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Runoff formation from plot, field, to small catchment with shallow groundwater table and dense drainage system in agricultural North Huaihe River Plain, China

S. Han[1,2], D. Xu[1,2], and S. Wang[1,2]

[1]State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100048, China
[2]National Center of Efficient Irrigation Engineering and Technology Research, Beijing 100048, China

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Correspondence to: D. Xu (xudi@iwhr.com)

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Abstract

Runoff formation processes at the experimental plot (1600 m^2), the field (0.06 km^2), and the small catchment (1.36 km^2) with shallow groundwater table and dense drainage system in North Huaihe River Plain (the northern part of the Huaihe River Basin, China) were analyzed based on observed rainfall, runoff and groundwater table depth data of 30 storm events during the flood seasons from 1997 to 2008. At the outlet of the furrow of the experimental plot, only the surface runoff was collected and measured, whereas both the surface and subsurface runoffs were collected at the drainage ditches outlets 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 all the three scales. When the ground water is close to surface, the runoff amount is a great percentage of rainfall amount. Significant linear relationships between the difference of rainfall and runoff amounts and the changes in water table or the initial water table depth were found. When the 30 events were divided into three groups with initial water table (as a parameter indicating the antecedent moisture condition) shallower than 0.5 m, deeper than 2.3 m or between 0.5 m and 2.3 m, significant rainfall-runoff relationships existed for each group. These imply that saturation-excess surface flow dominated the runoff response, especially when water table is shallow. For almost all the events, the water table rose above the bottom of drainage ditch during the event, and the total runoff amounts were larger at the field and the catchment than that at the plot with only surface flow measured, showing a great contribution of subsurface flow. Groundwater table depth, not only reflecting the antecedent moisture conditions, but also influencing the lateral sub-surface flow to the drainage ditches, would be an important parameter dominating runoff formation process in catchment like the study area with shallow water table and dense drainage system.

1 Introduction

Over the past decades, many studies have been conducted to investigate runoff generation mechanisms (Horton, 1933; Dunne and Black, 1970a; Li and Sivapalan, 2011; Hewlett and Hibbert, 1967). 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, 1970b; Hewlett and Hibbert, 1967). However, the hydrological conditions in agricultural catchments are altered by agricultural features, such as agricultural land use, ditch networks, and agricultural operations. They are significant factors controlling flood generation from plot to 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, agricultural operations tend to homogenize soil surface and vegetation characteristics. Infiltration capacity will be increased or decreased by different agricultural features (Leonard and Andrieux, 1998; Burt and Slattery, 2006; Assouline and Mualem, 1997). Plough and root growth would disturb the crust form of the soil, and infiltration capacity changes over a crop cycle (Imeson and Kwaad, 1990; Slattery and Burt, 1996). In the North Huaihe Plain of China, leaf area index (LAI) affecting interception was found to be one of the main factors controlling surface runoff in the experiment plots with bare land, corn, cotton, and soybean (Jiao et al., 2009a, 2010).

At the slope or field, the mechanisms whereby rainfall appears as runoff are infiltration-excess overland flow, saturation-excess overland flow, and subsurface flow (Mosley, 1979). In an agricultural catchment, the characterization of dominant runoff processes is difficult because storm runoff is always generated by a combination of three different mechanisms (Burt and Slattery, 2006). Infiltration-excess overland flow is widely regarded as the dominant response mechanism in impermeable and human-disturbed areas (vehicle wheelings 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, 1970a; Burt and Slattery, 2006; Latron and Gallart, 2008). The importance of shallow subsurface flow to runoff forming process has been documented in forested headwater catchments and fields with deep or moderate fields (Whipkey, 1966; Hewlett and Hibbert, 1967; Sklash and Farvolden, 1979; Latron and Gallart, 2008; Hrncır, 2010). Nevertheless, in an agricultural catchment with shallow water table, the water table is often close to the soil surface during a rainfall event. Groundwater not only maintains a basic flow but also feeds additional water to the ditch (Bouzigues et al., 1997). With the introduction of ditches or underground drainage, subsurface flow takes a greater part in storm runoff for agricultural catchment (DeWalle and Pionke, 1994; Wesstr m et al., 2003; Armstrong and Garwood, 1991; Cey et al., 1998; Burt and Slattery, 2006).

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

In rainfall-runoff studies in agricultural catchments, process knowledge originate mostly from the plot (Burt and Slattery, 2006), whereas runoff-generation mechanisms are often detected or simulated at the catchment (Cerdan et al., 2002). Therefore, research efforts are needed to investigate the evolution of runoff responses from plots to small catchments. Le Bissonnais et al. (1998) measured the runoff in 1, 20, and 500 m^2 plots and in a small catchment during two agricultural seasons. The authors found that the largest runoff coefficient was in the 1 m^2 plot, but it was the smallest in the small catchment. Cerdan et al. (2004) found a significant decrease in runoff coefficient as the area of agricultural regions in Normandy increased. The differences in runoff responses from plot and field to small catchment may be attributed to different dominant processes (Castro et al., 1999; Cammeraat, 2002; Cerdan et al., 2004).

Nevertheless, runoff generation mechanisms are always site or context specific, and depends on the size of monitored plots or catchments (Cerdan et al., 2004). The identification of runoff generation processes in an agricultural area requires further investigations from plots, fields to small catchments to characterize the dominant water flow pathways. The North Huaihe River Plain (the northern part of the Huaihe River Basin, China) is characterized with a shallow groundwater table, and a dense network of drainage ditches used to lower the water tables and artificially draining the crop land to optimize the plant moisture conditions. Accelerated overland flow and erosion (induced by human activities) resulted in a serious non-point pollution problem (Jiao et al., 2010), the settlement of which requires the knowledge on runoff generation. At the Wudaogou Experimental catchment located in the northern part of the Huaihe River Basin, three sites from a 1600 m^2 plot, a 60 000 m^2 field, and a 1.36 km^2 catchment were monitored during storm periods from 1997 to 2008. Using this extensive dataset, the runoff generation mechanism in the study area 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, China (33°09′ N, 117°21′ E). The climate is semi-humid temperate continental monsoon, with mean annual temperature and potential evaporation of 15 °C and 917 mm, respectively. Most of the annual precipitation falls in summer from June to September, which accounts for 60–80 % of the annual precipitation. At the field, the terrain was flat due to cultivation. The study area is flat with an average slope of 1.4 %. The soil is silty clay (a dark semi-hydromorphic soil), which is the most common soil type in the Huaihe River plain, with a saturation conductivity of 41.7 mm h^{-1} and a lateral hydraulic conductivity of 14.2 mm h^{-1} (Jing et al., 2009). The soil characteristic shows very little variability within the studied catchment.

A network of drainage ditches (cross-sectional areas of approximately 2.4 and 21 m^2) divide the site into five fields as shown in Fig. 1. The cross-sections of the two types of ditches are shown in the figure. The catchment with the outlet in the west is isolated from the outside region with roads and ditches. During the flood seasons, ephemeral runoff formats after storm and flows in the furrows and ditches. Stream-flows during storm runoff events were measured at three different scales (plot, field, and small catchment) from June to September. The plot and field were located west of the catchment. The plot is 40 × 40 m. The stream-flow of the plot was measured using the float method at the furrow outlet; only surface flow was generated since the furrow was shallow. The field is 200 × 300 m, with 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. Except for the events with missing data, thirty storm–runoff events were observed from eleven vegetation seasons (June–September) from 1997 to 2008. Stream-flow data were observed at the field from 24 events, and at the plot from 21 events out of the 30 selected events respectively. The other data were not available. The rainfall in the catchment was measured by a rain gauge located west of the study area. Ground water table level was measured at a monitoring well located near the center of the catchment. The ground water table depth at the initial and end of each storm-runoff event were collected.

Row-crop agriculture is the primary farming system adopted in the study area, which was planted to summer crops (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 the other 50 % were planted to corn and cotton. The percentage of the three crops changed little from 1997 to 2008.

3 Results

3.1 Runoff formation

The rainfall amount (mm), duration (h), maximum rainfall intensity (mm h^{-1}), initial ground water table depth (m), water table depth after the runoff event, and total runoff at the three scales during the thirty storm-runoff events are listed in Table 1. The variations in the amount of total rainfall and maximum rainfall intensity were obvious, from 24.3 to 197.2 mm and from 11.1 to 92.5 mm h^{-1} respectively. For the event with rainfall amount less than about 20 mm or maximum rainfall intensity less than 10 mm h^{-1}, there was no runoff observed. The initial groundwater table depths varied considerably between different events, which ranged from 0.22 to 3.96 m. From 29 June to 21 July 1997, seven storm runoff events occurred with obviously different amounts of rainfall and initial groundwater table depths are shown as the typical storm runoff processes (Fig. 2). At the plot with only surface flow were observed, stormflow rapidly increased after runoff generation, and its recession was also relatively rapid. Similar hydrographs were found between the stream-flows at the catchment and field.

Generally, for a single storm event, a significantly larger runoff depth was measured at the field, whereas the least runoff volume was measured at the experimental plot. The runoff at the field and plot are compared with those at the small catchment for the storm events in Fig. 3a. Approximately 24 % less runoff was generated at the experimental plot than that at the catchment, whereas approximately 10 % more runoff was generated at the field than that at the catchment. Similar results were found in previous studies (Cerdan et al., 2004; Le Bissonnais et al., 1998). For each event, the values of peak discharge per unit area were obviously different at the three scales. The peak discharge per unit area for the events at the plot and field are plotted against with that at the catchment in Fig. 3b. Except for four events with peak discharge per unit area close to zero, the peak discharge at the plot was larger than that at the other two scales, and the peak discharge at the catchment was smallest. For the events with a peak discharge of less than 5 mm h^{-1} at the catchment, the differences of the peak discharge per unit area between the experimental plot, field, and the catchment were relatively stable. For the events with a peak discharge more than 5 mm h^{-1} at the catchment, the differences were more obvious with increasing peak discharge.

3.2 Rainfall-runoff relationship with different initial water table

The rainfall-runoff processes of averaged daily groundwater table and precipitation from 25 June to 29 August 1999 are shown in Fig. 4 for instance. In the study area, rainfall reached the land surface and infiltrated into the ground, causing the groundwater table to rise. The time series of soil water content below the surface 15–30 m monitored by TDR sensor from one point in the plot are also shown in Fig. 4. The dynamics of soil moisture in the plot was related to the dynamics of ground water table of the well in the center of the catchment. Since there are no measurements on soil moisture or ground water table in the plot and field during the events, the water table depth measured in the center of the catchment also provides some sort of moisture conditions and water table characteristics of the plot and field.

The plots of rainfall-runoff relationships at the plot, field and small catchment are shown in Fig. 5. As expected, the storms with greater amounts of precipitation produced greater amounts of runoff, but the points were scattered. The storms with similar rainfall totals generated significantly different runoff amounts. For the seven storms with rainfall totals between 100 and 116 mm, the total runoff depths varied from 12.8 to 95.4 mm at the small catchment, from 27.3 to 105.7 mm at the field, and from 6.9 to 93.3 mm at the plot. The events with small runoff ratios usually occurred when initial groundwater table were deep, the points of which are located in the downside region in Fig. 5. For example, during the event which started on 30 June 2006 (No. 20 in Table 1), although the rainfall amount was 195.3 mm, the runoff was only 48.5, 44.0, and 29.3 mm at the catchment, field, and experimental plot, respectively. On the other hand, the events with large runoff ratios usually occurred when initial groundwater table were shallow, the points of which are located in the upside region in Fig. 5.

The plots of runoff ratio with the initial groundwater table depth at the three scales are shown in Fig. 6. At the small catchment, for the four events with initial groundwater tables deeper than 2.38 m, the runoff was around 10–25 % of the rainfall. The ten events with initial groundwater table depths shallower than 0.50 m were characterized with large percentage runoff of the rainfall with average value 86 %. For the events with initial groundwater table depths between 0.5 m and 2.1 m, the runoff ratios were between 34 % and 86 % with an average value 57 %. The plot at the field was similar to that at the catchment, with larger runoff coefficients.

An obviously different relationship between rainfall and total runoff depth was found at the plot. For all the 21 events, the runoff ratios varied from 0.03 to 0.91, which were smaller than those at the other two scales. Under certain rainfall amounts (~40–50 mm), little runoff was generated at the experimental plot, regardless if the initial groundwater was shallow or deep (cf. Storm Nos. 4, 6, and 7 in Table 1). A threshold for significant runoff generation may have existed at the plot. Except the three points with rainfall amounts less than 46 mm, the plots of runoff ratio with the initial groundwater table dept at the plot was similar to those at the catchment and field. For the three events with initial water table deeper than 2.38 m, the runoff was also less than 15 % of the rainfall; for the five events with initial water table shallower than 0.5 m and total rainfall more than 46 mm, the runoff were more than 64 % of the rainfall.

All the events were divided into three groups according to initial ground water table depth (storm-runoff events with initial water table shallow than 0.5 m; deeper than 2.3 m and between 0.5 m and 2.1 m). As is clear from Figs. 5 and 6, the catchment behavior changes as the initial ground water table depth. Within the three groups, strong linear rainfall-runoff relationships were found (Fig. 5 and Table 2). The interceptions was negative, implying that runoff was generated after the rainfall reaches a threshold point. At the field and catchment, the thresholds are larger for the group with shallow initial ground water table. For the plot, the interception is much larger than that for the catchment and field, indicating that the threshold is much larger which can be detected by three points with rainfall amounts less than 46 mm in Figs. 5c and 6c. As shown in Table 2, the slope is large when water table is shallow than 0.5 m, and small when water table is deep than 2.3 m, indicating that the rainfall with shallow water table generally producing a greater percentage of runoff.

3.3 Rainfall-runoff relationship at early or later growth stages

Runoff would be influenced by cover crops. It has been founded that surface runoff percentage is greater from crops at the seedling or early growth stage than it is later in the season (Bochet et al., 2006; Jiao et al., 2010). In the study area, the soybean and corn are seeded, and the cotton is transplanted in mid-June, and the early growing stage with small LAI lasts to late-July (Jiao et al., 2009b). Afterward, the canopy cover keeps relatively stable to the mid-September. For the 26 events, 19 occurred at the seedling or early growth stage (before 22 July), and 7 events occurred at the later growth stage (from 2 August to 19 September). The rainfall-runoff relationships at different growth stages were evaluated. Since only two events at the later growth stage were available, the rainfall-runoff relationship at the plot was was not analyzed separately at early and later growth stages. In order to eliminate the influences of initial water table, only the 26 events with initial water table shallower than 2.1 m were evaluated. The rainfall-runoff relationships of the two groups at the catchment and field were shown in Fig. 7. For both the catchment and field, larger runoff was generated at the early growth stage than these at the later growth stage with similar rainfall amounts. The runoff increases faster with rainfall at early growth stage than that at the later growth stage.

4 Discussions

For most of the events, the water table rose a lot, always above 0.5 m after the storm-runoff event except for the seven events with deep initial water table (Table 1). It implies that the soil would be saturated during the storm-runoff events. For the events of each group (Fig. 5), significant rainfall-runoff relationships existed. On the other hand, no obvious correlations were observed between total runoff or runoff coefficient and maximum rainfall intensity or average rainfall intensity at all the three scales. These suggest that saturation-excess surface flow would control the runoff response, while infiltration excess overland flow is generally minor, especially when initial water table is shallow. This finding was confirmed by the hydro-chemical tracing in a previous study (Tan et al., 2008). The hydrological model, which is based on the concept of saturation-excess surface runoff and considers the influences of groundwater table, performs well in this catchment (Wang et al., 2004).

Since only surface flow was observed, the characteristics of the saturation excess flow can be studied through the flow at the plot. When the initial water table is shallower than 0.4–0.5 m, the rising of water table is small, and the difference between rainfall and runoff ($P-R$) is small. It indicates that saturation excess occurs when the water table is less than 0.4–0.5 m. During the events with deep initial ground water table, a significant rise in the groundwater table occurred. This can be seen clearly from the event on 14 July 1997. Rainfall began at 08:51 a.m. LT, and the initial ground water table depth is 0.86 m. Runoff began at around 01:00 a.m. on 15 July, and the ground water table depth rose to 0.31 m at the end of the event. The long response time to rainfall pulses and shallow water table at the end suggest that runoff is also primarily dominated by saturation-excess surface flow.

The runoff can be predicted by the difference of the amount of rainfall minus the initial abstraction i.e. the water that infiltrate before the soil is saturated. The initial abstraction can be detected by changes in water table before and after the rainfall-runoff event. The differences between rainfall and runoff were regressed with the changes in water table at all the three 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 of rainfall and runoff and the initial water table depth were also founded, implying that the total rainfall amount and initial groundwater table depth were the two main factors influencing total runoff amount, and the runoff amounts can be predicted using total rainfall and initial water table depth data.

For all the events, the water table at the end was higher than the bottom of the drainage ditche I (3 m), and higher than the bottom of drainage ditche II (1.3 m) except for the two events occurred in 2 June 2000 and 7 July 2005. When water table is shallower than the bottom of the ditch, lateral subsurface flow would occurr. It would be deduced that groundwater would feed additional water to the ditches, and subsurface flow had a considerable contribution to the total runoff in the study area. At the experimental plot, no drainage ditch and only the surface runoff was collected, whereas both the surface and sub-surface runoff were collected at the field and small catchment. The information of the sub-surface flow of the field can be detected indirectly from the difference between the runoff at the field and the surface flow at the nearby experimental plot. The difference between the total runoff at the field and the experimental plot were plotted against the average water table depth in Fig. 8. When the initial water table is deeper than 1 m, a significant linear relationship between the difference and the average water table depth were found, and the differences decreased with the average water table depth. For the event 2 June 2000 with the water table shallower then the bottom of the ditch during the whole period, the total runoff at the field was even less than that at the plot. It would be deduced that flow exchange processes between the flow in the drainage ditches and the groundwater were influenced by water table. For the events with shallow initial water table all the time, the differences were between

10–50 mm, and there is no significant correlation between the difference and average water table depth. This may result from that the contributions of sub-surface flow to the total runoff were weaker than that of the surface flow. The difference between the total runoff at the catchment and the experimental plot were also plotted against the average water table depth in Fig. 8. Similar relationship was found, but the points are more scatter.

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, we arrive at the following conclusions:

1. The relatively narrow range of rainfall amount resulted in significantly different runoff amounts from the experimental plot, field, and small catchment. Initial groundwater table depth was the main factor influencing rainfall-runoff relationship in the study area. When the initial water table is shallow, large percentage of rainfall were converted to runoff. When the initial water table is deep, the runoff coefficient is small.
2. After the storm-runoff event, the ground water table rose a lot. The difference of rainfall and runoff amounts can be detected by initial water table depth or the changes in water table before and after then rainfall-runoff events. Significant rainfall-runoff relationships were founded for the events of three groups with different water table. These implies that saturation-excess surface flow would control the surface flow response, especially when water table is shallow.
3. Evaluated by the 26 events for both the catchment and field with initial water table shallower than 2.1 m, more runoff were generated at the early growth stage than

these at the later growth stage with similar rainfall amounts. The runoff increases much faster with rainfall at early growth stage than that at the later growth stage.

4. The water table at the end was higher than the bottom of the drainage ditches I (3 m) for all the events, and higher than the bottom of drainage ditches II (1.3 m) except for two events. Subsurface flow had a considerable contribution to the total runoff in the study area. When the initial water table is deeper than 1 m, the difference between stream flow at the field and plot was linear correlated with the average water table depth were found, and the differences increased with the average water table depth implying the increasing contribution of sub-surface flow.

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

No.	Rainfall (mm)	Duration (h)	Max. Rainfall Intensity ($\mathrm{mm\,h^{-1}}$)	Water 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	N/A*
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	36.6	36.2	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	115.7	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	67.2
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	22.8	N/A	N/A
15	65.5	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	N/A	36.0
17	53.0	14.8	11.8	0.70	0.37	18.1	38.7	N/A
18	176.8	31.0	38.7	0.50	0.33	141.1	N/A	N/A
19	35.8	22.5	22.0	0.35	0.35	28.7	N/A	N/A
20	195.3	17.6	37.5	3.08	1.09	48.5	44.0	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	0.271	17.9	N/A	N/A
23	61.7	4.0	71.4	0.65	0.29	46.6	55.2	37.0
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	N/A
26	155.4	39.0	26.4	0.62	0.22	110.2	N/A	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	17.1
30	49.9	17.5	17.2	0.26	N/A	41.5	43.8	N/A

N/A* data is not available.

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Table 2. Summary of linear rainfall-runoff relationships for three categories with different initial ground water table depth.

	Catchment			Field			Plot		
Catogory[*]	A	B	C	A	B	C	A	B	C
Slope	0.946	0.744	0.431	0.966	0.837	0.258	1.050	0.666	0.259
Intercept	−5.716	−13.152	−35.068	−0.540	−7.334	−9.841	−31.906	−24.781	−19.991
R^2	0.977	0.791	0.963	0.997	0.783	0.548	0.966	0.905	0.889

[*] Events were divided into three catogories according to initial ground water table: A shallower than 0.5 m, B: between 0.5 m and 2.3 m, C: deeper than 2.3 m.

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

	($P - R$) vs. initial water table depth			($P - R$) vs. changes in water table		
	Catchment	Field	Plot	Catchment	Field	Plot
Slope	33.685	36.066	31.718	53.863	56.581	51.317
Intercept	1.715	−11.583	17.829	6.545	−8.105	21.073
R^2	0.727	0.763	0.72	0.682	0.737	0.747

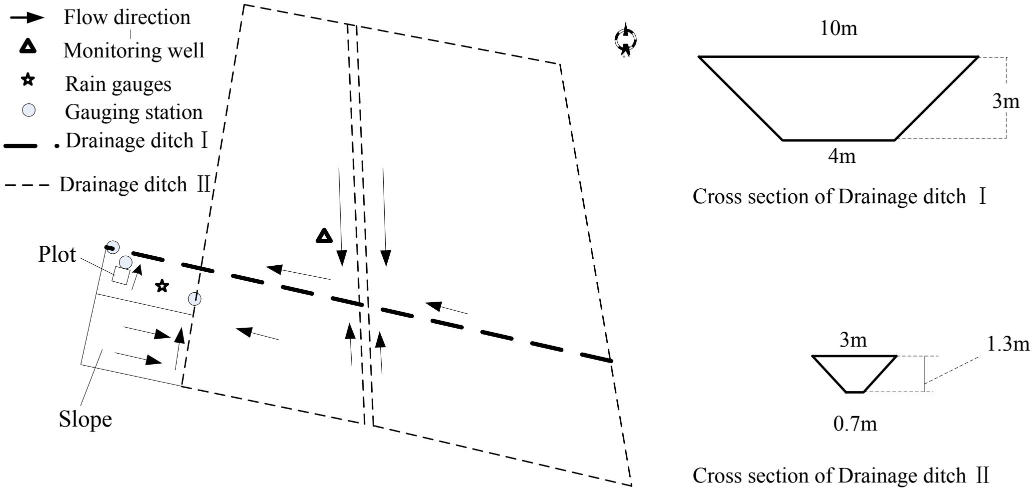

Fig. 1. Sketch map of the experimental catchment.

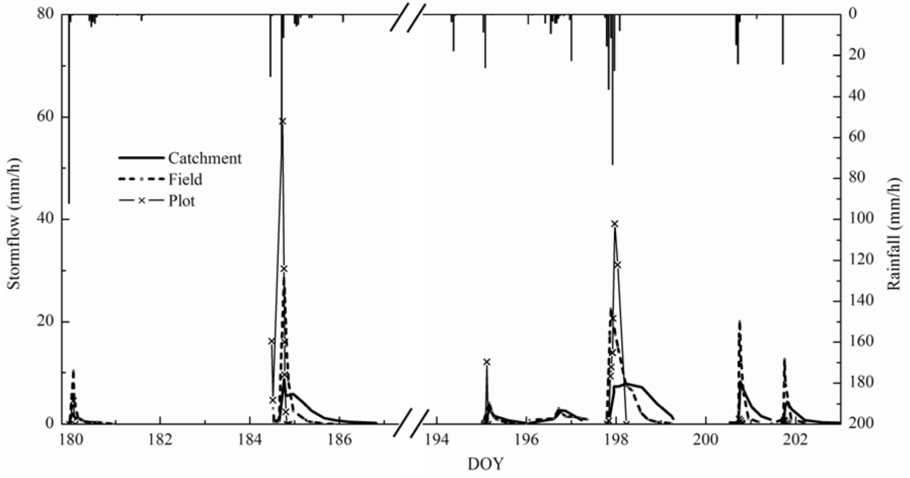

Fig. 2. Typical storm-runoff events from 29 June to 21 July 1997.

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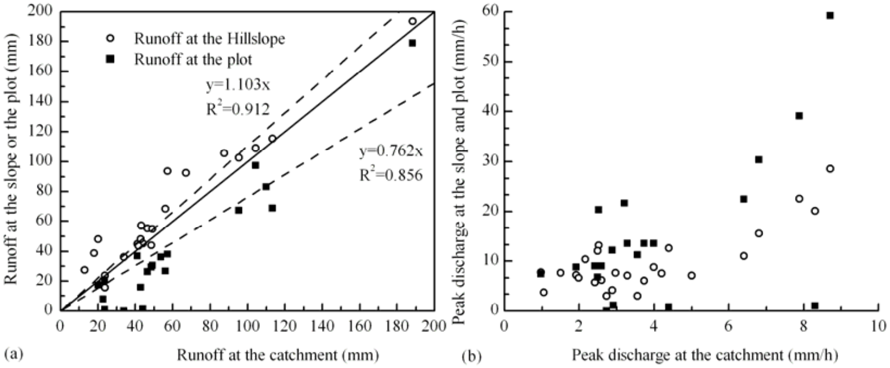

Fig. 3. Plots of **(a)** runoff and **(b)** peak discharge at the field and plot with respect to that at the small catchment for the storm events.

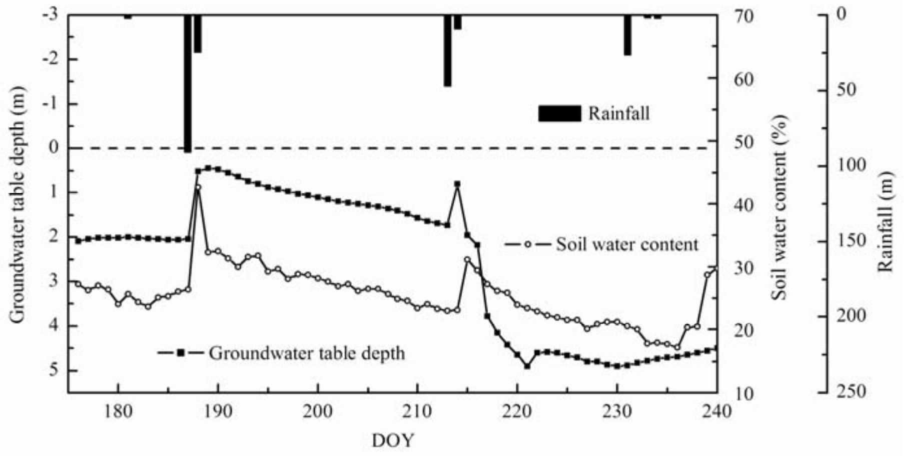

Fig. 4. Averaged daily groundwater table depth and precipitation from DOY 175–240, 1999.

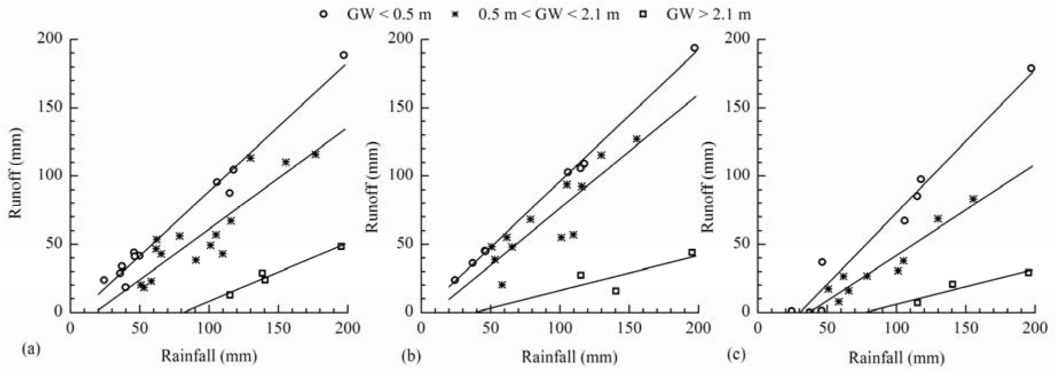

Fig. 5. Plots of rainfall-runoff relationships for the storm events **(a)** at the small catchment and field scales, **(b)** at the field scale, and **(c)** at the experimental plot scale.

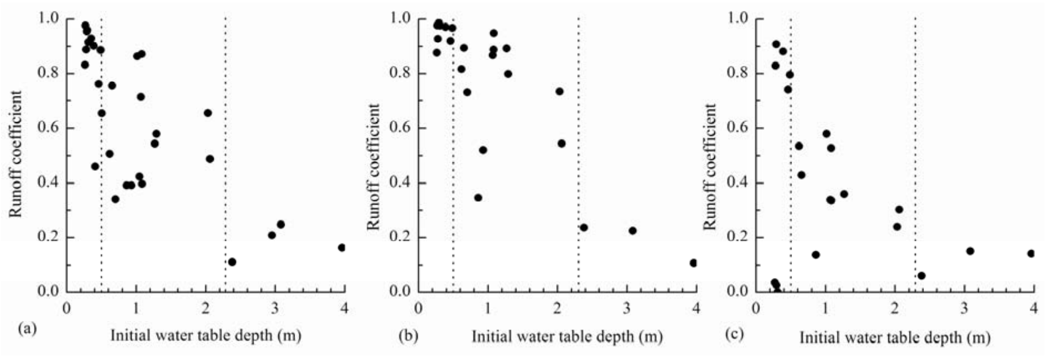

Fig. 6. Plots of runoff coefficient with initial water table depth for the storm events **(a)** at the small catchment, **(b)** field and **(c)** plot scales.

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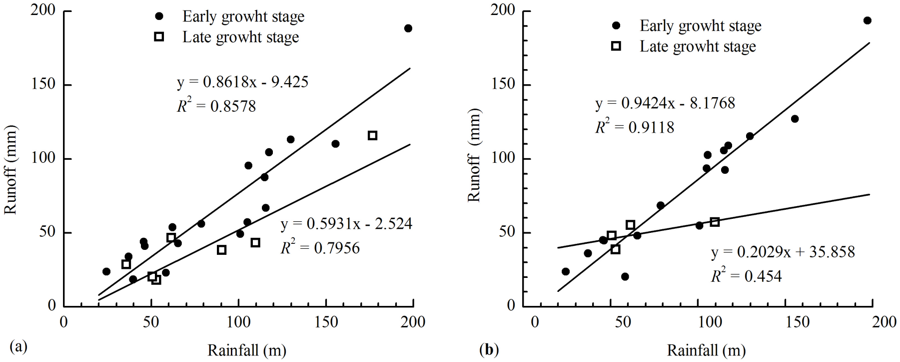

Fig. 7. Plots of rainfall-runoff relationship for the storm events with water table shallower than 2.1 m at the early and later growth stages **(a)** at the small catchment, **(b)** at the field.

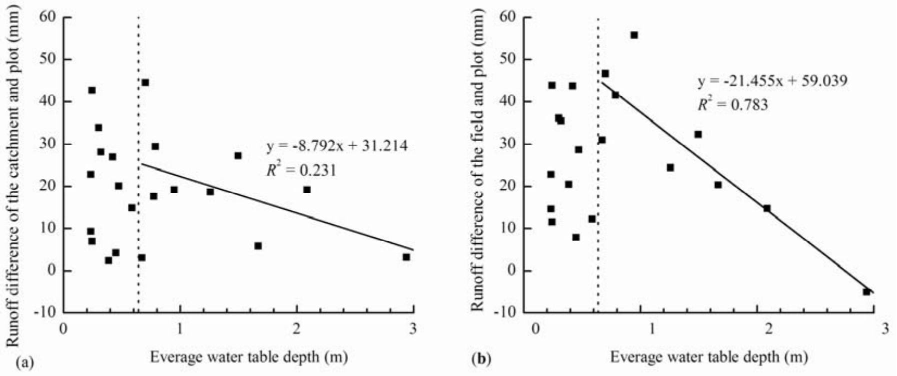

Fig. 8. Plots of runoff differences at the **(a)** catchment, **(b)** field and plot vs. average water table depth before and after the rainfall-runoff events.