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Runoff formation from experimental plot, field, to small catchment scales in agricultural North Huaihe River Plain, China

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Abstract. Runoff formation at an experimental plot (1600 m^2), a field (0.06 km^2), and a small catchment (1.36 km^2) with a shallow groundwater table and a dense drainage system in the agricultural North Huaihe River Plain (China) was analysed based on the observed rainfall, runoff, and groundwater table data of 30 storm events that occurred during the 1997 to 2008 flood seasons. The surface runoff was collected and measured at the outlet of the furrow of the experimental plot, whereas the total runoff was collected and measured at the outlets of the drainage ditches of the field and the small catchment. The present study showed that the relatively narrow range of rainfall amounts resulted in significantly different runoff amounts at the 3 scales. When the groundwater is close to the surface, the runoff amount is a large percentage of the total rainfall. The difference in rainfall and runoff amounts was regressed against changes in the groundwater table, and a significant linear relationship was determined. Significant rainfall-runoff relationships were indicated for the events divided into 3 groups according to the initial groundwater table depths (as indicators of the antecedent moisture conditions): less than 0.5 m, more than 2.1 m, or between 0.5 m and 2.1 m. These findings suggest that saturation excess surface flow dominated the runoff response, particularly when the groundwater table was shallow. For almost all events, the groundwater table rose above the bottom of the drainage ditch. The total runoff amounts were larger both at the field and at the catchment than at the plot with only the surface runoff collected, which shows a considerable contribution of subsurface flow. Groundwater table depth, which indicates antecedent moisture conditions and influences lateral sub-surface flow to the drainage ditches, is an important parameter that influences runoff formation in catchments, including the study area with a shallow groundwater table and a dense drainage system.

1 Introduction

Over the past decades, numerous studies have been conducted to investigate runoff generation mechanisms. Runoff generative processes are highly variable and dependent on rainfall characteristics, initial moisture conditions, soil, vegetation, and topographic features (Taylor and Pearce, 1982; Hewlett et al., 1984; Dunne and Black, 1970a; Hewlett and Hibbert, 1967; Horton, 1933; Li and Sivapalan, 2011). However, hydrologic conditions in agricultural catchments are altered by agricultural features, such as land use, ditch networks, and agricultural operations, which are significant factors that control runoff generation from a plot to a small catchment (Hewlett and Hibbert, 1967; Kang et al., 2001; Cerdan et al., 2004; Coles et al., 1997; Burt and Slattery, 2006; Moussa et al., 2002; Gallart et al., 1994).

An agricultural plot can be considered as the smallest response unit in farmed landscapes (Cerdan et al., 2004; Moussa et al., 2002). At the plot scale, agricultural operations tend to homogenize soil surface and vegetation characteristics. Infiltration capacity is influenced by different agricultural features (Leonard and Andrieux, 1998; Burt and Slattery, 2006; Assouline and Mualem, 1997). Plough and root growth disturb the crust form of the soil, and infiltration capacity changes over a crop cycle (Imeson and Kwaad, 1990; Slattery and Burt, 1996). The leaf area index (LAI), which affects interception, was found to be one of the main factors that control surface runoff in experiment plots with bare land, corn, cotton, and soybean in the North Huaihe Plain of China (Jiao et al., 2009a, 2010).

The mechanisms through which rainfall appears as runoff at the hillslope scale or at the field scale include infiltration excess overland flow, which occurs when rainfall exceeds the rate at which the unsaturated soil can absorb water (Horton, 1933); saturation excess overland flow, which occurs when the soil is saturated (Dunne and Black, 1970b); and subsurface flow (Mosley, 1979; Hewlett and Hibbert, 1967). In an agricultural catchment, dominant runoff processes are difficult to characterise (Burt and Slattery, 2006). Infiltration excess overland flow is widely regarded as the dominant response mechanism in impermeable and human-disturbed areas (vehicle wheeling and soil surface compacted by certain tillage implements) (Burt and Slattery, 2006). Saturation excess overland flow is often predominant during wetting up and wet conditions, or near streams and drainage channels (Dunne and Black, 1970b; Burt and Slattery, 2006; Latron and Gallart, 2008).

The relative importance of different mechanisms depends on catchment wetness, and increasing wetness often causes a higher fraction of saturation excess flow (Graeff et al., 2012; Latron and Gallart, 2008; Penna et al., 2011; Zehe et al., 2010; Li and Sivapalan, 2011). Catchment wetness is often detected by soil moisture (Hrnčíř et al., 2010; Latron and Gallart, 2008). The depth of the groundwater table controls the soil moisture deficit in the profile (Sivapalan et al., 1987; Troch et al., 1993). In a catchment with an unconfined aquifer, high catchment wetness causes higher groundwater tables, and rising groundwater tables indicate a shallower unsaturated zone (Graeff et al., 2012). Groundwater table information was used to define the concept of saturation excess overland flow (Dunne and Black, 1970a, b). Continuous groundwater table data were used in the studies of storm runoff processes (Peters et al., 2003; Latron and Gallart, 2008; Penna et al., 2011; Biron et al., 1999). Data on the groundwater table depth prior to a given flood event are essential to obtain useful results on runoff response.

Groundwater table information was also used to determine the existence of subsurface flow (Betson et al., 1968). Groundwater can be the main component of flood hydrographs (Sklash and Farvolden, 1979). The importance of shallow subsurface flow has been documented in humid environments (Whipkey, 1966; Hewlett and Hibbert, 1967; Sklash and Farvolden, 1979; Latron and Gallart, 2008; Hrnčíř et al., 2010; Lehmann et al., 2007; Zehe and Sivapalan, 2009; Weiler and McDonnell, 2007). In an agricultural catchment with a shallow groundwater table, the groundwater table is often close to the soil surface during a rainfall event. Groundwater maintains a basic flow and feeds additional water to the ditch (Bouzigues et al., 1997). With the introduction of ditches or underground drainage, subsurface flow has a greater control in storm runoff for an agricultural catchment (DeWalle and Pionke, 1994; Wesström et al., 2003; Armstrong and Garwood, 1991; Cey et al., 1998; Burt and Slattery, 2006).

At the small catchment, hydrological connectivity is influenced by the lateral preferential flow or rill induced by agricultural linear features, such as furrows, back furrows, ditches, and vehicle wheeling (Cerdan et al., 2004; Lesschen et al., 2009; Slattery et al., 2006). Specifically, water transfer from fields to catchment outlets is influenced by drainage ditch networks. Compared with the natural drainage networks, the average distance and slope between fields and catchment outlets are modified by ditch networks (Moussa et al., 2002). Ditch networks may accelerate runoff by concentrating the flow and avoiding natural obstacles (Moussa et al., 2002). However, an ecology ditch that is constructed using compost, sand, gravel, and a perforated drain pipe increases the time to peak and reduces peak discharge (Yonge, 2003). Flow exchange between the surface and the groundwater is also influenced by ditch networks. When the groundwater table is low, the runoff produced at the field may reinfiltrate at the ditch networks. When the groundwater table is high, the ditch network drains the groundwater (Moussa et al., 2002; Armstrong, 2000). Nevertheless, the actual effects of ditch networks on the total runoff remain under discussion (Robinson, 1990; Holden et al., 2006; Konyha et al., 1992).

For rainfall-runoff studies in agricultural catchments, knowledge of the process originates mostly from the plot or the field (Burt and Slattery, 2006), and mechanisms of runoff generation are often detected or simulated at the catchment (Cerdan et al., 2002). Therefore, research efforts are necessary to investigate the evolution of runoff responses at plot, field, and small catchment scales. Le Bissonnais et al. (1998) measured runoff at 1, 20, and 500 m^2 plot scales and at 1100 hm^2 small catchment scale during two agricultural seasons. Cerdan et al. (2004) observed a significant decrease in runoff coefficient as the area of agricultural regions in Normandy increased. The differences in runoff responses at plot, field, and small catchment scales may be attributed to the variety of dominant processes (Castro et al., 1999; Cammeraat, 2002; Cerdan et al., 2004).

Nevertheless, mechanisms of runoff generation are always site- or context-specific (Cerdan et al., 2004). Identification of runoff generation processes in an agricultural area requires further investigation at plot, field, and small catchment scales to characterise the dominant water flow pathways. The North Huaihe River Plain is characterised by a shallow groundwater table, and a dense network of drainage ditches is used to lower the groundwater table and artificially drain the cropland to optimise moisture conditions. The mechanisms of runoff generation in the cultivated North Huaihe River Plain are indistinct. Accelerated overland flow and erosion resulted in serious non-point pollution problems (Jiao et al., 2010), the settlement of which requires knowledge of runoff generation mechanisms. At the Wudaogou experimental catchment in the northern part of the Huaihe River Basin, 3 sites

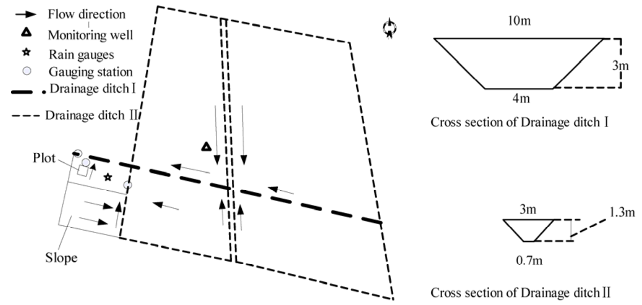

Fig. 1. Sketch map of the experimental catchment.

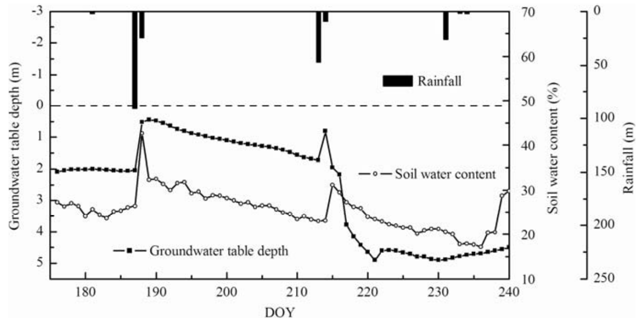

Fig. 2. Averaged daily rainfall, groundwater table depth and soil water content below the surface 15–30 cm of one point in the plot from DOY 175 to 240, 1999.

were monitored during storm events from 1997 to 2008. These sites included a 1600 m^2 plot, a 60 000 m^2 field, and a 1.36 km^2 catchment. With this extensive data set, the runoff generation mechanism was evaluated in this study.

2 Study area and methods

The Wudaogou experimental catchment (Fig. 1) with an area of 1.36 km^2 is located in the northern part of the Huaihe River Basin (33°09′ N, 117°21′ E). The climate is semi-humid temperate continental monsoon with a mean annual temperature and potential evaporation of 15 °C and 917 mm, respectively. Most precipitation (60 % to 80 %) falls in summer from June to September. The catchment is flat with an average slope of 1.4 %. The soil is silty clay (a dark semi-hydromorphic soil common in the North Huaihe River Plain), with a saturated hydraulic conductivity of 41.7 $mm\,h^{-1}$ and a lateral hydraulic conductivity of 14.2 $mm\,h^{-1}$ (Jing et al., 2009). The field capacity of the surface soil is between 27 % and 34 %, with an average of 30.7 % within the studied catchment.

A network of drainage ditches with cross-sectional areas of approximately 2.4 and 21 m^2 divides the catchment into different fields, as shown in Fig. 1. The cross-sections of the two types of ditches are also shown in the figure. The catchment is isolated from the outside region by roads and ditches. The outlet of the catchment is in the west. During the flood season, ephemeral runoff forms and flows into furrows and ditches after the storm. The rainfall was measured by a rain gauge located west of the study area. Stream flows during storm runoff events were measured at 3 different scales: plot, field, and small catchment. The plot and field were located west of the catchment. The plot is 40 m × 40 m, with its stream flow measured using the float method at the furrow outlet; only the surface flow was generated because the furrow was shallow. The field is 200 m × 300 m, with its stream flow measured at the ditch outlet. The stream flows of the catchment and field were measured using a flow meter with water surface width, cross-sectional area, and average water depth data. The measurement was conducted manually according to the change in flow. The stream flow was measured intensively when obvious changes were observed. The smallest time interval was 20 min, whereas the largest interval was more than 2 h. The rainfall-runoff events were separated from the rest of the time when the runoff was lower than 0.08 $m^3\,s^{-1}$ at the catchment scale and was 0.003 $m^3\,s^{-1}$ at the field scale or when no flow was observed at the plot scale.

The groundwater table level was measured at a monitoring well near the centre of the catchment. The groundwater table depth at the beginning and at the end of each storm runoff event was collected. In the study area, rainfall reached the land surface and infiltrated into the ground, causing the groundwater table to rise. Figure 2 shows the rainfall-runoff processes of the average daily groundwater table and precipitation from 25 June 1999 to 28 August 1999. Figure 2 also shows the time series of soil water content from 15 cm to 30 cm below the surface, as monitored by a time-domain reflectometer sensor from 1 point in the plot. The dynamics of soil moisture in the plot were related to the groundwater table dynamics of the well at the centre of the catchment. Groundwater table as a wetness indicator is a proxy to soil moisture status. In the absence of soil moisture and groundwater table measurements at the plot and field during the events, the groundwater table depth measured at the centre of the catchment also reflects the soil moisture conditions and groundwater table characteristics of the plot and the field.

Row-crop agriculture is the primary farming system adopted in the study area, which was planted with soybean (*Glycine max* (L.) Merr.), cotton (*Gossypium hirsutum* L.), and corn (*Zea mays* L.) when the storm runoff events occurred. At the experimental plot, only soybean was planted. At the small catchment and field, soybean occupied approximately 50 % of the area, whereas corn and cotton occupied the remaining 50 %. The percentages of the 3 crops changed slightly from 1997 to 2008.

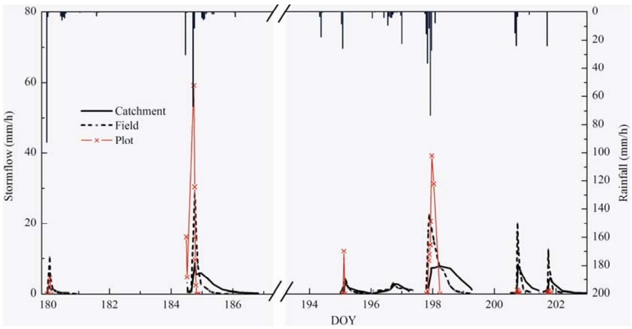

Fig. 3. Typical storm-runoff events from 29 June to 21 July 1997.

3 Results

3.1 Runoff formation

Except for the events with missing data, 30 storm runoff events were observed in 11 vegetation seasons (June to September) from 1997 to 2008. Stream flow data were observed at the field from 25 events and at the plot from 21 events, out of the 30 selected events. Other field and plot data were not available. The rainfall amount (mm), duration (h), maximum rainfall intensity (mm h^{-1}), initial groundwater table depth (m), groundwater table depth after the runoff event, and total runoff at the 3 scales during the 30 storm runoff events are listed in Table 1. Obvious variations in the amount of total rainfall and maximum 1-h rainfall intensity were observed, from 24.3 mm to 197.2 mm and from 11.1 mm h^{-1} to 92.5 mm h^{-1}, respectively. For the events with a rainfall amount of less than approximately 20 mm or with a maximum rainfall intensity of less than 10 mm h^{-1}, stream flow was not observed. Initial groundwater table depths varied from 0.22 m to 3.96 m between different events.

A total of 7 storm runoff events from 29 June 1997 to 21 July 1997 with obviously different rainfall and initial groundwater table depths were chosen as the typical storm runoff processes. The distribution of rainfall and runoff processes are shown in Fig. 3. The event beginning on day-of-year (DOY) 180 with a deep groundwater table at an initial depth of 2.38 m was characterised by a total rainfall of 115.2 mm and a maximum rainfall intensity of 92.5 mm h^{-1} at the first hour. The runoff is a small percentage of total rainfall (12.8 mm at the catchment with a runoff coefficient of 0.11). By contrast, the subsequent event with an initial groundwater table depth of 1.08 m was characterised by a total rainfall of 129.9 mm and a maximum intensity of 73.7 mm h^{-1} at the eighth hour. The runoff is a large percentage of the total rainfall (113.3 mm at the catchment with a runoff coefficient of 0.87). The event beginning at DOY 198 with an initial groundwater table depth of 0.29 m was characterised by a total rainfall of 197.2 mm and a maximum intensity of 73.7 mm h^{-1} at the fifth hour. The runoff is a very large percentage of the total rainfall (188.4 mm at the catchment with a runoff coefficient of 0.96). As detected from the typical events, the runoff response was related to the initial groundwater table depth, which can be used as the catchment wetness indicator.

Rainfall characteristics (e.g. total rainfall, rainfall duration, and maximum intensity) may also influence hydrological response (Martinez-Mena et al., 1998). For all 30 events, total rainfall was the characteristic that was more highly correlated with the runoff. Figure 4 shows the rainfall–runoff relationships at plot, field, and small catchment scales. As expected, the storms with greater amounts of rainfall produced greater amounts of runoff, although the points are scattered. However, the runoff was not correlated with the maximum value and distributions of rainfall intensity.

Generally, for a single storm event, a significantly larger runoff depth was generated at the field, whereas the least runoff volume was generated at the experimental plot. The runoff at the field and at the plot is compared with that at the small catchment for the storm events in Fig. 5a. Approximately 11 % more runoff was generated at the field than that at the catchment, and 20 % less runoff was generated at the experimental plot than that at the catchment. The typical storm runoff processes in Fig. 3 show that similar hydrographs were found between the stream flows at the catchment and at the field. Stream flow rapidly increased after rainfall and immediately receded at the plot where only surface flow was observed. For each event, the peak discharge values per unit area at the 3 scales obviously varied. Figure 5b shows the peak discharge values per unit area of the events at the plot and at the field plotted against that at the catchment. Except for the peak discharge per unit area at the plot of the four events (which was close to zero), the peak discharge at the plot was the largest, followed by that at the field. The peak discharge at the catchment was the smallest. For the events with a peak discharge of less than 5 mm h^{-1} at the catchment, the differences in the peak discharge per unit area amongst the experimental plot, field, and catchment were relatively stable. For the events with a peak discharge of more than 5 mm h^{-1} at the catchment, the differences became more obvious with the increase in peak discharge.

3.2 Rainfall–runoff relationship with different initial groundwater table depths

The storms with similar amounts of total rainfall generated significantly different runoff amounts (Fig. 4). For the seven storms with total rainfall amounts between 100 and 116 mm, the total runoff depths varied as follows: 12.8 mm to 95.4 mm at the small catchment, 27.3 mm to 105.7 mm at the field, and 6.9 mm to 93.3 mm at the plot. The events with small runoff coefficients frequently occurred when the initial groundwater table was deep, the points of which are located in the down-side region, as shown in Fig. 4. For example, for the event that started on 30 June 2006 (no. 20 in Table 1), despite the rainfall amount of 195.3 mm, runoff was only 48.5, 44.7, and

Table 1. Characteristics of the storm-runoff events from 1997 to 2008.

No.	Rainfall (mm)	Duration (h)	Max. rainfall intensity ($mm\,h^{-1}$)	Groundwater table depth (m)		Runoff (mm)		
				Initial	End	Catchment	Field	Plot
1	115.2	15.3	92.5	2.38	0.95	12.8	27.3	6.9
2	129.9	22.8	73.7	1.08	0.32	113.3	115.4	68.6
3	58.3	27.1	26.1	0.86	0.31	22.9	20.2	7.9
4	37.1	22.4	10.7	0.31	0.29	34.0	36.1	0.0
5	197.2	13.1	73.3	0.29	0.18	188.4	193.7	179.1
6	45.8	11.5	39.0	0.29	0.19	44.0	45.2	1.2
7	24.3	0.5	24.3	0.27	0.20	23.7	23.7	0.9
8	119.5	25.5	23.1	1.29	0.31	67.1	92.4	N/A*
9	105.8	21.2	27.0	0.39	0.25	95.4	102.8	93.3
10	146.4	55.0	19.3	3.96	1.91	23.8	15.6	20.6
11	78.7	38.1	21.3	1.07	0.50	56.2	68.2	26.7
12	46.4	35.7	12.8	0.49	0.40	41.1	44.9	36.9
13	117.6	29.2	19.4	0.28	0.21	104.5	109.1	97.5
14	138.5	25.3	40.3	2.95	1.65	28.9	N/A	N/A
15	81.6	21.0	20.1	2.03	0.96	43.0	48.1	15.7
16	62.1	34.0	11.1	1.02	0.53	53.6	61.4	36.0
17	53.0	14.8	11.8	0.70	0.37	18.1	39.3	N/A
18	171.5	31.0	38.7	0.50	0.33	115.9	N/A	N/A
19	35.8	22.5	22.0	0.35	0.35	33.3	N/A	N/A
20	195.3	17.6	37.5	3.08	1.09	48.5	44.7	29.2
21	105.0	26.7	18.2	1.27	0.63	57.1	93.7	37.9
22	39.8	21.9	15.2	0.41	0.27	18.3	N/A	N/A
23	86.6	4.0	71.4	0.65	0.29	46.6	55.7	26.5
24	101.0	52.5	19.2	2.06	0.46	49.3	55.0	30.6
25	114.9	12.0	20.4	0.46	0.31	87.6	105.7	85.1
26	155.4	39.0	26.4	0.62	0.22	110.2	127.0	83.2
27	109.7	32.5	32.2	0.93	0.32	43.0	57.1	N/A
28	90.5	20.7	23.1	1.05	0.38	38.3	N/A	N/A
29	50.8	4.1	30.5	1.08	0.26	20.2	48.2	N/A
30	49.9	17.5	17.2	0.26	N/A	41.5	43.8	17.1

* N/A: data is not available.

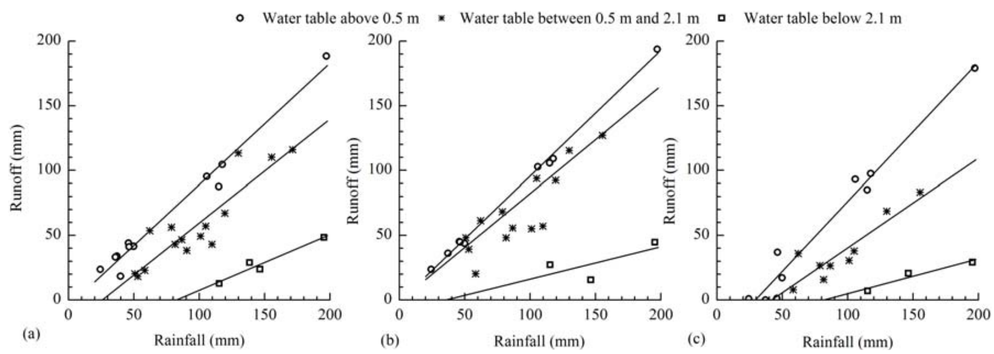

Fig. 4. Rainfall–runoff relationships for the storm events **(a)** at the small catchment scale, **(b)** at the field scale, and **(c)** at the experimental plot scale.

29.2 mm at the catchment, field, and experimental plot, respectively. On the other hand, the events with large runoff coefficients frequently occurred when the initial groundwater table was shallow, the points of which are located in the upside region, as shown in Fig. 4.

Figure 6 presents the plots of the runoff coefficient with the initial groundwater table depth at the 3 scales. For the 4

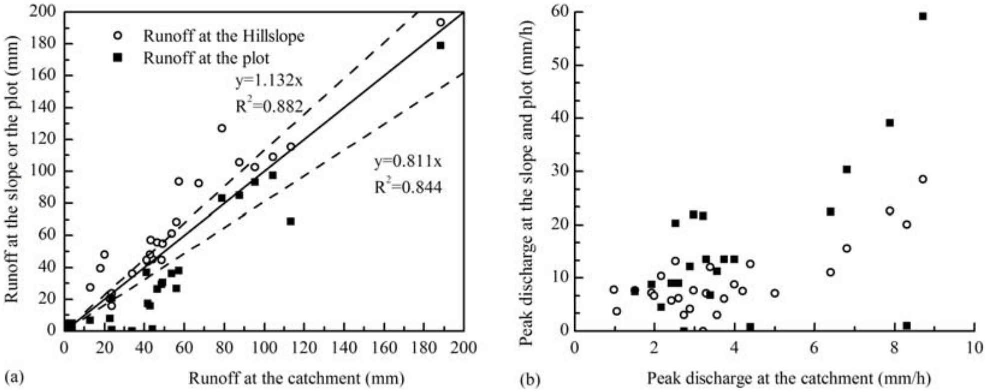

Fig. 5. (a) Runoff and **(b)** peak discharge at the field and plot with respect to that at the small catchment for the storm events.

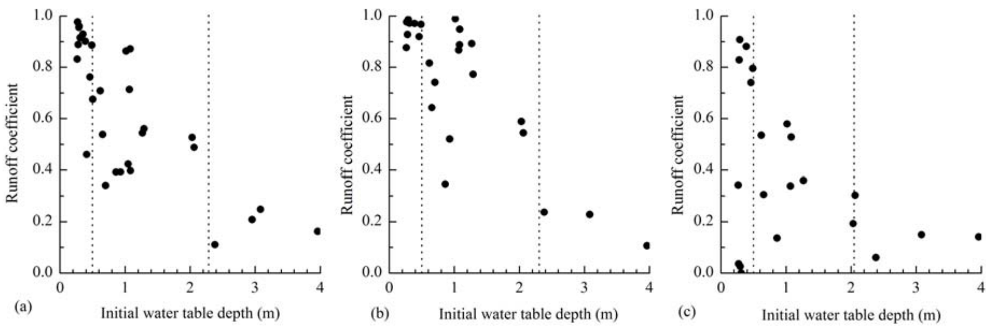

Fig. 6. Runoff coefficient with initial groundwater table depth for the storm events **(a)** at the small catchment **(b)** the field and **(c)** the plot scales.

events with initial groundwater tables deeper than 2.38 m, the runoff ranged from 10 % to 25 % of the rainfall at the catchment. The 10 events with initial groundwater table depths less than 0.50 m were characterised by a large percentage runoff of the total rainfall with an average value of 86 %. For the events with initial groundwater table depths between 0.5 and 2.1 m, the runoff coefficients were between 34 % and 86 %, with an average value of 57 %. The relationship between the runoff coefficient and the initial groundwater table depth at the field was similar to that at the catchment, although the runoff coefficients at the field were larger.

An obviously different relationship between rainfall and total runoff depth was observed at the plot. For all 21 events, the runoff coefficients varied from 0.03 to 0.91, which were smaller than those at the other 2 scales. Under certain rainfall amounts approximately ranging from 40 mm to 50 mm, a small amount of runoff was generated at the experimental plot, regardless of the initial groundwater depth (cf. storm no. 4, 6, and 7 in Table 1). Except for the 3 points with rainfall amounts of less than 46 mm, the plots of the runoff coefficient with an initial groundwater table depth at the plot was similar to those at the catchment and at the field. For the 3 events with an initial groundwater table depth of more than 2.38 m, a runoff of less than 15 % of the rainfall was obtained; for the 5 events with an initial groundwater table depth of less than 0.5 m and total rainfall of more than 46 mm, a runoff of more than 64 % of the rainfall was obtained.

All events were divided into 3 groups according to their initial groundwater table depths (storm runoff events with initial groundwater table depth of less than 0.5 m, between 0.5 m and 2.1 m, and more than 2.1 m). Figures 4 and 6 indicate that catchment behaviour changes with the initial groundwater table depth. Strong linear rainfall–runoff relationships were observed amongst the 3 groups (Fig. 4 and Table 2). Table 2 shows that the slope is large when the groundwater table depth is less than 0.5 m; the slope is small when the groundwater table depth is more than 2.1 m, which indicates that rainfall with a shallow groundwater table generally produced a greater volume of runoff. The intercept of the linear relationship was negative, which suggests that the runoff was generated after the rainfall had reached a threshold point. For the catchment and the field, the group with a deep initial groundwater table had higher thresholds. For the 2 groups with initial groundwater table depths of less than 2.1 m, the intercepts are larger for the plot than these for the catchment and the field, indicating that the plot had much higher thresholds.

Table 2. Summary of linear rainfall–runoff relationships for three categories with different initial groundwater table depth.

	Catchment			Field			Plot		
Category*	A	B	C	A	B	C	A	B	C
Slope	0.939	0.802	0.430	0.971	0.830	0.250	1.078	0.693	0.269
Intercept	−4.844	−20.724	−35.539	−1.423	−0.827	−8.902	−31.751	−29.071	−22.087
R^2	0.976	0.811	0.942	0.997	0.749	0.476	0.969	0.813	0.935

*: Events were divided into three categories according to the initial groundwater table: A: shallower than 0.5 m, B: between 0.5 m and 2.1 m, C: deeper than 2.1 m.

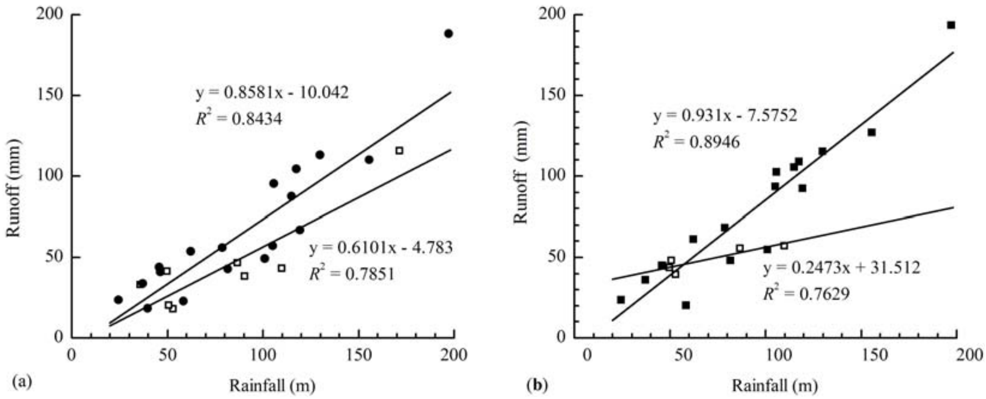

Fig. 7. Rainfall–runoff relationship for the storm events with groundwater table shallower than 2.1 m at the early growth stage (before 22 July) and the later growth stage (from 2 August to 19 September) **(a)** at the small catchment and **(b)** the field.

3.3 Rainfall–runoff relationship at early or late growth stages

Surface runoff occurrence is more frequent with crops at the seedling or early growth stage than later in the season (Bochet et al., 2006; Jiao et al., 2010). In the study area, soybean and corn are seeded, whereas cotton is transplanted in mid-June. The early growth stage with small LAI extends to late July (Jiao et al., 2009b). The canopy cover is maintained relatively stable up to mid-September. A total of 19 out of 26 events occurred at the seedling or early growth stage (before 22 July), and 7 occurred at the late growth stage (from 2 August to 19 September). The rainfall–runoff relationships at different growth stages were evaluated. Considering that only 2 events at the later growth stage were available, the rainfall–runoff relationship at the early and late growth stages at the plot was not analysed. To eliminate the influence of initial groundwater table, only the 26 events with initial groundwater table depth of less than 2.1 m were evaluated. Figure 7 depicts the rainfall–runoff relationships of the 2 groups at the catchment and at the field. For both the catchment and the field, the runoff generated at the early growth stage was larger than that at the late growth stage with similar rainfall amounts. The runoff increases faster with rainfall at the early growth stage than at the late growth stage.

4 Discussion

Significant rainfall–runoff relationships were indicated for the events of the 3 groups with different initial groundwater table depths. On the other hand, no obvious correlations were observed between total runoff or runoff coefficient and maximum rainfall intensity or average rainfall intensity. The groundwater table depth was less than 0.6 m for 25 of the 30 events after the storm runoff. For the other 5 events with a deep initial groundwater table, the groundwater table rose by more than 1 m (Table 1), which suggests soil saturation during the storm runoff events. Both the rise in the groundwater table and the difference between rainfall and runoff (P-R) were minimal when the initial groundwater table depth was less than 0.4 m. These observations suggest that saturation excess surface flow controlled runoff response, whereas the infiltration excess overland flow is generally minor given a shallow initial groundwater table. This finding was consistent with the results in previous studies using hydrochemical tracers (Tan et al., 2008). The hydrological model, which is based on the concept of saturation excess surface runoff and considers the effects of groundwater table, performed well in this catchment (Wang et al., 2004).

Runoff can be predicted by the difference between the amount of rainfall and the initial abstraction (i.e. the water that infiltrates before the soil is saturated). The initial abstraction can be detected by changes in the groundwater table

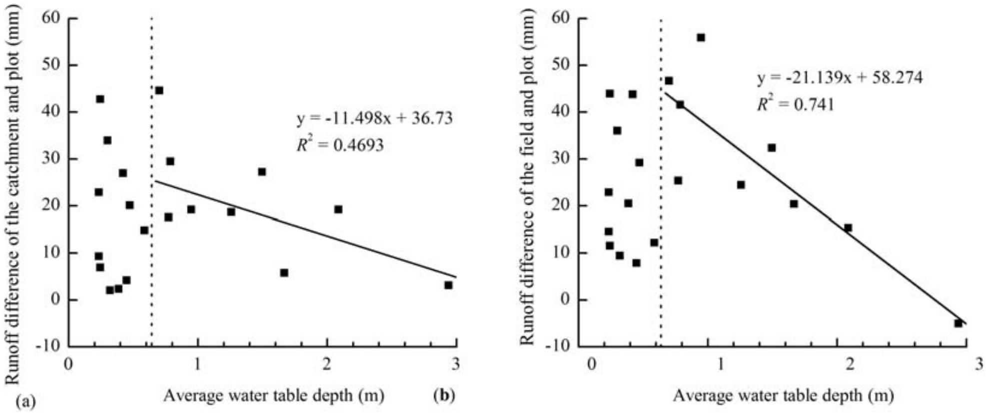

Fig. 8. Runoff difference between **(a)** the catchment and the plot, **(b)** the field and the plot vs. average groundwater table depth before and after the rainfall-runoff events.

Table 3. Summary of linear relationships between the difference of rainfall and runoff (P-R) and the initial groundwater table depth and the changes in groundwater table depth.

	(P-R) vs. initial groundwater table depth			(P-R) vs. changes in groundwater table		
	Catchment	Field	Plot	Catchment	Field	Plot
Slope	34.23	37.044	33.283	54.925	57.626	54.662
Intercept	3.5331	−10.6	18.291	8.094	−6.649	21.649
R^2	0.723	0.796	0.765	0.698	0.758	−0.800

before and after the rainfall-runoff event. The differences between the rainfall and the runoff were regressed with the changes in groundwater table at all 3 scales (Table 3). The significant linear relationships also confirm that the saturation excess flow is the dominant response to rainfall. Significant linear relationships between the difference in rainfall and runoff as well as the initial groundwater table depth were also indicated. Total rainfall and the antecedent soil water availability detected by the initial groundwater table depth were identified as the 2 main factors affecting the total runoff amount. The runoff amounts can be predicted using the data on total rainfall and initial groundwater table depth.

For all aforementioned events, the groundwater table at the end was higher than the bottom of drainage ditch I (3 m) and drainage ditch II (1.3 m), except for the 2 events on 2 June 2000 and 7 July 2005 (No. 10 and 14 in Table 1). When groundwater table is shallower than the bottom of the ditch, a lateral subsurface flow occurs. Therefore, groundwater would feed additional water to the drainage ditches, and subsurface flow would have a considerable contribution to the total runoff in the study area. The experimental plot had no drainage ditch, and only surface runoff was collected, whereas both surface and subsurface runoffs were collected at the field and at the small catchment. The subsurface flow of the field can be obtained indirectly from the difference between the runoff at the field and the surface flow at the nearby experimental plot. Figure 8 shows the difference between the total runoff at the field and that at the experimental plot plotted against the average groundwater table depth. At an initial groundwater table deeper than 1 m, a significant linear relationship between the difference and the average groundwater table depth was indicated, and the differences decreased with the average groundwater table depth. For the event on 2 June 2000 (no. 10 in Table 1), the total runoff at the field was less than that at the plot when the groundwater table was shallower than the bottom of the ditch during the entire period. Therefore, flow exchange processes occurred between the drainage ditches and the groundwater. These processes were influenced by the groundwater table depth. For the events with a shallow initial groundwater table during the entire period, the differences ranged from approximately 10 mm to 50 mm, and no significant correlation was indicated in the difference and the average groundwater table depth. The reason may be that the contributions of subsurface flow to the total runoff were weaker than those of the saturation excess surface flow. Figure 8 also shows the plotting of the difference between the total runoff at the catchment and that at the experimental plot against the average groundwater table depth. A similar relationship is observed, but the points are more scattered.

The runoff coefficient at the catchment was smaller than that at the field. The runoff coefficient at the plot scale is smaller than that at the catchment and field scales, which is not completely consistent with the results in previous studies, which suggest that runoff coefficient decrease with area (Stomph et al., 2002; Cerdan et al., 2004; Van de Giesen et al., 2010). For the plot, only the surface runoff was collected and observed. Considering that subsurface flow influences the total stream flow, the runoff at the plot is expected to be much smaller. The different travel times and dispersion of the peak discharge in the hydrograph may be explained by the location of the plot and of the field, which is the edge of the catchment. Nevertheless, the scaling behaviour of runoff generation in this area needs further study.

5 Conclusions

Based on our analysis of the observed rainfall and runoff data of 30 rainstorm events obtained from an experimental plot, a field, and a small catchment during the flood seasons from 1997 to 2008 at the North Huaihe Plain, the following conclusions are presented:

1. The relatively narrow range of rainfall amount resulted in significantly different runoff amounts from the experimental plot, field, and small catchment. The antecedent soil water moisture, which can be approximated by the initial groundwater table depth, was identified as the main factor influencing the rainfall–runoff relationship in the study area. A large percentage of rainfall was converted to runoff when the initial groundwater table is shallow, whereas a small runoff coefficient is obtained when the initial groundwater table is deep.

2. Significant rainfall–runoff relationships were indicated for the events of the 3 groups with different groundwater table depths. The difference between the rainfall amount and the runoff amount can be detected by the initial groundwater table depth or by the changes in the groundwater table before and after the rainfall-runoff events. The observations suggest that the saturation excess surface flow would control the surface flow response, particularly with a shallow groundwater table.

3. Based on the evaluation of the 26 events at the catchment and at the field with initial groundwater table depths of less than 2.1 m, more runoff was generated at the early growth stage than at the late growth stage with similar rainfall amounts. Runoff increases faster with rainfall at the early growth stage compared with that at the late growth stage.

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