Research Paper /

Unsaturated zone flow processes and aquifer response time in the Chalk aquifer, Brighton, South East England

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Impact Statement: *Flow processes of water through an unsaturated dual porosity system are characterised from statistical analysis of groundwater monitoring data, and quantified utilizing laboratory unsaturated flow experiments.*

Abstract

The Chalk aquifer is one of the main sources of water in South East England. The unsaturated zone in the aquifer plays an important role controlling the time and magnitude of recharge and is major pathway for contaminant transport to the water table. A range of previous work has addressed flow processes in the Chalk unsaturated zone, but physical understanding is still incomplete. Here we present the results of a study on flow mechanism in the Chalk unsaturated zone using a combination of statistical analysis and novel laboratory methods. The study was undertaken at three sites (North Heath Barn, Pyecombe East and Preston Park) on the Chalk of the Brighton block, South East England. Daily and hourly time series data of groundwater level and rainfall were correlated. The results show that a slower groundwater level response to rainfall occurs during dry seasons (summer and autumn) when the amount of effective rainfall is less than 4 mm/day, with a thicker and drier unsaturated zone. A faster response occurs during wet seasons (winter and spring) when the daily effective rainfall exceeds 4 mm/day with a thinner and wetter unsaturated zone. Periods of very rapid response (within 15 hours) were observed during wet seasons at North Heath Barn and Pyecombe East sites, with unsaturated hydraulic conductivity (K_u) inferred to reach 839 mm/day. A slower response was observed at an urbanised site (Preston Park) as a result of reduction in direct recharge due to reduced infiltration, due to presences of impermeable infrastructure covering the area around Preston Park borehole. Laboratory measurements of K_u of the Chalk matrix using a geotechnical centrifuge show variation from 4.27 to 0.07 mm/day, according to the level of saturation. Thus, the rapid responses cannot be linked to matrix flow only but indicate the contribution of fracture and karstic flow processes in conducting water.

Introduction

The timing and magnitude of recharge reaching the water table have significant consequences of water resources and the movement of pollutants to the groundwater. Chalk aquifers present complex issues in this area, because of contributions to flow from matrix intergranular flow, fracture flow across a range of scales and flow within karstic features (Price et al. 1993). The Chalk is an important source of water in the North West Europe particularly in Britain, northern Germany, Belgium and northern France (Downing 1993; Brouyère et al. 2004). Locally the Chalk aquifer is of critical importance for groundwater supply and maintenance of base flow to rivers (Price et al. 1993). Topographic variation within the Chalk generates a thick unsaturated zone in interfluve areas. This thick unsaturated zone, 20 - 80 m BGL depending on the season and antecedent rainfall, leads to significant delays in rainfall reaching the water table and to attenuation of the recharge process. The influence of this attenuation on groundwater availability, the timing of recharge and contaminant transport is still poorly understood and not well quantified. This is related to the complexity of flow mechanisms through the dual-porosity system in the Chalk (Price et al. 1993), and the difficulty of monitoring water content and matric potential for the entire unsaturated zone.

Several studies have evaluated the relative contribution of matrix and fracture flow within the Chalk, including Smith et al. (1970); Downing et al., (1979); Wellings and Bell (1980); Wellings (1984a); Gardner et al. (1990) and Cooper et al. (1990). Jones and Cooper (1998) observed that fracture flow accounted for approximately 30% of the total flow in a year at Fleam Dyke on the Cambridgeshire Middle Chalk. In contrast, Wellings (1984a) observed only one occasion of fracture flow in a year at Bridget's Farm on the Hampshire Upper Chalk. The data measured in these studies were collected on a weekly basis and hence short duration fracture flow events may have been missed. Other studies (Ireson & Butler 2013; Zaidman et al. 1999) have suggested that the mechanism of water flow through the Chalk unsaturated zone might be controlled, not only by the water table depth but also by a combination of additional factors. Ireson and Butler (2013) suggested that fracture flow may be controlled by a combination of rainfall events and level of saturation in the unsaturated zone, and they observed that among 536 rainfall events recorded in their study, only 18 of them lead to bypass recharge. Ireson and Butler (2011) study control on preferential recharge to the Chalk aquifers, they used an empirical and a physically based modelling approaches. They inspect response of groundater to rainfall event by visual inspection (events perturbing water table) without recording the time required of the rainfall pulse reaching groundwater level. Many of these studies, mainly the studies by Ireson et al. (2006); Mathias et al. (2005) and Haria et al.

(2003) have focused on the development of integral physical recharge models to reproduce field observations. However, these studies lead to a complex methodology and a large number of parameters with detail and expensive numerical solution.

Studies completed by Molyneux (2012) and Gallagher,et al. (2012) on the catchment studied here, linked the variation in the mechanism of flow to the lithological variation in the unsaturated zone using field and laboratory methods. They observed that wet zones in the unsaturated zone are linked to the presence of marl seams with low matrix permeability in the unsaturated zone profile. The presence of the marl seam may increase the possibility of fracture flow. These studies reveal the need for high frequency measurements of rainfall and groundwater levels, which may give improved insight into the flow mechanisms in the Chalk unsaturated zone. In addition, a new novel method used to measure hydraulic conductivity and comparing field and laboratory result in better understanding of the Chalk unsaturated flow mechanism.

Study site

This study is focused on the Chalk catchment in the Brighton area, southeast England. Three boreholes have been selected in the area, for analysis of water table response to rainfall events, North Heath Barn (NHB), Pyecombe East (PE) and Preston Park (PP) (Fig. 1). These sites were chosen to represent different unsaturated zone conditions (rural, artificial recharge and urban respectively). The study area has been monitored since 2006, mostly focussing on the NHB site (Adams et al. 2008). At the NHB site, a tipping bucket and an accumulative rain gauge are installed close to the monitoring boreholes to measure rainfall simultaneously with groundwater level. The observations of rainfall and groundwater level were recorded hourly and in some cases every 15 minutes. Potential evapotranspiration at the site was calculated using a modified version of the Turc equation (Allen 2000). This method is an adequate approach in an area where the relative humidity is greater than 50% (Turc 1961). The effective rainfall that passes into the unsaturated zone was calculated by subtracting potential evapotranspiration from total rainfall. Surface runoff was neglected as, according to Butler et al. (2009), Foster (1975); Ragab et al. (1997) and Ireson and Butler (2013), runoff in the Chalk surface area is usually absent due to high transmissivity and rainfall infiltration rates. A summary of the borehole locations, monitoring period and other information is given in Table 1. Figure 2 shows parts of the rainfall and groundwater level records of the three monitoring sites used in this study. The North Heath Barn site is unusual compared to the other boreholes sites as the groundwater recession consistently ends at 21.5m above ordnance datum (AOD), recession does extend beyond 21.5m AOD during the monitored period. Molyneux (2012) and Hadlow (2014) suggested this was linked to the presence of highly conductive fracture or karst feature at the top of the Holywell Nodular Chalk, which acted to maintain groundwater levels. In other words, the groundwater elevation measured at North heath Barn site never drops below 21.5m AOD, because it is in contact with a constant head feature such as a karst feature. As our analysis is focussed on the lag time between rainfall and increases in groundwater level this does not affect the time series analysis.

The Upper Chalk group is the dominant geological unit that covers the area. Within the study area, it consists of Lewes Nodular Chalk, Seaford Chalk, Newhaven Chalk and Culver Chalk formations. The main place from which it was possible to collect samples of the Chalk was from local quarries, where it is also possible to collect large block samples. Shoreham quarry (Easting:520403, Northing: 108855) was chosen as it has a large open outcrop and several Chalk formations are accessible, including the Seaford and Lewes Nodular Chalk formations.

Table 1. Details of the boreholes in the study area.

Borehole grid reference	Lithology	Monitoring period	Dominant land use	Borehole depth m BGL	Well design	Borehole level m AOD	AGWF (m)*
North Heath Barn (NHB) (E:528804, N:110429)	Upper Chalk	Since 2006	Undisturbed site	80.5	Open hole	91.50	37
Pyecoomb East (PE) (E:529266, N:112765)	Lower Chalk	Since 2010	Effluent disposal site	79.6	Open hole	113.28	23
Preston Park (PP) (E:530283, N:106570)	Upper Chalk	Since 2010	Urban site	70.5	Open hole	29.41	17

*Average groundwater level fluctuation (m)

Figure 1. (A) Simplified geological map of the study area showing borehole locations. (B) sratigraphic logs of the North Heath Barn (NHB1) and Pyecombe East (PE) boreholes. (Rutter et al. 2012). Detailed stratigraphic is not available for Preston Park (PP), but it is dominantly in the Seaford and Lewes Nodular Chalk. Coordinates are UK National Grid.

Figure 2. Time series of effective rainfall and groundwater level for the three studied boreholes. (a) North Heath Barn (NHB); (b) Preston Park (PP); (c) Pyecombe East (PE).

Methodology

Cross-correlation method

Before analysis, any daily trend in the time series data was removed by differencing consecutive values. Differencing means taking the difference between two values. a lag-1 difference (also called first difference) means taking the difference between every two consecutive values in the series (Y_1-Y_{t-1}) (Shmueli and Lichtendahl, 2018). This step is important in order to identify any hidden seasonal dependencies in the series. Also, it makes the series stationary which is necessary to show any response time correlation in the time series data (Davis, 2002). Cross-correlation is used to find the response time of rainfall and groundwater level were carried out using daily and hourly time series data. The data were then subdivided into a set of monthly durations according to seasons (winter, spring, summer, and autumn) for each year. These subdivisions were selected to identify seasonal differences in response to weather conditions for each site.

Cross-correlation (used to find the response time) can be defined as the comparison of two-time series data to determine positions of pronounced correspondence (response time) (Davis, 2002). In this correlation, it is possible to calculate the strength of the comparison between sets of two time series data (in this study rainfall and groundwater level) and measure the response time or offset of time corresponding to each other. The equation of the cross-correlation can be defined as below (Equation 1). The two time series are designated as (x) and (y), (n) is the number of overlaps between the two time series, and r_m is the cross-correlation for match position m (Davis, 2002). (x) represent rainfall correlated to (y) which represent the groundwater level, the response time between this time series data represent the response time.

$$r_m = \frac{n*\sum xy - \sum x \sum y}{\sqrt{[n*\sum x^2 - (\sum x)^2][n*\sum y^2 - (\sum y)^2]}} \tag{1}$$

This correlation is used most appropriately to measure similarity, differences, and the response of two time series data one relative to the other. The cross-correlation between rainfall and groundwater level can reveal the significance in the response to rainfall events after a given lag time (in days or hours). The response time can then be interpreted in terms of the flow mechanism in the Chalk unsaturated zone. The relation between the two variables results in the cross-correlation function (CCF) which varies between 1.0 and -1.0. Significant correlation at 95% confidence level is selected to be greater than the standard error $\sim\frac{2}{\sqrt{N}}$ (Diggle, 1990), where N is the number of values in the time series data set. This will efficiently test the assumption of no correlation and consider that the variance is finite and normally distributed about a mean of zero. The response time in cross-correlation is automatically calculated in this study (using equation 1) from time series data (rainfall and groundwater level) using the Statistical Package for the Social Sciences (SPSS), by IBM (IBM SPSS statistics 22) (SPSS, 2013).

Figure 3 shows an example of a cross-correlation between rainfall and daily change in groundwater level, in December 2012, at NHB site. 29 mm of rainfall occurs on the first day and the pulse reached the groundwater on the third day. During this period most of the correlation was positive except in the first two days and day nine where the correlation was negative. On the third day, the positive correlation is above the significant level and is hydrogeologically significant, interpreted as showing the groundwater response to the rainfall event.

Figure 3. a. rainfall and response of groundwater level, b. cross-correlation result, NBH site.

Laboratory methods

In order to interpret the lag times derived from the statistical analysis a geotechnical centrifuge was used to measure the saturated (K_s) and unsaturated (K_u) hydraulic conductivity of the Chalk. This method was developed by Nimmo et al. (1987) to measure unsaturated the hydraulic conductivity (K_u) of soil using unsaturated flow apparatus (UFA) (Nimmo et al., 2002). Following this study, several studies (McCartney, 2007; Nimmo & Mello, 1991; Šimůnek & Nimmo, 2005; Zornberg & McCartney, 2010) have used centrifuge results, alongside inverse analysis, to investigate transient infiltration processes. The technique provides an accelerated water flow through low permeability materials that would take long periods under normal conditions. The centrifuge technique has been employed in hydrogeology studies to minimize the time needed to reach steady state flow. There are several advantages of using centrifuge acceleration rather than high pressure to measure hydraulic properties (Nimmo & Mello, 1991). The main advantage is generating a pressure gradient that is a scaled model of the pressure gradient in the field. During experiments with the geotechnical centrifuge, the matric potential (ψ in kPa) was measured using a miniature water pressure transducer (wpt) simultaneously with Frequency Domain Reflectometry (FDR) to measure the volumetric water content (θ in %) (Siddiqui et al., 2000). A known amount of water was added to the top of the Chalk sample, and the amount of water passing through the Chalk sample was collected in a reservoir and measured using a pore pressure transducer (ppt).

The Broadbent Geotechnical Centrifuge (GT6/0.75) was used in this study, which is an upgraded geotechnical centrifuge that can produce a high acceleration environment. It is used to subject a soil or a rock specimen to a high artificial gravity to allow small scale models tested over a short time to be representative of much larger real-life structures over a much longer time. This high artificial gravity is produced by centrifugal acceleration due to high-speed rotation which depends on the rotation speed and radius of the beam (750mm) (rotational axis). A Chalk sample with dimensions 300mm x 180mm x 120mm were used in each test.

To calculate K_u under centrifuge conditions, the flow equations require modification to be applicable under centrifuge acceleration. The transient infiltration method requires numerical solution, while steady state flow requires physical modification of the flow equations. The equation used by Zornberg and McCartney (2010) is physicaly modified and solved from Darcy's equation under centrifuge conditions at steady state infiltration. The equation calculates K_u as below.

$$K_u = -\frac{v_m}{\frac{\omega^2}{g}(r_0 - z_m) - \frac{1}{\rho_w g}\frac{d_\psi}{dz_m}} \tag{2}$$

Where υ_m is the inflow rate per unit area of the Chalk sample, ω is the centrifuge angular velocity, g is the acceleration due to gravity (9.807 m/s²), ρ_w is the density of water at 30°C (995.7 kg/m^3), d_ψ is the change in matric potential from one point to another, dz_m is the change in depth (z_m) and r_0 is the centrifuge conatiner outlet face radius . The equation shows that K_u strongly depends on the amount of water added (saturation) which in turn depends on the centrifuge acceleration. Therefore, it is possible to get different target values of K_u by changing the imposed value of flow rate and centrifuge angular velocity. Similarly, the equation does not neglect the matric potential gradient and allows demonstration of a change of hydraulic conductivity with a change in the Chalk suction gradient. Different Chalk samples from Seaford and Lewes Nodular Chalk formations were tested using different angular velocities to test the change in K_u with variable flow rate, matric potential and water content.

Results

Cross-correlation

Cross-correlation analysis of rainfall and groundwater level response was carried out using daily and hourly time series data. The daily time series data were subdivided into seasonal datasets of three-month duration, but hourly data were selected according to the seasons and individual events. The three-month intervals were chosen so that seasonal changes in groundwater level response could be identified. Results varied significantly in shape and pattern for each season and between sites, which depended on the amount of rainfall, potential evapotranspiration, and the recharge-discharge balance. The majority of rapid responses were observed during winter. For example, in the NHB site in winter 2012 the groundwater level responded to rainfall events (daily average 2.2 mm/day) within 2 days (Fig.4a), whereas in winter 2013, groundwater level responded to a rainfall event (daily average 4.4mm/day) within the day of the event (Fig. 4b). Also, in winter 2014 groundwater responded to a rainfall event (daily average 5.6 mm/day) within the 24 hours of the event (Fig. 4c). In both Pyecombe East and Preston Park, the response was within the day of the rainfall event during the winter 2013 and 2014.

It is notable that the lag time with significant correlation (response time with a correlation coefficient above 95% of the standerd error) are heavily dependant on seasons, with shorter response time (in hours) during wet seasons (winter) than in dry seasons (mainly summer and autumn). However, the response time is also generally dependent on the amount of rainfall and depth of unsaturated zone. For example, summer 2012 was wet with daily average effective rainfall (1.8 mm/day) causing rise of groundwater within 2 days in NHB and Pyecombe East and 1 day in Preston Park, while, with less rainfall during spring 2012 (0.64 daily average rainfall/day) lead to a response time of 15 days at the NHB site.

During many of the seasons, a secondary groundwater level response period was observed. This period come after the first response period and interrupted with the first period by a non correlation period. The maximum significant correlations for each season are identified by bold in Table 3, Table 4. andTable 5.. The response time varied from 0 days (within 24 hours) of the rainfall event and extended to 68 days after the event. This response varied during each season, and most of the responses occurred consecutively (as a continuous pulse during the recharge period). However, in some periods there are delays between the pulses causing a non-consecutive response, for example, a delay of 13 days during winter 2012 at Preston Park (Fig. 4d).

Non-correlated periods were mainly observed during seasons where the amount of evapotranspiration exceeded the amount of rainfall or the amount of the rainfall is not enough to overcome the unsaturated zone moisture deficit (Molyneux, 2012), particularly during summer and autumn. In all the study sites there was a noncorrelation period during summer 2013 were the daily average rainfall was less than evapotranspiration (Table 3-5). The longest response time correlations were mainly observed during autumn as the unsaturated zone is thicker and drier. for example, at the NHB site during autumn 2013, groundwater level responded after 60 days, at PE after 59 days, and at PP after 50 days. In contrast, shorter response times (0-day response time) were observed during the winter season where the unsaturated zone was wetter and had a minimum thickness. For example, at the NHB site during winter 2014, groundwater responded to rainfall events at a 0 day-response time, while in both PE and PP, a 0 day-response time was observed during winter 2013 and 2014. When responses were within a day of rainfall, the groundwater responses to rainfall were analysed using hourly data and used to estimate field unsaturated hydraulic conductivity (K_u).

Figure 4. Cross-correlation between rainfall and groundwater level for daily integrated data, a. NHB, winter 2012, b. NHB winter 2013, c. NHB winter 2014, d. PP winter 2012.

Hourly cross-correlation analyses of rainfall and groundwater level were carried out for the winter season with 0 day lag time, as the response is within a day. The hourly time series analysis is important to identify how fast water passes through the unsaturated zone during these particular seasons. The results of hourly data correlation are shown in Figure 5 (a, b and c) for the three sites during winter 2014. At NHB the groundwater level responded to the rainfall within 13 hours, but the maximum significant correlation is found 37 hours after the rainfall event (Fig. 5a). At PE the response time was 12 hours, and the maximum significant correlation was at 20 hours (Fig. 5b), and at Preston Park, the maximum significant correlation was at 1 hour response time (Fig. 5c).

Figure 5. Cross-correlation show groundwater response to rainfall events, a. NHB, b. PE and c. PP, during winter 2014.

Measurements of hydraulic conductivity (*K*) using the centrifuge method

The hydraulic conductivity (*K*) of the Chalk samples was determined using several centrifuge tests at steady state conditions. These samples were collected from the Shoreham quarry, where several outcrops of different Chalk formations are accessible including Seaford and Lewes Nodular Chalk formations. The results for unsaturated hydraulic conductivity (K_u) of these formations are shown in Table 2. The values of K_u were calculated using equation 2. It is expected that the measured values of K_u increase with increasing ψ and θ. Where the ψ is -4 kPa, the K_u value is 4.27 mm/day, but with decreasing ψ to about -40 kPa, the K_u value became 0.072 mm/day (Table 2). The same situation is observed with the change in θ (Fig. 6).

The K_u of the Chalk samples measured using the centrifuge technique provides enough data to characterise the relationship of K_u to ψ and θ. Extrapolating the data to saturation, the saturated matrix hydraulic conductivity (K_{sm}) was estimated to be 6 mm/day. This result generally agrees with the published literature. Price et al. (1993) state that the Chalk K_{sm} varies between 0.1 and 10 mm/day. Similarly, Mahmood-ul-Hassan and Gregory (2002) determined K_{sm} between 1 to 15 mm/day. The results are therefore close to those found in previous studies, however, using the centrifuge technique only 50 to 100 min were required to reach steady state conditions to measure K_u.

The K_u results measured in the tests represent the flow through the Chalk matrix, as the majority of the flow occurs at ψ below -5 kPa except for the ψ at -4 kPa. At this point, the measured K_u is higher as a result of the contribution of micro-fractures/and or macropores to the flow. Figure 6 shows that there is a gradual increase in the K_u with an increase in both ψ and θ. This indicates that there is a gradual filling of pore space from the smallest pore to a larger pore, from micro-pores to large fractures. Most previous work follows the assumption that fractures start to transmit water at a -5 kPa threshold. This idea was first presented by Wellings (1984a) for flow in the Chalk unsaturated zone. Nevertheless, the data obtained from the centrifuge tests (K_u vs ψ and K_u vs θ; Fig. 6) show that instead of the presence of an inflection point, there is a more gradual increase in K_u with the change in both ψ and θ which may reflect a continuous size distribution of pores from matrix to fractures.

Table 2. K_u value for each test showing changes according to change in ψ and θ

ψ kPa	θ %	K_u (mm/day)
-4	31	4.27
-6	29	3.78
-8	28	3.17
-14	24	1.54
-40	18	0.072
-45	17	0.07
-50	16	0.072

Figure 6. a. matric potential and b. volumetric water content related to unsaturated hydraulic conductivity Ku measured using Eq. 2.

Field measurement of unsaturated hydraulic conductivity (K_u)

The field unsaturated hydraulic conductivity (K_u) of the Chalk was estimated from the maximum significant response time (t) over the unsaturated zone thickness (Z) at a specific moisture capacity (C) in a one dimensional flow system using equation 5 (Barker, 1993; Price et al., 2000):

$$K_u = \frac{Z^2 C}{2t} \tag{3}$$

Where C is the specific moisture capacity ($\frac{d_\theta}{d_\psi}$), which can be defined as the volume of water released (or taken) in storage per unit volume of unsaturated zone per unit change in pressure head (Stephens, 1995). According to Price et al. (2000), laboratory values of C range from 1×10^{-4} to 7×10^{-4} m^{-1} corresponding to matric potential ranging from -150 to -10 kPa. The value of C varies according to the variation in matric potential. Accordingly, this will affect the estimated value of unsaturated hydraulic conductivity (K_u). Using specific moisture capacity (C) in equation (3) along with the unsaturated zone thickness (Z) and significant response time (t) values from the significant response time from all the sites gives a range of unsaturated hydraulic conductivity (K_u) in the unsaturated zone depending on seasons as shown in Table 3, 4 and 5, based on daily data. The C value used in the calculation varied according to seasons, in summer and autumn when the matric potential is close to -150 kPa, the value of 1×10^{-4} m^{-1} is used. While in winter and spring the matric potential is close to -10 kPa, the 7×10^{-4} m^{-1} is used. The factor of variation noted by Price et al. (2000) means that the calculation is relatively insensitive to variation in C relative to the squared dependence on unsaturated zone thickness (Z).

Table 6 shows the cross-correlation results with an hourly lag time of the three sites during winter 2014. The unsaturated hydraulic conductivity K_u values calculated in the three boreholes are much greater than the matrix hydraulic conductivity measured using the centrifuge technique. Therefore, these fast responses cannot be associated with flow through the Chalk matrix only.

Table 3. Cross-correlation of groundwater level with rainfall in NHB site compared with seasonally active rainfall and unsaturated zone thickness. The maximum correlations are in bold.

Seasons	**Response time (day)**	**ADER (mm/day)***	**AUZT (m BGL)+**	**K_u (mm/day)**
Winter 2012	2, 3, 4, **6**, **7**	2.15	69.57	282
Spring 2012	15, 16, 17, 18, 19, **20**, 21, 22	0.64	67.65	80
Summer 2012	2, 3, 4, 5, 6, 7, **8**, 9, 10, 11	1.84	50.96	16
Autumn 2012	**28**,29	2.42	62.96	7
Winter 2013	0,**1**,2,3,4,5	4.42	38.81	527
Spring 2013	15,16,17,18,19,20,**21**,22	1.30	48.59	39
Summer 2013	No correlation	-1.70	67.35	--
Autumn 2013	**60**,61,62	0.72	66.73	4
Winter 2014	0,**1**,2,3,6,7,8,9,10	5.58	31.44	346

* Average daily active rainfall for the season (3 month interval)

+ Average unsaturated zone thickenss during the season (3 month interval)

Table 4. Cross-correlation of groundwater level with rainfall in PP site compared with seasonally active rainfall and unsaturated zone thickness. The maximum correlations are in bold.

Seasons	**Response time (day)**	**ADER(mm/day)***	**AUZT (m BGL)+**	**K_u (mm/day)**
Winter 2012	2,3,4,**5**,6,7,20,21,22,23,24	2.15	21.08	31
Spring 2012	2,3,4,5,6,7,**8**,9	0.64	19.57	17

Summer 2012	1,4,5,6,7,8,9,**10**,11,12	1.84	13.77	0.9
Autumn 2012	39,**40**,41,42	2.42	16.56	0.3
Winter 2013	0,**1**,2,3,4,5,6,7,8,9	4.42	5.81	12
Spring 2013	4	1.30	10.19	9
Summer 2013	No correlation	-1.70	18.46	--
Autumn 2013	50,**68**,69	0.72	19.88	0.4
Winter 2014	**0**	5.58	2.99	31

* Average daily active rainfall for the season (3 month interval)

+ Average unsaturated zone thickenss during the season (3 month interval)

Table 5. Cross-correlation of groundwater level with rainfall in PE site compared with seasonally active rainfall and unsaturated zone thickness. The maximum correlations are in bold.

Season	**Response time (day)**	**ADER(mm/day)***	**AUZT (m BGL)+**	**K_u (mm/day)**
Winter 2012	3, 4, **5**, 6	2.15	55.48	215
Spring 2012	3,4,5,6,7,8,9,10,14,15,16,17,18,**19**,20	0.64	49.86	46
Summer 2012	2, 3, 4, **5**, 6, 7, 8, 9, 10	1.84	45.70	21
Autumn 2012	**10**, 12, 13	2.42	51.62	13
Winter 2013	0, **1**, 2, 3, 4,5,6,7,8	4.42	40.84	584
Spring 2013	2, 3, 4, **5**	1.30	44.99	142
Summer 2013	No correlation	-1.70	52.65	--
Autumn 2013	59, **60**, 61, 62	0.72	54.04	2
Winter 2014	**0**,1,2,3	5.58	33.14	769

* Average daily active rainfall for the season (3 month interval)

+ Average unsaturated zone thickenss during the season (3 month interval)

Table 6. Cross-correlation of groundwater level with rainfall at the three sites during winter 2014, hourly response time.

Location	**Response time (hours)**	**K_u (mm/day)**

NHB	13	638
	17	487
	36	231
	70	119
	92	90
PE	11	839
	25	384
	57	165
PP	1	75
	4	19
	23	3.3
	38	2
	62	1.2
	69	1.1
	87	0.9
	91	0.8

Groundwater response related to unsaturated zone thickness and rainfall

For each site, the statistically first significant correlation was plotted as a function of the daily average effective rainfall and average unsaturated zone thickness for each season (Fig 7, 8 and 9) to illustrate the change in response time to rainfall and unsaturated zone thickness. At the NHB site, the unsaturated zone varies from 68 to 31 mBGL and the daily effective rainfall varies from 0.65 mm/day to 5.6 mm/day. At the PE site, the unsaturated zone thickness varies from 56 to 33 mBGL and at PP, it varies from 20 to 3 mBGL. It is observed that a fast response occurred when the unsaturated zone was at minimum thickness with high effective rainfall, in contrast, the longest response occurred when the unsaturated zone was at maximum thickness with low effective rainfall.

During winter 2014 at NHB a rapid response (13 hours response time) was observed when the groundwater level was 31 mBGL and the daily effective rainfall was 5.6 mm/day, Also during winter 2013 a rapid response (1-day response time) was observed when the unsaturated zone thickness was 36 mBGL and daily effective rainfall was 4.4 mm/day. However, in autumn 2013, when effective rainfall decreased to 0.72 mm/day and the unsaturated zone thickness increased to 66.73 mBGL, the response time increased to 60 days, (Fig. 7).

Figure 7. a. the response time for first significant groundwater response versus Unsaturated zone thickness, b. versus daily effective rainfall, NHB site. The lines are the best fit using exponential function.

During winter 2014 at Pyecombe East, the groundwater level was at 33m BGL; the response was observed within 11 hours of a 5.6 mm/day effective rainfall, and during winter 2013, a response was observed at depth 40 mBGL within 1 day of a 4.4 mm/day effective rainfall. This response time increased to 59 days with a decrease in the effective rainfall to 0.72 mm/day and groundwater level dropping to 54.04 mBGL (Fig. 8).

Figure 8. a. the response time for first significant groundwater response versus Unsaturated zone thickness, b. versus daily active rainfall, Preston Park site. The lines are the best fit using exponential function.

During winter 2014 at Preston Park, the groundwater level response was observed at a depth of 3 mBGL within 1 hour of a 5.6 mm/day effective rainfall, and during winter 2013, a response was observed at a depth of 5 mBGL within 1 day of a 4.4 mm/day effective rainfall. This response time increased to 50 days with a decrease in the effective rainfall to 0.72 mm/day and the groundwater level 19.88 mBGL (Fig. 9).

Figure 9. a. the response time for first significant groundwater response versus Unsaturated zone thickness, b. versus daily active rainfall, Pyecombe East site. The lines are the best fit using exponential function.

Discussion

Unsaturated zone flow

Flow through the Chalk unsaturated zone occurs through the matrix, fractures or both pathways. Flow in the matrix occurs through the Chalk pores as a function of piston flow (matrix pulse) where water at a higher level displaces that lower in the profile. This type of flow is generally slow. According to Price et al. (1976), the saturated hydraulic conductivity of the Chalk matrix is 3 to 5 mm/day. In some cases, flow as a function of piston flow generates fast flow responses depending on the water content, as with higher water content the flow becomes faster. Flow through the fractures can occur much faster, at rates ranging from 100 to 1400 mm/day (Lee et al., 2006), but this only happens under specific circumstances. These are mainly dependent on the unsaturated zone conditions, rainfall intensity and duration (Ireson, 2009). Fracture flow mainly occurs in the Chalk when the rainfall intensity exceeds the matrix hydraulic conductivity.

Rainfall is one of the main parameters controlling flow mechanism in the Chalk unsaturated zone (Fig. 7b,8b and 9b), the daily average rainfall plus unsaturated zone condition may trigger fracture flow, which in turn may cause groundwater flooding and facilitate contaminate transport to the aquifer. According to Jimenez-Martinez et al (2015), daily rainfall events may exceed 50 mm doubles by the end of this century, this in return, may shorten the response time of water to reach the aquifer due to fracture flow and increase risk of flooding event and contaminant transport to the aquifer. Managing use of pesticides and fertilizer during winter time, which most of the fracture flow occur, may minimize this risk in the future.

The unsaturated hydraulic conductivity (K_u) measured in the laboratory tests varies from 0.07 mm/day to 4.27 mm/day according to saturation level. These results represent matrix flow in the Chalk unsaturated zone. Similar results were obtained by Hadlow (2014) and Price et al. (1993) on their work on the Chalk matrix. Thus, if flow through the matrix is the only path of water through the Chalk unsaturated zone, the response time of groundwater level is expected to be within a year for less than 10m unsaturated zone thickness. In contrast, the field unsaturated hydraulic conductivity (K_u) extends to 839 mm/day. This value is much greater than the matrix unsaturated hydraulic conductivity of the Chalk measured in the laboratory. Thus, this response cannot be related to the matrix flow only, but it must be linked to the contribution of fracture flow during recharge periods. Furthermore, at PP, the unsaturated hydraulic conductivity (K_u) is generally much smaller compared to NHB and PE sites. This is due to the presence of impermeable infrastructure covering the area around the PP borehole, which decreases infiltration of water to the unsaturated zone and increases runoff.

Using Equation 3, possible values of unsaturated hydraulic conductivity (K_u) and C are plotted in Figure 10 together with the response time (t) and the unsaturated zone thickness (Z) for the three study sites. The fastest possible matrix response is given by K_u = 10 mm/day, C = $1\text{x}10^{-4}$ m^{-1}. The curve was obtained using the highest possible value of matrix unsaturated hydraulic conductivity (K_m) and the lowest possible value of C. The curve shows that most of the response at NHB and PE cannot be attributed to matrix flow only and there might be a fracture contribution to flow during recharge periods. Groundwater level responses at these sites during the winter periods are too rapid for a matrix pulse and can therefore only result from a combination of both matrix and fracture flow.

Figure 10. Response time vs unsaturated zone thickness for all the three sites with best fit lines (in black) using exponential function. The solution of equation 5 is given for different K_u and $\boldsymbol{C}$ values in red.

Relative influence of rainfall and unsaturated zone conditions

The plots of groundwater response versus average daily effective rainfall and groundwater response versus unsaturated zone thickness at NHB (Fig. 7), PE (Fig. 8) and PP (Fig. 9) show that the response time of the groundwater level strongly depends on the amount of rainfall and depth of water table. The three sites show a rapid decrease in response time when the daily effective rainfall exceeds 4mm/day and when the water table reaches a critical depth. It has been inferred that the response does not only depend on the amount of rainfall and water table depth, but also on the state of the unsaturated zone (Ireson & Butler, 2011). Most of the fast responses are observed during winter seasons where the unsaturated zone is not only thin but also at it's wettest (highest relative saturation). Fast response during summer 2012, within 2 days at NHB and PE and 1 day at PP were observed. This, in combination with relatively high rainfall, may lead to faster response during the summer season.

The sudden change in gradient in Figures 7, 8 and 9 indicates a possible change in the flow pathway domain. This change in flow mechanism may relate to the contribution of fractures to the flow alongside the matrix. The contribution of fracture flow starts with partial fracture flow through a thin film (Malek-Mohammadi & Nimmo, 2012), then gradually develops into saturated fracture flow. The rapid response of groundwater during winter seasons may lead to groundwater flooding and the contribution of fractures in the flow and transmission of water through the unsaturated zone may reduce transit times for contaminants to reach the Chalk aquifer.

There is no general trend observed linking the amount of rainfall and unsaturated zone thickness to the groundwater level response for the Chalk and would not be expected. This is because the shape of the curves for each site is influenced by the location and lithology of the unsaturated zone and climatic conditions. The location of NHB is in an undisturbed area with abundant marl seams and fractures, a horizontal unsaturated fracture below the percolation threshold can acts as barries to flow, while fully saturated fracture are flow conducted. These act as hydraulic barriers which may cause lateral flow to the lower elevations and create wet horizons (Hadlow, 2014). The influence of different climate conditions for each site was also considered. However, the study area is quite small and there are limited variations in rainfall and evapotranspiration. Therefore the most significant difference between each site is the variation in the lithological conditions and depth of the groundwater, which may not allow determination of a general trend in relation to climate.

Separate delayed time responses

In all the study sites, more than one time delayed response follows the initial rapid groundwater level response. These separate responses may indicate separate flow mechanisms in fractures and/or matrix. These distinct responses are more obvious in hourly based data correlation and mainly occur during winter seasons when groundwater recharge is most significant. For example, at PP during winter 2014, the hourly groundwater level response to rainfall events with the unsaturated zone was used to estimate unsaturated hydraulic conductivity (K_u) and the results were compared to the matrix unsaturated hydraulic conductivity (K_{um}) from the laboratory method. The results are shown in Figure 8c, where there are several groundwater responses to a rainfall event. The first two responses are greater than the unsaturated hydraulic conductivity (K_u) of the Chalk matrix (75 and 19 mm/day) indicating that flow may occur with fracture contribution, while the other response is located on the limit of the matrix unsaturated hydraulic conductivity (K_m), assuming that the flow occurred through the Chalk matrix only. From Figure 4d the secondary response at PP occurred 10 days after the first response, despite the presence of impermeable infrastructure covering the area to cause a secondary response. This situation may come from flow accretion from the higher in the catchment.

From both NHB and PE, the unsaturated hydraulic conductivity (K_u) was much higher during winter 2014. At NHB the first response time K_u decreased from 638 mm/day to 119 mm/day. At PE, the first response time K_u decreases from 839 mm/day to 165 mm/day. At PE, the borehole is adjacent to an artificial recharge discharge chamber, thus the unsaturated zone is always close to saturation in the environment of the borehole. This enhances fracture flow. These results from the two locations indicate that the water flows faster in PP; where the unsaturated hydraulic conductivity (K_u) is higher than matrix unsaturated hydraulic conductivity (K_m) which may indicate the flow of water through fractures or as a film of water in fracture walls. Generally, the secondary response occurs during the winter season where the unsaturated zone is wetter. During the drier periods, the rainfall has lower intensity and duration which may not cause such intense pulses to pass through the Chalk and hence produce a secondary delayed response.

Limitations

Cross-correlation analysis can only establish whether or not a significant correlation occurs between two data time series, which in this study are rainfall and groundwater level. The correlation does not indicate what causes the response of the groundwater level, although we have interpreted this in terms of matrix and fracture flow in this study. Some other factors may cause variable groundwater level response, for example, lateral flow from higher in the catchments and changes in atmospheric pressure. Lateral flows have been discussed in the previous section, as the Preston Park borehole is located down valley and recharge from higher in the catchment has been observed to generate a delayed response. Lateral recharge generally occurs after the main response with more than 1-day lag time. However, groundwater level response may be occurring laterally from recharge reaching the aquifer earlier in the interfluves where the groundwater level is close to the surface. This is speculation at this stage, and it will be necessary to perform 2 or 3-dimension modelling to give more insight to the lateral flow process.

The water level data were corrected for atmospheric pressure using an additional logger held at the surface at the University of Brighton (30m AOD). However, change in atmospheric pressure may still affect borehole water level in unconfined aquifers (Healy & Cook, 2002). This phenomenon has not been widely reported from the Chalk (Lee et al., 2006), and the size of changes in groundwater level identified here are much greater than those predicted from changes in atmospheric pressure (Fig. 2).

Conclusions

This study has examined the correlation between rainfall events and rises in groundwater level in the Chalk aquifer at three sites within the Brighton block, South East England. The time for the groundwater level to respond to rainfall events varies from hours to more than 60 days according to the ground and rainfall conditions. The slower responses mainly occur during dry seasons when the amount of effective rainfall was less than 4mm/day the unsaturated zone thicker, and unsaturated zone storage is at a minimum. Rapid responses were observed during wet seasons where the amount of effective rainfall exceeded 4mm/day with a thin and high storage unsaturated zone.

A fast response, within hours, was observed in the three sites during winter recharge, 13 hours at North Heath Barn, 11 hours at Pyecombe East and just 1 hour at Preston Park. The faster response at the Pyecombe East site is a result of the artificial recharge that keeps the unsaturated zone close to saturation in the environment of the borehole. The response at the North Heath Barn site is inferred to be representative behaviour for this level in the stratigraphy. Urbanisation at the Preston Park site has reduced surface infiltration, but flow accretion from higher in the catchment may give more significant secondary lags. Results from centrifuge tests indicate that flow through the Chalk matrix is slow, and vary according to the Chalk saturation between 0.07 and 6mm/day. These results indicate that most of the slow response can be explained as matrix flow, while the rapid responses represent flow through a combination of both matrix and fractures. The rapid response of groundwater during the winter seasons may lead to groundwater flooding and the contribution of fractures flow and transmit of water through the unsaturated zone may reduce transit times for contaminant to reach the Chalk aquifer. Groundwater level responses to rainfall at multiple, sequential response times can be related to separate contributions from fractures and matrix during the same event.

The approach used here is applicable to any dual porosity aquifer, and the results have relevance to chalk groundwater systems. Of particular importance are the observations of rapid groundwater level response times in high frequency monitoring records that may be missed in daily or longer period data, and the observations of multiple responses to the same infiltration event as a result of different flow paths and mechanisms. We have also demonstrated the applicability of centrifuge testing techniques to the determination of unsaturated hydraulic conductivity. Further application of such techniques may improve the determination of unsaturated flow properties in many aquifers.

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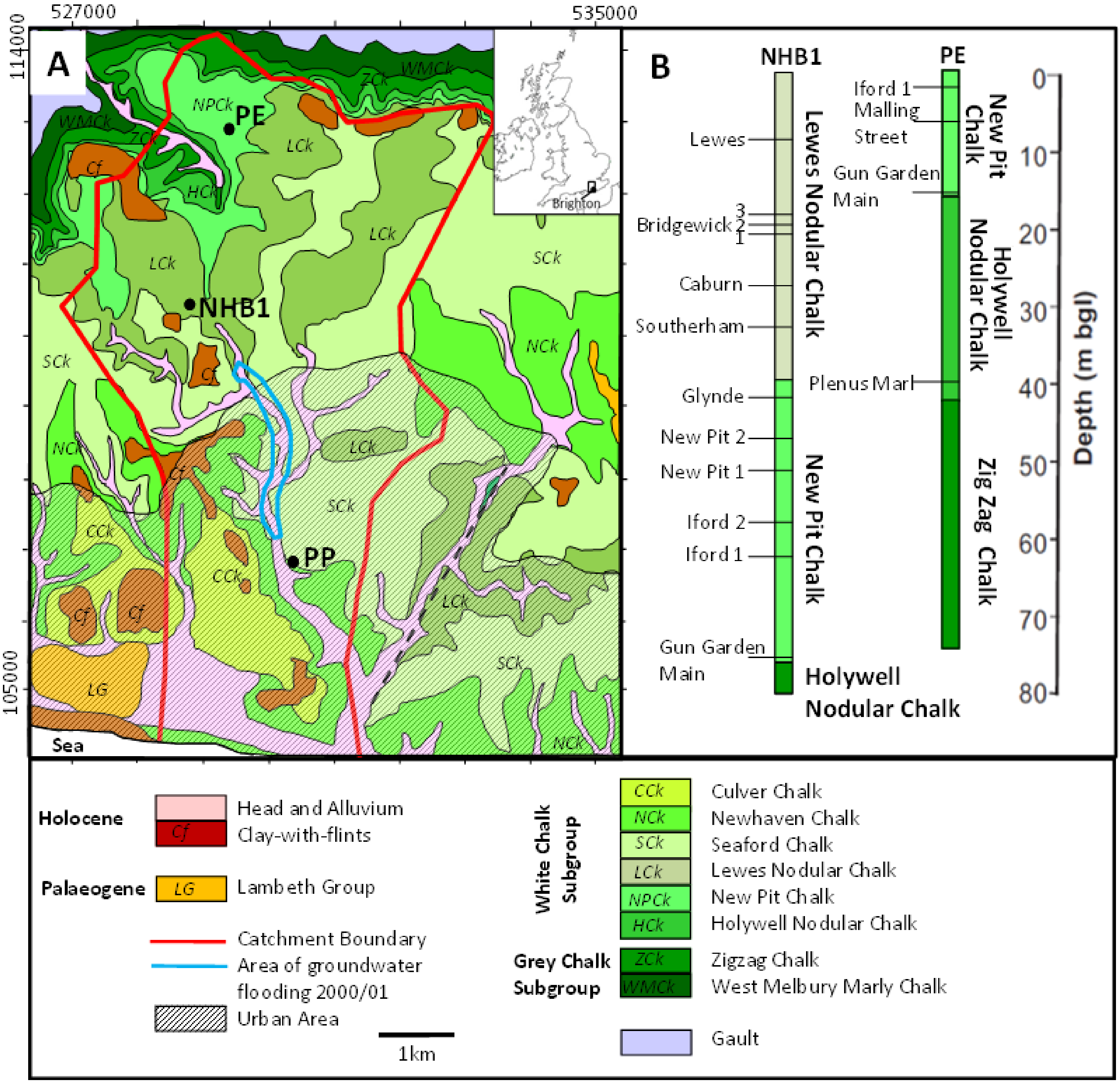
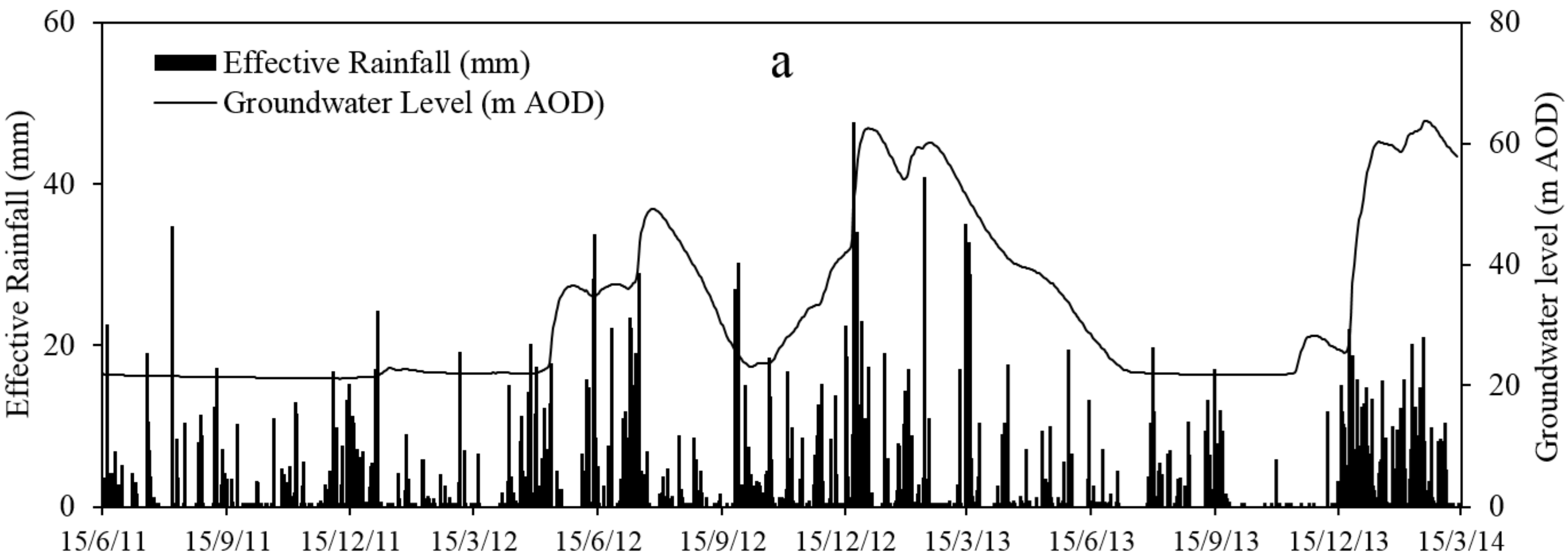
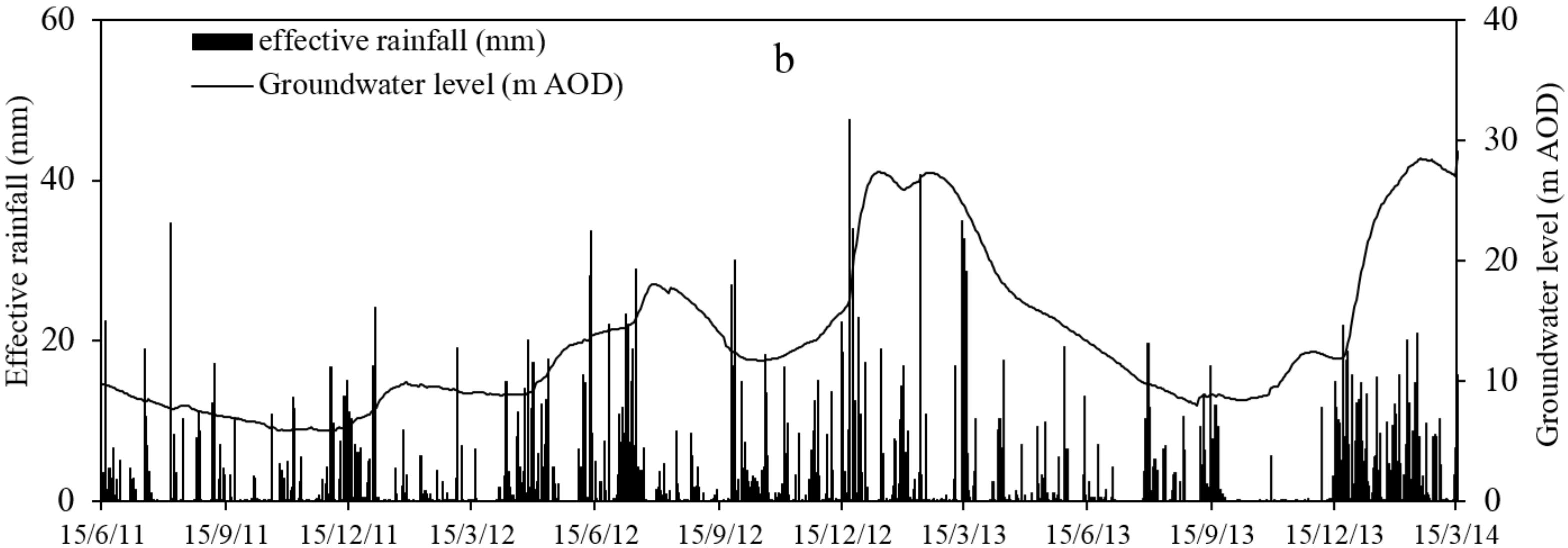
List of Figures



527000
535000
114000
105000
A
PE
NHB1
PP
Sea
Brighton
B
NHB1
PE
Lewes
Bridgewick 3
2
1
Caburn
Southerham
Glynde
New Pit 2
New Pit 1
Iford 2
Iford 1
Gun Garden
Main
Lewes Nodular Chalk
New Pit Chalk
Holywell Nodular Chalk
Iford 1
Malling Street
Gun Garden Main
Plenus Marl
New Pit Chalk
Holywell Nodular Chalk
Zig Zag Chalk
Depth (m bgl)
0
10
20
30
40
50
60
70
80
Holocene
Head and Alluvium
Cf Clay-with-flints
Palaeogene
LG Lambeth Group
Catchment Boundary
Area of groundwater flooding 2000/01
Urban Area
1km
White Chalk Subgroup
CCk Culver Chalk
NCk Newhaven Chalk
SCk Seaford Chalk
LCk Lewes Nodular Chalk
NPCk New Pit Chalk
HCk Holywell Nodular Chalk
Grey Chalk Subgroup
ZCk Zigzag Chalk
WMCk West Melbury Marly Chalk
Gault



a
Effective Rainfall (mm)
Groundwater Level (m AOD)
Effective Rainfall (mm)
Groundwater level (m AOD)
0
20
40
60
0
20
40
60
80
15/6/11
15/9/11
15/12/11
15/3/12
15/6/12
15/9/12
15/12/12
15/3/13
15/6/13
15/9/13
15/12/13
15/3/14



effective rainfall (mm)
Groundwater level (m AOD)
b
Effective rainfall (mm)
Groundwater level (m AOD)
0
20
40
60
0
10
20
30
40
15/6/11
15/9/11
15/12/11
15/3/12
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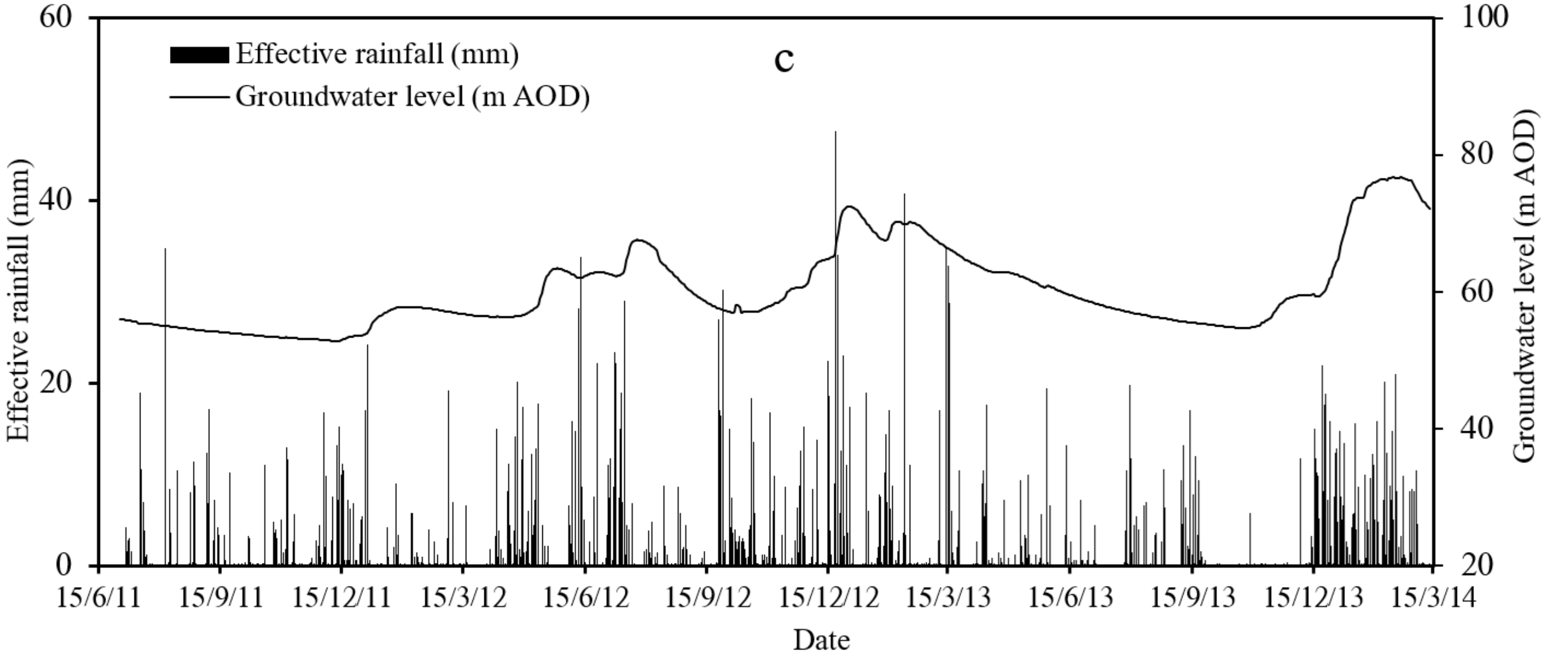
15/9/13
15/12/13
15/3/14



Effective rainfall (mm)
Groundwater level (m AOD)
c
60
40
20
0
100
80
60
40
20
15/6/11
15/9/11
15/12/11
15/3/12
15/6/12
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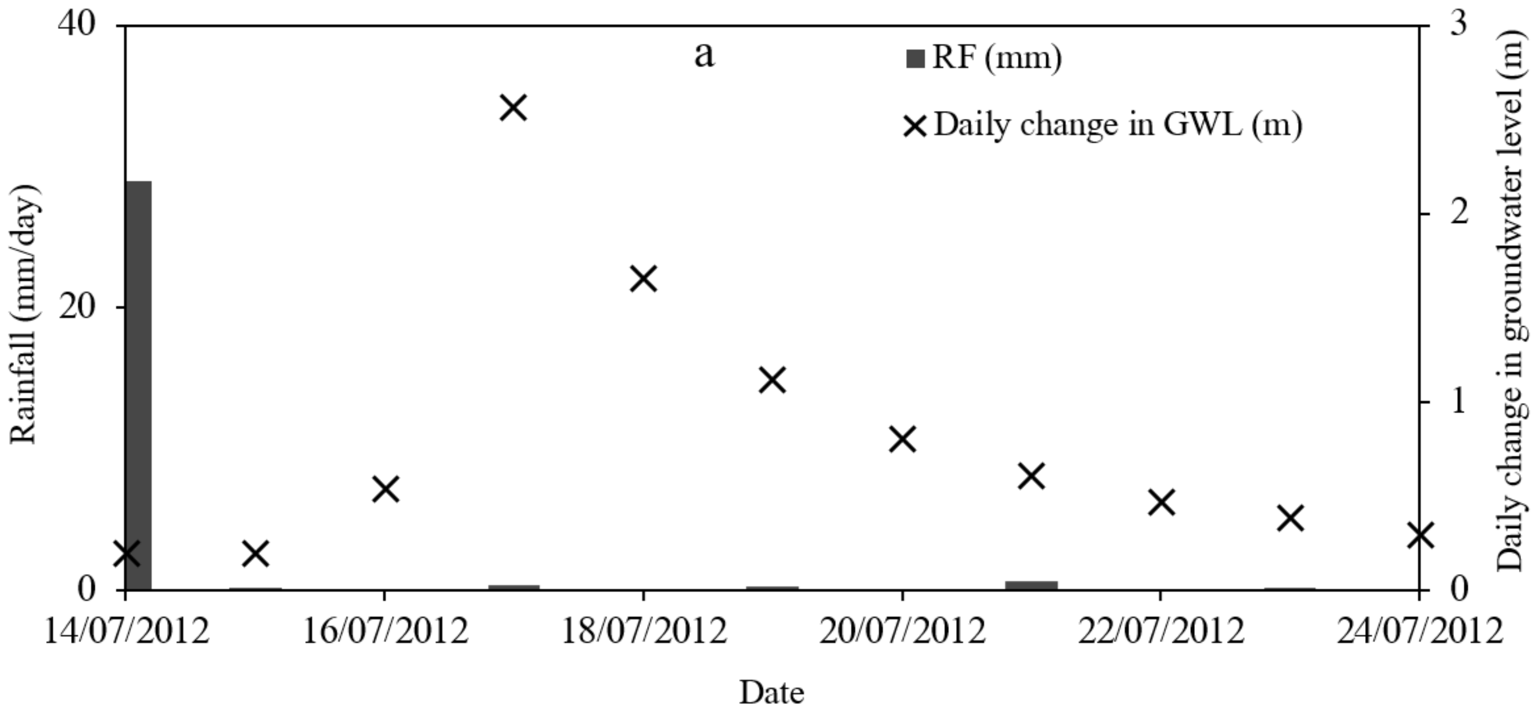
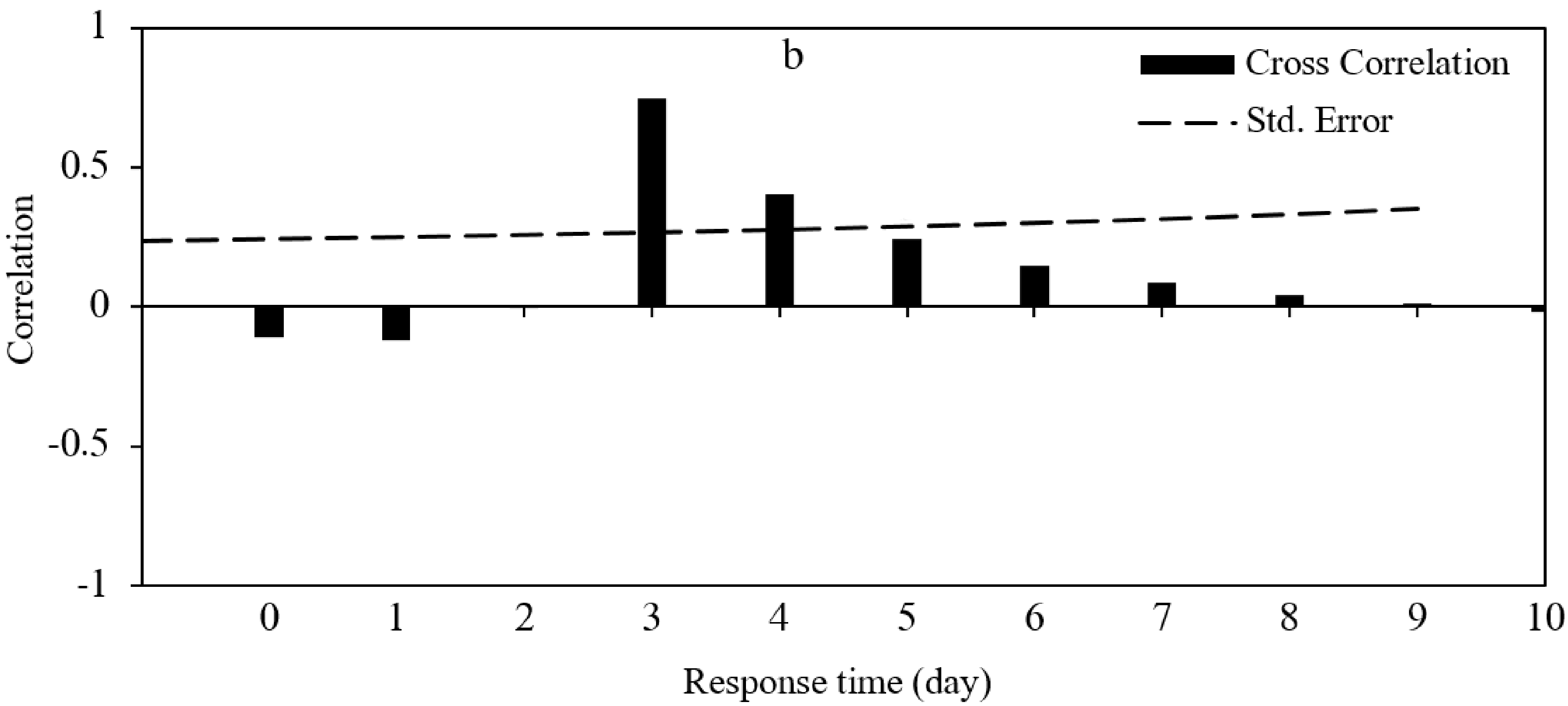
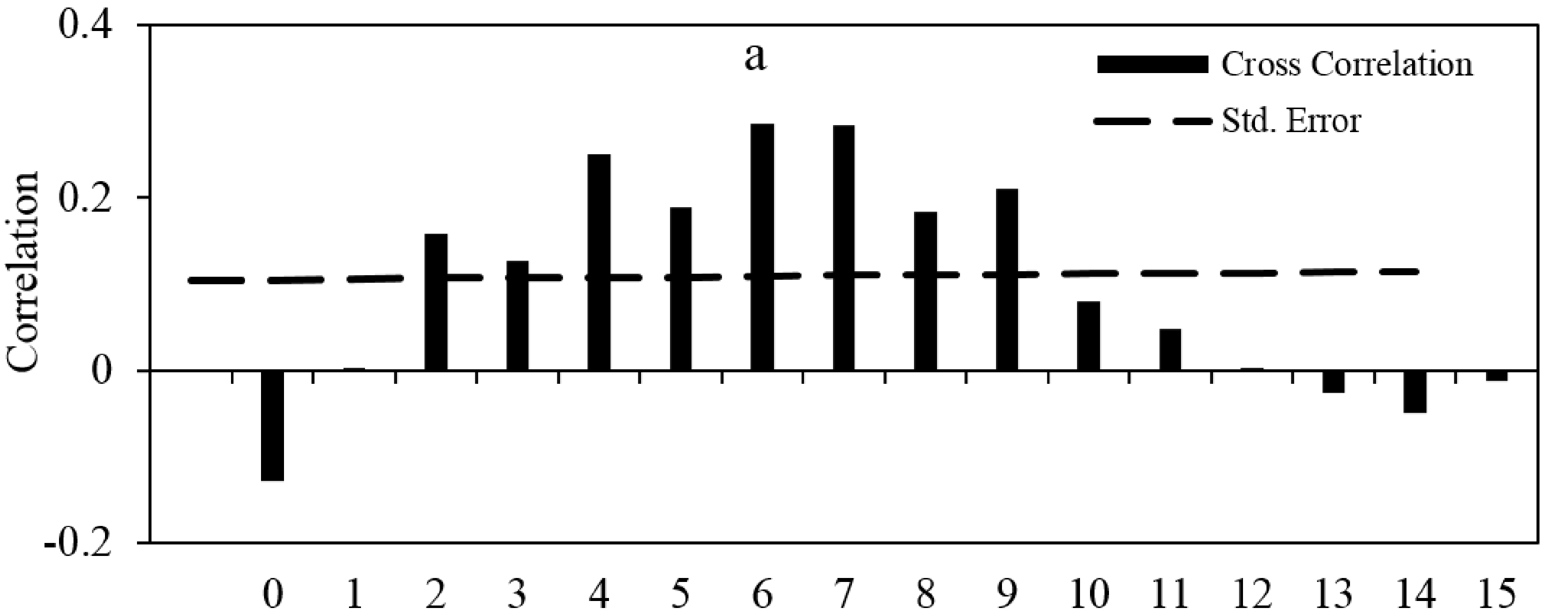
15/9/13
15/12/13
15/3/14
Date

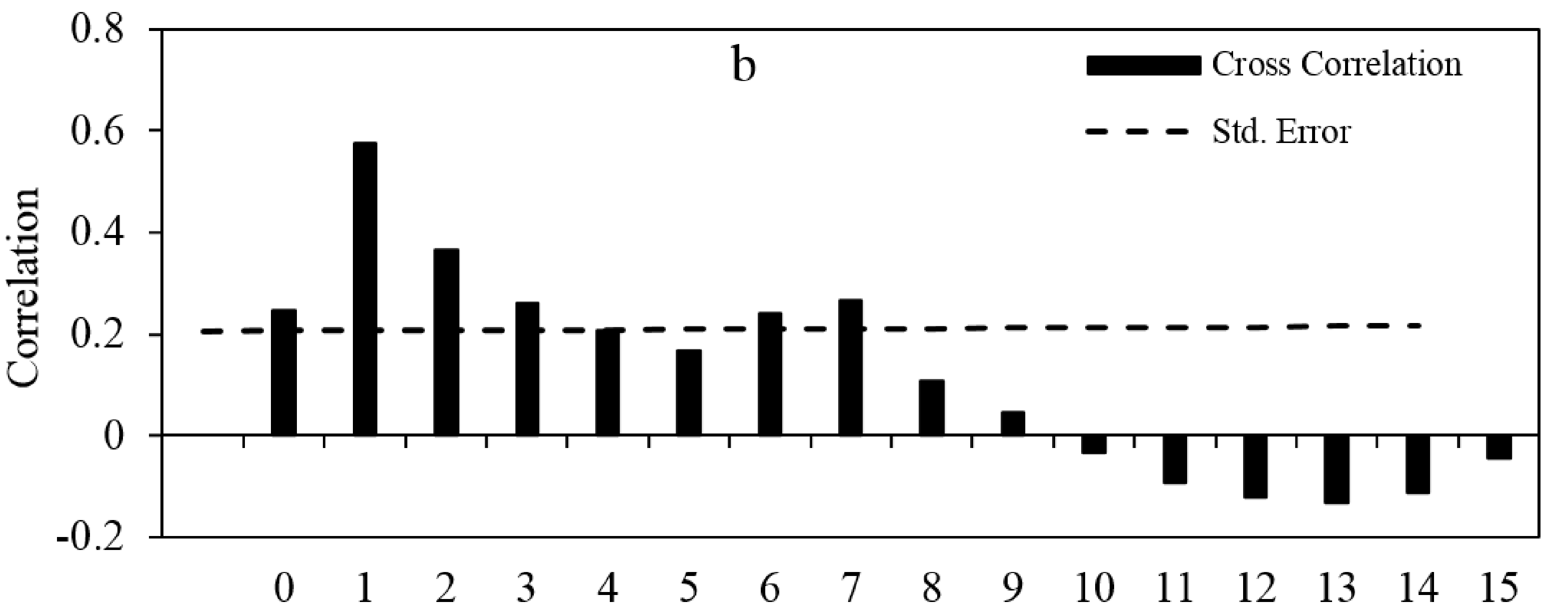


a
RF (mm)
Daily change in GWL (m)
Rainfall (mm/day)
Daily change in groundwater level (m)
Date
40
20
0
3
2
1
0
14/07/2012
16/07/2012
18/07/2012
20/07/2012
22/07/2012
24/07/2012



b
Cross Correlation
Std. Error
Correlation
1
0.5
0
-0.5
-1
0
1
2
3
4
5
6
7
8
9
10
Response time (day)


a
Cross Correlation
Std. Error
Correlation
0.4
0.2
0
-0.2
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15



b
Cross Correlation
Std. Error
Correlation
0.8
0.6
0.4
0.2
0
-0.2
0
1
2
3
4
5
6
7
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9
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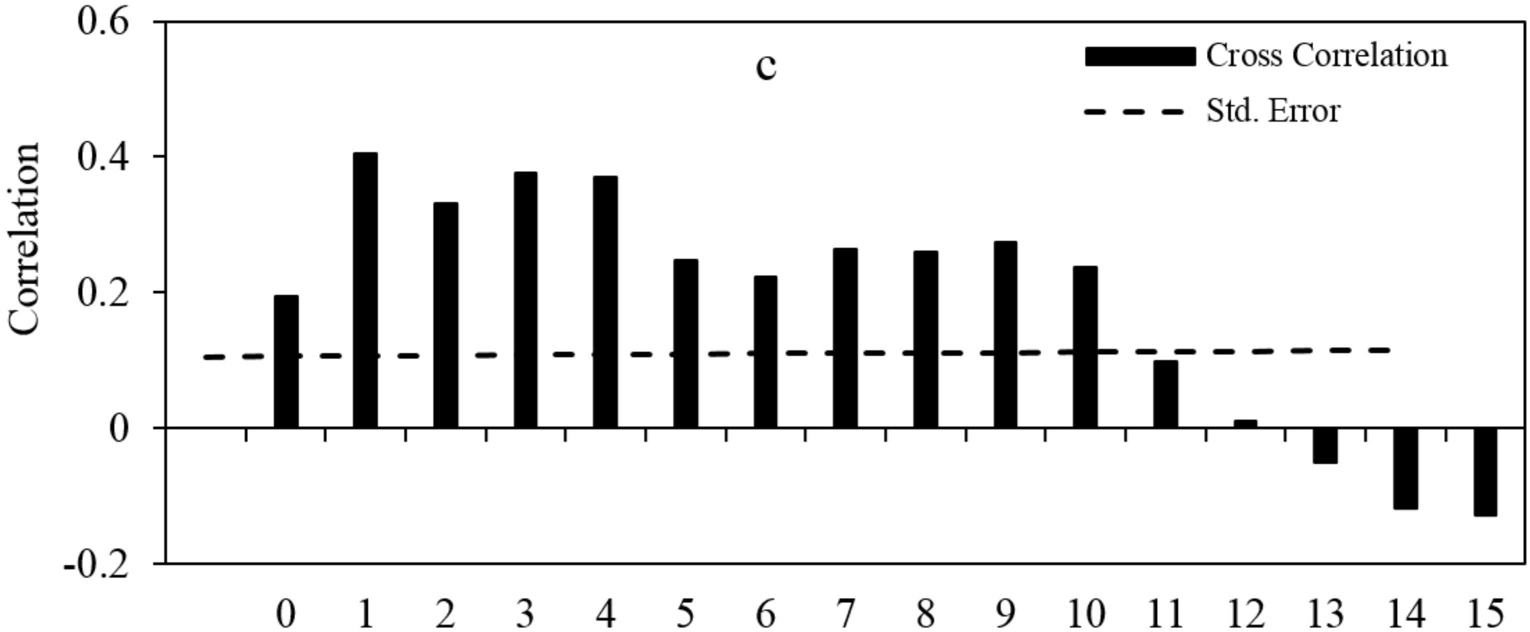
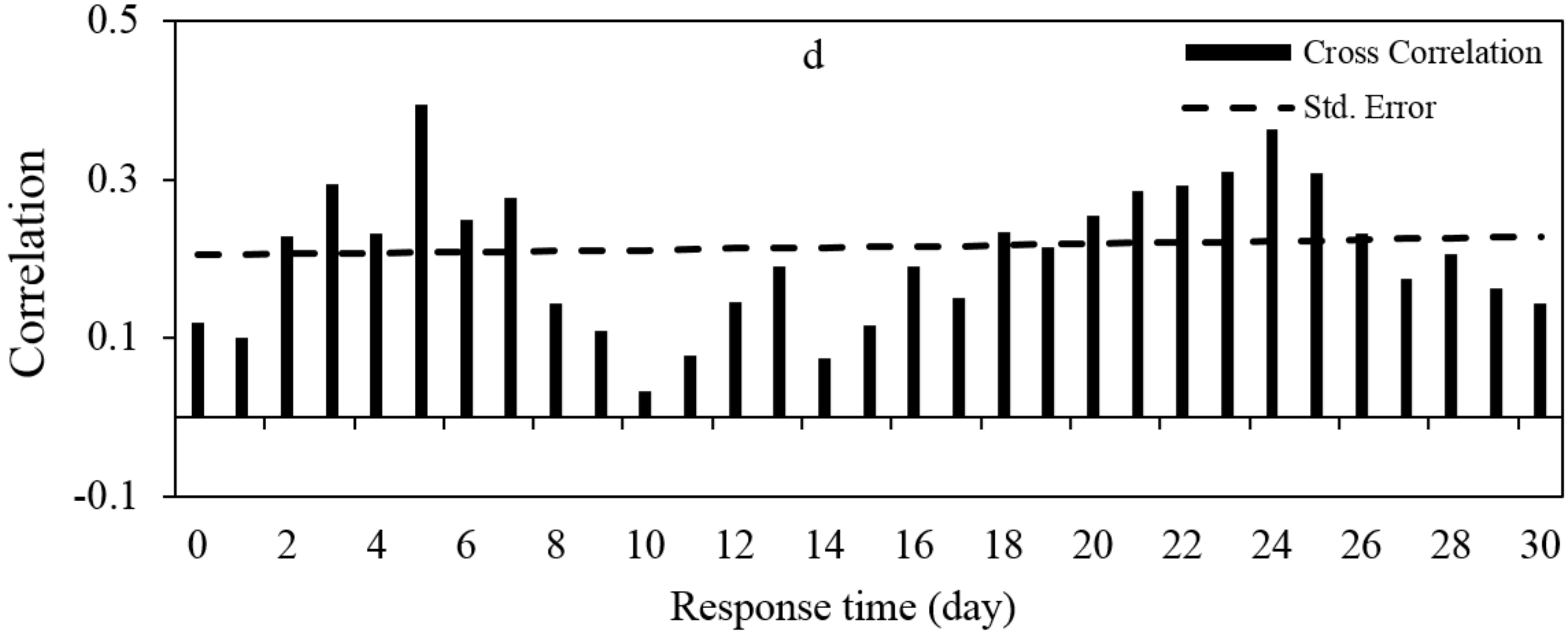
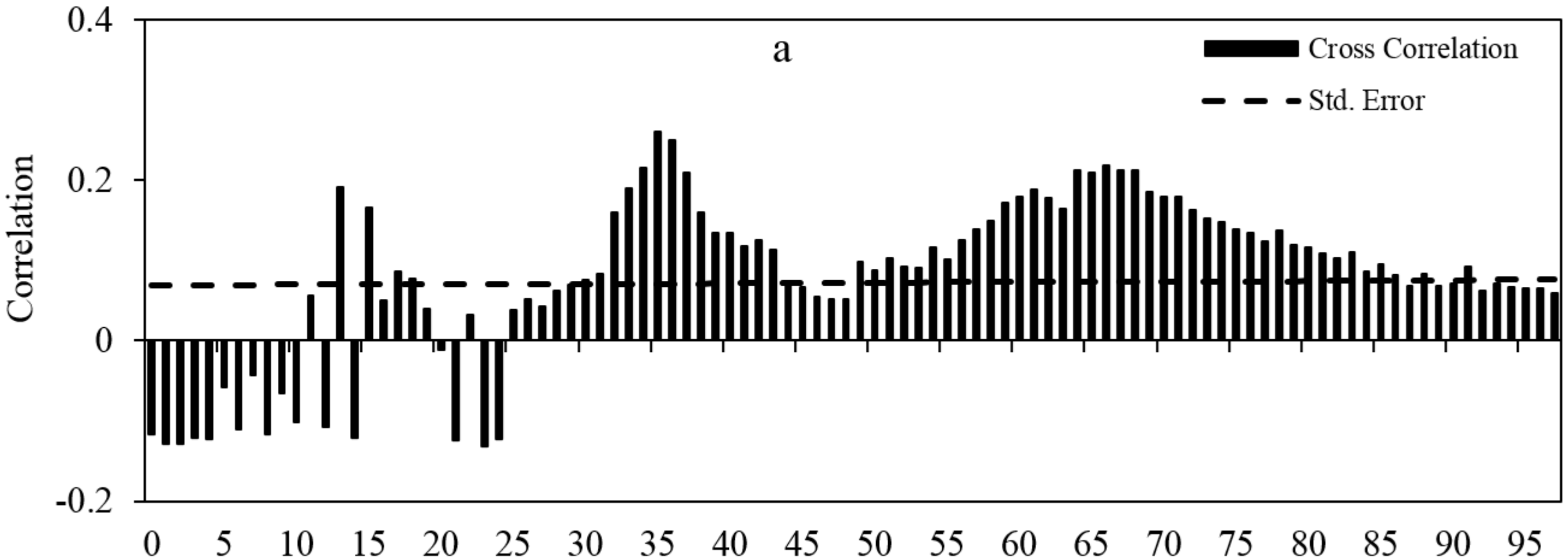
11
12
13
14
15



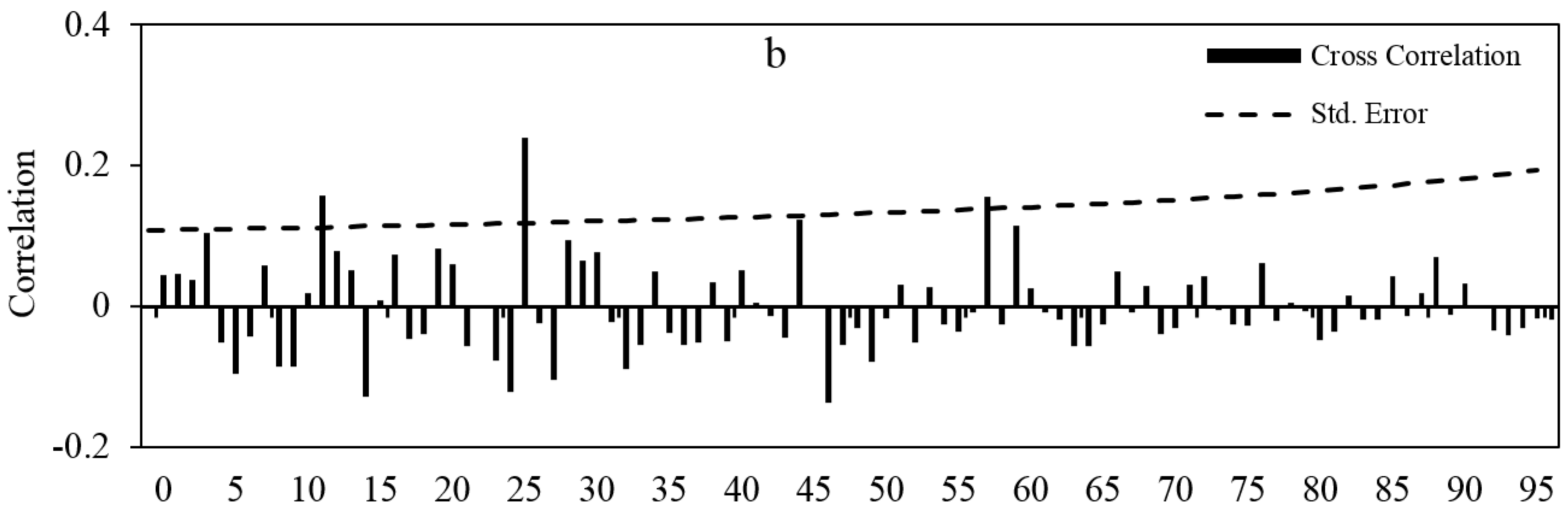
c
Cross Correlation
Std. Error
Correlation
0.6
0.4
0.2
0
-0.2
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15



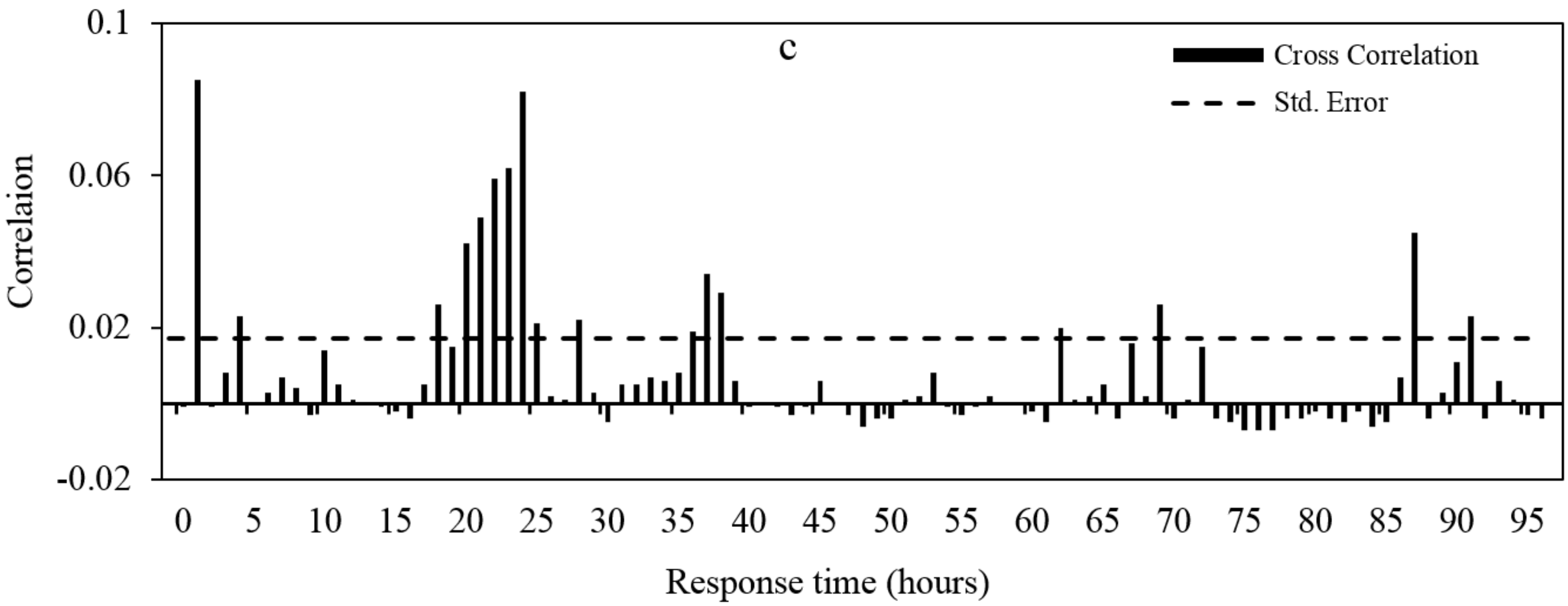
0.5
0.3
0.1
-0.1
Correlation
d
Cross Correlation
Std. Error
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Response time (day)



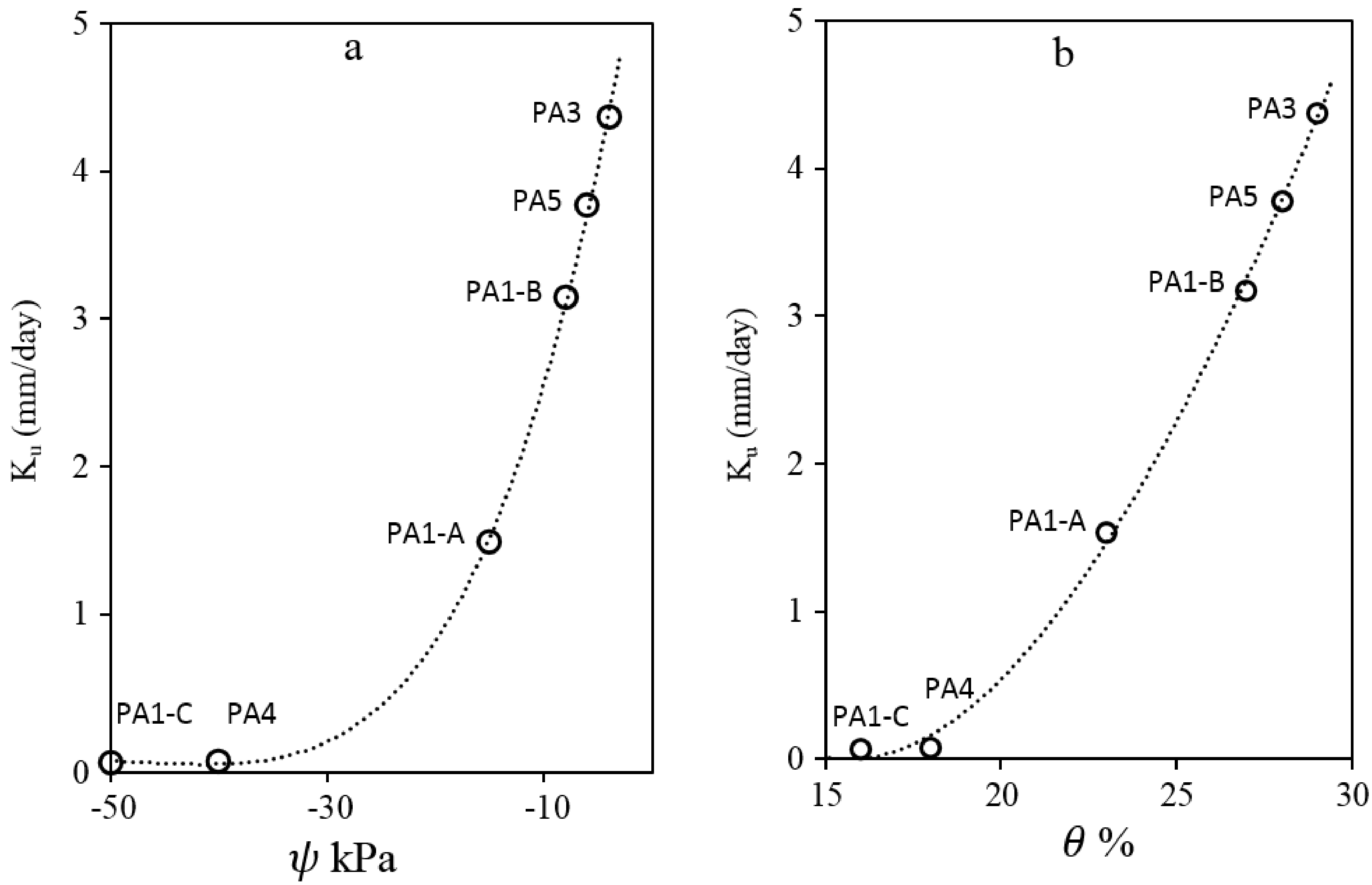
0.4
0.2
0
-0.2
Correlation
a
Cross Correlation
Std. Error
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95



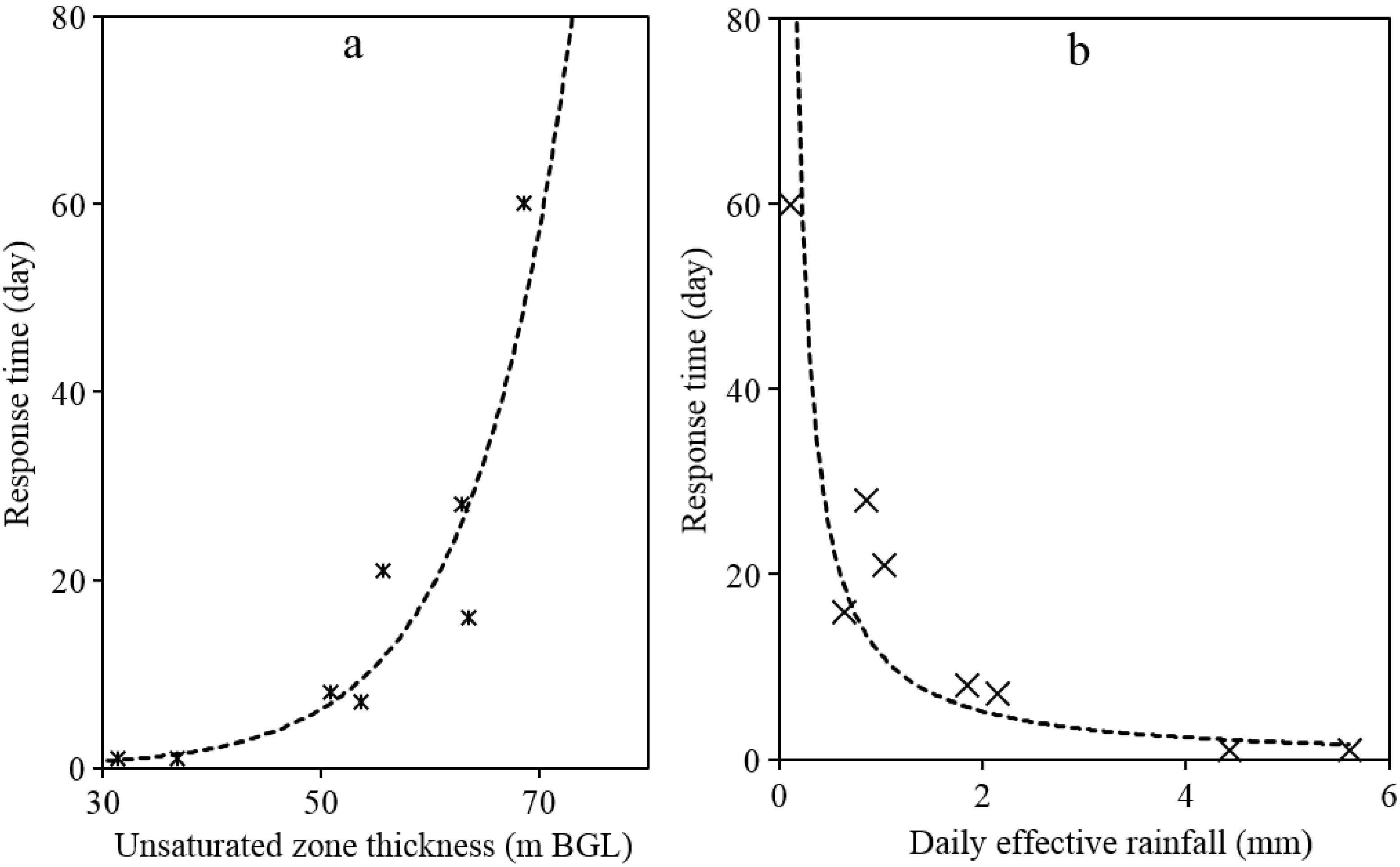
b
Cross Correlation
Std. Error
Correlation
0.4
0.2
0
-0.2
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95



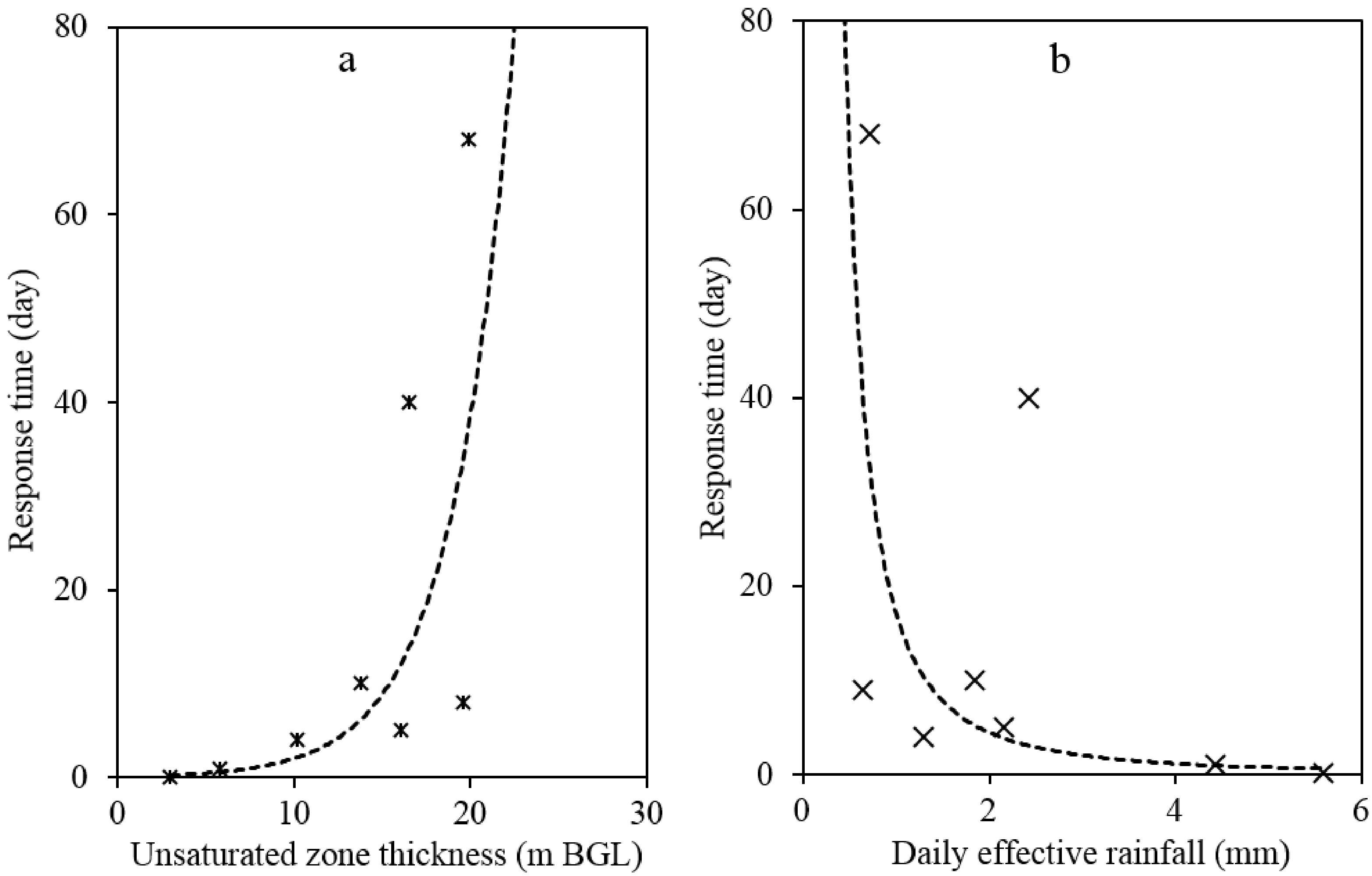
c
Cross Correlation
Std. Error
Correlaion
0.1
0.06
0.02
-0.02
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95
Response time (hours)



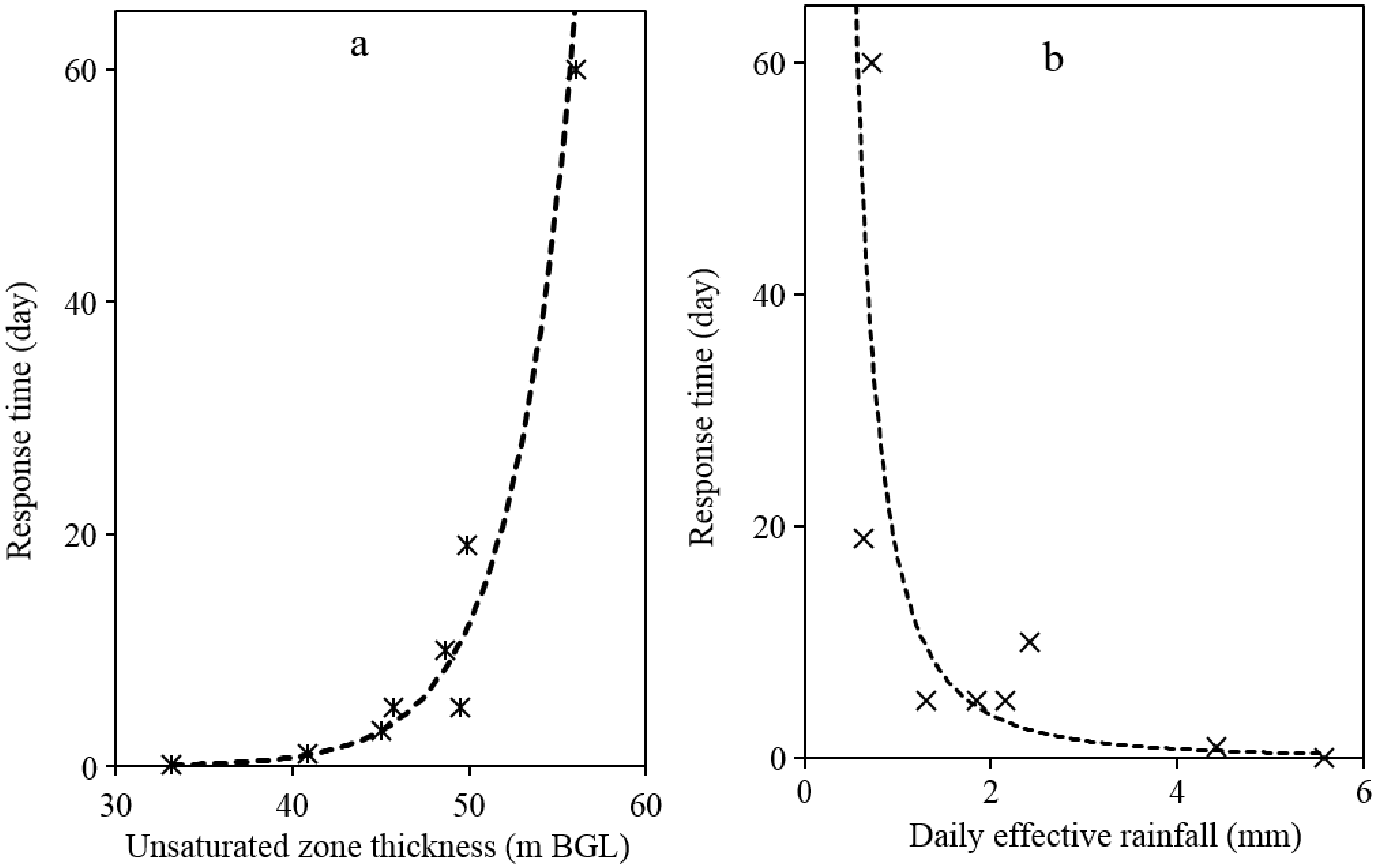
a
b
PA3
PA5
PA1-B
PA1-A
PA1-C
PA4
K_u (mm/day)
ψ kPa
θ %
-50
-30
-10
15
20
25
30
0
1
2
3
4
5

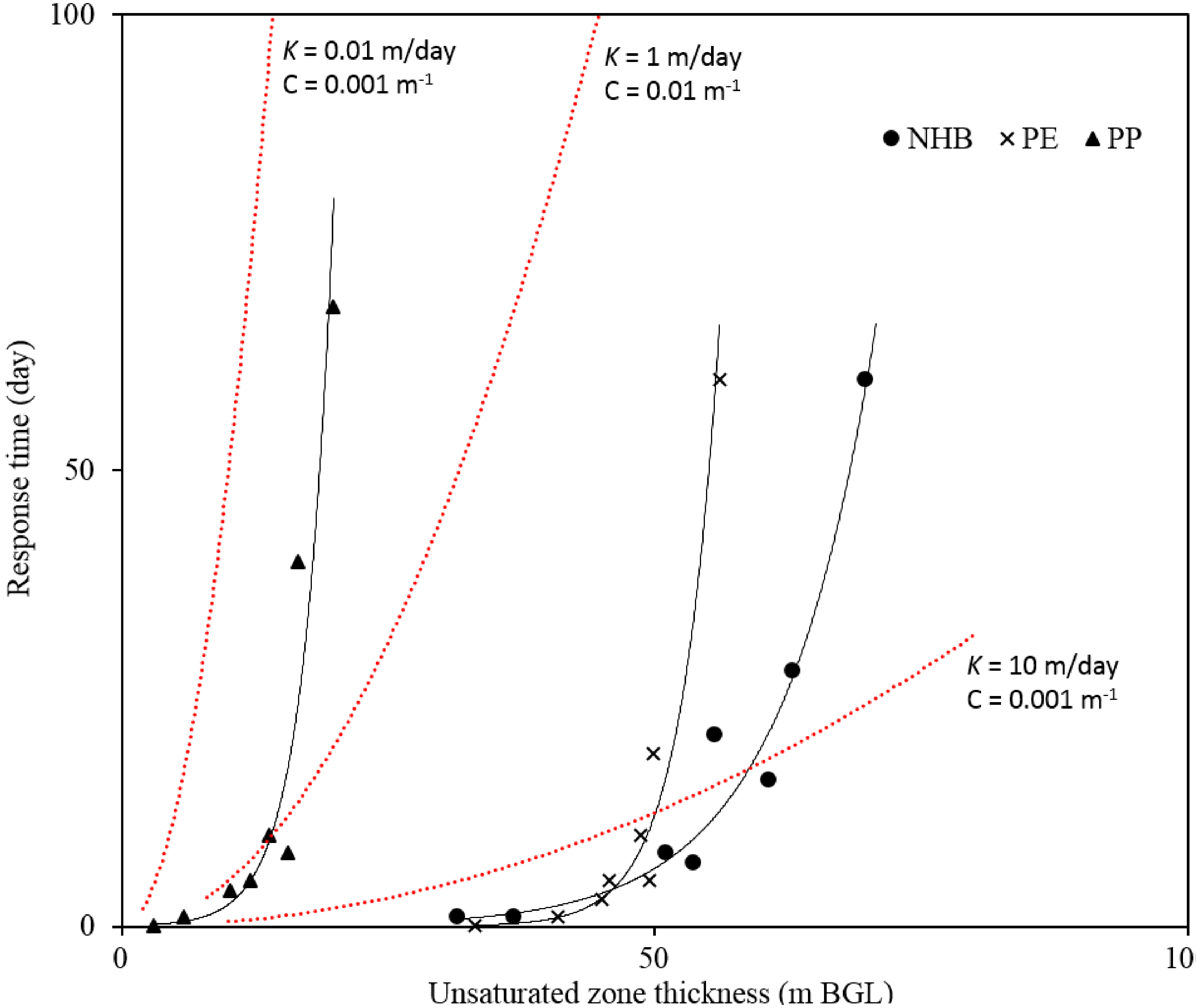


a
b
Response time (day)
Unsaturated zone thickness (m BGL)
Daily effective rainfall (mm)
0
20
40
60
80
30
50
70
2
4
6



a
Response time (day)
Unsaturated zone thickness (m BGL)
0
20
40
60
80
0
10
20
30
b
Response time (day)
Daily effective rainfall (mm)
0
20
40
60
80
0
2
4
6


a
Response time (day)
0
20
40
60
30
40
50
60
Unsaturated zone thickness (m BGL)
b
Response time (day)
0
20
40
60
0
2
4
6
Daily effective rainfall (mm)


100
50
0
Response time (day)
0
50
100
Unsaturated zone thickness (m BGL)
K = 0.01 m/day
C = 0.001 m-1
K = 1 m/day
C = 0.01 m-1
K = 10 m/day
C = 0.001 m-1
NHB
PE
PP