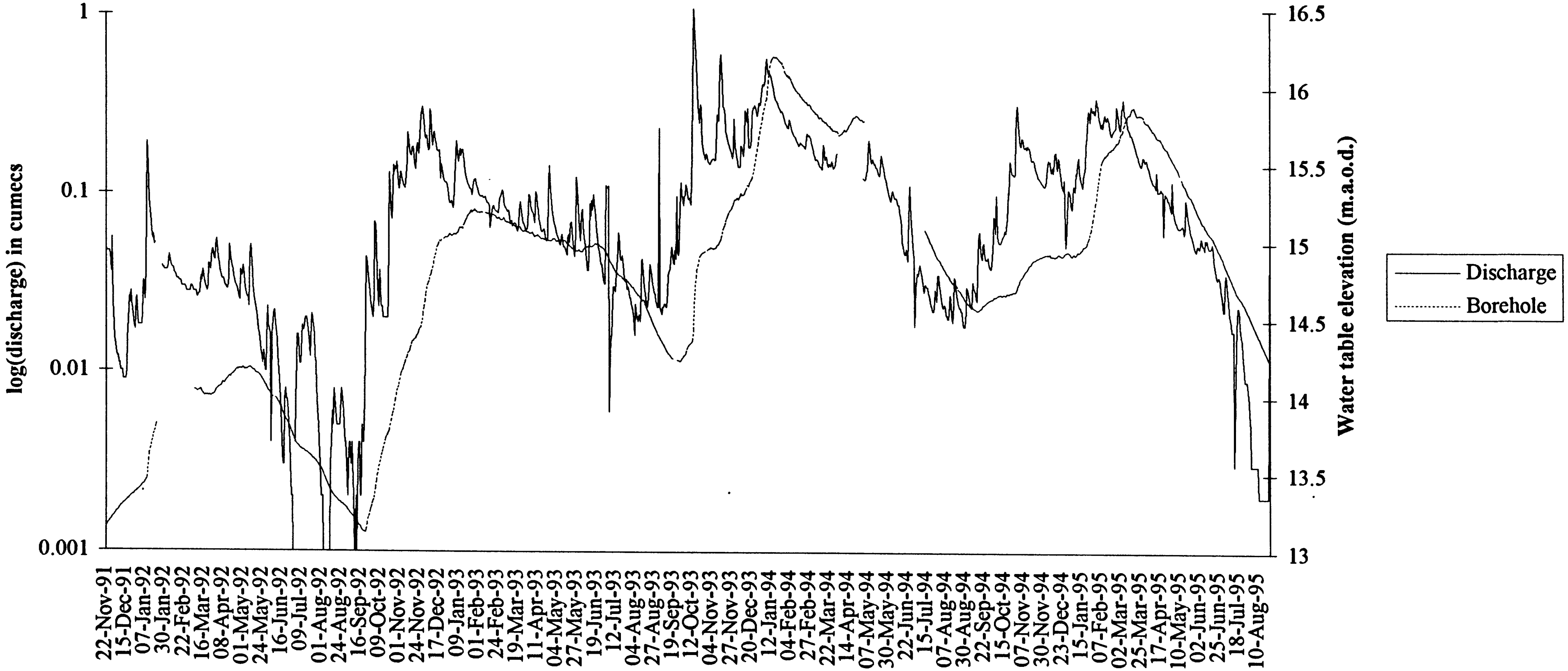


Figure 3.9: Scattergraph of borehole water table elevation above ordnance datum and log(discharge)

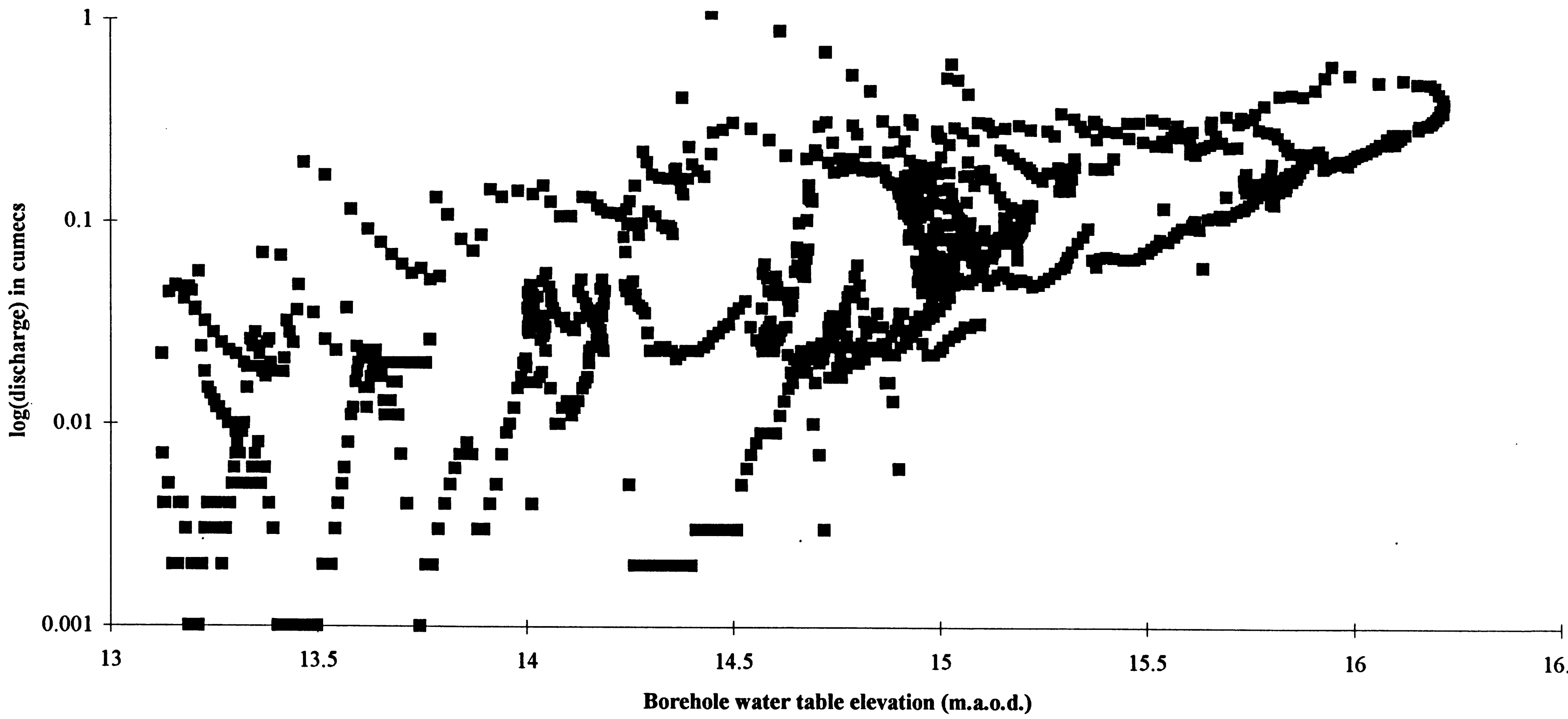


Figure 3.10: Scattergraph showing water table elevation above ordnance datum at the principal spring piezometer compared with discharge

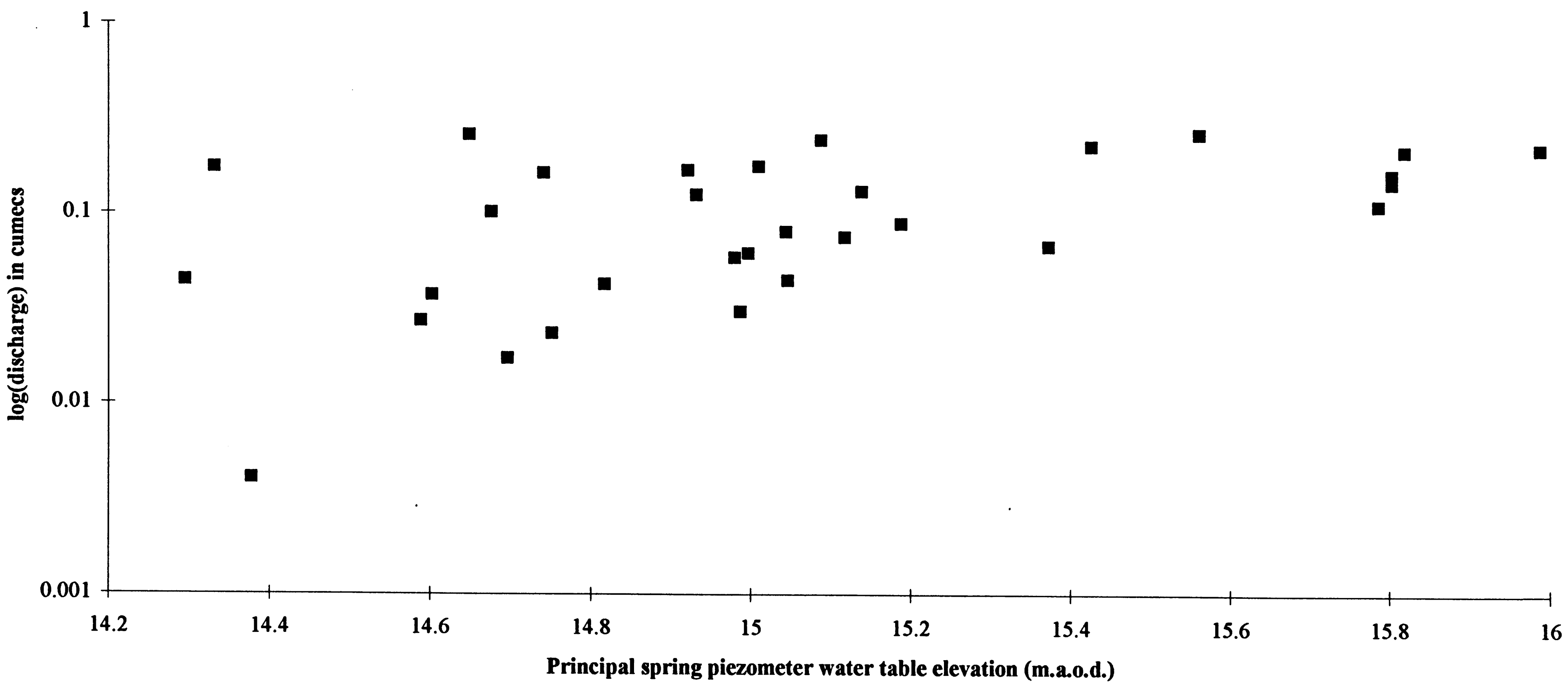


Figure 3.11a: Daily rainfall recorded at the Isleham raingauge compared with daily mean discharge 1991-1995

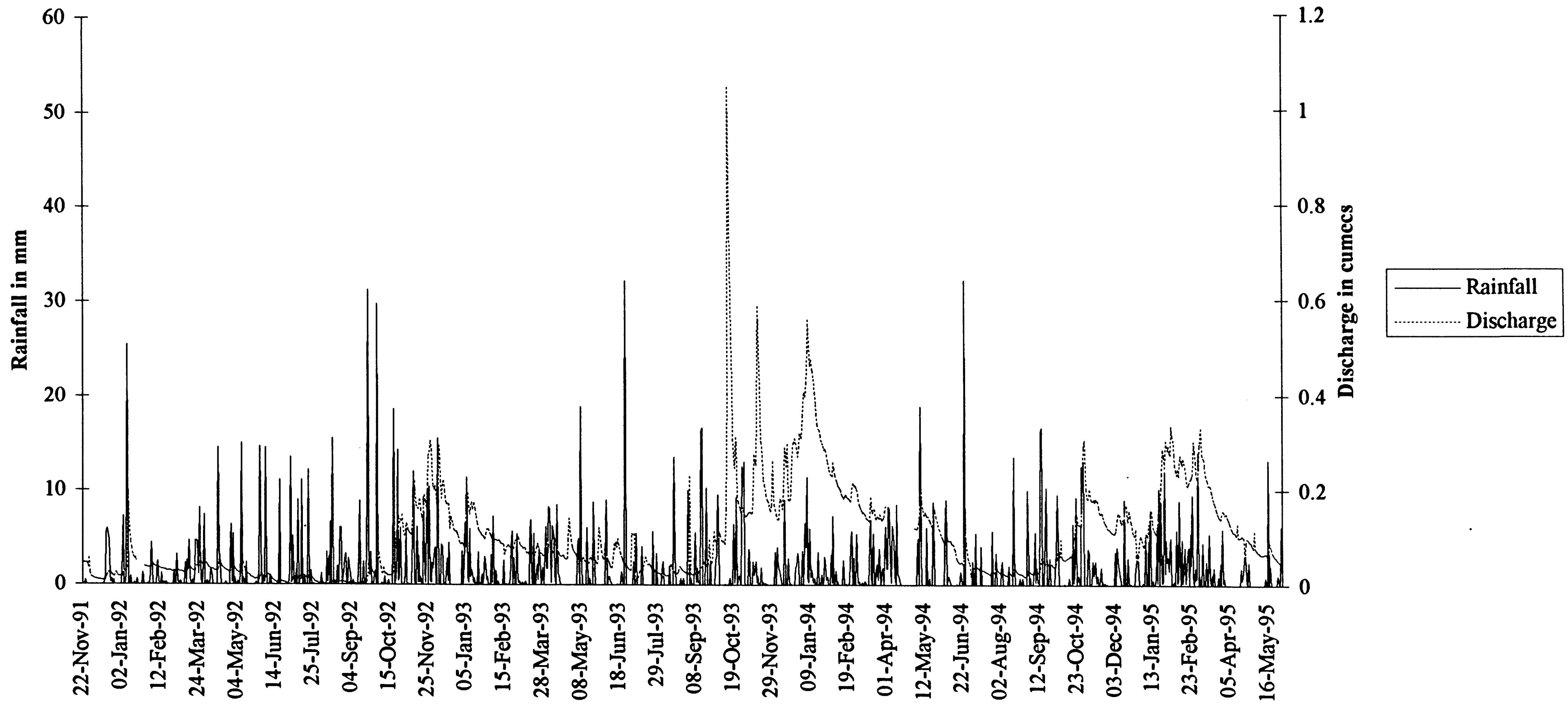


Figure 3.11b: Daily rainfall recorded at the Chippenham raingauge compared with daily mean discharge 1991-1995

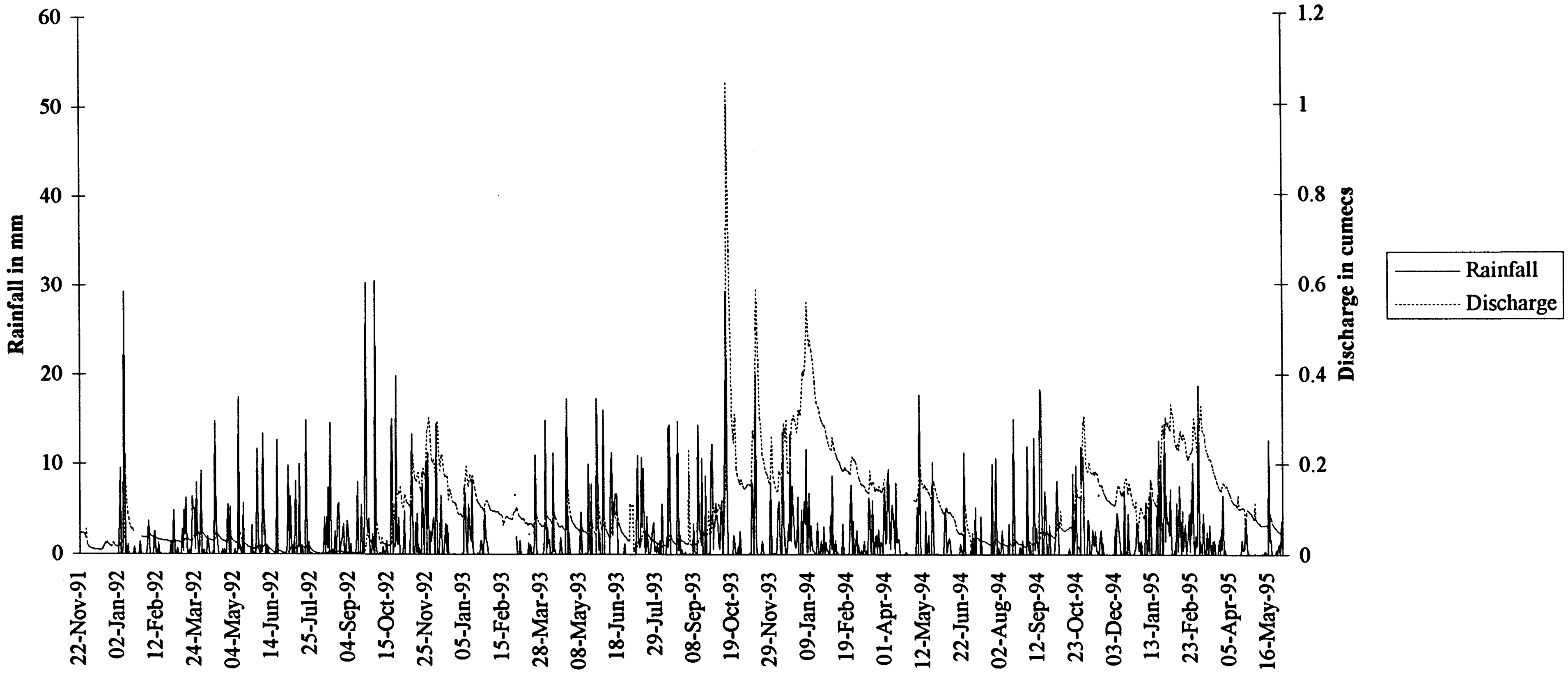


Figure 3.11c: Daily rainfall recorded at the Chippenham tipping bucket raingauge compared with daily mean discharge 1992-1995

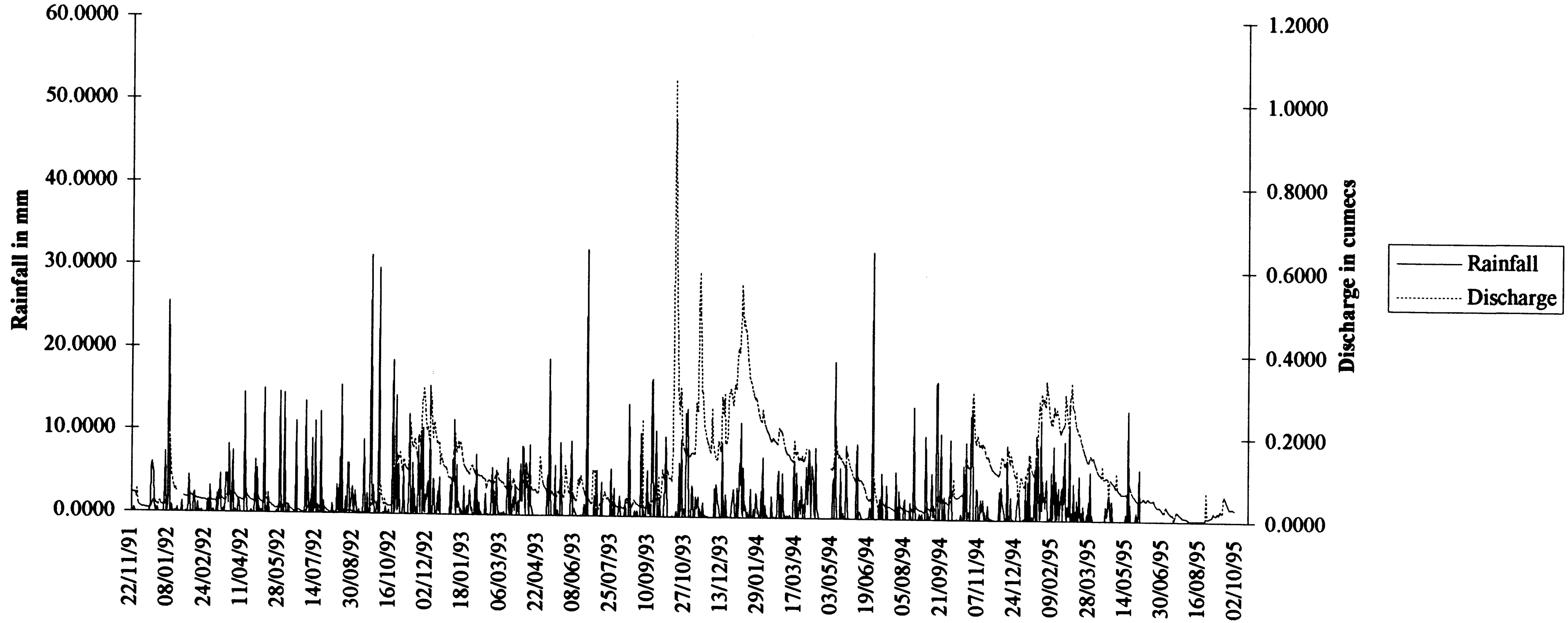


Figure 3.12a: Daily rainfall recorded by the Isleham raingauge compared with daily mean water table elevations at the observation borehole, 1991-1995

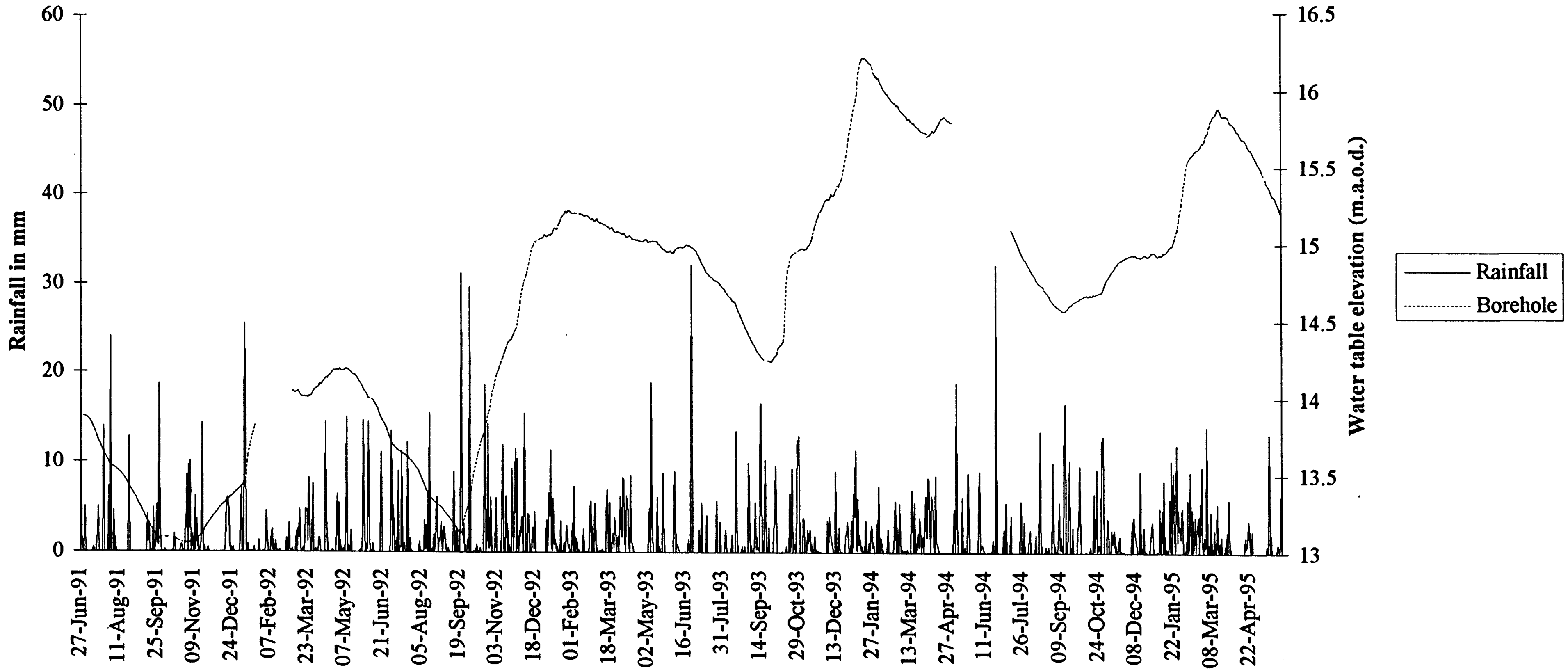


Figure 3.12b: Daily rainfall recorded by the Chippenham raingauge compared with daily mean water table elevations at the observation borehole, 1992-1995

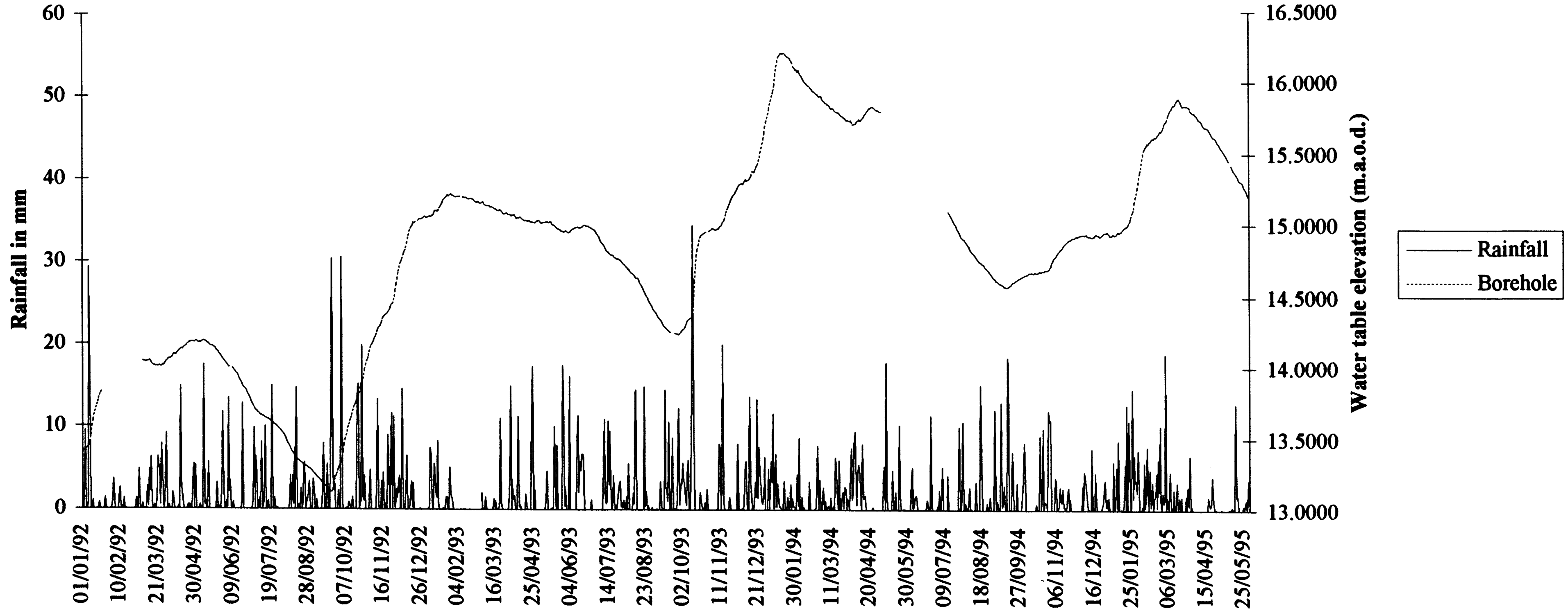


Figure 3.12c: Daily rainfall recorded by the tipping bucket raingauge compared with daily mean water table elevations at the observation borehole, 1992-1995

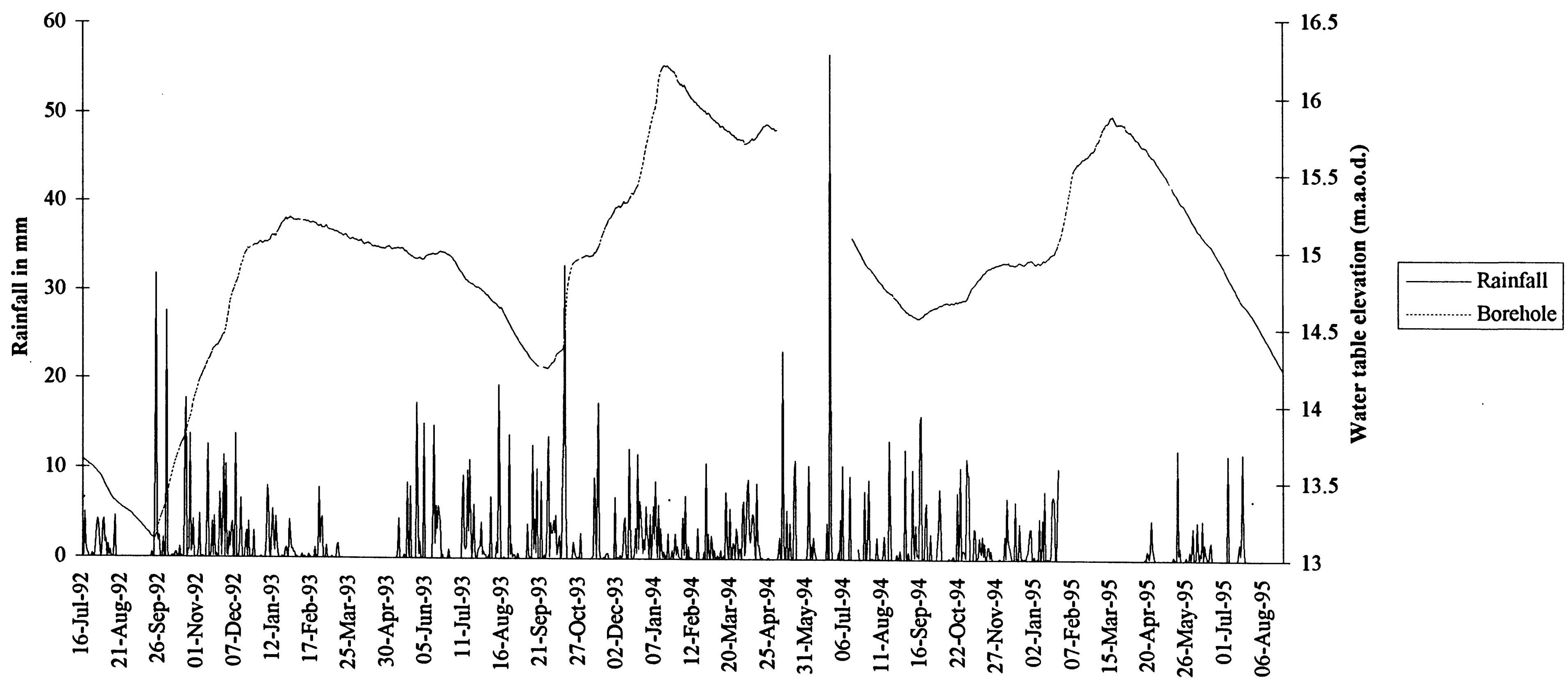


Figure 3.13: Monthly rainfall totalscompared with mean monthly water table elevations from Chippenham Fen dipwells, 1993-1995

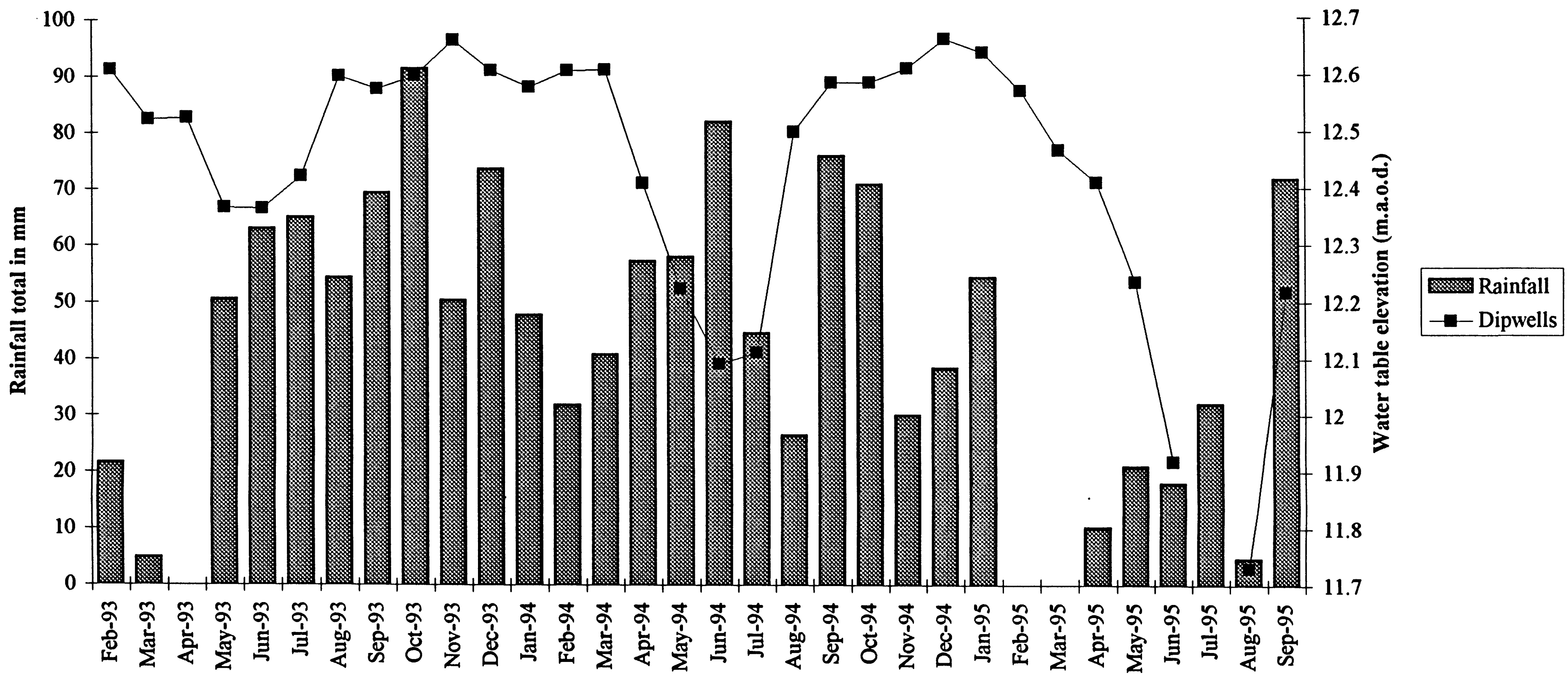


Figure 3.14: Monthly rainfall totals compared with mean monthly water table elevations above ordnance datum at the principal spring piezometer, 1993-1995

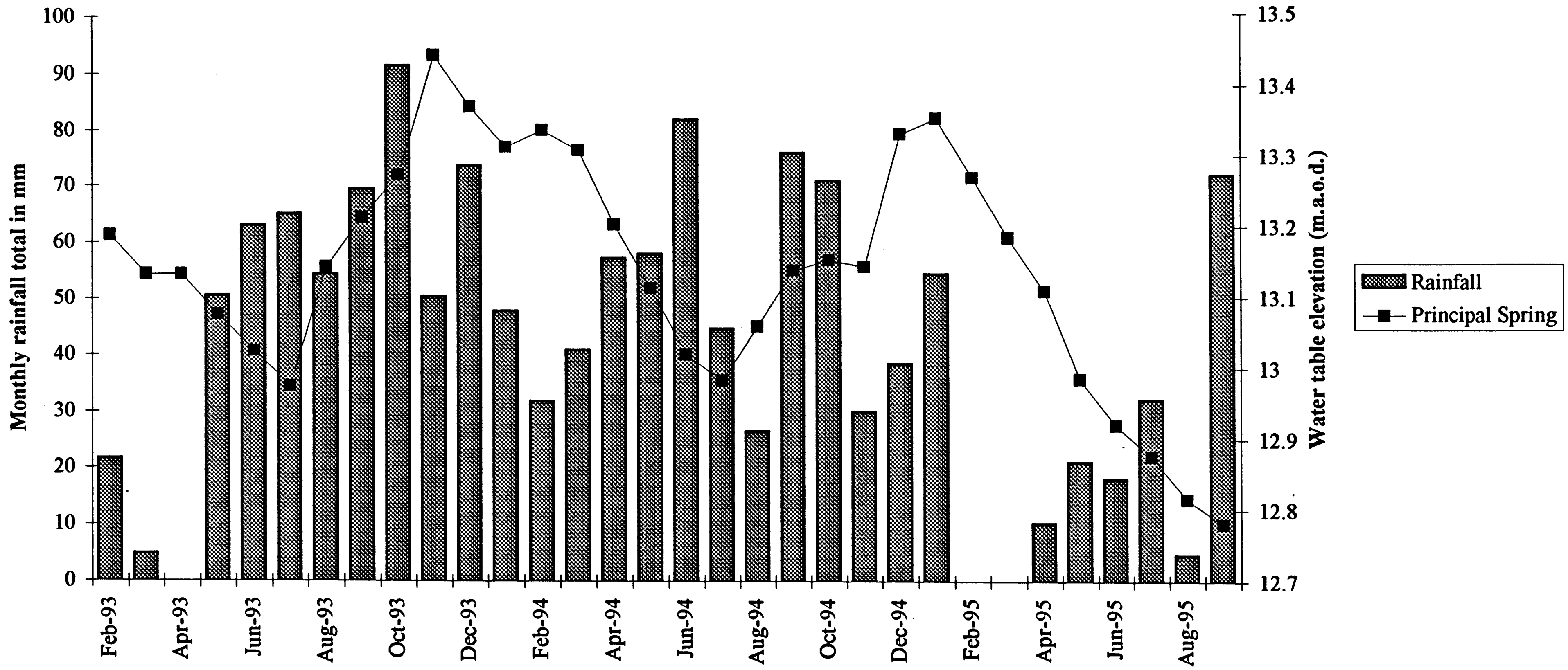


Figure 3.15: Data over time for dipwells 5 and 14, 1991-1995 Chippenham Fen

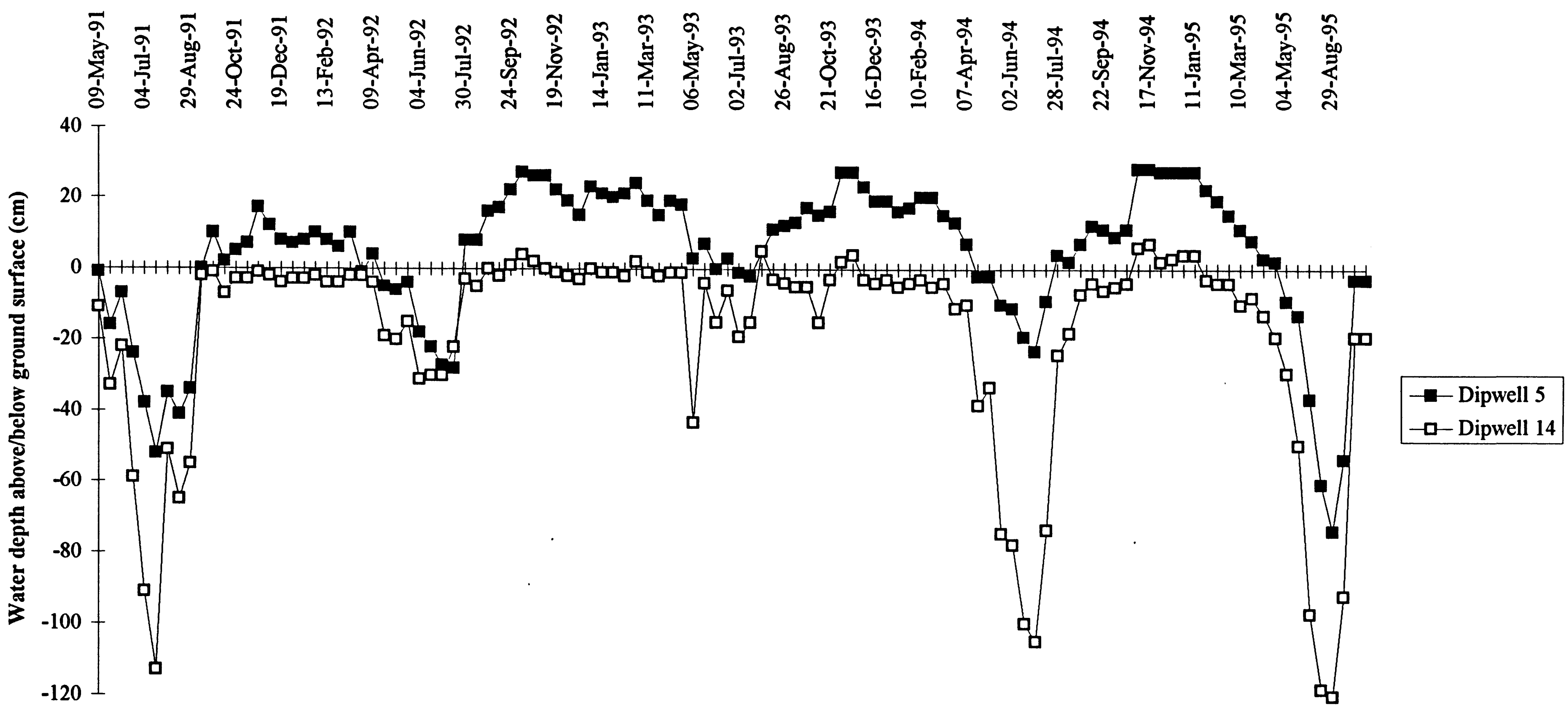


Figure 3.16: Water table elevation above ordnance datum over time for dipwells 7 & 12 and gaugeboard GB2, 1991-1995, Chippenham Fen

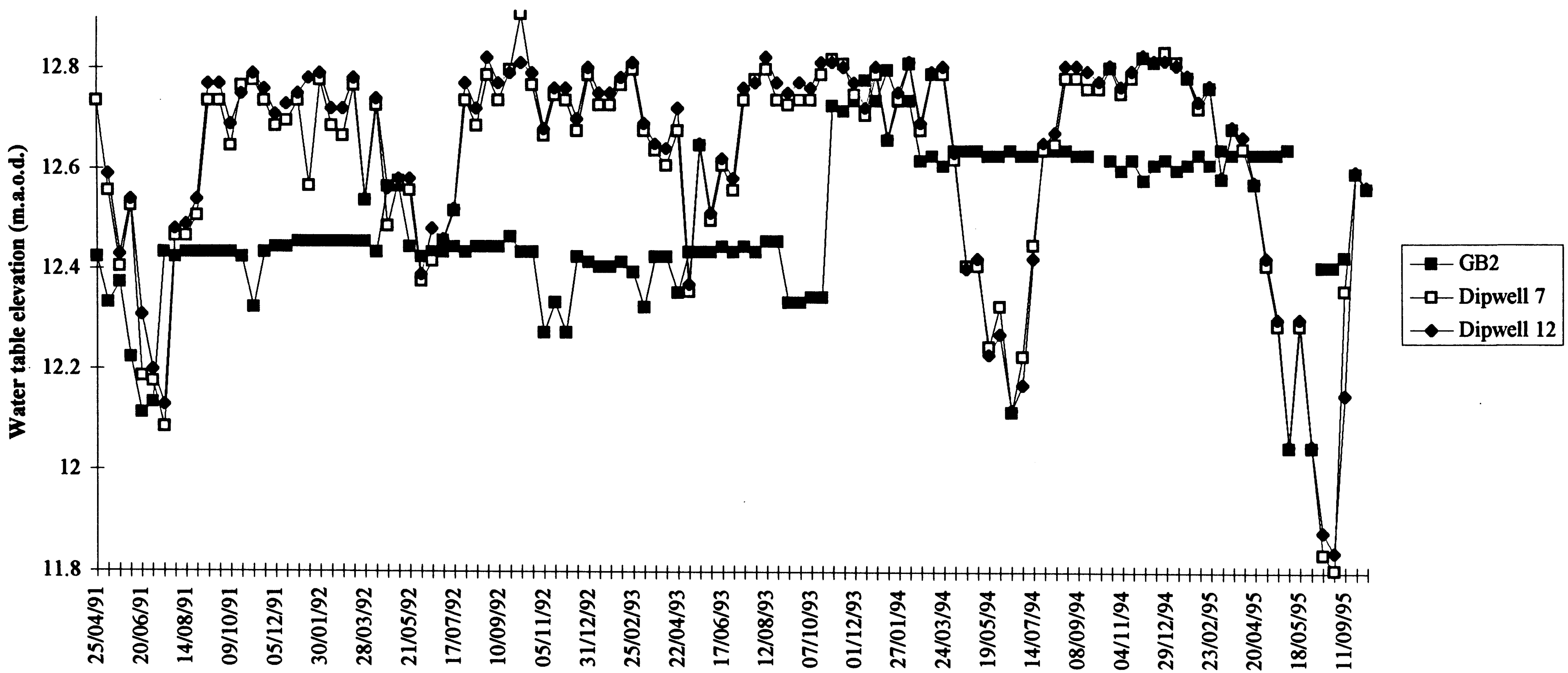


Figure 3.17: Chippenham river discharge over time in comparison with daily abstraction from the Moulton borehole, 1991-1995

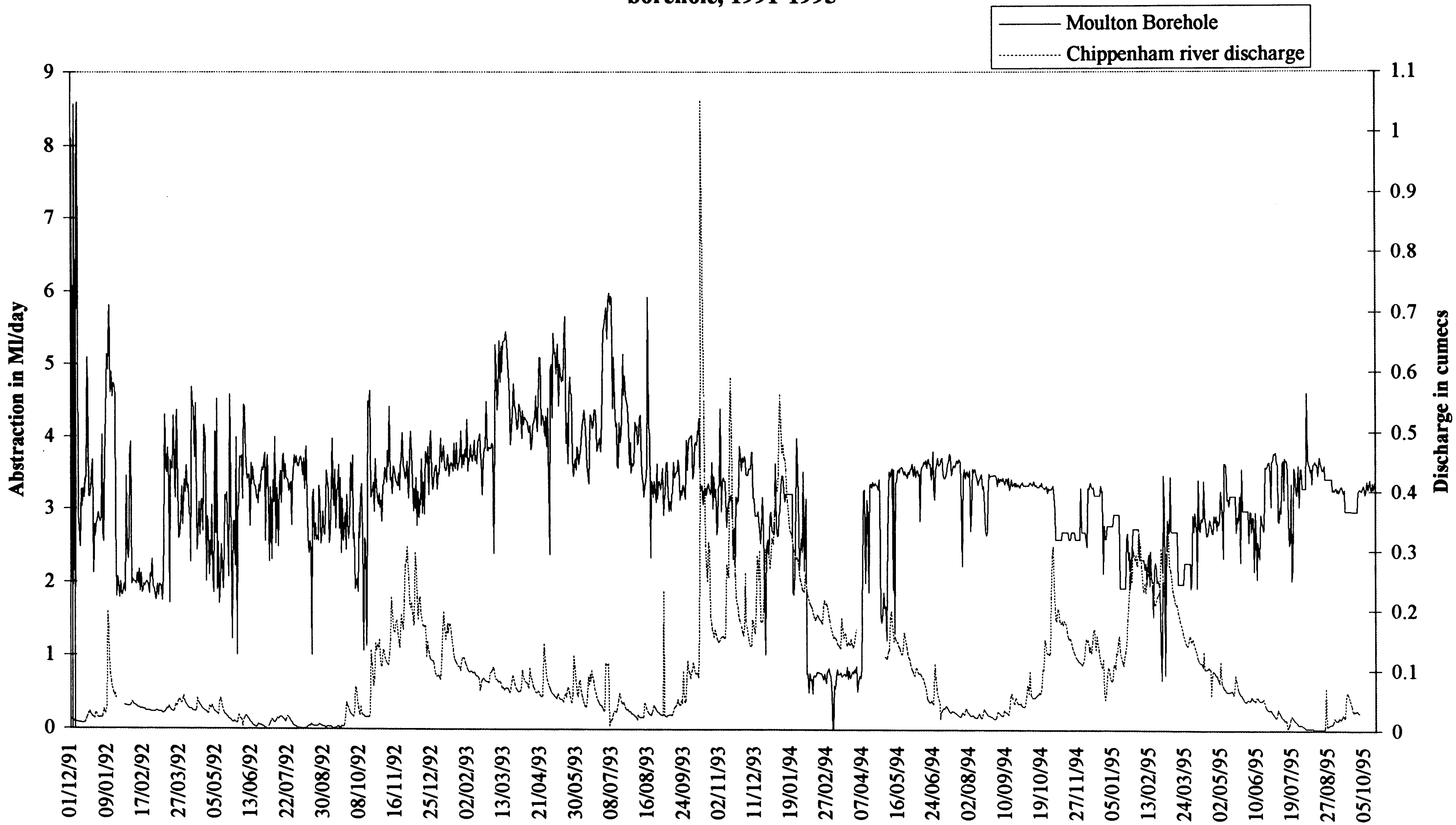


Figure 3.18: Daily discharge in the Chippenham river compared with a 5 point moving average of daily abstraction from the Longhill borehole

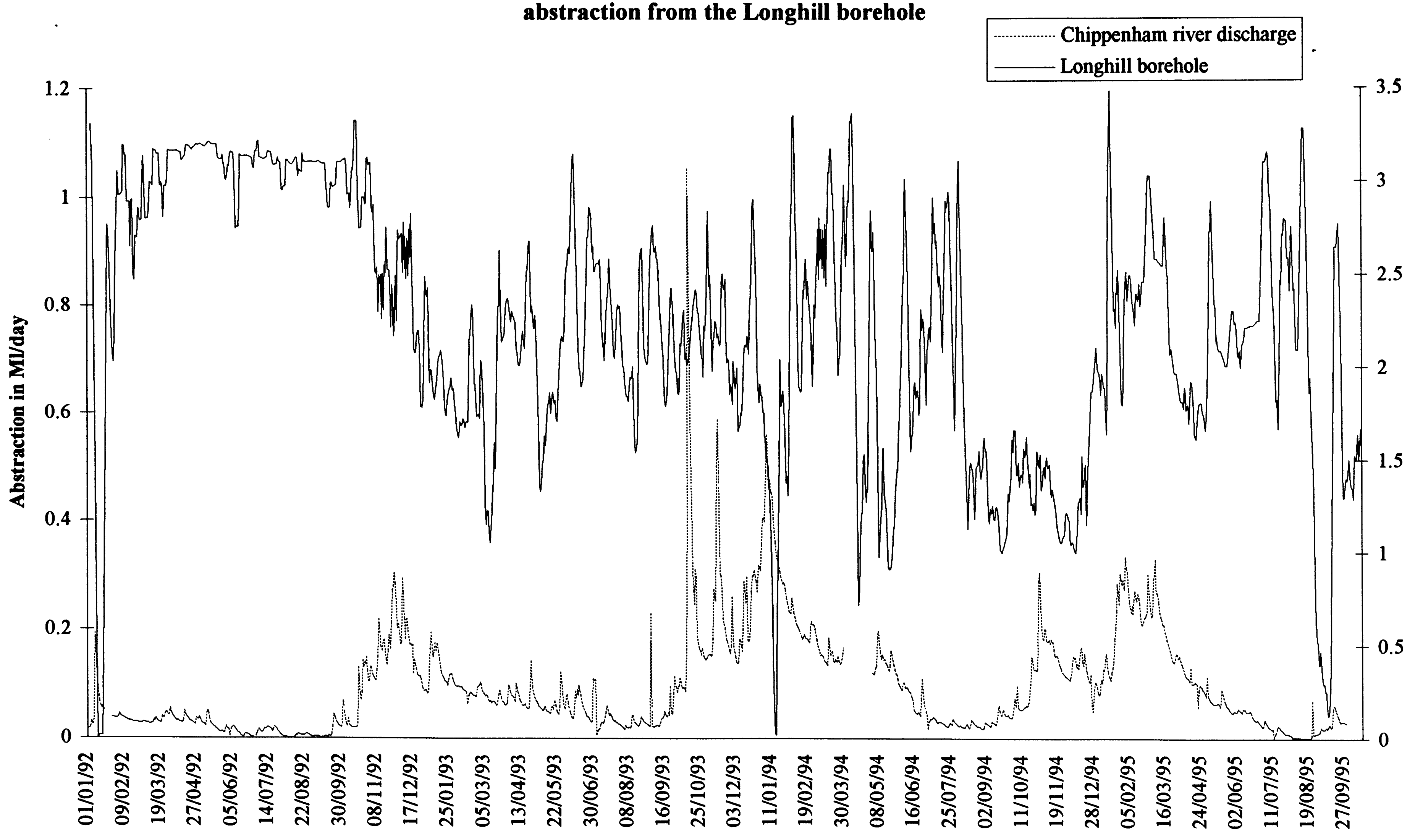


Figure 3.19: Daily abstraction rates at the Gazeley borehole compared with Chippenham river discharge

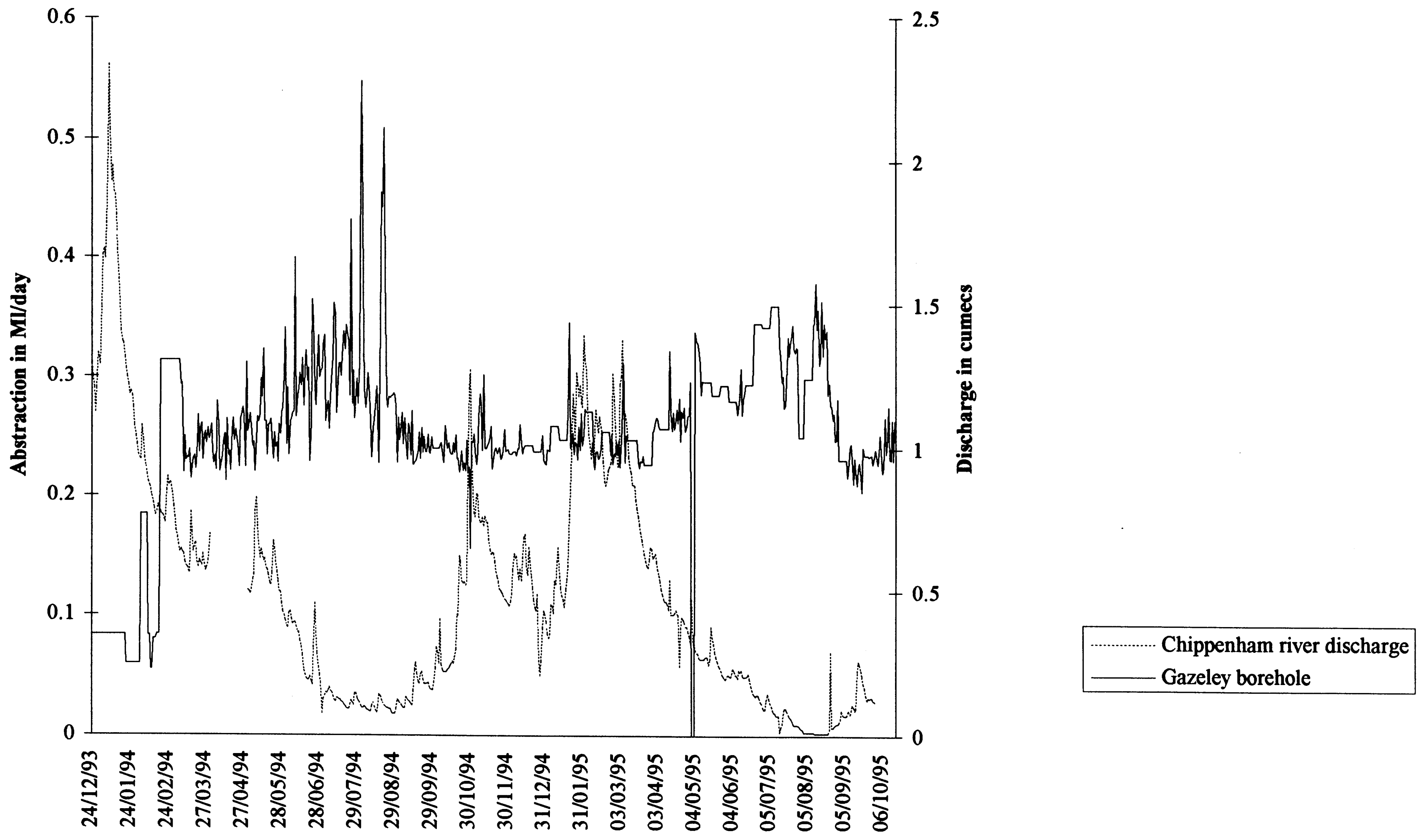


Figure 3.20: Daily water table elevations at the Chippenham observation borehole compared with daily abstraction rates from the Moulton borehole

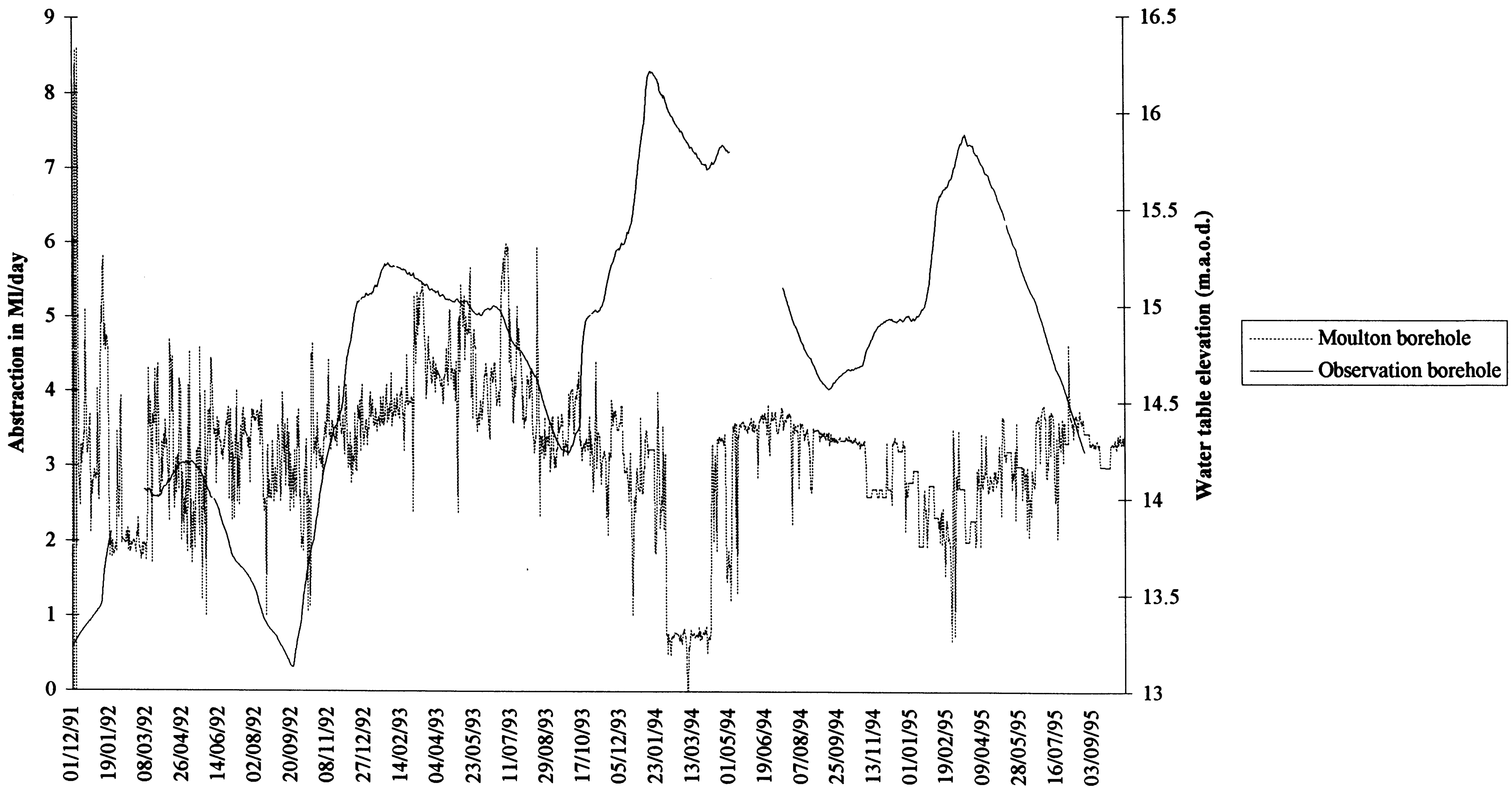


Figure 3.21: Daily water table elevation levels at the Chippenham observation borehole compared with daily abstraction from Longhill borehole

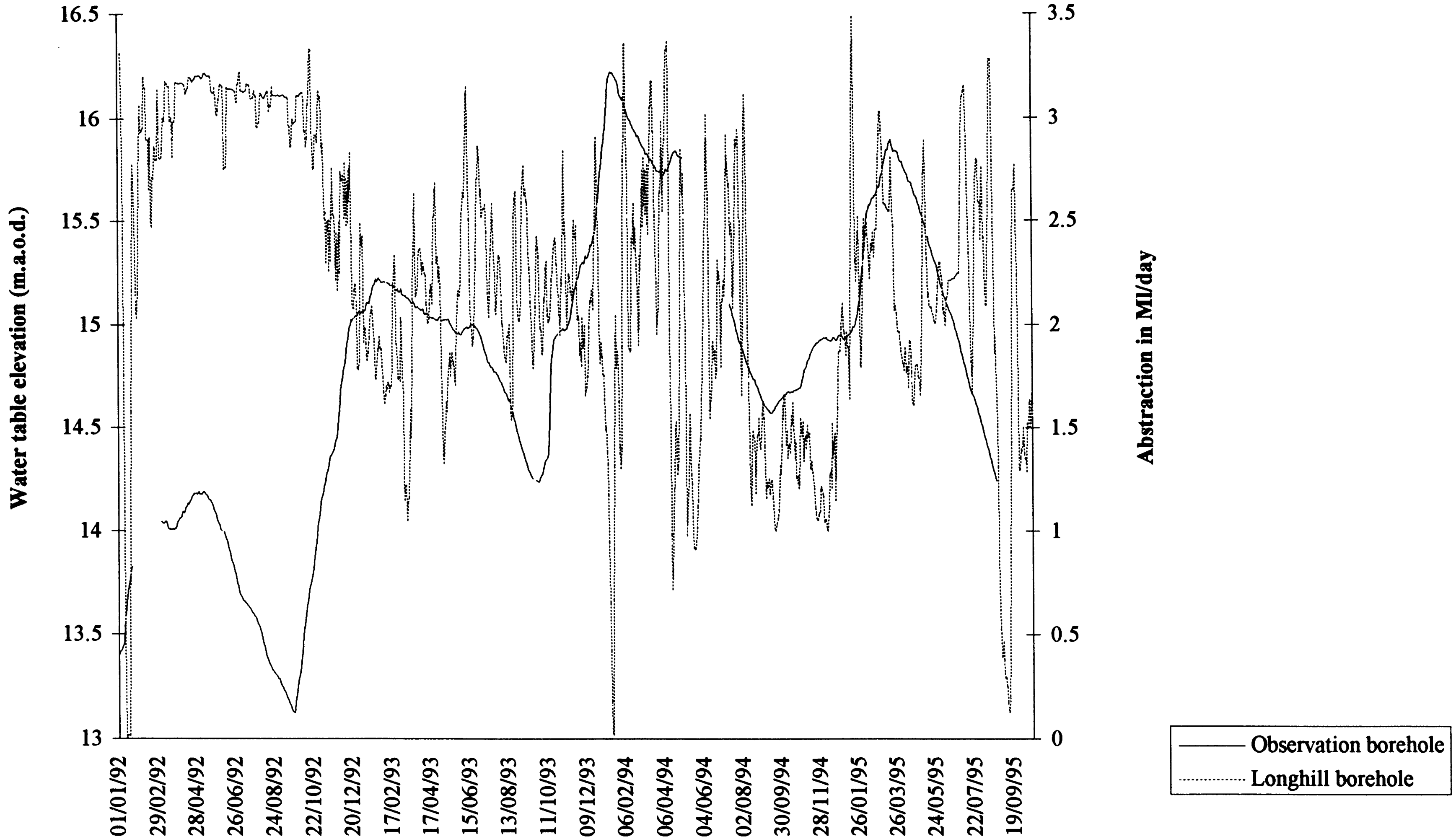


Figure 3.22: Daily water table elevation at the Chippenham observation borehole compared with daily abstraction from Gazeley borehole

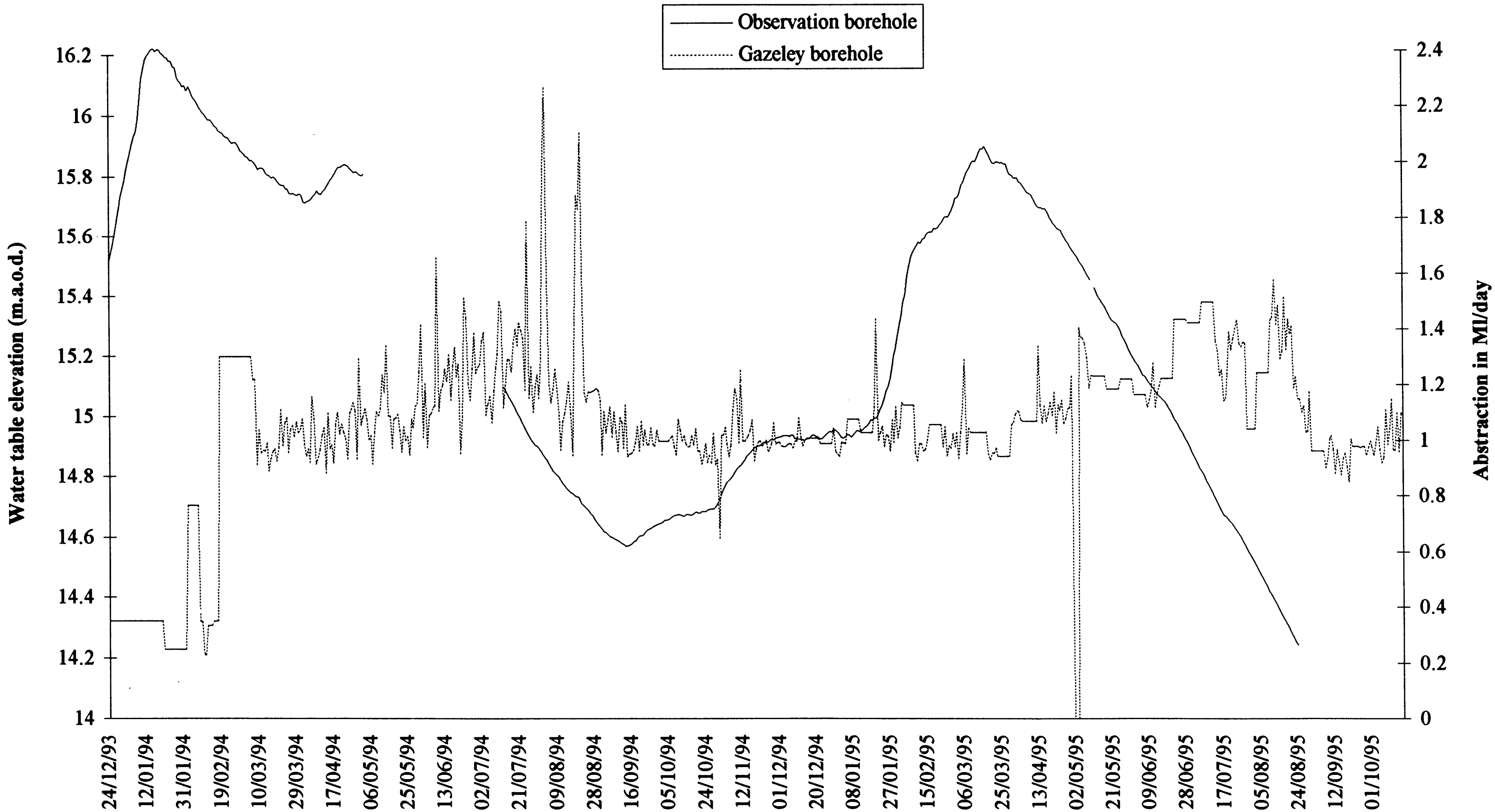


Figure 3.23: Monthly mean daily discharge at the Chippenham river compared with monthly mean daily abstraction in cumecs

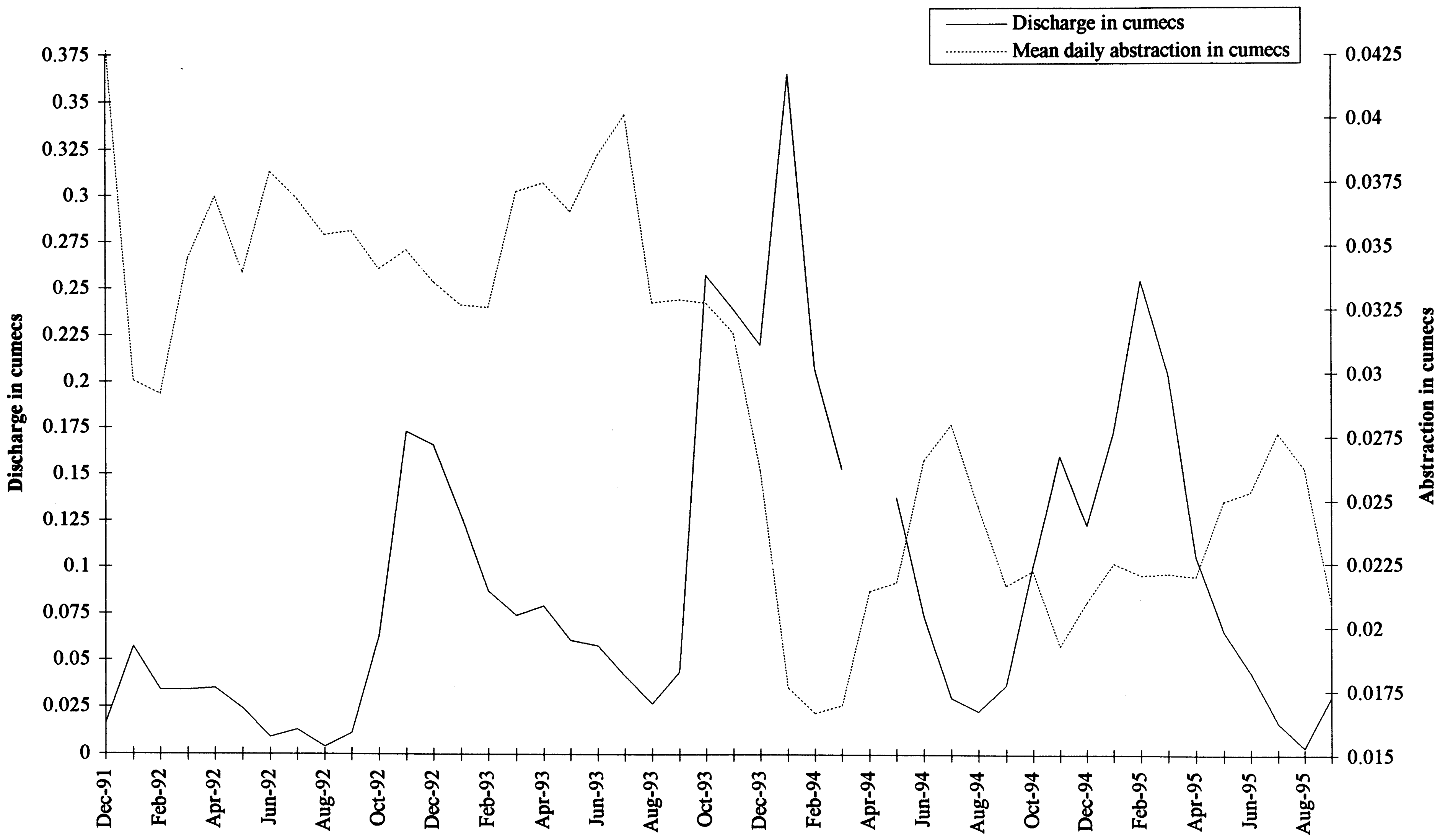


Figure 3.24: Mean monthly dipwell & Principal Spring water table elevation over time compared with monthly averages of daily abstraction rates from Moulton Borehole

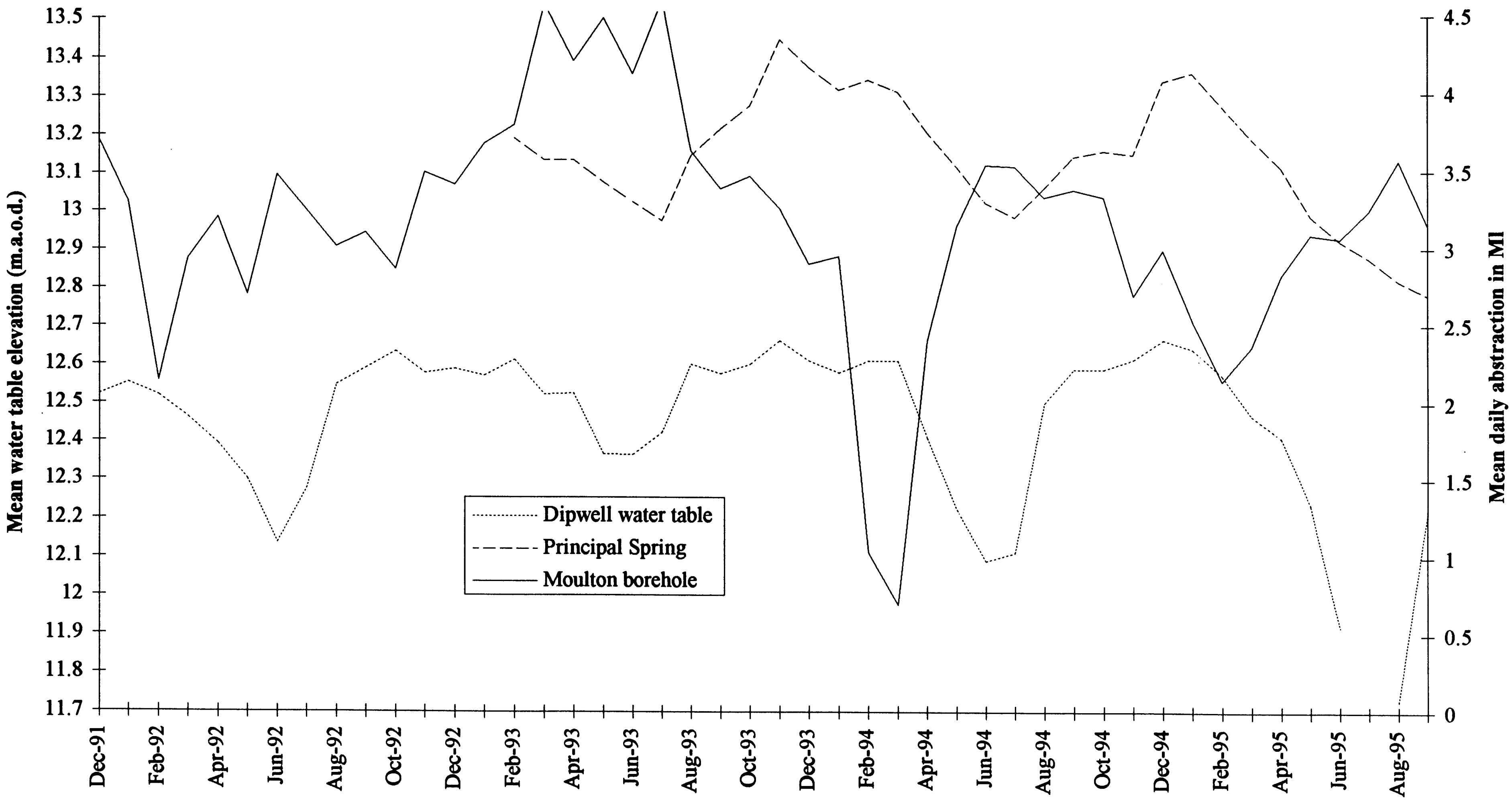


Figure 3.25: Mean monthly dipwell & Principal Spring water table elevation compared with monthly averages of daily abstraction from the Longhill borehole

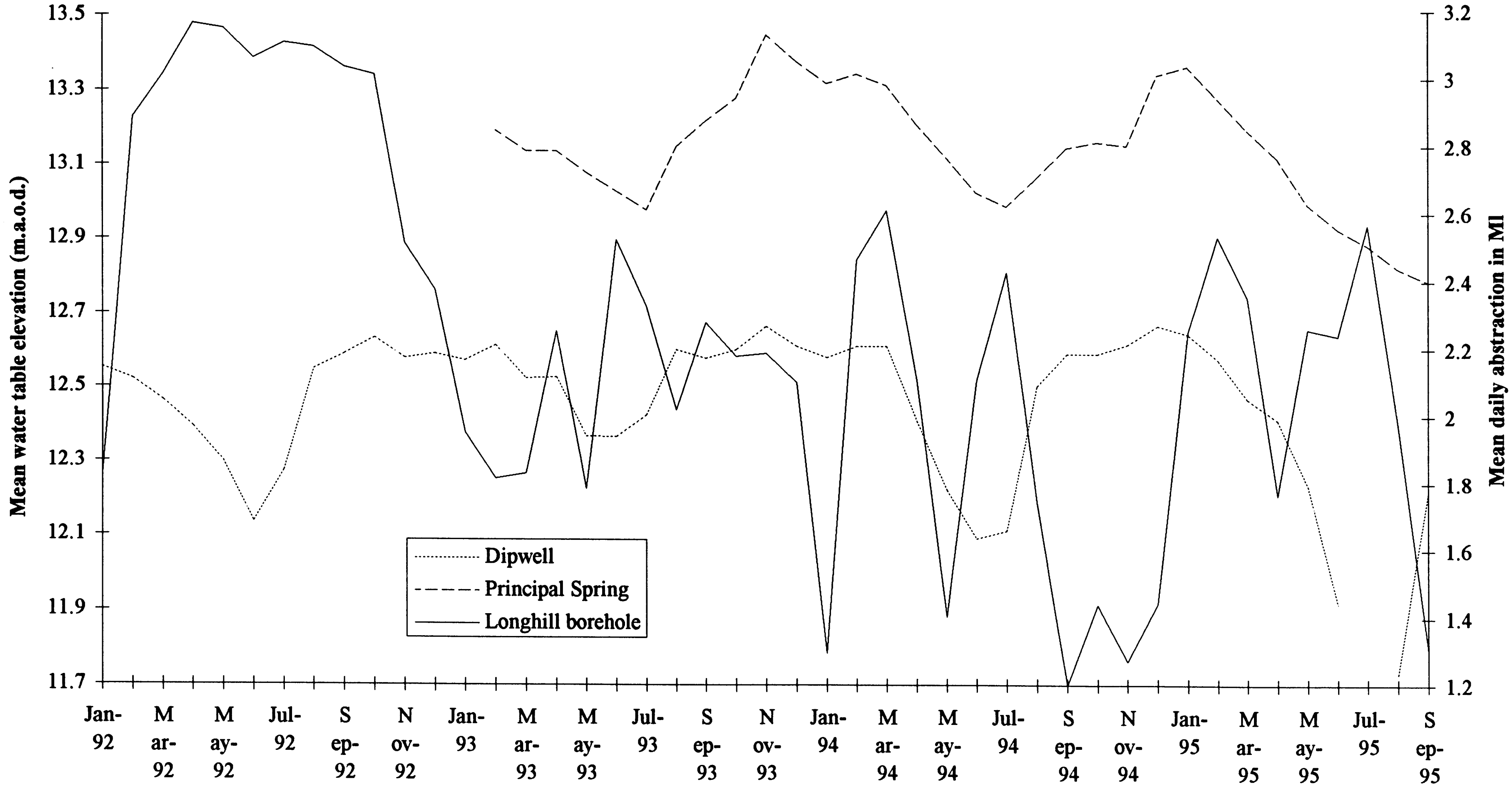


Figure 3.26: Mean monthly dipwell & Principal Spring water table elevation compared with monthly averages of daily abstraction rates from the Gazeley borehole

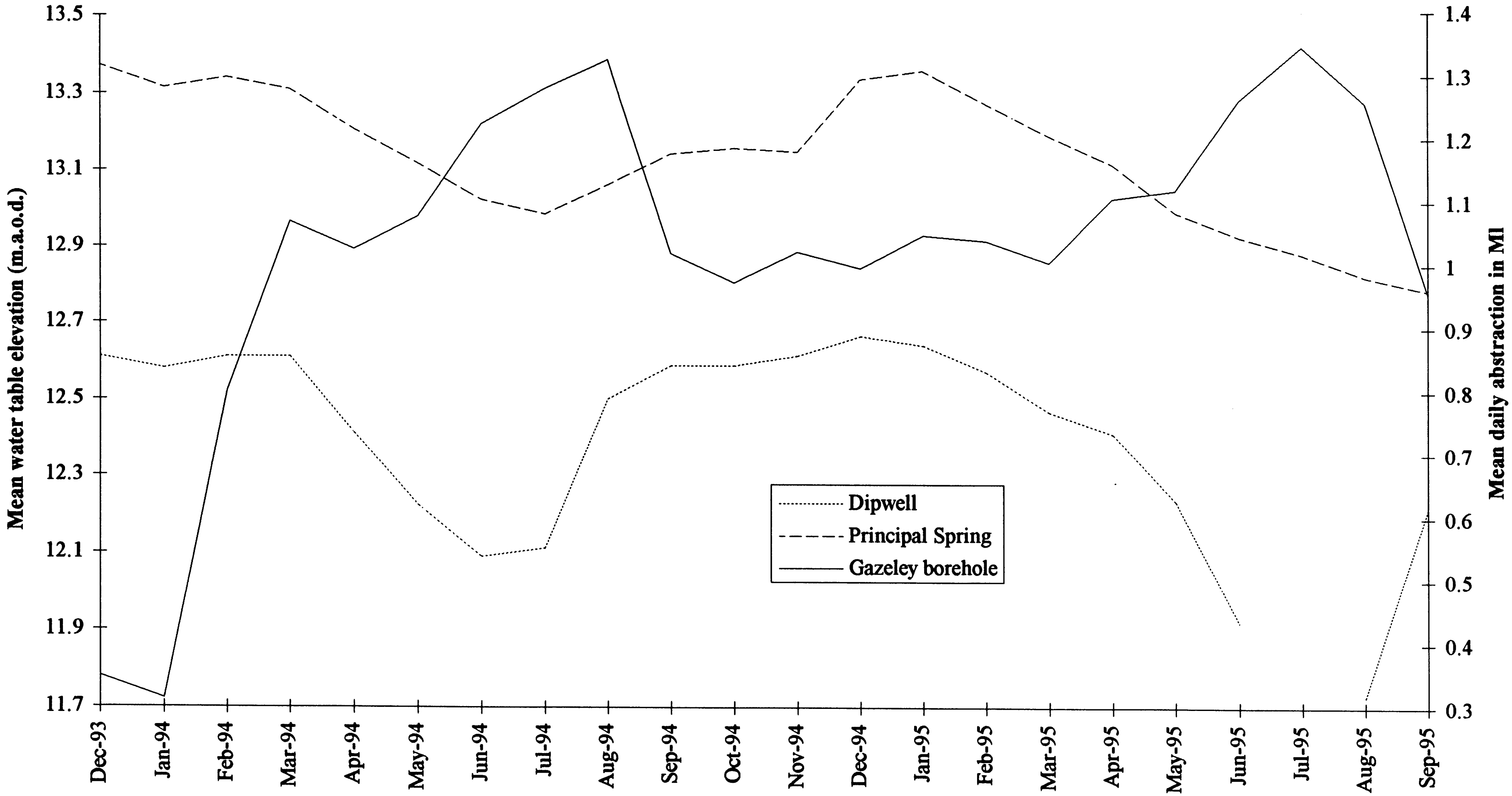


Figure 4.1a: Daily mean discharge readings at Chippenham river before, during and after changes in sluice gate levels in 1992

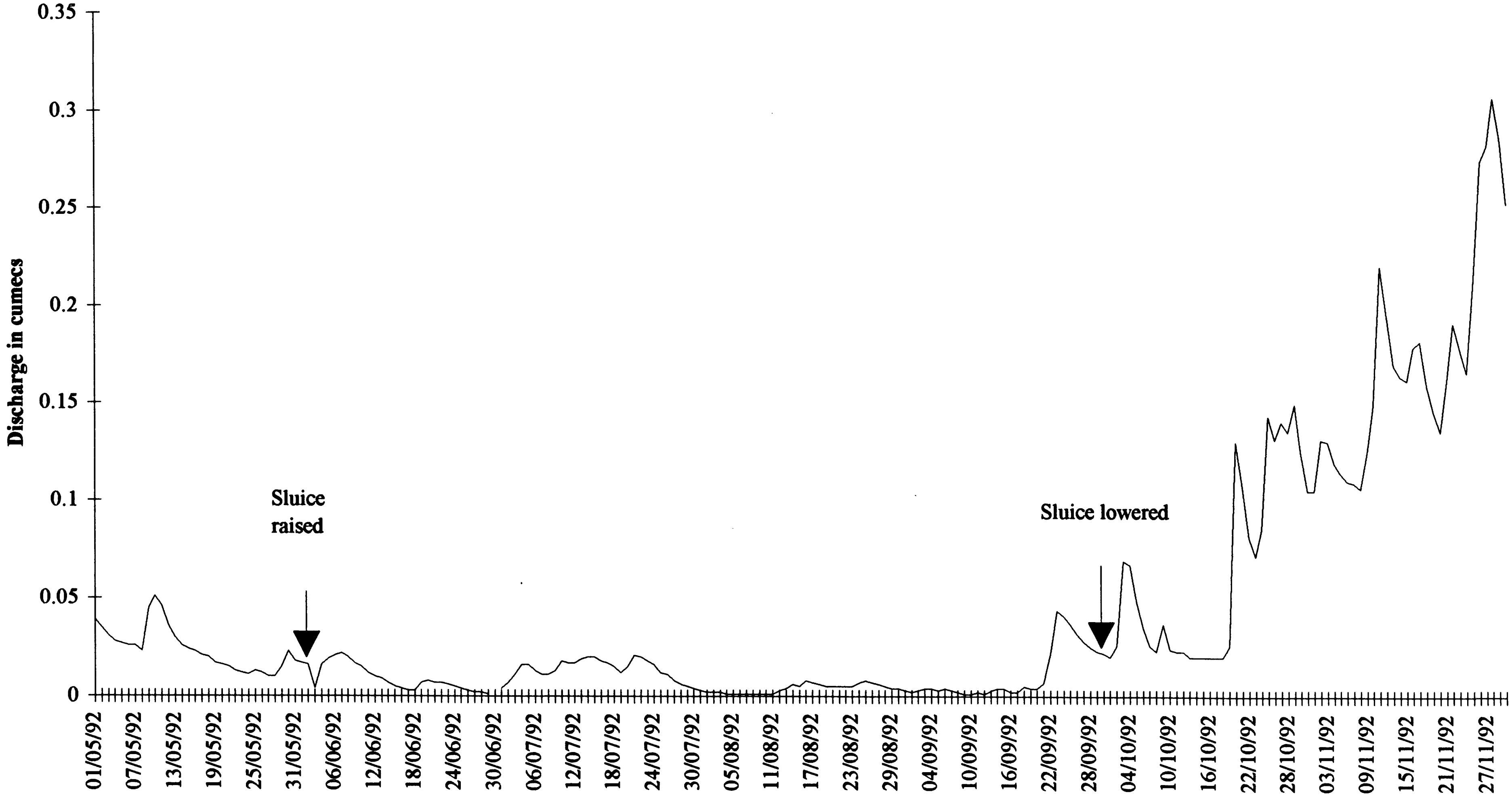


Figure 4.1b: Daily mean discharge readings at Chippenham river before, during and after changes in sluice gate levels in 1993

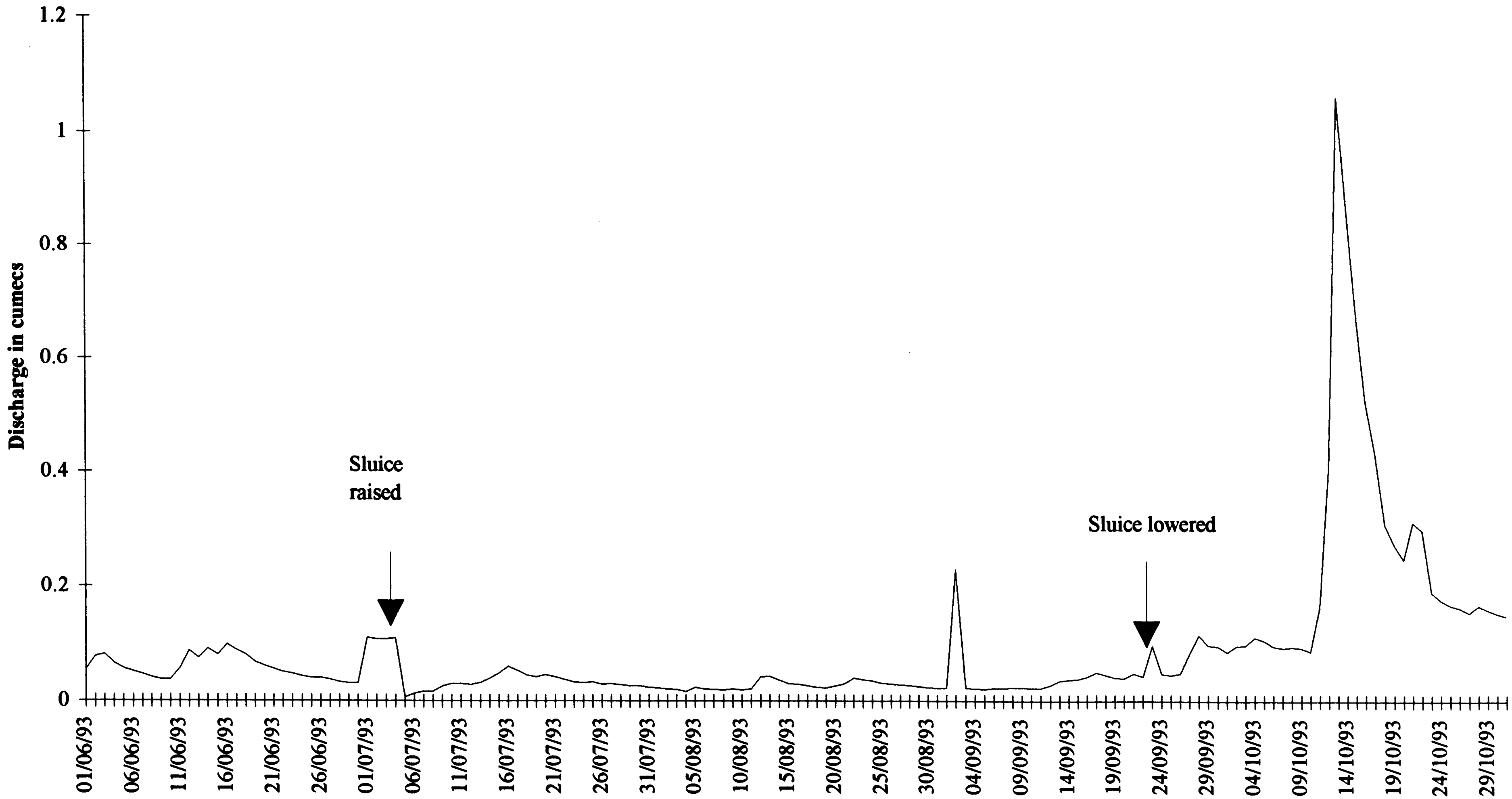


Figure 4.1c: Daily mean discharge readings at Chippenham river before, during and after changes in sluice gate levels in 1994

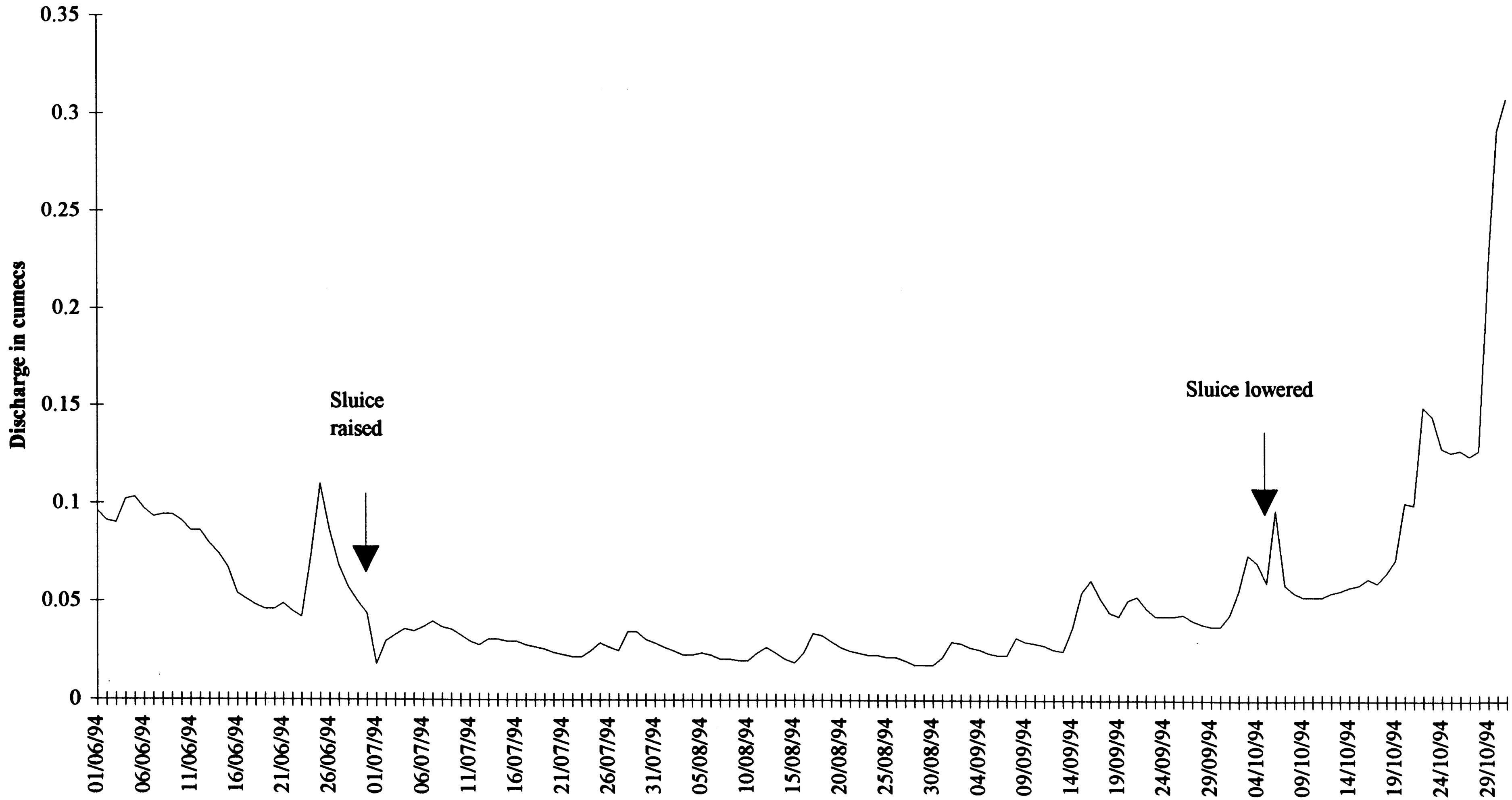


Figure 4.2a: Water table depths at dipwells 2 and 3 before, during and after changes in sluice gate level in 1992

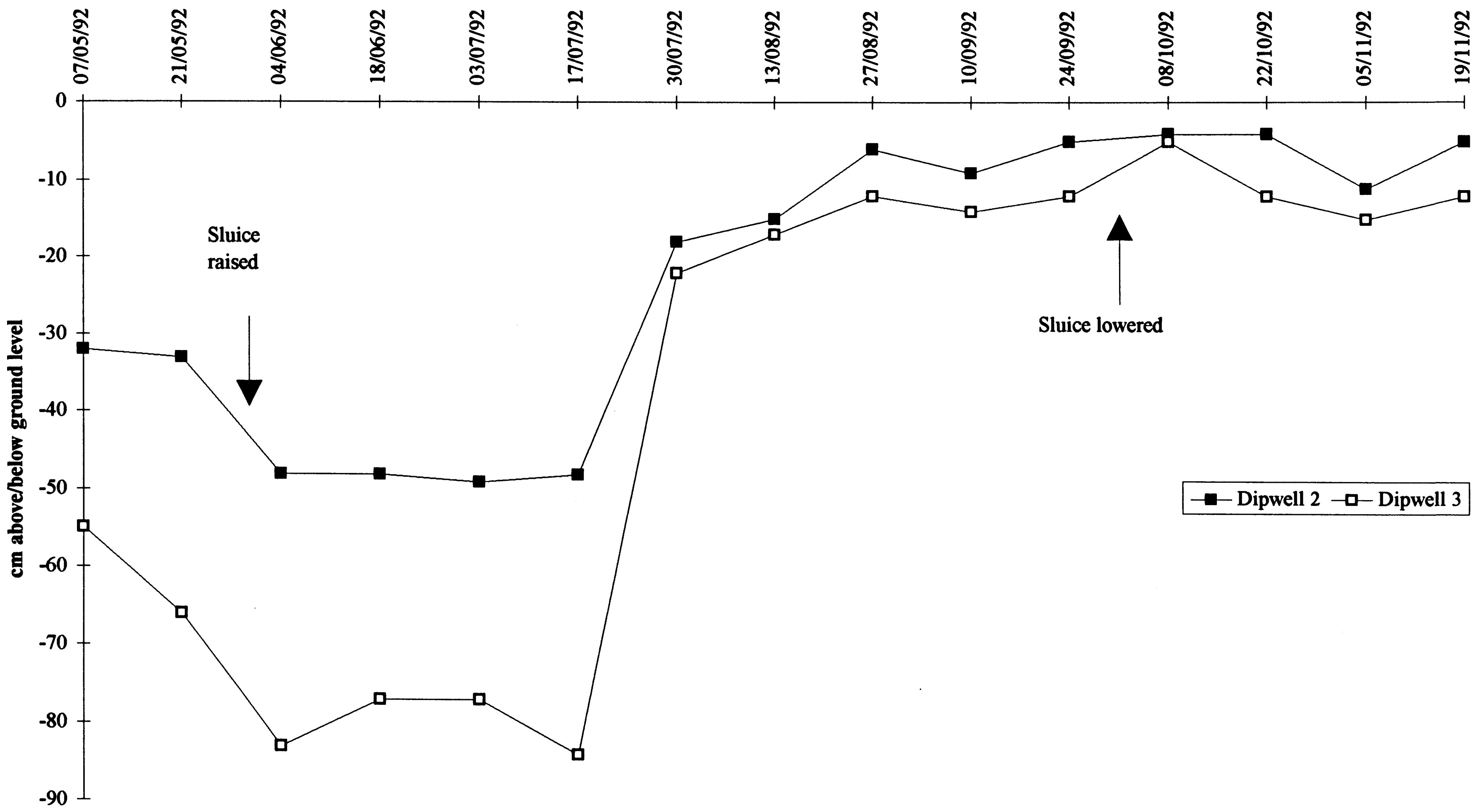


Figure 4.2b: Water table depths at dipwells 2 and 3 before, during and after changes in sluice gate level in 1993

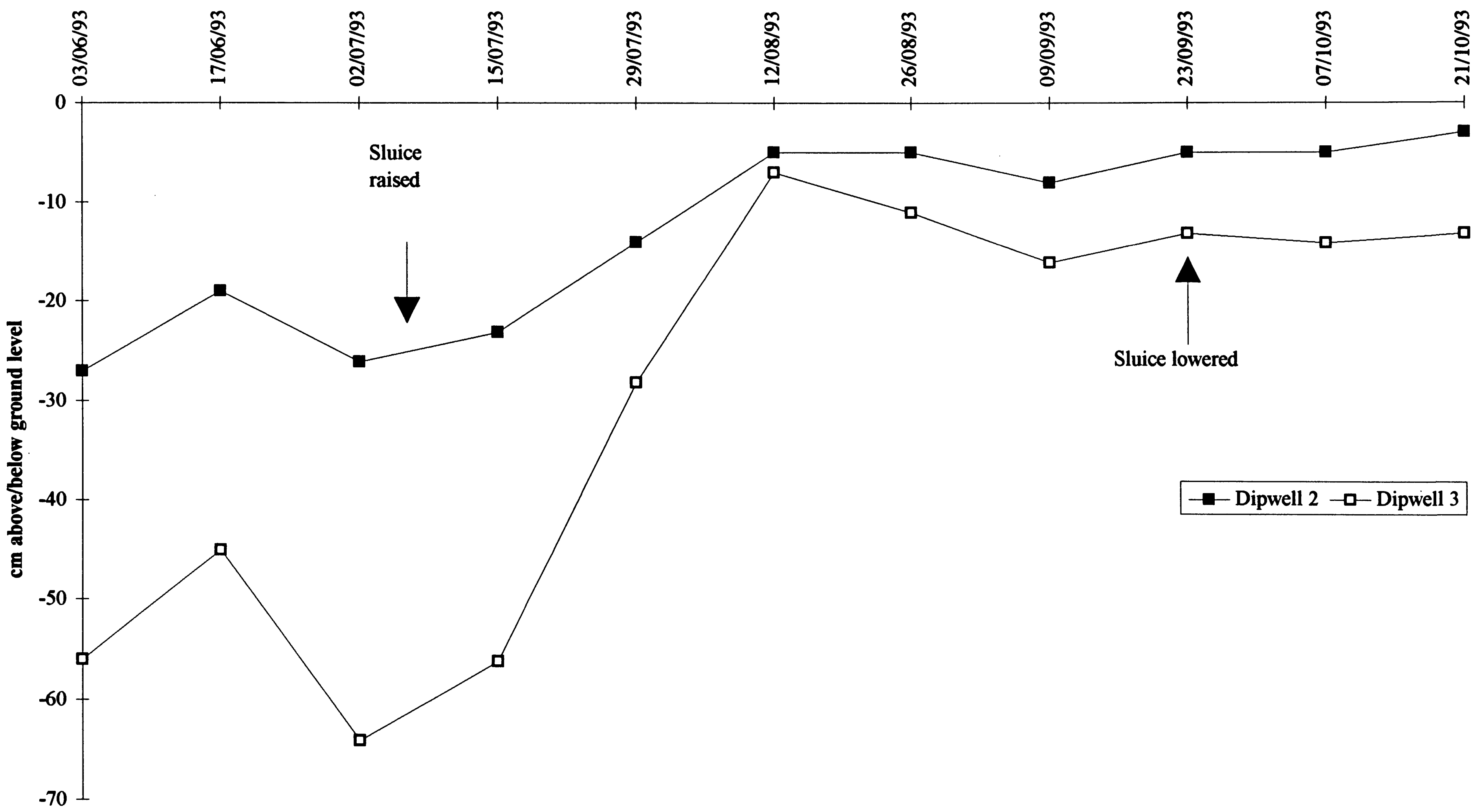


Figure 4.2c: Water table depths at dipwells 2 and 3 before, during and after changes in sluice gate level in 1994

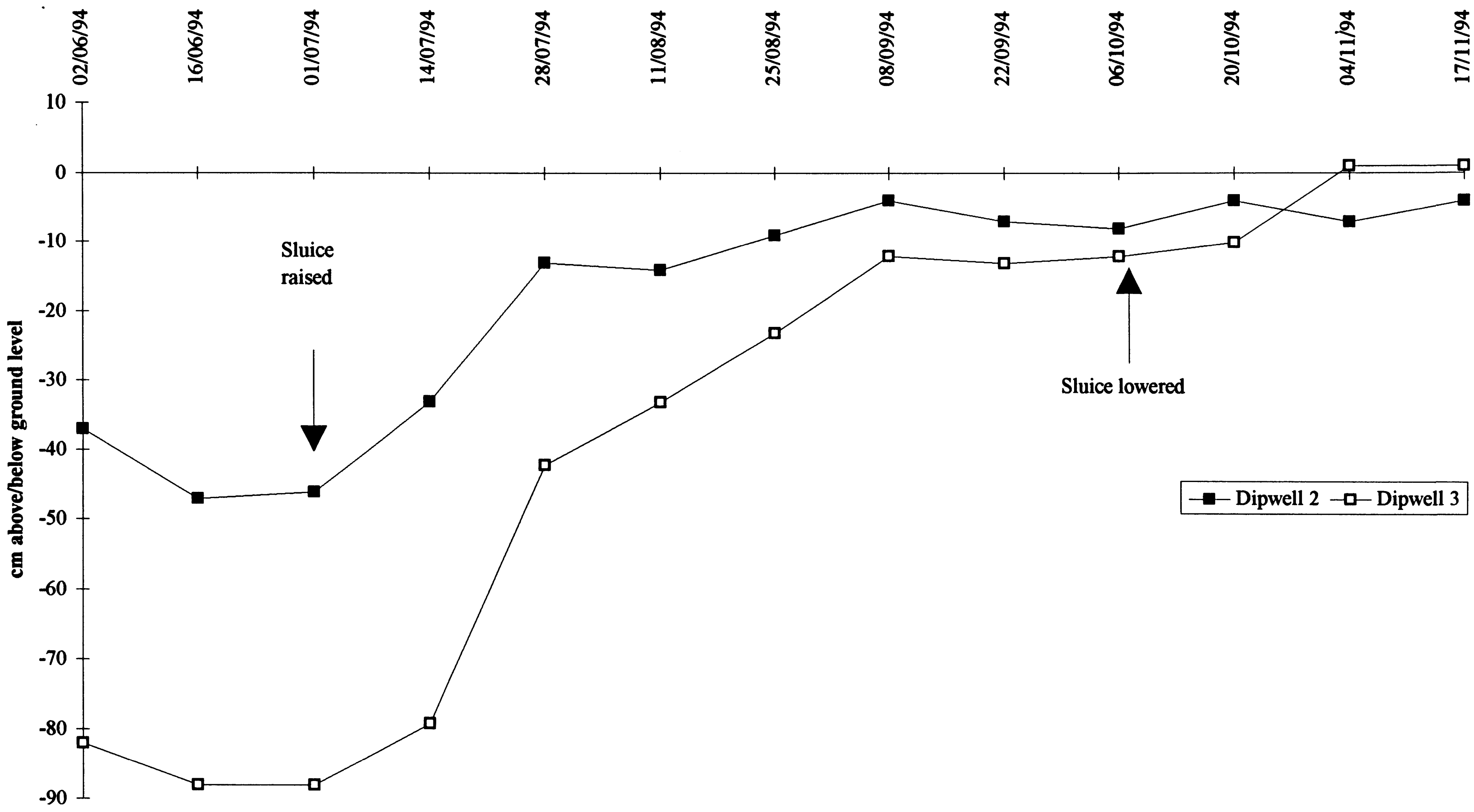


Figure 4.3a: Water table depths for dipwells affected by water level adjustments in nearby drains, 1992-1994

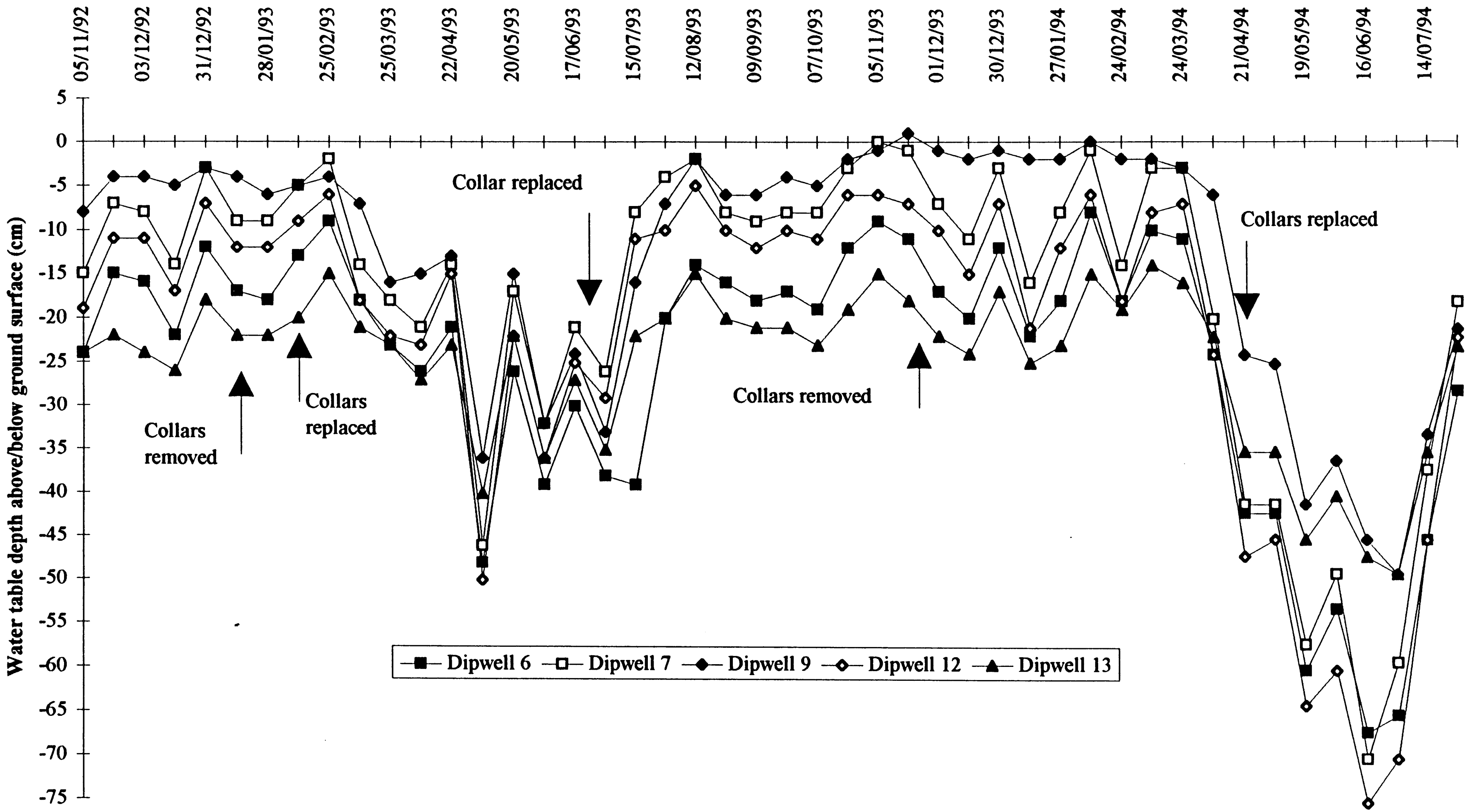


Figure 4.3b: Readings over time for gaugeboards GB2 and GB3, Chippenham Fen

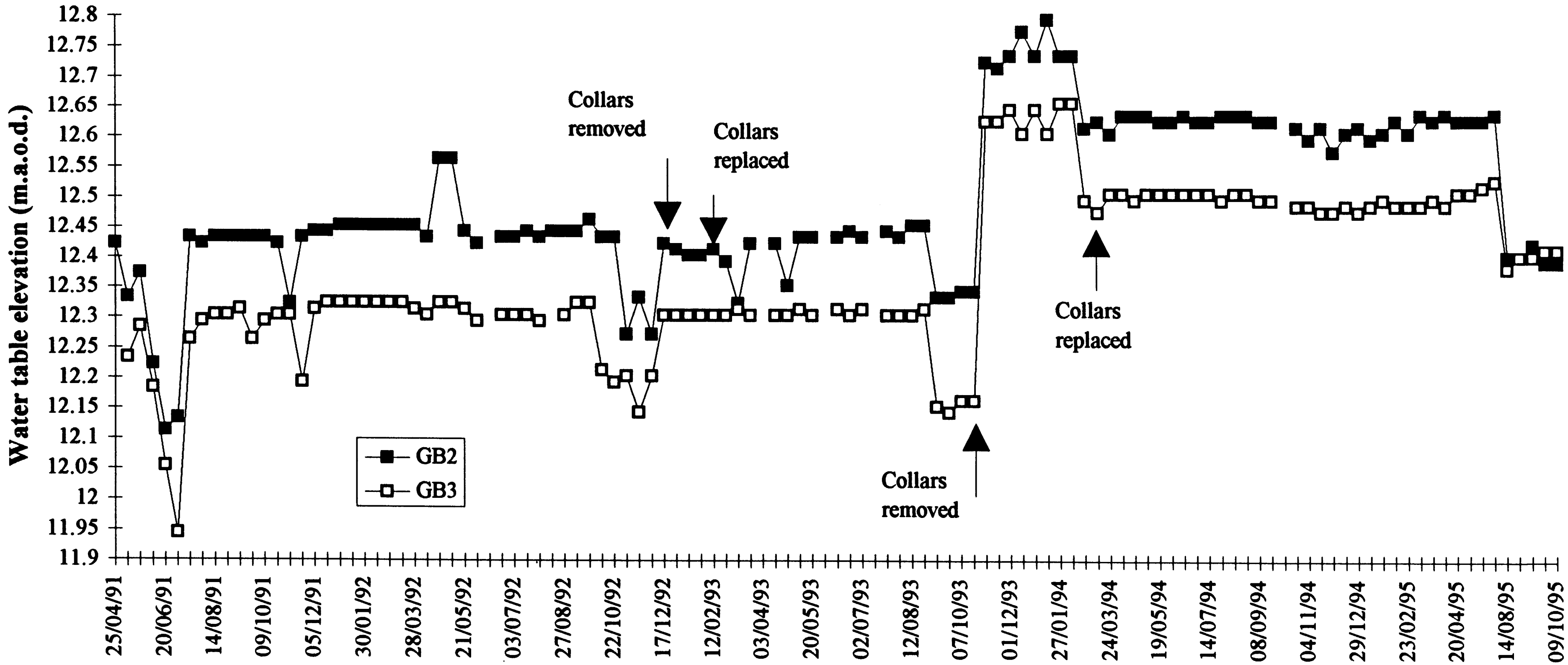


Figure 4.4: Water table changes over time for dipwells 5, 14 and 16 after raising bund 6 on the 26/12/94

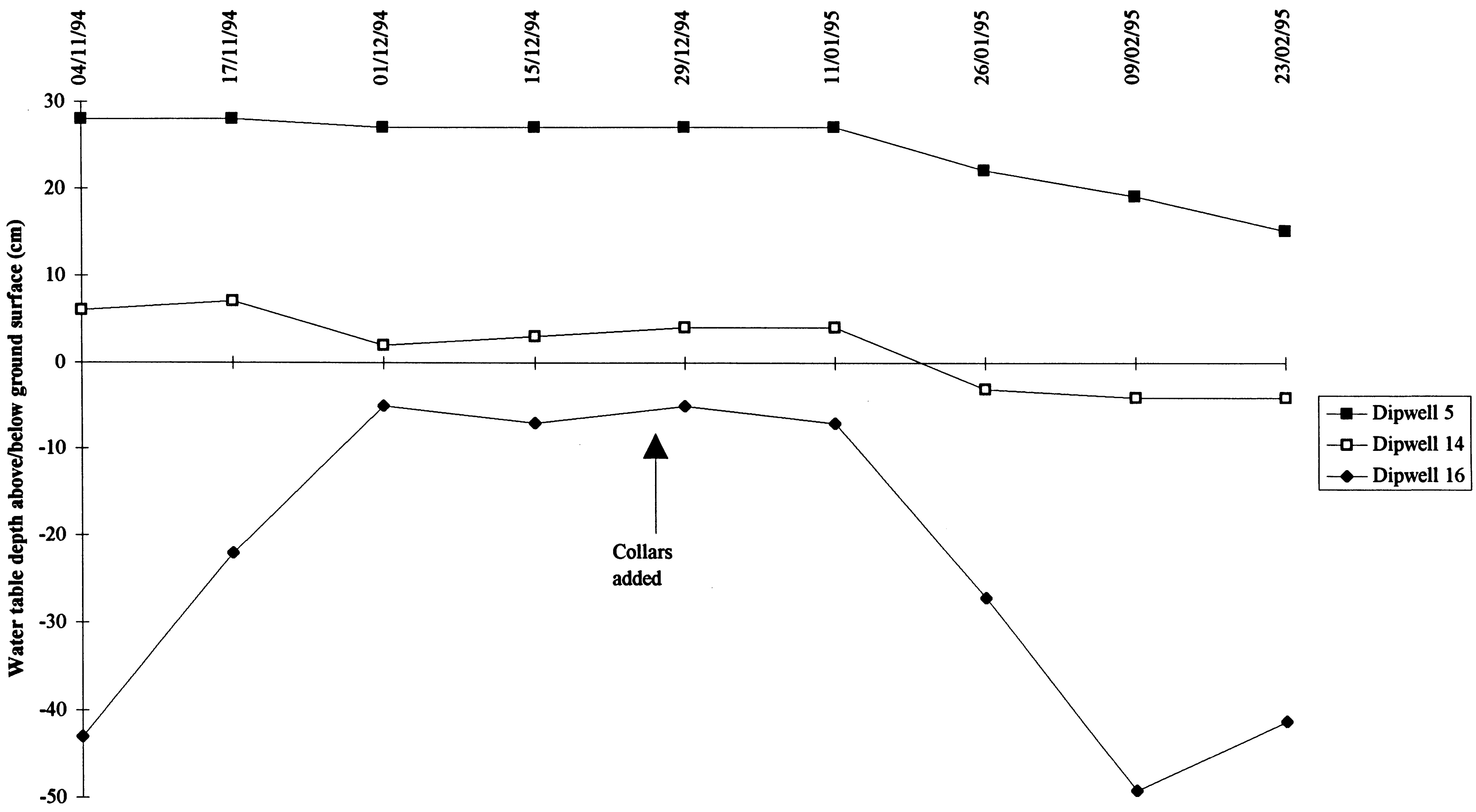


Figure 4.5: Mean dipwell water table level before, during and after pumped discharge inflow, Chippenham Fen 1992

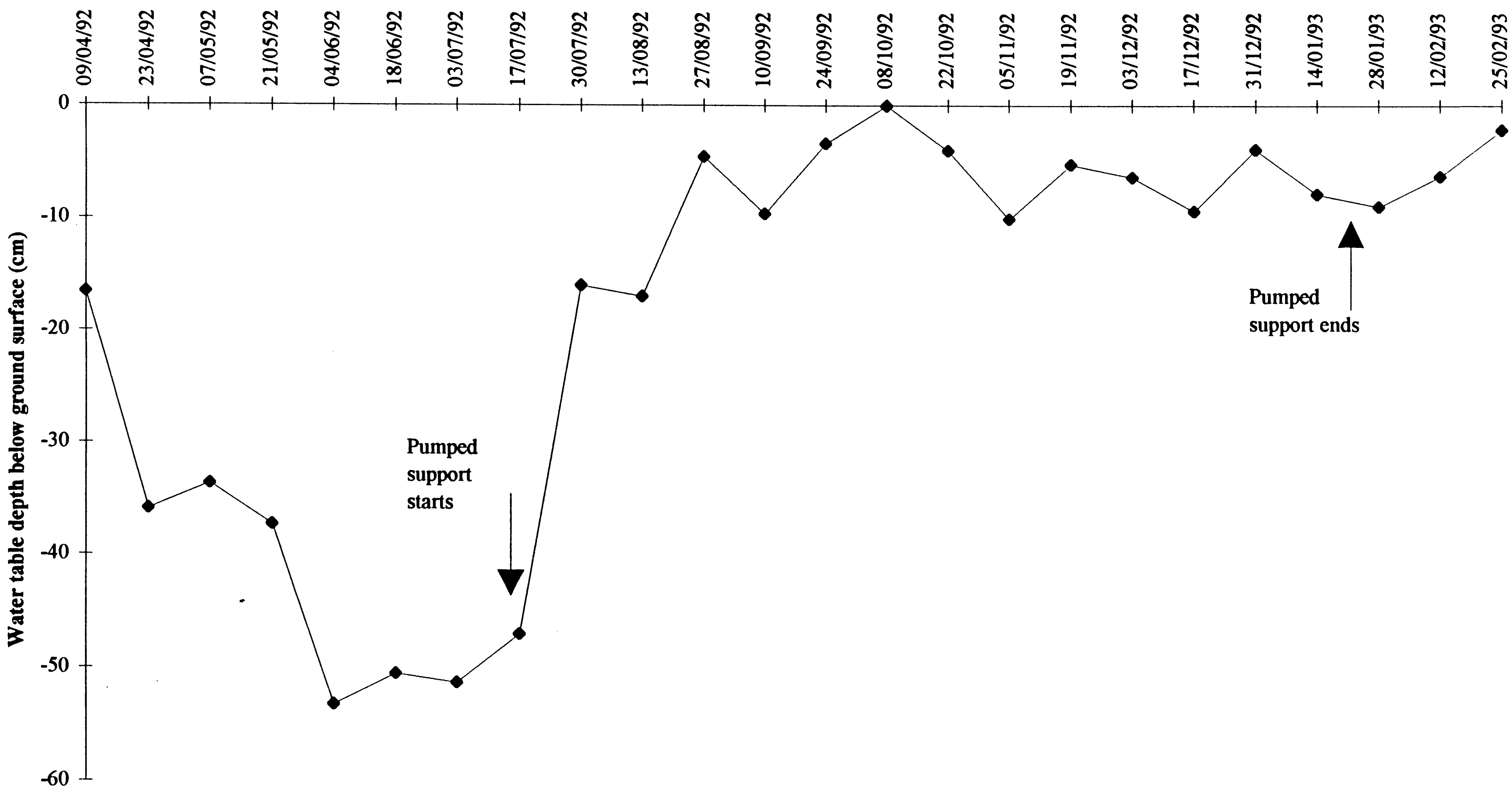


Figure 4.6: Gaugeboard readings above ordnance datum before, during and after pumped discharge to Chippenham Fen, 1992

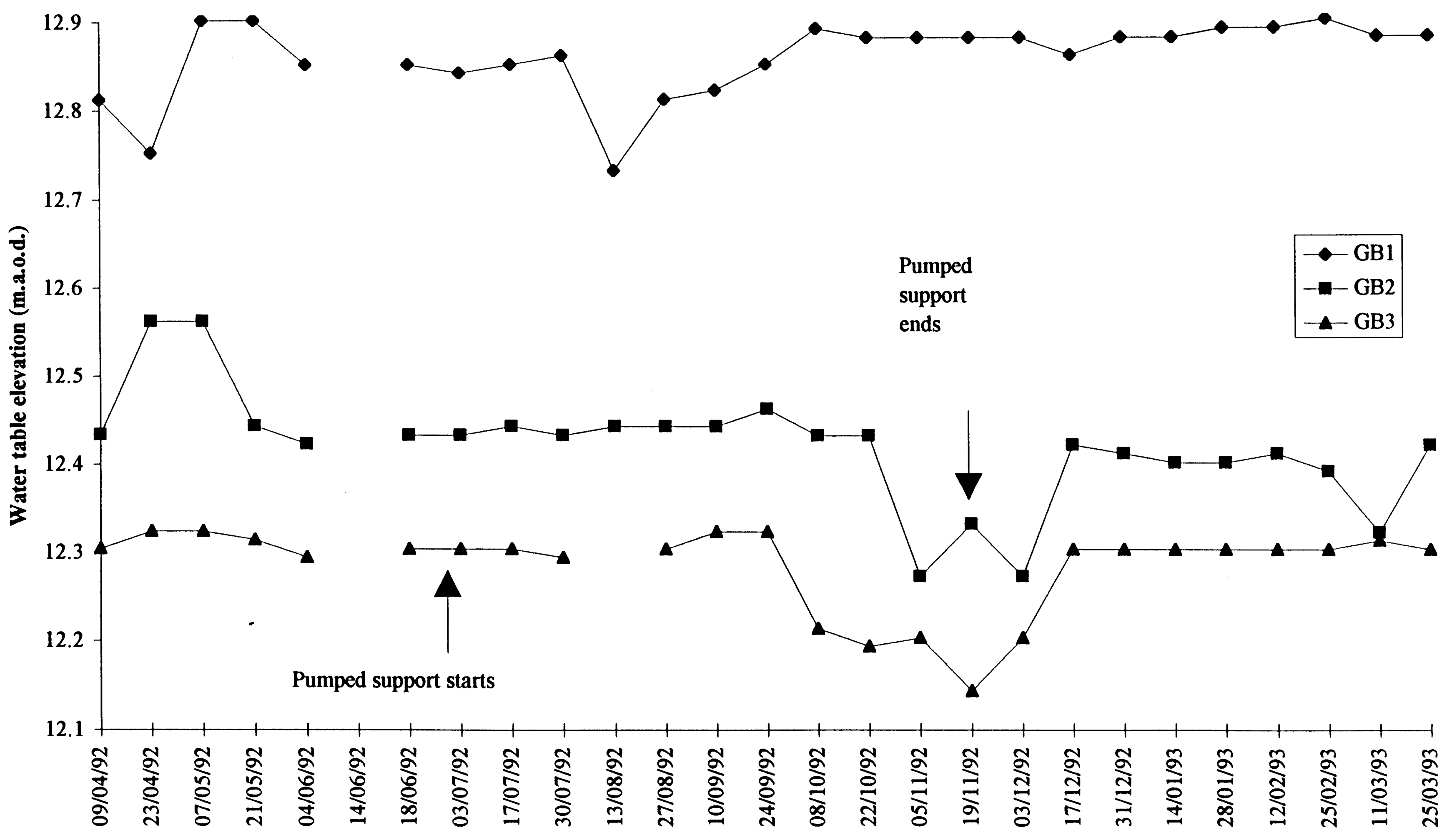


Figure 4.7: Mean daily discharge before, during and after pumped discharges to Chippenham Fen, 1992

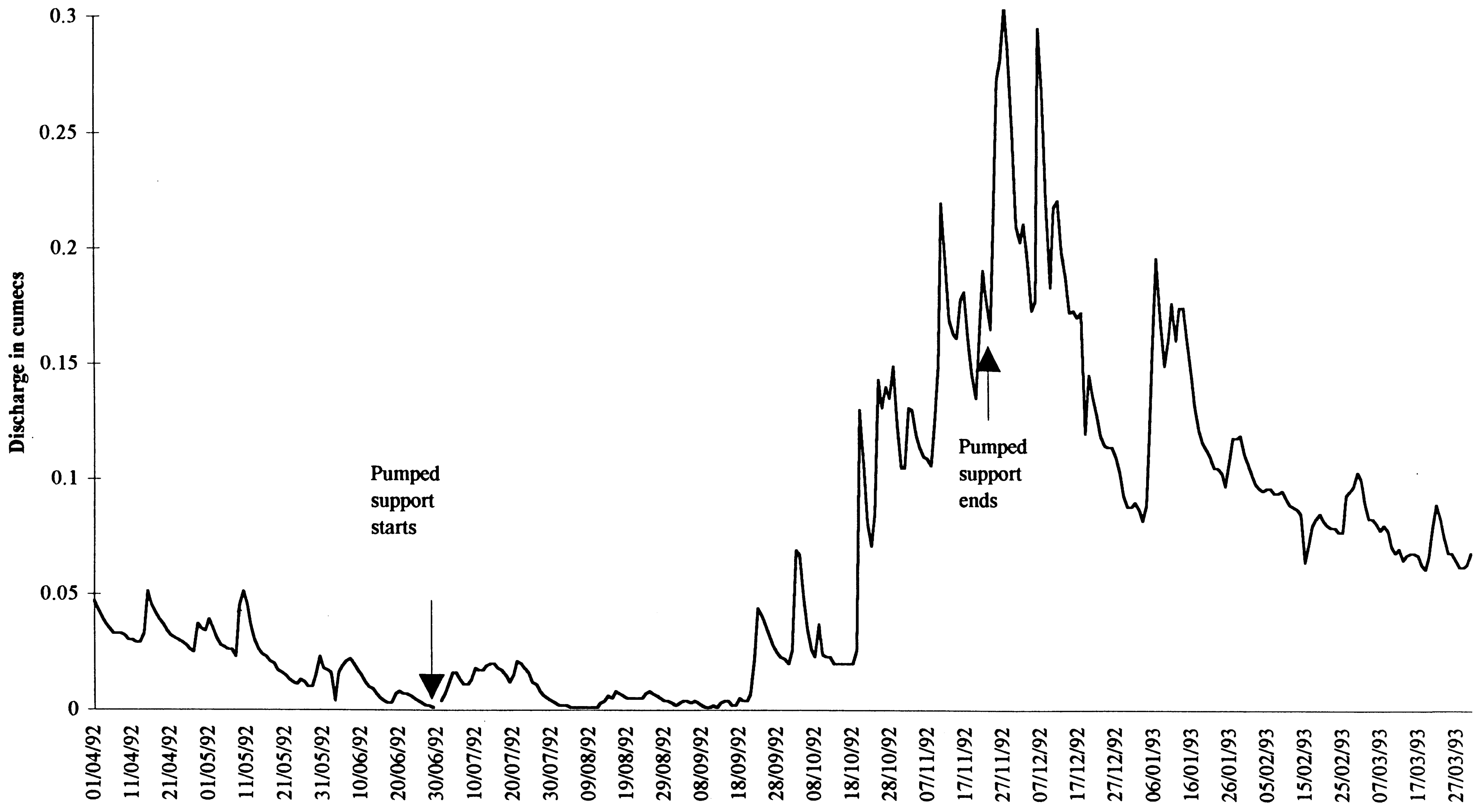


Figure 4.8: Daily rainfall recorded at the Isleham raingauge before, during and after pumped discharge to Chippenham Fen, 1992

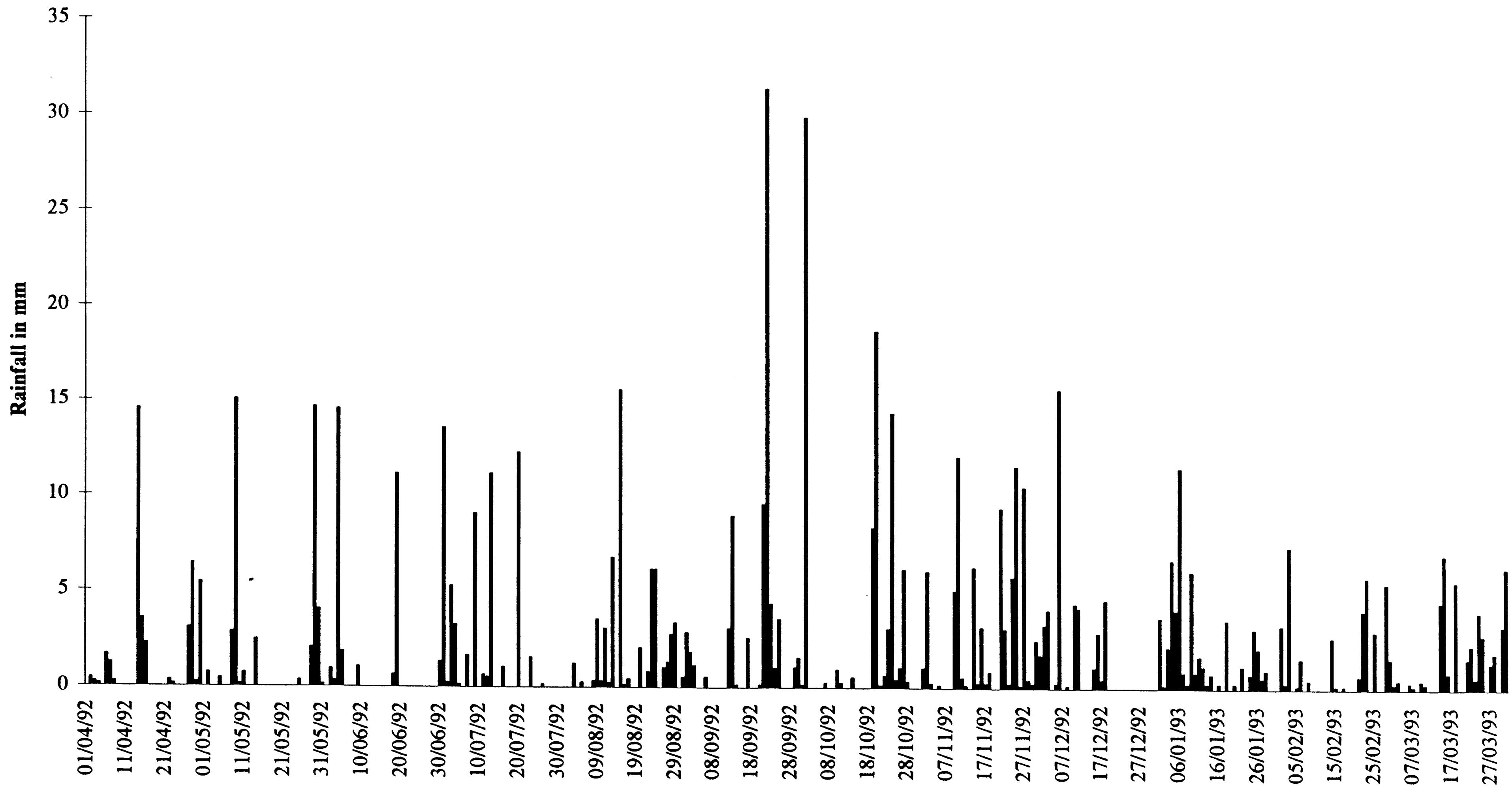


Figure 4.9: Mean dipwell water table level before, during and after pumped discharge inflow, Chippenham Fen 1993

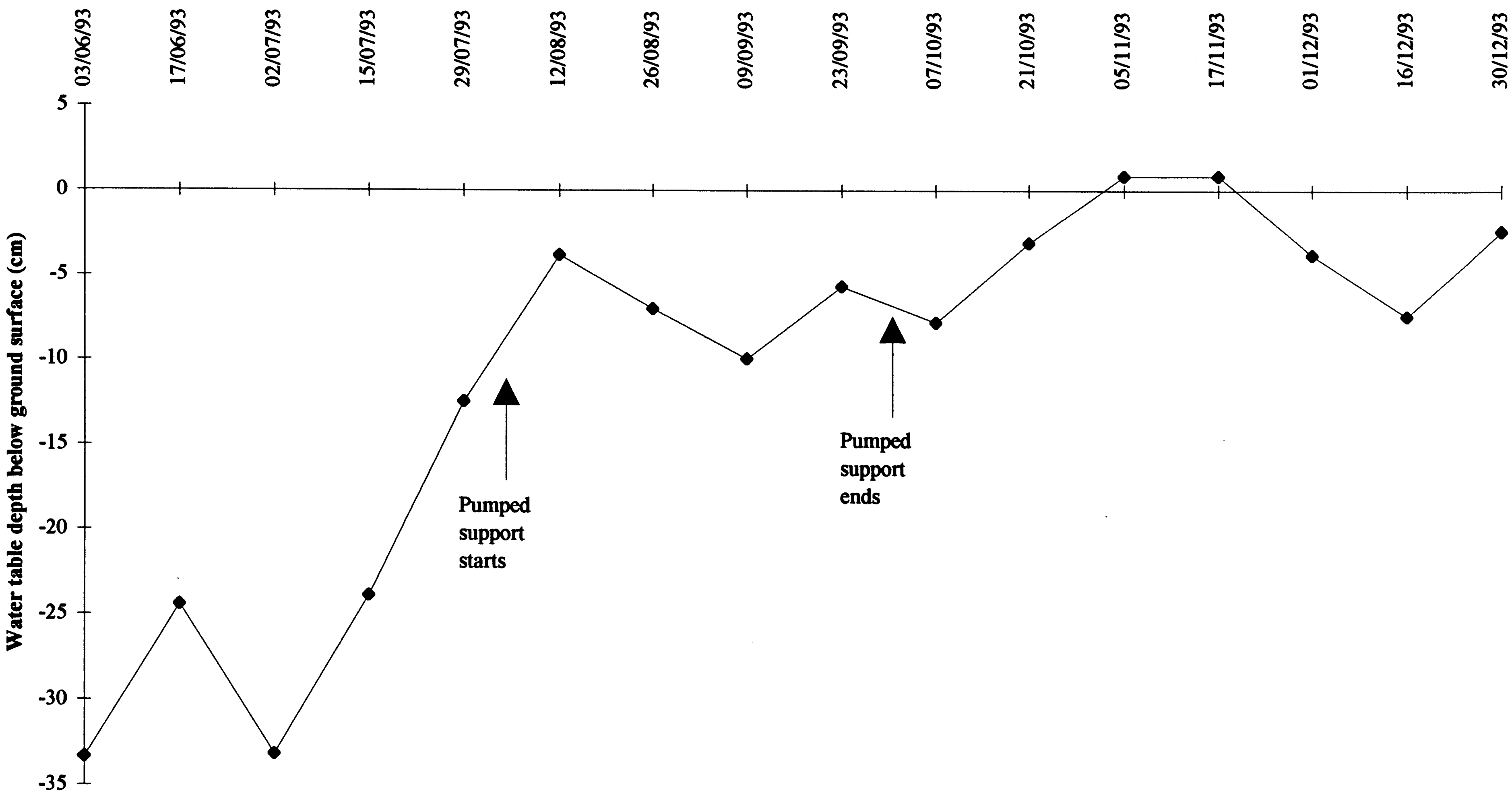


Figure 4.10: Principal Spring and Gaugeboard readings above ordnance datum before, during and after pumped discharge to Chippenham Fen, 1993

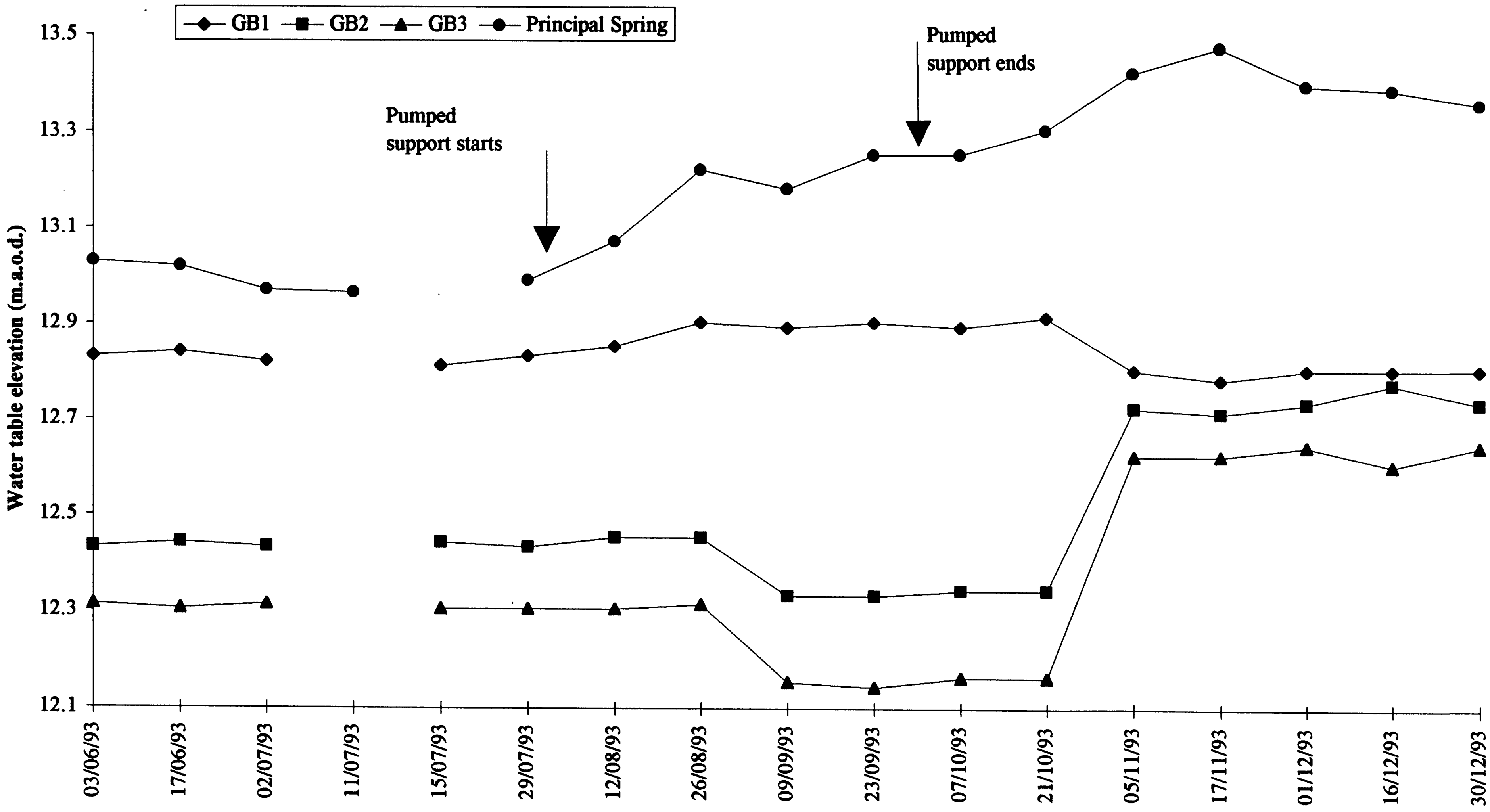


Figure 4.11: Mean daily discharge before, during and after pumped discharges to Chippenham Fen, 1993

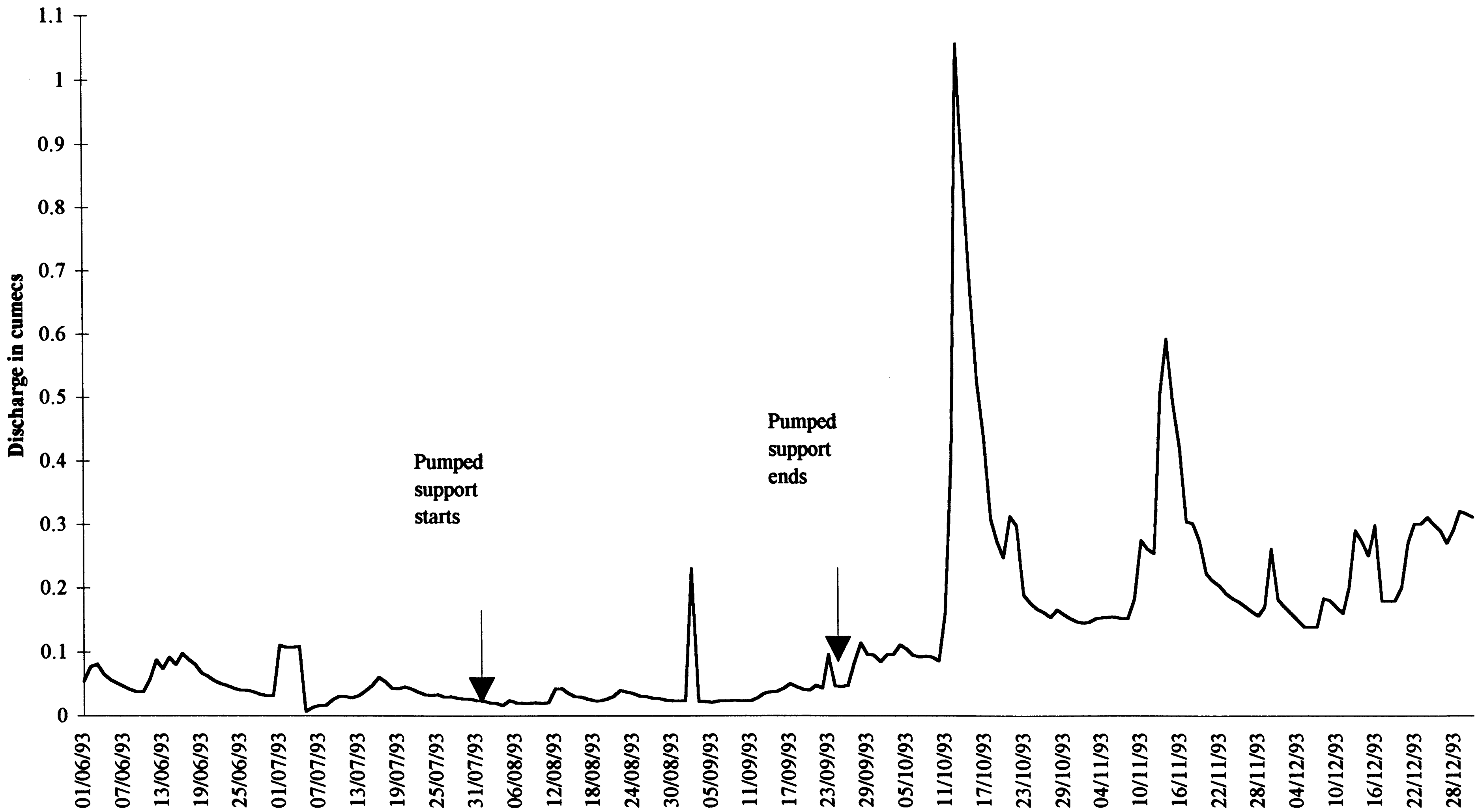


Figure 4.12: Daily rainfall recorded at the Isleham raingauge before, during and after pumped discharge to Chippenham Fen, 1993

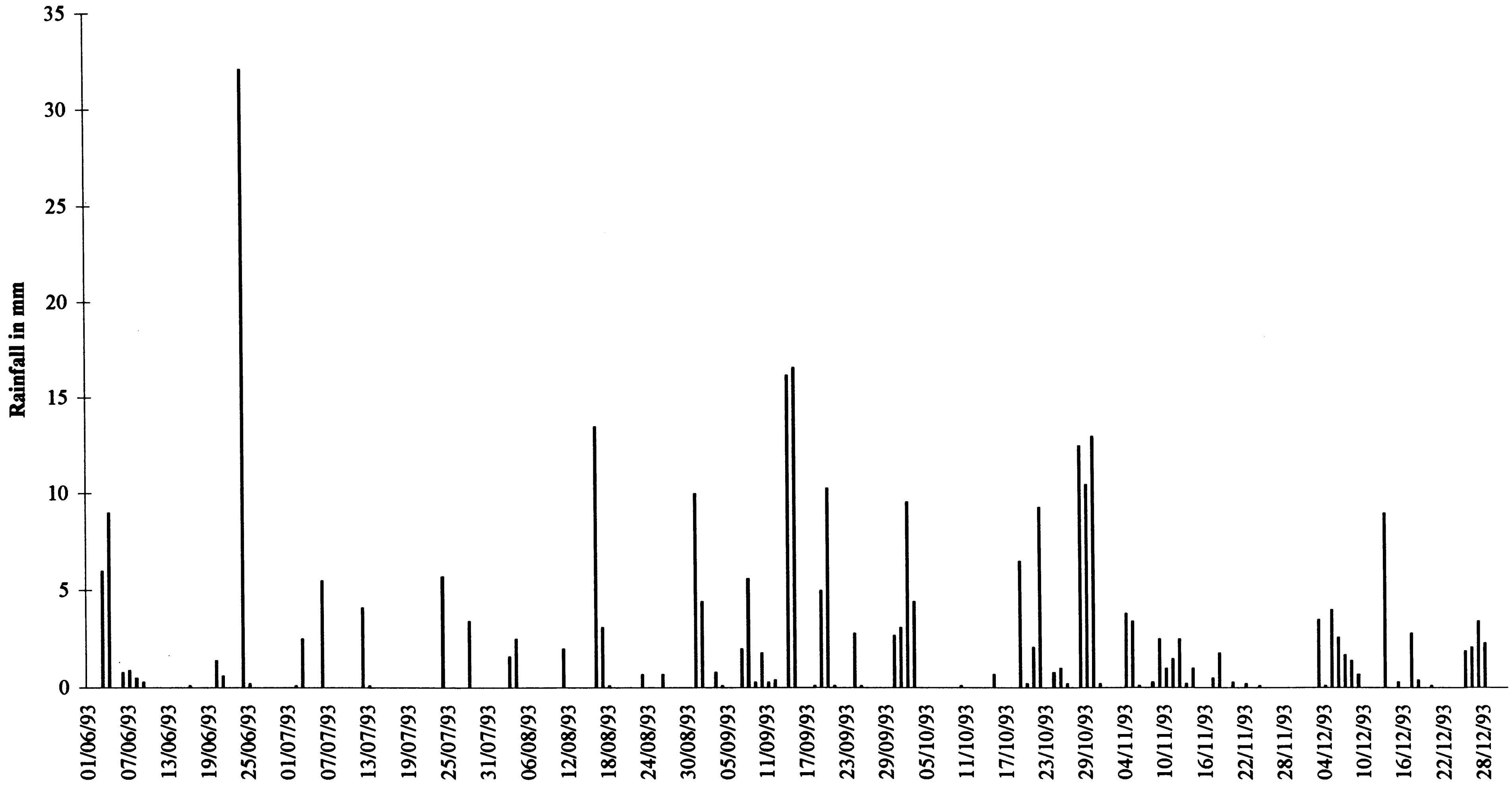


Figure 4.13: Mean dipwell water table level before, and during pumped discharge inflow, Chippenham Fen 1995

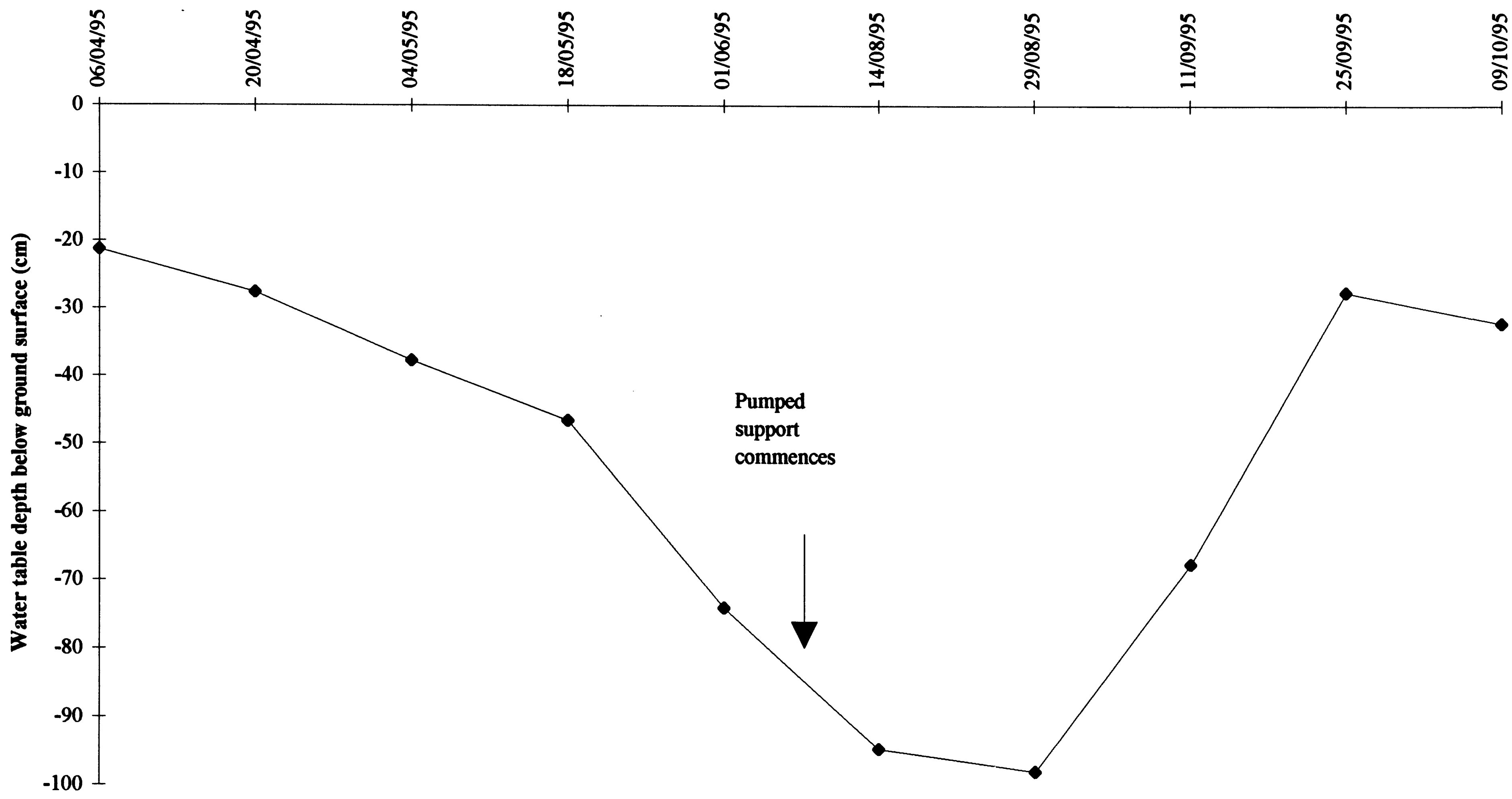


Figure 4.14: Principal Spring and Gaugeboard readings above ordnance datum before and during pumped discharge to Chippenham Fen, 1995

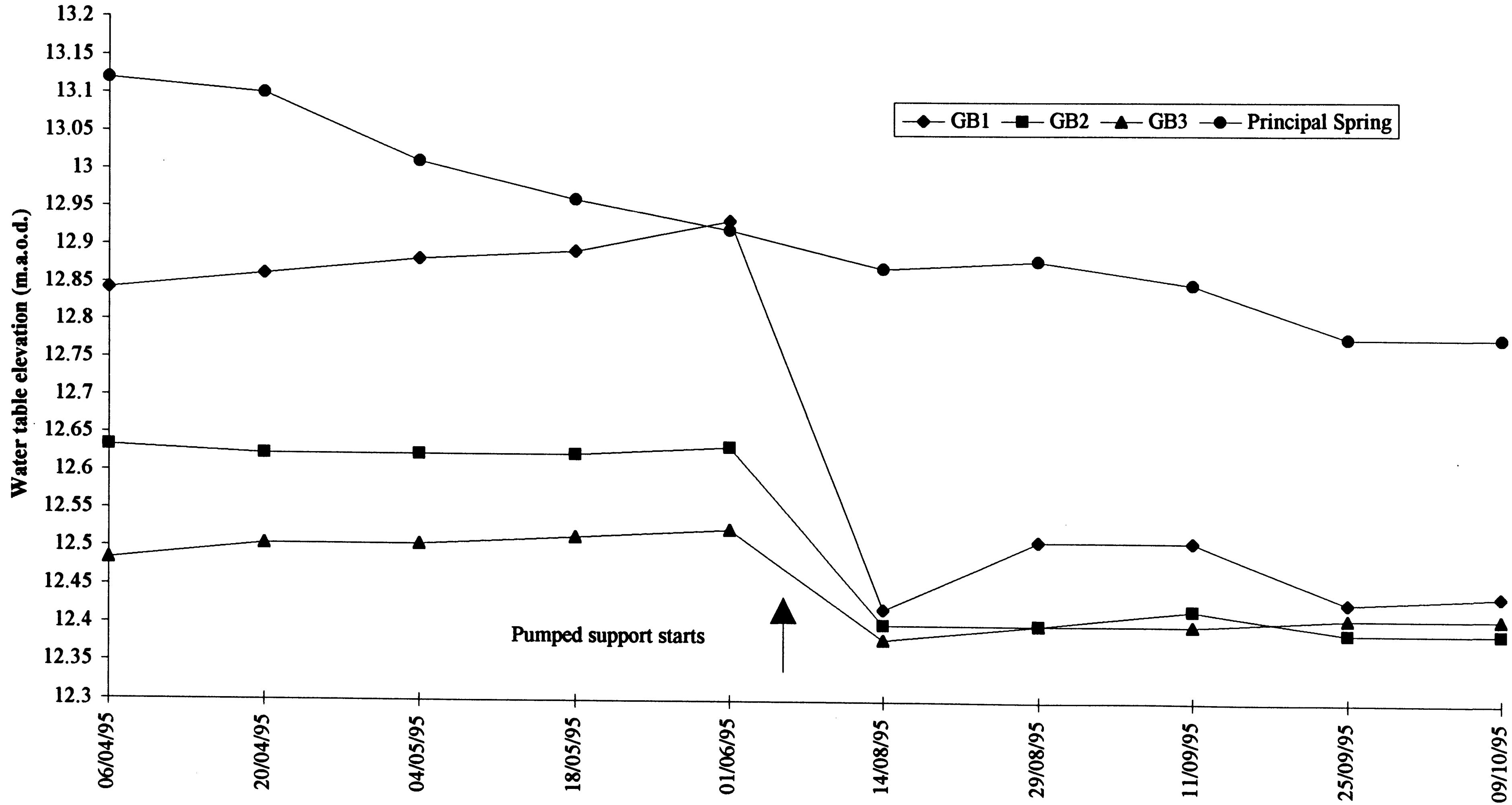


Figure 4.15: Mean daily discharge before and during pumped discharges to Chippenham Fen, 1995

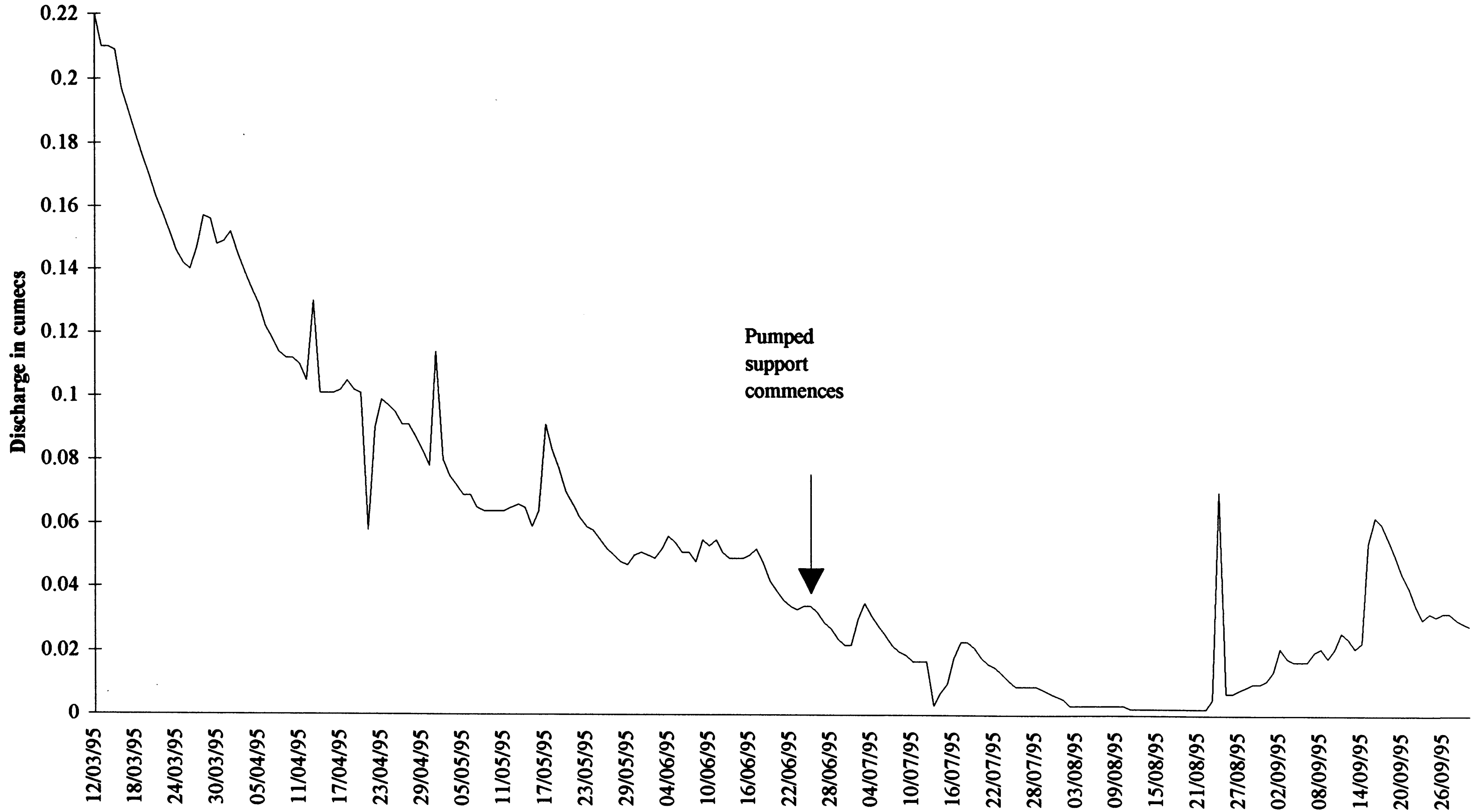


Figure 4.16: Daily rainfall recorded at the Chippenham tipping bucket raingauge before and during pumped discharge to Chippenham Fen, 1995

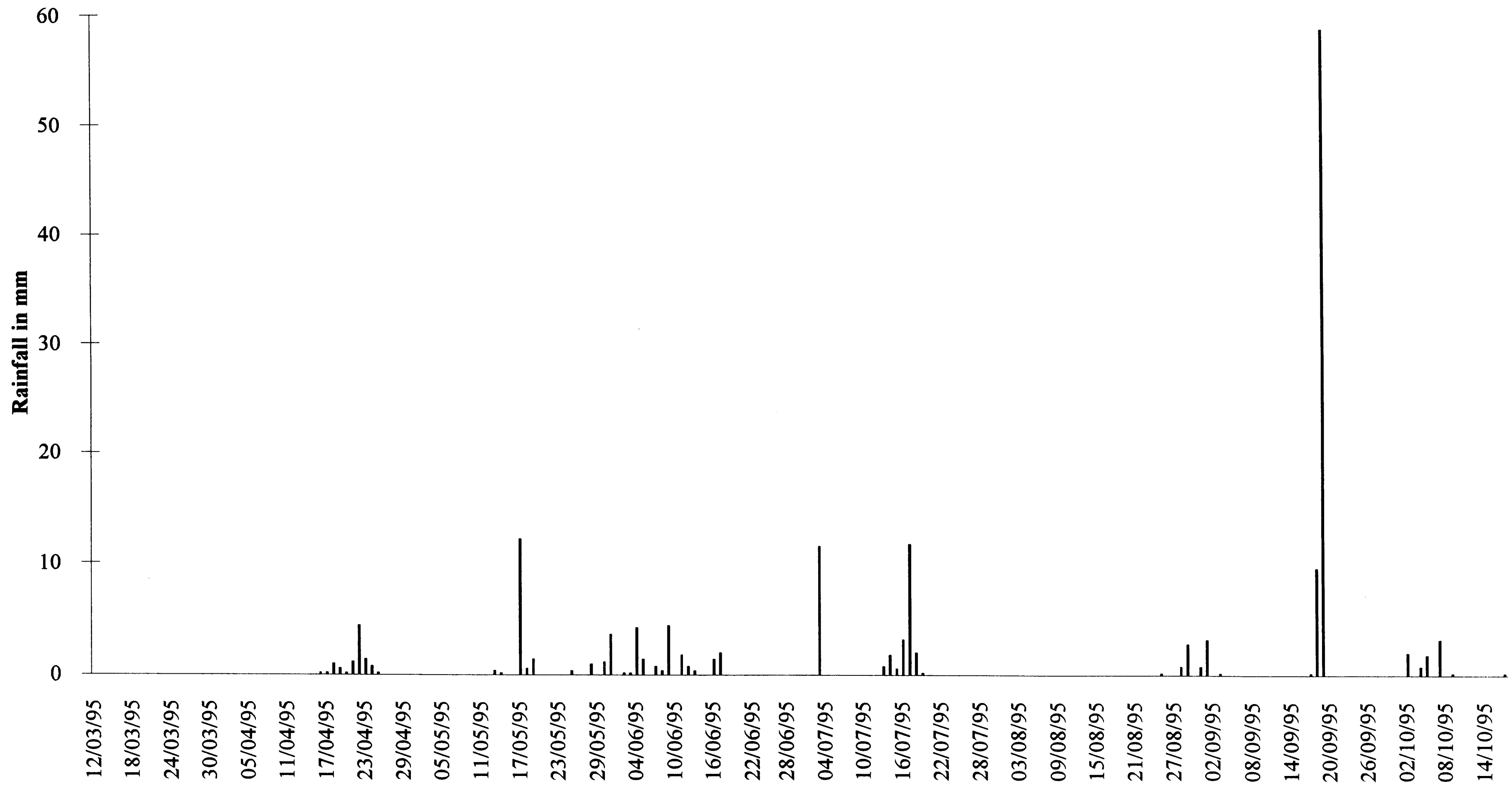


Figure 4.17: Comparison of total daily discharge in the Chippenham river with predicted daily discharge without river support pumping, 1992