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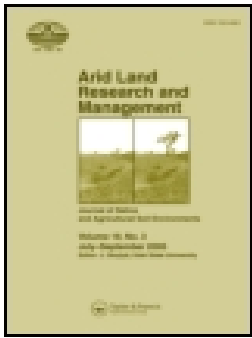
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Infiltration-excess runoff properties of dryland floodplain soil types under simulated rainfall conditions

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ABSTRACT

The study estimated infiltration-excess runoff properties of three floodplain soil-types under aquifer water management at Anglo American Kolomela Iron Ore mine in Postmasburg, Northern Cape Province of South Africa. Rainstorm regimes of amounts 60 (high), 30 (medium), and 15 (low) mm with respective intensities of 1.61, 0.52, and 0.27 mm min⁻¹ were simulated on 1 m² plot with 1% slope. Infiltration-excess runoff properties were affected by a rainstorm, but not soil-type. When combined with rainstorm, soil-type affected accumulative run-off rates. High rainstorm had different ($p \leq 0.05$) accumulative runoff rates (0.1–0.61 mm min⁻¹) and increased with clay content. Different response times of 4, 10, and 17 min for respective high, medium, and low rainstorms were quickest on higher clay plus silt content and bulk-density under high and lower rainstorms, respectively. Lower rainstorms had similar effects on accumulative runoff rates (0.01–0.05 mm min⁻¹), total runoff yield (0.59–18 mm), and runoff coefficients (4.29–18%). Under the high rainstorm, total runoff yields (11.4–25.8 mm) and runoff coefficients (19–42.9%) were different and increased with clay plus fine-silt content. Although simulated rainstorms had constant intensities, results showed high rainstorms to be of primal influence on infiltration-excess runoff. Clay plus silt content and bulk-density influenced infiltration-runoff properties for respective high and lower rainstorms. Apart from rainstorm characteristics, surface clay plus silt content and bulk-density are important for harnessing surface runoff in floodplains for aquifer recharge.

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Bulk-density; clay plus silt; infiltration-excess runoff; rain-drop impact rainstorm regimes

Introduction

The low and erratic nature of rainfall in arid drylands makes infiltration-excess runoff an important component of the water balance. During isolated heavy rainstorms, infiltration-excess run-off facilitates downslope distribution of precipitation and water resource recharge. Dryland floodplains are important in this respect because they serve as zones of surface runoff distribution and groundwater recharge. Knowledge of infiltration-excess runoff properties of dryland floodplains is, therefore, essential for sustainable

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management of related water resources. However, characterization of floodplains runoff properties can be a challenge in surface conditions with small-scale differences in land use, topography, and soil properties.

Lack of information about Southern African dryland floodplains runoff properties could be attributed to a number of factors. One key factor is lack of comprehensive research because rainfalls are low, spatial, and random and are seldom widespread (Knighton and Nanson 2001). Another factor is the remoteness and irregular geometry of dryland floodplains with some segments several kilometers wide, making frequent visits and surveys impractical (Costelloe et al. 2003). Low population and seasonal dependence of human activity on rain and flood events also contribute to insufficient knowledge about dryland floodplains. Tooth (2000) also raised concern that there is a paucity of long-term data for most Southern African dryland floodplains. Data from monitoring stations would provide valuable insight into runoff distribution patterns and characteristics. Availability of such data would also provide useful inferences about infiltration-runoff relationships of floodplains under different rainstorm events.

In the absence of floodplains runoff data, plot-scale studies have provided an alternative approach for physical environmental research. Plot-scale studies allow complete control of experimental conditions and provide clear insight about the basic actions and reactions of open system processes (Wainwright, Parsons, and Abrahams 2000). Apart from having limited scale-boundary conditions, plot experiments have found wide application in rainfall-runoff studies. These studies included amongst others, investigation on tillage practices (Mzezewa and van Rensburg 2011), soil surface properties (Bothma, van Rensburg, and Le Roux 2012), and hillslope erosion (Xu et al. 2013). Rainfall simulation has become an integral part of rainfall related studies in small plots (Wainwright, Parsons, and Abrahams 2000). Reliable rainfall simulation requires adequate representation of a natural rainstorm event or process. Spatial and temporal variability of rainstorms with respect to intensity, amount, raindrop size, and frequency usually pose as a challenge in producing reliable simulations. For practical purposes, rainfall simulation studies have often used simplified assumptions and conceptual models that narrow the focus of the parameters or processes under investigation (Wainwright, Parsons, and Abrahams 2000).

In natural ecosystems like floodplains, isolating primal variables and determining infiltration-excess runoff is not a straightforward process. Apart from rainfall characteristics, surface conditions and soil type influence near-surface infiltration-runoff properties (Lange et al. 2003; Mayor, Bautista, and Bellot 2009; Huang, Wu, and Zhao 2013). Surface conditions embrace factors like vegetation, bareness, roughness, stoniness, crust cover, slope gradient, and so on (Mayor, Bautista, and Bellot 2009) and influence surface storage and time to runoff (Bothma, van Rensburg, and Le Roux 2012). Soil texture and structure are main factors of soil type, which control soil surface permeability and hydraulic conductivity (Ben-Hur et al. 1985; Scherrer et al. 2007). Surface conditions and near-surface soil properties are always changing, thus their dynamic behavior can be better-understood *in situ* (Wainwright, Parsons, and Abrahams 2000).

Other soil related factors include soil depth, soil profile layers, wetness, compaction, and surface crusting tendencies (Scherrer et al. 2007; Mayor, Bautista, and Bellot 2009; Huang, Wu, and Zhao 2013). Compaction and crusting are of importance in arid

drylands because soil surfaces are usually bare and sparsely covered with vegetation. Bare soil patches are usually compacted and crusted, functioning as sources of runoff while, on the other hand, vegetation patches function as runoff sinks (Mayor, Bautista, and Bellot 2009). Surface crusting is associated with high clay plus fine silt deposits common on floodplains (Knighton and Nanson 1994; Dahan et al. 2007; Morin et al. 2009). Crusted soil surfaces could have infiltration 2000 times lower than underlying soil layers (Huang, Wu, and Zhao 2013). However, high-intensity rainstorms can erode surface crusts and seals (Tooth 2000; Bothma, van Rensburg, and Le Roux 2012). The depth of water table and frequency of major flood events also have bearing on the long-term infiltration-excess runoff characteristics of floodplains and ephemeral rivers (Knighton and Nanson 1994; Costelloe et al. 2003; Morin et al. 2009).

In this study, infiltration-excess runoff under different rainstorm intensities and amounts was simulated on an arid dryland floodplain under aquifer recharge water management. The aim was to understand the floodplain surface-runoff distribution characteristics in order to develop conceptual ideas on improving water-resource capture in dryland floodplains. An aquifer recharge program was established in the iron-ore mining town of Postmasburg in 2013 (Kumba Iron Ore 2013) and involved dewatering of open cast mining pits and pumping water into alluvial aquifer boreholes distributed along the dryland floodplain (Figure 1). Although the long-term response of groundwater levels from this initiative is yet to be determined, integrating other surface water harvesting technologies can be useful, given the growing challenges of climate change (Gregory, Ingram, and Brklacich 2005). Infiltration-excess runoff is an important aspect of water-resource capture and depends on near-surface soil physical properties such as texture, bulk density, and porosity. These physical properties on dryland floodplains are highly affected by colluviation and sedimentation, which are in turn, influenced by fluvial processes, geometry, and topography. Soil types associated with



Figure 1. Borehole infrastructure of the aquifer recharge program at the Postmasburg dryland floodplain.

periodic slow moving water or ponding and fast running water are affected by fluvial deposits of fine and coarse grained sediments, respectively. In this study, the hypothesis was that infiltration-excess runoff properties of dryland floodplains were affected by soil-type and rainstorm characteristics. The study-specific objective was, therefore, to estimate infiltration-excess runoff properties of dryland floodplains as affected by soil type and simulated rainfall regimes.

Material and methods

Experimental site

The study was carried out in 2014 on the dryland floodplains of the Kolomela Iron Ore mine situated 30 km south of the town of Postmasburg (Figure 2(A)). Three experimental sites were selected inside the floodplain, corresponding to three dominant soil types observed during a field survey.

Long-term rainfall data constituting monthly maximum, minimum, and averages over a 98-year period for the Postmasburg area is summarized in Table 1. A profile of rainstorms was not available. The wettest months are January to March and the driest months are June to August. Rainfalls of 130 mm and 104.5 mm for February and January, respectively, were the highest recorded rainstorms over the 98-year period. Given that the study was carried out in October before the wettest months, most of the vegetation of tussock grasses and short shrubs were withered and dormant (Figure 2(C)).

Floodplain soil types

The three dominant soil types were Addo, Augrabies, and Brandvlei according to the South African Soil Classification Working Group (1991). These soil types are also respectively referred to as Greysols, Ferralsols, and Cambisols by the IUSS Working Group WRB (2007). The FAO world reference base (1998) for soil resources generally refers to floodplain soil types as fluvisols.

The soil types were characterized from individual soil profiles. Disturbed and undisturbed core soil samples were taken from each horizon. Disturbed soil samples were subjected to chemical and textural analysis. The samples were oven dried at 105 °C for 24 hours and particle size distribution determined using the pipette procedure proposed by the Non Affiliated Soil Analysis Work Committee (1990). Core soil samples with an inner diameter of 103 mm and a height of 77 mm were used to calculate bulk density. Double ring infiltrometer experiments were conducted using the falling head method (Jury, Gardener, and Gardener 1991) to calculate saturated hydraulic conductivity (K_s , mm hour⁻¹). Soil profiles were excavated in a stepwise manner to allow the fitting of both rings with diameters of 400 and 600 mm to a depth of 200 mm. A summary of physical and chemical properties of the soil types is presented in Table 2.

The Addo soil type occupied a central position in the floodplain at an altitude of 1252 m (Figure 2(B)). Its soil profile was characterized by dry, friable, non-sticky calcareous apedal fine loamy sand. A dry white powdery apedal horizon was associated with the underlying horizon. Diagnosed horizons were the Orthic A (–250 mm),

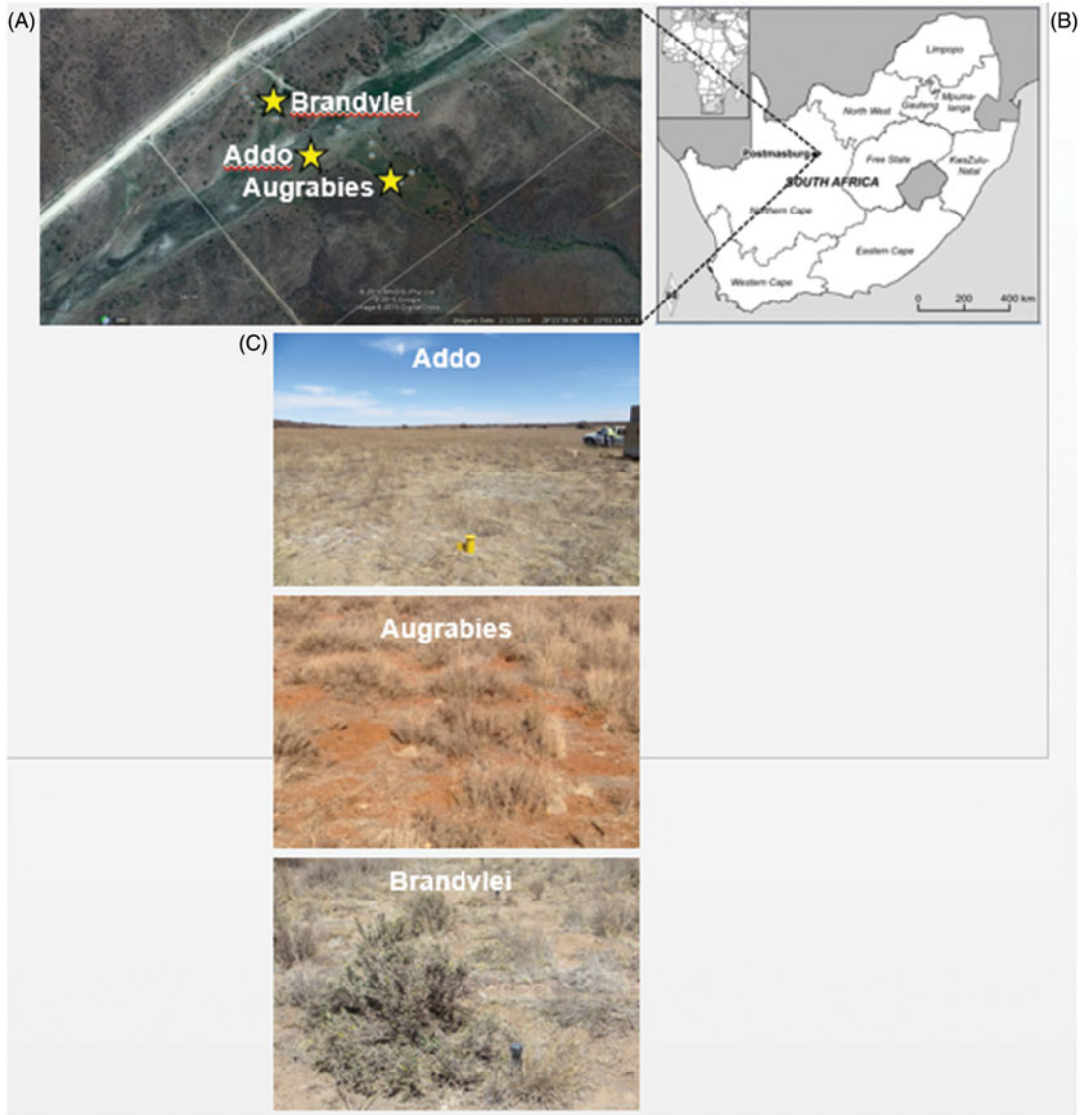


Figure 2. A location map of Postmasburg town, Northern Cape Province, South Africa (A), aerial photograph of the floodplain (B) and the vegetative cover of the Addo, Augrabies and Brandvlei soil forms at the experimental sites (C).

Table 1. Long-term (98 years) mean monthly rainfall (mm) for the Postmasburg area.

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
Min	0.2	0.1	0.2	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2
Max	104.5	130	77.5	69.6	46.2	39.5	31	34	39.5	66.5	66	69
Mean	9.6	12.3	10.7	9.0	7.0	5.7	5.3	5.1	6.2	8.0	8.7	9.4

Table 2. Summary of the physical and chemical properties of flood plain soil types.

Soil Characteristics	Soil types and master horizons								
	Addo			Augrabies			Brandvlei		
	A	B1	C	A	B1	B2	A	B1	C
Physical properties									
Coarse sand (%)	1.68	1.0	1.7	12.4	14.0	16.1	1.9	0.9	0.9
Medium sand (%)	2.42	2.1	3.0	3.6	3.9	3.1	1.8	1.4	1.7
Fine sand (%)	14.4	19.4	19.9	40	45.5	43.0	55.0	51.1	56.6
Very fine sand (%)	19.1	18.9	18.0	16.4	11.1	16.2	20.7	22.1	19.5
Coarse silt (%)	13.6	12.4	12.3	7.6	6.4	5.7	3.0	5.0	3.0
Fine silt (%)	23.6	19.7	18.8	6.0	4.8	5.7	2.6	6.3	5.5
Clay (%)	24.1	25.0	26.0	14.6	15.8	11.7	15.1	13.5	12.8
K_s (mm min ⁻¹)	0.06	0.05	0.05	1.67	2.0	2.5	1.54	2.0	2.5
Bulk density (g cm ³)	1.52	1.52	1.48	1.76	1.73	1.66	1.69	1.59	1.53
Exchangeable cations									
Calcium (cmol + kg ⁻¹)	38.26	25.45	24.25	8.94	7.83	5.27	31.6	31.2	14.75
Magnesium (cmol + kg ⁻¹)	11.17	14.25	13.33	2.54	2.90	6.83	5.83	7.67	12.07
Potassium (cmol + kg ⁻¹)	0.80	0.54	0.40	0.84	0.45	0.53	0.48	0.62	0.72
Sodium (cmol + kg ⁻¹)	0.26	0.18	0.20	0.08	0.08	0.09	0.11	0.13	0.44

Neocarbonate B (−550 mm), and soft carbonate C (−1500 mm). Vegetation in the Addo soil type included sparsely distributed tussock grasses and plants with needle-like stems. Ground vegetation cover per 1 m² area was estimated to be 50% (Figure 2(C)). The Augrabies soil type was located at an altitude of 1260 m (Figure 2(B)) and had a soil profile characterized by a dry reddish brown apedal with soft, friable and non-sticky calcareous fine loamy sand. Diagnosed horizons were the Orthic A (−250 mm), Neocarbonate B1 (−800 mm), and B2 (−1500 mm). Corresponding vegetation were clusters of tussock grasses and short thick shrubs with conspicuous bare patches (Figures 2(C) and 3). The Brandvlei soil type was found at an altitude of 1252 m (Figure 2(b)). A dry white apedal horizon was observed in the Orthic A (−250 mm) while a dry powdery white apedal horizon was associated with the Neocarbonate B horizon (−1500 mm). Vegetation was typical of thick tussock grasses alongside thorny plants with an estimated 70% vegetation cover for the Augrabies soil type (Figure 2(C)).

The Hofrey rainfall simulator

Runoff properties of the different soil types were studied under different rainfall intensities using a mobile field rainfall simulator (Figure 3). The mobile simulator constitutes a closed compartment with a height adjustable oscillating sprinkler nozzle (Figure 3(A)). Water pump, pressure gauges, and timer control are also fitted to the simulator. Inside the closed compartment, there is a metal runoff frame of 1 m × 1 m area that can be inserted at 10 cm soil depth. A gutter is fitted on the downslope side of the frame and connects with an outlet pipe for runoff collection (Figure 3(B)). Although literature has shown that runoff and streamflow controlling factors are highly variable and scale-dependent (Wainwright, Parsons, and Abrahams 2000), valuable insight on catchments and hill slopes runoff generation properties has been provided by plot scale studies (Lange et al. 2003; Scherrer et al. 2007; Truman et al. 2007; Zhao et al. 2013).



Figure 3. Hofrey rainfall simulator (A) being mounted on the experimental plot (B) fitted with a $1\text{m} \times 1\text{m}$ metal frame and surface runoff collecting pipe (C).

Selection of rainfall intensities and amounts

Three rainstorms with different intensities and amounts were studied. The three rainfall intensity treatments were 0.27 (low), 0.52 (medium), and 1.61 (high) mm min^{-1} . Selected rainfall intensities were determined within the efficient operation range of the mobile simulator. During the calibration process, intensities higher than 1.61 mm min^{-1} or 80 mm hr^{-1} and lower than 0.27 mm min^{-1} or 16 mm hr^{-1} were marked with many discharge irregularities and inconsistencies. Mechanical and automation difficulties that the mobile simulator had at the time of this study, limited this research to constant rainstorm intensities even though natural rainstorms exhibited high temporal variability (Wainwright, Parsons, and Abrahams 2000). Despite constant intensities not representative of the area's rainstorms, the selected intensities of 0.27 , 0.52 , and 1.61 mm min^{-1} were selected using long-term data approximated to have recurrence intervals of 2, 5, and 10 years, respectively (Walker and Tsubo 2003). Rainstorm intensities in increasing

order had simulated times of 56, 50, and 45 minutes to obtain corresponding accumulative amounts of 15, 30, and 60 mm. The low rainstorm regime represented more than 75% of the rainfalls in the area, with average rainfall below 20 mm that usually evaporates before any meaningful contribution to soil water storage and vegetation growth (Moeletsi, Walker, and Landman 2011). The medium and high rainstorm regimes represented the few rainfall events, which contributed to the annual rainfall. The assumption was that rainstorm simulation period and amount was sufficient to affect infiltration-excess runoff generation on all soil types. Another assumption was surface storage by ponding, soil erosion by rills was negligible, and runoff ceased at the same time as the rainstorm simulation. To ensure that the correct rainfall amount was applied for a particular intensity, a time-based calibrated automated rain gauge was placed inside the simulation plot.

Rainfall simulations and measurements

Three experimental plots per soil type were prepared by inserting the simulator's 1 m × 1 m metal frame at a depth of 10 cm, each on a 1% slope. On the downsloping side of the metal frame, the gutter was mounted to a central draining opening. A 40 mm runoff pipe was attached to the drainage outlet for collecting surface runoff into a container placed below ground level. Installation of the metal frame was carried with caution to minimize disturbance of natural soil surface conditions and vegetation inside plots (Figure 3(C)).

In the center of each plot, a 1 m long DFM Continuous Logging Soil Moisture Probe was installed to a depth of 1 m. The water sensors on the probe were installed such that they were located at 5 cm, 25 cm, 45 cm, 65 cm, and 85 cm soil depths. The probes were programmed to measure soil water content at minute intervals during rainstorm simulations. In this regard, antecedent soil water-content and final soil water-content was obtained. Gravimetric soil water content and bulk density values were used to calibrate water sensors of the probe. Time from the onset to end of rainstorm simulations was recorded along with time to runoff and accumulative runoff amounts after every 5 min intervals. Runoff amount or yield was measured using a measuring cylinder (ml) and volume collected was converted into mm using the factor 10 (Equation 1).

Data analysis

Raw data measured during rainstorm simulation and collection of runoff was processed to estimate total runoff yield (mm) and accumulative runoff rate (mm min⁻¹) from the 1 m² plot. Runoff coefficient (%) was also determined by the ratio of total runoff yield (mm) to total simulated rainstorm amount. Runoff rate (R_r) in mm min⁻¹ was calculated using the expression (Zhao et al. 2013):

$$R_r = \frac{v \times 10}{c \times t} \quad (1)$$

Where v is runoff volume (ml), 10 is the unit converting coefficient, c is simulated plot area in cm², t is the runoff time (min). Average infiltration rate (I_{av} , mm min⁻¹) was estimated from residual between total rainfall (P , mm) and runoff (R , mm) over

Table 3. A summary of analysis of variance of runoff parameters as affected by floodplain soil types (ST) for simulated rainstorms (SR).

Runoff parameters	Factors	End of rainfall simulation
Time to runoff (min)	ST	ns
	SR	*
	ST × SR	ns
Accumulated runoff rate (mm min ⁻¹)	ST	ns
	SR	*
	ST × SR	*
Total runoff yield (mm)	ST	ns
	SR	*
	ST × SR	ns
Runoff coefficient (%)	ST	ns
	SR	*
	ST × SR	ns

*=significant at $p \leq 0.05$; ns = not significant.

the actual simulation time (t , min) expressed in Equation 2:

$$I_{av} = \frac{(P-R)}{t} \quad (2)$$

The field experiment comprised three floodplain soil types each subjected to three rainstorm sizes (intensities with fixed amounts) with three replications, thus giving 27 rainfall simulations. A one-way analysis of variance (ANOVA) was used to determine the effect of dryland floodplain soil types and rainstorm treatments on infiltration excess runoff properties. All possible soil-types and rainstorm treatment combinations were paired and Duncan's Multiple-Range Test (DMRT) (Gomez and Gomez 1984) was used to evaluate means at 5% level of significance. Means with computed differences smaller than the largest shortest significant range (R_p) were not significantly different from each other (Gomez and Gomez 1984). Means that were not similar were marked using different superscript symbols.

Results and discussions

Infiltration-excess runoff parameters including time to runoff, accumulative runoff rate, and total runoff yield as well as runoff coefficient were studied using 1 m² plot of rainfall-simulation on three floodplains soil types. A summary of how runoff parameters were affected by the three simulated rainfall regimes of respective intensity and amounts, high (1.61 mm min⁻¹, 60 mm), medium (0.52 mm min⁻¹, 30 mm) and low (0.27 mm min⁻¹, 15 mm) and soil type is presented in Table 3. Runoff parameters were significantly affected ($p \leq 0.05$) by rainfall regime, but not soil type. In all instances, runoff parameters were significantly different ($p \leq 0.05$) on the Duncan Multiple Range Test (DMRT) with high rainfall and similar with medium and low rainfalls (Table 4). Time to runoff was the exception and showed significant differences for all rainfall regimes (Figure 4). Soil type affected accumulative runoff rate through an interaction effect with rainfall regime, especially for the lower rainstorms (Figure 5). While soil types accumulative runoff rate was significantly different for the high rainfall, it was similar for all rainfall regimes in the Augrabies soil type. Mean runoff coefficient was affected differently and similarly by the respective high and lower rainfall regimes and indifferently by medium rainfall in the Augrabies soil type (Figure 6). Irrespective of

Table 4. Runoff properties of three floodplain soil-types under different rainstorm regimes.

Runoff characteristics	Soil type	Rainstorm regimes		
		High	Medium	Low
	Addo			
Rainstorm intensity (mm min ⁻¹)		1.61	0.52	0.27
Applied amount (mm)		60	30	15
Time to runoff (min)		4 ^c	11 ^b	22 ^a
Accumulated runoff rate (mm min ⁻¹)		0.61 ^a	0.03 ^b	0.01 ^b
Total runoff yield (mm)		25.77 ^a	3.14 ^b	0.59 ^b
Runoff coefficient (%)		42.92 ^a	10.47 ^b	4.29 ^b
Average infiltration rate (mm min ⁻¹)		0.92	0.47	0.26
	Augrabies			
Rainstorm intensity (mm min ⁻¹)		1.61	0.52	0.27
Applied amount (mm)		60	30	15
Time to runoff (min)		4 ^c	9.3 ^b	18.67 ^a
Accumulated runoff rate (mm min ⁻¹)		0.1 ^a	0.05 ^b	0.02 ^b
Total runoff yield (mm)		20.12 ^a	5.48 ^b	0.83 ^b
Runoff coefficient (%)		32.51 ^a	17.98 ^{ab}	5.56 ^b
Average infiltration rate (mm min ⁻¹)		0.91	0.43	0.28
	Brandvlei			
Rainstorm intensity (mm min ⁻¹)		1.61	0.52	0.27
Applied amount (mm)		60	30	15
Time to runoff (min)		4.33 ^c	11.67 ^b	19.67 ^a
Accumulated runoff rate (mm min ⁻¹)		0.18 ^a	0.02 ^b	0.01 ^b
Total runoff yield (mm)		11.42 ^a	1.97 ^b	0.70 ^b
Runoff coefficient (%)		19.03 ^a	6.56 ^b	4.68 ^b
Average infiltration rate (mm min ⁻¹)		1.17	0.52	0.27
Treatment interaction	Soil type			
		High	Medium	Low
Rainstorm intensity (mm min ⁻¹)		1.61	0.52	0.27
	Addo	0.61 ^a	0.03 ^c	0.01 ^c
	Augrabies	0.1 ^c	0.05 ^c	0.02 ^c
	Brandvlei	0.18 ^b	0.02 ^c	0.01 ^c

Row means followed by different superscript letters indicate DMRT significant difference at $p \leq 0.05$. Mean pairs from treatment interaction was compared using computed shortest significant ranges (R_p) from 0.011 to 0.012 mm min⁻¹.

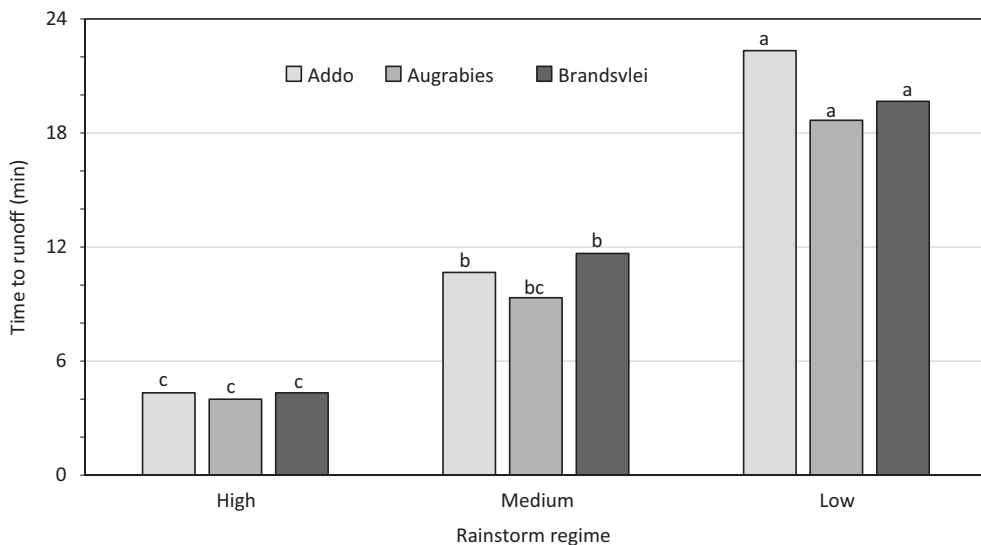


Figure 4. Mean time to runoff (min) of floodplain soil types for the high, medium, and low rainstorm regimes. Means followed by different letters indicate DMRT significant difference at $p \leq 0.05$ and computed shortest significant ranges (R_p) from 6.12 to 6.43 min.

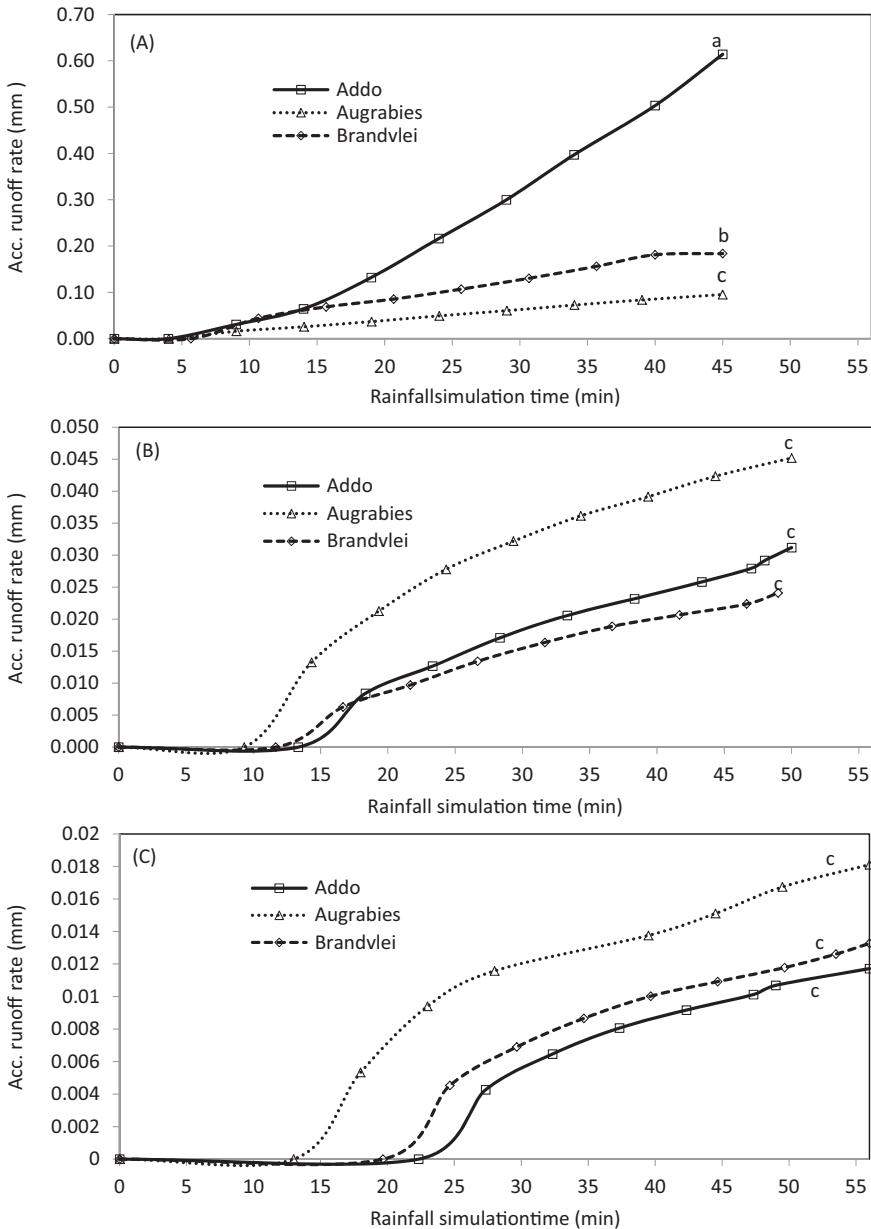


Figure 5. Mean accumulated (Acc.) runoff rates of floodplain soil types during rainstorm simulations of high (A), medium (B), and low (C) regimes. Means followed by different letters indicate DMRT significant difference at $p \leq 0.05$ and computed shortest significant ranges (R_p) from 0.011 to 0.012 mm min⁻¹.

soil type, the high rainfall regime had an average mean time to runoff of 4 min, accumulative runoff rates ranging from 0.61 to 0.1 mm min⁻¹, mean runoff coefficient of 43–19% and mean total runoff of 26–19 mm. The mean antecedent soil water content (ASWC) and infiltrated soil water content (ISWC) are presented in Table 5 illustrating the significant effect of the higher rainfall on soil-types infiltration-excess runoff

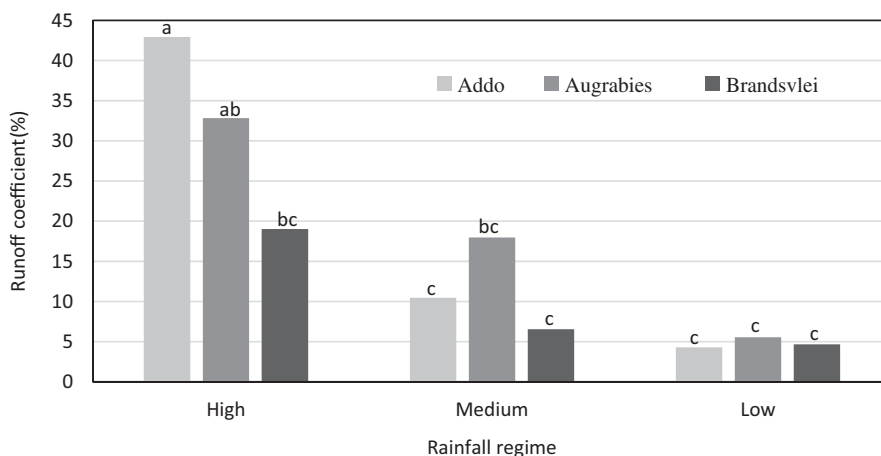


Figure 6. Mean runoff coefficient (%) of floodplain soil types for the high, medium, and low rain-storm regimes. Means followed by different letters indicate Duncan Multiple Range Test significant difference at $p \leq 0.05$ and computed shortest significant ranges (R_p) from 16.51 to 17.34%.

Table 5. Mean^a antecedent (A) and infiltrated (I) soil-water content (SWC) (mm mm^{-1}) of simulated rainstorms for the Addo, Augrabies, and Brandsvlei soil types.

Soil water sensor depth (mm)	Antecedent and infiltrated soil water content (mm mm^{-1})					
	Low		Medium		High	
	ASWC	ISWC	ASWC	ISWC	ASWC	ISWC
Addo type						
50	0.25	0.13 ^d	0.26	0.13 ^d	0.26	0.15 ^{cd}
250	0.27	0.01	0.30	0.01	0.29	0.06
450	0.29	0.00	0.29	0.00	0.28	0.01
650	0.28	0.00	0.29	0.00	0.27	0.00
850	0.25	0.00	0.24	0.02	0.25	0.00
Augrabies soil type						
50	0.06	0.13 ^d	0.17	0.32 ^a	0.18	0.38 ^a
250	0.08	0.00	0.10	0.24	0.20	0.18
450	0.09	0.00	0.13	0.00	0.19	0.01
650	0.11	0.00	0.17	0.00	0.16	0.00
850	0.15	0.00	0.10	0.00	0.20	0.00
Brandsvlei soil type						
50	0.01	0.26 ^c	0.02	0.29 ^{cb}	0.08	0.30 ^b
250	0.09	0.02	0.09	0.03	0.07	0.07
450	0.13	0.00	0.07	0.00	0.10	0.00
650	0.14	0.00	0.15	0.00	0.06	0.00
850	0.16	0.00	0.08	0.00	0.02	0.00

^aAverage of three simulated rainstorms, each replicated three times. ASWC: antecedent soil water content; ISWC: infiltrated soil water content. Mean pairs from ISWC compared using DMRT computed shortest significant ranges (R_p) from 0.08 to 0.09 mm mm^{-1} at $p \leq 0.05$.

properties. The Augrabies and Brandsvlei soil types recorded respective first and second highest ISWC while significantly lower ISWC for all rainfall treatments were from the Addo soil-type.

Lack of statistical differences ($p \leq 0.05$) among runoff parameters from soil types was unexpected although not surprising, given that little is known about floodplain soil type

runoff characteristics. Literature has shown that floodplain soil types with gravel and coarse sand sediments near the surface produce high infiltration and low runoff and the opposite is observed from surface horizons with high clay and silt sediments (Tooth 2000; Costelloe et al. 2003; Morin et al. 2009). The Addo surface horizon had the highest clay plus fine silt content (48%) and lowest bulk density (1.52 g cm^{-3}). The Brandvlei surface horizon had highest very fine plus fine sand (76%) and lowest clay plus fine silt (18%) fractions. The Augrabies surface horizon had highest coarse plus medium sand fraction (16%) and bulk density (1.76 g cm^{-3}). Despite this variability in surface texture composition, particle analysis (Table 2) showed that at least 41% of mineral fractions could not pass the 0.05 mm sieve. This suggested that soil surface horizons were highly affected by clay plus silt fluvial sediment deposits, a phenomenon supported by the nearly level slope of the dryland floodplain. During a rainstorm, particle sizes of less than 0.05 mm readily clog and seal conducting pores forming a surface crust that supports infiltration-excess runoff generation (Scherrer et al. 2007; Mayor, Bautista, and Bellot 2009; Humann et al. 2011). The prevalence of finer sediments explains the lack of significant differences in soil types infiltration-excess runoff properties.

Apart from the higher fine sediment fraction, other infiltration-runoff factors modulated the impact of soil type heterogeneity on runoff parameters. One of such factor was the 1% slope gradient of the experimental plots. Low-slope gradients are associated with increased surface storage and reduced runoff rates (Huang, Wu, and Zhao 2013); a phenomenon that is likely to have homogenized the threshold values of runoff and infiltration rates of the floodplain soil types (Lange, Liebundgut, and Schick 2000; Nicolau 2002). Another critical factor is the prevalence of crusted surfaces in most floodplain soil types as a result of fine-textured sediment deposits from a previous rainstorm or flood events. Saturated hydraulic conductivity for surface horizons were 0.06, 1.54, and 1.67 mm min^{-1} for the respective Addo, Brandvlei, and Augrabies soil types. However, differences in K_s values could not be proven, because of finer sediments clogging hydraulic active pores forming a surface crust (Lange 2005). Another factor that modulated the effect of soil type was the very low ($0.01\text{--}0.3 \text{ mm mm}^{-1}$) antecedent soil water content (Table 5) that prevailed in October. Lower antecedent soil-water content supports infiltrability at the expense of runoff (Bothma, van Rensburg, and Le Roux 2012). In addition, most vegetation in the floodplain was withered and dormant, which provided surface conditions favoring infiltration-excess runoff. Dormant vegetation produces dead foliage, which falls to the ground and the organic material can alter surface roughness and runoff generation potential (Kirkby, Bracken, and Reaney 2002). The less than expected impact of soil-types on runoff could have been attributed to similarities in surface horizon conditions instead of pedo-physical characteristics such as soil profile depth or horizons.

Floodplains' runoff parameters

Time to runoff

Time to runoff is a parameter that is directly related to rainfall intensity and surface conditions. Surface conditions include elements that delay the onset of runoff such as above ground interception on the vegetal canopy, soil surface interception on litter, and

surface depression storage as well as soil water storage (Kirkby, Bracken, and Reaney 2002). High, medium, and low rainstorm regimes produced significantly different ($DMRT_{.05}$) time to runoff responses with corresponding average mean times of 4, 11, and 20 min, respectively (Table 4 and Figure 4). This result was expected given that time to runoff responses was consistent with rainstorm intensity and amounts. Runoff response times as fast as 3 min after the onset of rainfall was observed from a soil type with high silt and fine sand contents (Nicolau, 2002). Interestingly, response times from the high rainfall regime showed little variation among soil types suggesting that its intensity was of high magnitude. High-intensity rainstorms often exceed surface water storage and infiltration capacity of most unsaturated soils resulting in shorter runoff times (Lange, Liebundgut, and Schick 2000; Mzezewa and van Rensburg 2011; Zhao et al. 2013; Zhang et al. 2014).

In all rainstorms, the Augrabies soil type recorded quickest times to runoff followed by Addo and then Brandvlei soil types. Despite the early response times to runoff, the Augrabies soil type recorded higher total infiltrated soil water (0.56 mm mm^{-1}) with the exception of the low rainstorm. The lower rainfall threshold for runoff generation of Augrabies soil type was attributed to the higher surface bulk density (1.76 g cm^{-3}). The distinct bare soil- and vegetation-patches justified the respective early runoff time and higher infiltration water content. Mayor, Bautista, and Bellot (2009) observed that bare soil patches served as runoff sources given their compacted and crusted surfaces while the vegetation patches served as runoff sinks or infiltration zones. Response time to runoff was generally longest for the low rainstorm regime in all soil types (19 to 22 min) and was consistent with previous studies (Xu et al. 2013; Zhao et al. 2013). The longest response time came from the Addo soil type, despite its higher clay plus fine silt content. Although the quality of the rainstorm simulation water was not available, the mineralogical activity of the high exchangeable calcium ($8.25 \text{ cmol} + \text{kg}^{-1}$) and magnesium ($11.17 \text{ cmol} + \text{kg}^{-1}$) could have supported aggregate stability against raindrop impact and caused delayed surface runoff responses.

Accumulated runoff rate

Runoff rate is one of the most variable runoff parameter and for analysis purposes, accumulated runoff rate was used as a standard parameter. Differences ($DMRT_{.05}$) in accumulated runoff rates observed from the interaction between soil type and rainfall regime were limited to the high rainstorm regime (Table 4). Accumulated runoff rates for each rainfall treatment on the Augrabies soil type did not differ ($p \leq 0.05$) and ranged from 0.1 to 0.61 mm min^{-1} , 0.02 to 0.05 mm min^{-1} , and 0.01 to 0.02 mm min^{-1} for the high, medium, and low rainstorm regimes, respectively (Figure 5). The result was crucial for dryland floodplain under aquifer recharge management because soil type with higher runoff generation provided an opportunity to adopt runoff harvesting strategies that would support the recharge of groundwater table through ponded infiltration and deep drainage.

High rainfall intensity is known for high kinetic energy raindrops, which deform or detach soil particles resulting in compacted and crusted soil surfaces (Huang, Wu, and Zhao 2013). First and second highest accumulation runoff rates of 0.61 and 0.18 mm min^{-1}

were respectively from the Addo and Brandvlei soil types. These results corresponded with the higher clay content (>15%) in the soil types' surface horizons. Floodplain soil types are associated with clays of swelling and cracking properties and superficial layers of surface fine material that has very low infiltration and higher runoff production (Knighton and Nanson, 2001; Lange, 2005). The high clay content (24%) and exchangeable sodium (60 mg kg^{-1}) of the Addo soil type suggested that clay dispersion was responsible for the sharp increase in accumulated runoff rates (Lal and Shukla, 2004; Carmi and Berliner 2008; Huang, Wu, and Zhao 2013). The fine texture characteristics of the Addo soil type makes it ideal for adopting water management strategies, which could harvest and divert runoff to adjacent soil types where it would benefit groundwater recharge by deep infiltration. The Addo soil type's central position in the floodplain also favored frequent fluvial deposits of fine-sediments and dissolved salts (Tooth, 2000, Costelloe et al. 2003; Lange 2005). Near soil-surface fine sedimentation of clay, silt and very fine sand fractions were shown in various studies to favor surface crusting and sealing, which reduced steady-state infiltration by one or more order of magnitude in favor of runoff rates. (Scherrer et al. 2007; Hussein, Awad, and Abdul-Jabbar 2010; Bothma, van Rensburg, and Le Roux 2012; Zhao et al. 2013). Apart from surface crusting and sealing, Lange et al. (2003) observed that rocky areas increase runoff generation by producing lateral runoff. The lateral runoff accelerates soil saturation and once saturated, 80–90% of applied rainfall becomes surface runoff. Ash from burnt areas reduced steady-state infiltration by one order of magnitude through the blocking of soil surface hydraulic pores (Kinner and Moody 2010).

The second highest accumulated runoff rate on Brandvlei soil type was indicative of its intermediate physical and chemical properties. The bulk density (1.69 g cm^{-3}) limited infiltration during the high-intensity rainstorm. The clay content (15.1%) of Brandvlei soil type was insufficient to support clay-dispersion and hence, it produced the lowest runoff rates under the medium and low rainstorms. Ben-Hur et al. (1985) observed that soils with clay content less than 20% had limited amount of clay to disperse and risk of surface crust formation was minimum. The Augrabies soil type produced lower accumulated runoff rates from all three rainstorms, a result that was consistent with the high coarse plus medium sand fraction (16%) of the surface horizon. The coarseness of the Augrabies soil type also explained the higher total infiltrated soil water content of 56 mm (Table 5) observed in the higher rainfall regimes. Apart from the higher bulk density (1.76 g cm^{-3}), coarse texture and spatial vegetation patches made the Augrabies soil type favorable to support deep infiltration and served as a sink for runoff generated from other floodplain soil types.

Runoff coefficient

Runoff coefficient is widely expressed as a percentage of total runoff to rainfall applied and is dependent on slope gradient, amount and intensity of rainfall, soil infiltration capacity and antecedent soil water content (Shahin 2007). Mean runoff coefficients were affected ($\text{DMRT}_{0.05}$) differently by high rainfall and similarly by lower rainfall regimes. High, medium, and low rainfall regimes produced runoff coefficients ranging from 19 to 43%, 7 to 18%, and 4 to 6%, respectively (Figure 6). Runoff coefficients showed a

decline with rainstorm regime, a result that suggested rainfall intensity was the major driver of runoff generation in fine-textured soils (Martinez-Mena, Albaladejo, and Castillo 1998; Shahin 2007; Guo, Hu, and Jiang 2008; Zhao et al. 2013). Addo had the highest rainfall runoff coefficient, a confirmation of the high surface clay plus fine silt content (48%). Coarser soil types as the Augrabies and Brandvlei had a respective second (32.5%) and third (19%) highest runoff coefficients for high rainfall regime and decreased with surface bulk density. This result matched the observation made by Martinez-Mena, Albaladejo, and Castillo (1998) that runoff coefficients from fine-textured soils are three times higher compared to coarse-textured soils. This observation showed that fine-textured and coarse-textured soil types could serve as respective runoff generation and sink zones in the dryland floodplain. Mean runoff coefficients as high as 50% were recorded from crusted soil surfaces with clay plus fine silt content of 84% on crusted soil surfaces (Mzezewa and van Rensburg 2011). In another study, runoff coefficients of 32 and 2% were respectively produced from fine-textured soil with 32% surface clay content and coarse-textured soil with 7% clay content and an 82% sand fraction (Castillo, Gomez-Plaza, and Martinez-Mena 2003). Several other studies have also seen a close relationship between surface clay and silt content and higher runoff coefficients (Mzezewa and van Rensburg 2011; Bothma, van Rensburg, and Le Roux 2012; Zhao et al. 2013).

Lack of statistical differences ($DMRT_{.05}$) between runoff coefficients from the medium and low rainfall regimes suggest soil-type infiltration and surface water-storage properties could not discriminate between intensities of the high and lower rainstorms. Reasons could be uniform slope gradient, very-low antecedent soil water content (Table 5), and higher very-fine and fine sand fractions. Lange et al. (2003) showed that dry soils produced runoff coefficients as low as 16% compared to 80–90% from wet soils. Mean runoff coefficient from the Augrabies soil type was the highest for all rainstorm treatments. The medium rainstorm runoff coefficient of the Augrabies soil type did not differ significantly from either the high or low rainfall treatments. This result was attributed to the high surface bulk density (1.76 g cm^{-3}) and localized bare soil patches (Figure 3(c)). Bare soils from 80 m^2 plots produce runoff coefficients between 14 and 49% and runoff of 3–10 mm from low-intensity simulated rainstorms of 0.35 mm min^{-1} (Marques et al. 2007). Apparently, bare soil increases runoff generation while vegetation patches does the opposite (Castillo, Gomez-Plaza, and Martinez-Mena 2003; Espigares et al. 2013). Wainwright, Parsons, and Abrahams (2000) noted that spatial pattern of bare and vegetation patches at plot scale could be highly variable resulting in non-uniform distribution of runoff; a phenomenon when harnessed can support low infiltration-excess runoff generation.

Total runoff yield

Mean total of runoff yield determined from cumulative runoff totals were affected ($DMRT_{.05}$) differently by high rainfall and similarly by lower rainfall regimes. The effect of rainfall regime on runoff yield was similar to that of accumulative runoff rates and mean runoff coefficients. Mean total runoff yields from high, medium, and low rainfall regimes ranged from 11.4 to 25.8 mm, 2 to 5 mm, and 0.6 to 0.8 mm, respectively

(Table 4). The expected decline in runoff yield with decreasing rainstorm intensity collaborated with infiltrated soil water content (Table 5). However, the infiltrated soil water content of Addo soil type up to 250 mm depth was of equal amounts (0.14 mm mm^{-1}) for the low and medium rainstorms; a result attributed to low infiltration properties of clayey soils. In the Augrabies soil type, medium and high rainstorms also had equal total infiltrated water content (0.56 mm mm^{-1}) at 250 mm depth. Lower antecedent water content ($\leq 0.17 \text{ mm mm}^{-1}$) from medium rainstorm plots was the reason (Wainwright, Parsons, and Abrahams 2000).

Despite the less than expected impact of soil type on runoff-yields, the effect of rainstorms on infiltration-excess runoff responses was useful. The Addo and Augrabies soil types produced highest runoff yields from the high and lower rainstorms, respectively. The Brandvlei soil type had lowest runoff yields (0.7–11.4 mm) for all rainfall regimes and was indicative of the soil type permeable characteristics, which is suitable for rain-water capture by deep infiltration. Under high rainstorm, the Addo soil type had highest mean total runoff yield that corresponded with earliest mean time to runoff (4 min), highest accumulative runoff rate (of 0.61 mm min^{-1}), and runoff coefficients (43%). Apart from the higher clay plus fine silt content (48%), higher runoff parameters of the Addo soil type can be attributed to the higher antecedent soil water content ($\geq 0.25 \text{ mm mm}^{-1}$) and significantly lower ISWC, particularly from the higher rainfalls (Table 5). Finer textures and higher initial moisture contents supported infiltration-excess runoff, especially under high-intensity rainstorms (Martinez-Mena, Albaladejo, and Castillo 1998; Castillo, Gomez-Plaza, and Martinez-Mena 2003; Bothma, van Rensburg, and Le Roux 2012; Zhao et al. 2013). These attributes provide the opportunity to adopt water management strategies that would harvest and divert runoff to the Augrabies and Brandvlei soil types with coarser texture that would support deep infiltration for aquifer recharge. Higher runoff volumes from medium and low rainstorms for the Augrabies soil type are attributed to the compacted surface horizon. Lack of differences between the runoff yields suggested lower rainstorm intensities were unable to break the crusted soil surface compared to the high rainstorm. Other studies observed little differences in runoff yields between lower intensity rainstorms even though reasons could not be given (Mzezewa and van Rensburg 2011; Bothma, van Rensburg, and Le Roux 2012). Low-intensity rainstorms were observed to be more sensitive to surface roughness and antecedent soil water content (Martinez-Mena, Albaladejo, and Castillo 1998). Surface layers of fine material alter threshold values of runoff and infiltration runoff rates (Knighton and Nanson 1994; Lange 2005; Mudd 2006; Dahan et al. 2007). Destruction of compacted surface layers was demonstrated to reduce runoff yields (Carmi and Berliner 2008); a phenomenon that could enhance runoff capture, especially in the Augrabies soil type. However, under natural circumstances, it calls for a flood event of very high magnitude to disrupt superficial surface layers of fine material in dryland floodplains (Tooth 2000; Lange 2005).

Conclusion

Infiltration-excess runoff properties including time to runoff, accumulative runoff rates, total runoff yield, and runoff coefficients, were studied using a rainfall simulator on

three floodplain soil types. Analysis showed that infiltration-excess runoff properties were affected ($p \leq 0.05$) by rainstorm (high, medium, and low) regime, but not soil-type, suggesting rainstorm size had a primal influence on dryland floodplain surface runoff processes. The less than expected impact of soil type on runoff properties was attributed to the nearly level slope (1%), fine textured surface horizons and dormancy of sparsely distributed vegetation common to all test plots. When combined with rainstorm regime, soil type affected accumulative runoff rates. Apart from time to runoff, accumulative runoff rates and the other runoff properties were significantly different (DMRT_{.05}) under the high rainstorm regime and increased with surface clay-content, but not bulk density. Surface horizons with higher clay-content of 24% or more provided the opportunity to adopt runoff water harvesting strategies for the benefit of aquifer recharge in the floodplain. Runoff properties were not different (DMRT_{.05}) for lower rainstorm regimes and the highest and second highest values were dependent on surface bulk-density and clay plus fine-silt content, respectively. Despite the lack of differences in runoff properties, this result suggested that breaking of compacted surface layers could enhance runoff capture in dryland floodplains. Differences ($p \leq 0.05$) in response time to runoff of 4, 10, and 17 min for the respective high, medium, and low rainstorms suggested that manipulation of floodplain surface roughness could delay runoff response times in favor of aquifer recharge by deep infiltration. Higher runoff coefficients from 19 to 43% showed that floodplains runoff generation properties were spatially variable, a result that provides an opportunity to adopt water management practices that capture and divert runoff from high to low runoff generation zones in the floodplain for the benefit of aquifer recharge program.

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