

Salt Balance of Moderately Saline-Alkaline Rangeland Soil and Runoff Water Quality from Rainfall Simulation Studies near Moab, Utah U.S.A.

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Abstract: A Walnut Gulch rainfall simulator was used to determine runoff water quality and salt balance of a Sandy Loam moderately saline-alkaline site containing 0.27% of gypsum near Moab, Utah. Four rainfall intensities corresponding to 2, 10, 25 and 50-year storm return intervals were applied to dry soil. During each rainfall simulation, time-stamped runoff samples were also collected for the determination of ions concentration. Soil water and solute content by depth increments were determined before and after simulations. All correlation coefficients between the applied simulation water and the amounts of Cl^- , SO_4^{2-} , NO_3^- and sum of anions in runoff water were positive and ranged between 0.922 and 0.999. The correlation coefficients for Ca^{2+} , Mg^{2+} , Na^+ , K^+ and sum of cations ranged between 0.783 and 0.983. We concluded from the data analysis that: (1) The amounts of ions in simulation water and in runoff water represent less than 1% of sum of the soil soluble content before rainfall simulation. (2) The CEC contained about 250% the sum of cation in saturated extract. (3) The very small amount of gypsum in the soil contained 50% the sum of saturated extract ions. This means that special attention should be paid to CEC and gypsum content in the management of such soils. Moreover, when modeling runoff and water quality from soils with these properties the modelers must include suitable subroutines considering gypsum and CEC of the soil for accurate prediction of runoff water quality.

Key words: Erosion modeling, rainfall simulation, rangeland, water quality, salinity.

1. Introduction

Overland flow from rainfall excess on salt affected rangeland contributes to salt transport from the soil-plant-water-atmosphere continuum to surface water reservoirs causing their deterioration [1-3]. Salinity-control efforts have largely focused on reducing anthropogenic sources of dissolved-solids, especially irrigation of agricultural lands. Nearly half of the salts concentration in the Colorado River Basin river system comes from natural sources [1]. This suggests a better understanding of the atmosphere-water-plant-soil continuum and the contribution of each component for

further reducing dissolved-solids loading to the Colorado River through management activities on rangelands.

Salts in the Upper Colorado River Basin (UCRB) are mostly contained in soils of marine sedimentary origins [2, 3]. Halophytic plants, such as *Atriplex* L. (saltbush), *Salsola vermiculata* (Mediterranean saltwort), *Halogeton glomeratus* (saltlover), and *Tamarix* spp. (saltcedar) [4-6] can uptake salts and either retain salt within the leaf or exude the salt through specific glands. This can result in the plant leaf canopy being a significant source of salts deposited on the soil surface through leaf fall or salts being flushed from the surface of the leaf during rainfall events. Litter on the soil surfaces and roots

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decomposition of these shrubs and other halophytic plant species are additional sources of salts contributing to surface water quality deterioration of the Colorado River and its tributaries. The growth of halophytic plant species on saline and alkaline soils improves the quality of the supporting soil, reduces possible ground water quality deterioration, and at the same time contributes to deterioration of the surface soil and water quality. To quantify canopy contribution of salts, scientists have partitioned rain water into incident gross precipitation, intercepted precipitation that is retained by vegetation and later evaporated as a primary water loss which needs to be considered in water balance calculation and at the same time as an additional source of salt leading to increasing the concentration of salts in stem flow, free through fall, release through fall and net precipitation [7, 8]. A rainfall event-based study allowed the examination of factors affecting the amounts and chemical concentrations of through fall and stem flow substantially alters its physical-chemistry properties when it contacts plant surfaces by increasing the concentration of dissolved ions [9]. This is due to the process of enrichment of through fall and stem flow with elements leached out of leaves and stems (Na^+ , Ca^{2+} , Mg^{2+} , and K^+) and coming from dry deposition (NH_4^+ , Cl^- , Na^+ , Mg^{2+} , SO_4^{2-} , NO_3^-) washed out from plant surfaces [10, 11]. Relatively few studies have focused on stemflow production of shrubs, which is the dominant plant community in dryland ecosystem [12] leading to the paucity of information on shrub stemflow production and the mechanisms that influence it [13, 14]. According to Ref. [15], the shrub stemflow depth increased linearly with the amount of precipitation, and stemflow percentage increased to approach the asymptotic value of 7.61%. The threshold precipitation of 2.1 mm was required to initiate shrub stemflow. Based on the 10-year mean storm size distribution on a study site, interception loss from curly mesquite dominated sites would be 10.8% [16].

In individual shrubs of semi-arid vegetal community in Northeastern Mexico in the summer of 1987, net precipitation averaged 167.6 mm, of which throughfall formed 160.5 mm and stemflow 7.1 mm. Infiltrated water penetrates the soil surface and reacts directly with the soil's solid components and redistributes cations and anions through the soil. Some of which dissolve readily the soluble salts and others dissolve the slightly soluble salts [8].

The dominant ions in saline soils affected by transport are Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cl^- , NO_3^- , SO_4^{2-} , and HCO_3^- ions. The amount of each constituent depends on the kinds and amounts of the minerals and organic matter in the soil solid phase, the kind and activity of the vegetation, and the source of applied rain or simulation water [17]. Fresh simulation water or rainwater contacts vegetation before infiltration through the soil surface may dissolve some of the cations and anions from the rangeland canopy cover. Infiltrated water redistributes cations and anions through the soil. Water also penetrates the soil surface directly without contacting plant canopy and reacts with the soil's solid components. Some of which dissolve readily and others dissolve slowly soluble and slightly soluble salts [8, 9]. Zwickel et al. [18] analyzed the effects of soil microenvironments and climatic conditions on the temporal dynamics of salt concentrations and found that mainly Na^+ and Cl^- concentration responded rapidly to changes in rain amount, soil moisture, and temperature.

To assess salt mobility and transport processes, the concentrations of major cations and anions in the simulation water, runoff water, soil saturated extract, and on the colloidal surfaces have to be determined before and after each simulation to determine the possible reactions and processes affecting the changes in concentration of the ions. The changes of water content and ion concentration between pre- and post-simulation at consecutive soil layers allow determination of direction of flow of water and salts in the soil and possible enrichment of the ground water

or evaporation of water from the soil surface. The ability of detached solids during erosion processes to release dissolved salts is still poorly understood. Typically, all chemical reactions are classed into two groups; one group with sufficiently fast and reversible reactions, such as the exchange reaction [5] models the equilibrium reactions, and the other group with slower and/or irreversible reactions characterizes the kinetically dominated reactions [19]. Presenting simulation water quantity, soil water content before and after rainfall simulation, runoff water, interception, streamflow, through fall, and other components using different units do not permit knowing the relative contribution of each component to the overall water content in the system [20, 21]. And knowing the salt content of each component in the soil-plant-water atmosphere continuum helps scientists manage such systems for reducing risks potential associated with the presence of salts.

To assess the state-of-knowledge on rainfall/runoff-driven salt pickup and transport processes from rangeland, a bibliographic search [22] and synthesis [23] was first conducted covering salt transport processes revealing a strong emphasis on water erosion and subsurface hydrological processes as the main driving mechanisms of salt delivery to surface waters. There is minimal peer reviewed literature that directly documents salt mobilization and transport from rangelands [22]. This research aims at partitioning water and salts into infiltrated, moved between soil segments, transported to surface reservoirs with runoff water or eroded soils under salt affected rangelands.

2. Material and Methods

2.1 Site

Twelve rainfall simulations were conducted during Jun 6-14, 2016 at Moab Utah (109.89677 W, 38.80083 N) at an altitude of 1,361 m a.s.l. on Muff Family-Badlands Complex soil. The introduced *Halogeton glomeratus* from Amaranthaceae family

commonly known as saltlover and halogeton was the only annual herb vegetation cover in the studied site (Fig. 1a-c). *Halogeton glomeratus* has a high oxalate content, with up to 30% of plant's dry weight made of oxalate crystals, making it toxic to livestock that graze on it [24]. The pre-simulation soil is strongly saline-alkaline (electrical conductivity of saturated paste extract (EC_e) = 16.35 dS/m and exchangeable sodium percentage (ESP) = 37.77) according to NSSH Part 618, Subpart A. The texture is Sandy Loam and has a very small amount of gypsum (0.27%), starts as trace at the surface crust (0 to 1 cm) and increases to reach 0.38% at 6 to 11 cm depth. The values of EC_e , ESP and % gypsum increase with depth and have almost identical trend, where the correlation coefficient and two tail significance between the three data sets of EC_e -ESP, EC_e -% gypsum, and ESP-% gypsum are 0.999**, 0.999 and 0.999* respectively that represent very high correlation coefficients. Ground and vegetation cover on each plot were assessed using a laser point frame [25] to provide information on canopy cover, litter cover, rock content and the fraction of bare ground. The site has on average low canopy cover (4.81%), high bare soil (32.61%), high rock cover (64.06%) and on average the hillslope was 20.97% making the site at high risk of accelerated soil erosion.

A Walnut Gulch Rainfall Simulator (WGRS) [26] was used in this study with a plot size of 600 cm × 200 cm × 11 cm (length, width and depth respectively) (Fig. 1). Four rainfall intensities corresponding to 2, 10, 25 and 50-year storm return intervals were applied and replicated 3 times. These intensities were determined from the Atlas 14 data [27] by multiplying the 5-minute 2, 10, 35 and 50-year return period storm depth by 12. At the downslope end of the plot, a runoff collection pan conveyed runoff into a supercritical flume where a rainfall continued until a trendless real-time hydrograph was observed for 10 minutes, marking steady state conditions. During each rainfall simulation, time-stamped runoff samples were also

collected for the concentration of cations and anions determination. The net amounts of cations and anions removed with runoff water were calculated after subtracting their concentrations in the simulating water. Water quality samples were collected in 60 mL bottles.

Pre-simulation soil samples were collected on control plots to provide information on soil characteristics. At each plot, soils were collected at three locations under the vegetation canopy and three interspace locations. Cores were then separated by depth increments into the surface crust (0-1 cm), depth increment 1 (1-6 cm), and depth increment 2 (6-11 cm). Finally, soil samples were made into composite samples with respect to under canopy versus interspace and by depth increment, resulting in 6 composite samples per plot. Soil bulk density was determined using core samples to convert soil

moisture content from weight to volume basis. Soil samples were then placed in beakers with distilled water to perform a saturated water extract using the immiscible displacement method [28].

This extraction was then analyzed to determine available cations and anions in the soil, where ions (Ca^{2+} , Mg^{2+} , Na^+ , K^+ , NH_4^+ , Cl^- , NO_3^- and SO_4^{2-}) in the simulation water, runoff water, soil saturated extract and ammonium acetate exchangeable cations (without leaching the salts) were determined using Ref. [29], which is the recommended method for the Western United State non-saline soils. Runoff and sediment chemical attributes from the rainfall simulation were determined using Dionex Ion Chromatography (IC), cations were analyzed using Atomic Absorption Spectroscopy (AAS), ammonium acetate exchangeable cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+) were analyzed using

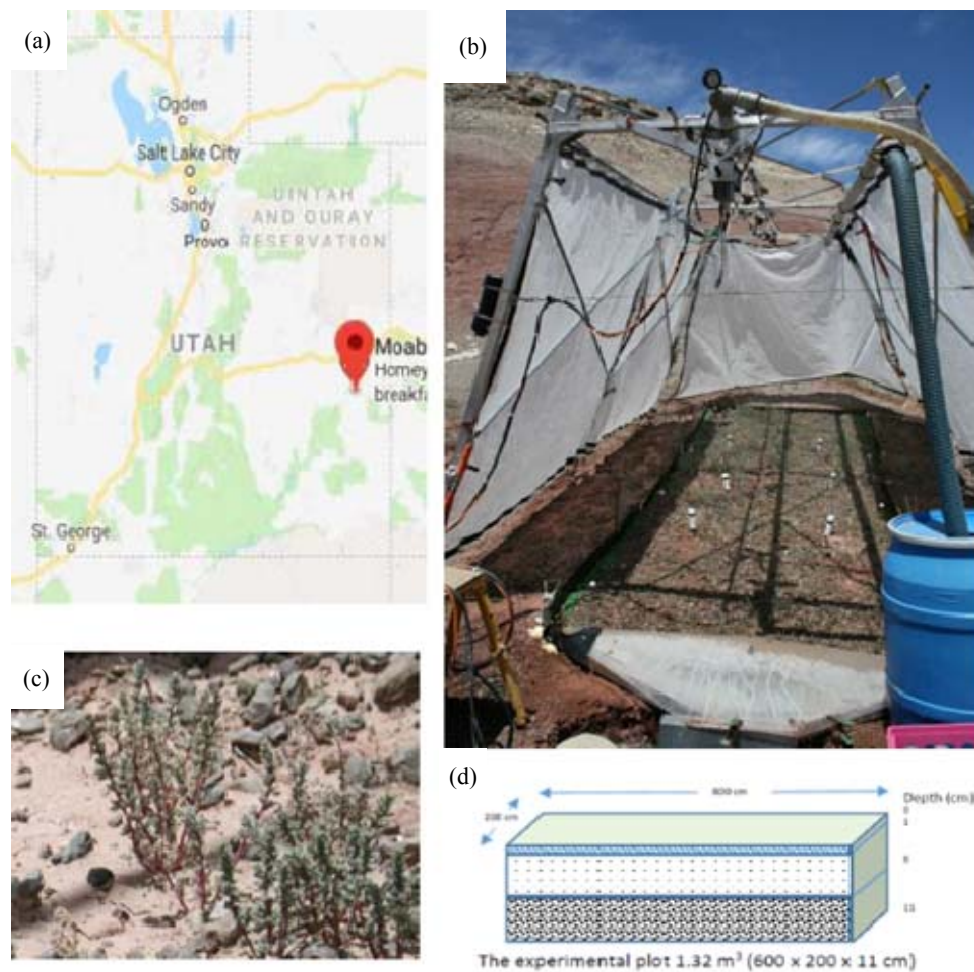


Fig. 1 (a) The experimental site, (b) WGRS, (c) dominant shrub, (d) soil sampling depths, and plot dimensions.

AAS, cation exchange capacity (NH_4^+) was determined using Latchet Quikchem Flow Injection Analyzer (FIA) System, KCl ($\text{NH}_4^+/\text{NO}_3^-$) using Latchet Quikchem FIA System, EC using VWR EC Meter (model 2052). Gypsum was determined by dissolution and measurement of SO_4^{2-} in the dilute extract [30].

The changes in salinity and specific ions with depth in the soil profile were evaluated in this study as a function of various rainfall intensities. Overall runoff water quality and soil water quality over the rainfall simulation period were evaluated along with sediment that was captured at discrete time periods during the rainfall event. Therefore, the calculations of the exchangeable and saturated soil water extract were based on 12 m^2 area and for 11 cm depth.

The presence of the slightly soluble gypsum in the second and third depths was confirmed by acetone test [17] and determined quantitatively by dissolution and SO_4^{2-} measurement in the dilute extract. The predominance of calcium and sulfates of the saturated soil extract required special selection of ions determination method and calculation procedures [31-33].

2.2 Water Balance Calculations

To perform the water balance and compare the magnitude of the parameters, soil water content (kg/kg), simulation intensity (mm/h), runoff (L/plot) on the left side of Fig. 2, were converted to the same unit (liter/plot) on the right side.

2.3 Salt Balance Calculations

The available analytical results (different units) for

salt balance calculations, in the left side of Fig. 3, are:

- The concentration of cations and anions in simulation/runoff water (mg/L);
- The concentration of cations and anions in saturated paste extract (mg/L);
- The CEC and exchangeable cations (mg/L);
- Gypsum content (%).

The conversion of these values to the same unit of measurements (mmol/plot) for comparisons and balance on plot scale is described in Fig. 3. The process is converting the measured parameters in different units (the left side) to a single unit (mmol/plot) on the right side for comparison and balance.

3. Results

3.1 Site Characteristics

The characteristics of the selected plots (Table 1) show high percent coefficient of variation (CV%) ranging from 16.75 for rock % to 158.41 for litter %. Averaging these parameters according to simulation intensities reduced CV% dramatically (Table 2), where rock cover reached a value of 69% with average CV% of 11.50% for the 127 mm/h intensity. The highest average canopy cover 9.85%, which consisted of 100% shrubs, was for the 101.6 mm/h intensity and had a 52.49 CV%. The average CV% of the parameters between the intensity densities decreased to range between 8.01 and 90.01%. Moreover, the average values of the parameters of the simulation density do not have a clear trend (Fig. 4). This makes running simple ANOVA analysis for 4 density treatments with 3 replicates not acceptable.

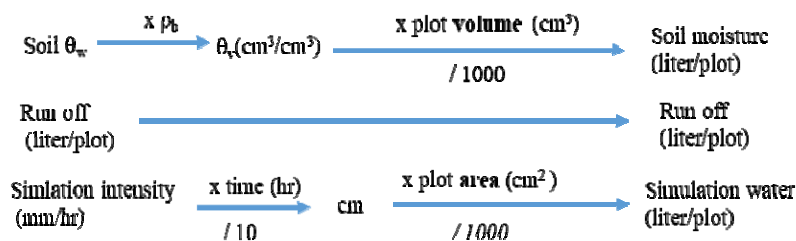


Fig. 2 Calculations sequence for final unit of water balance calculation (L/plot).

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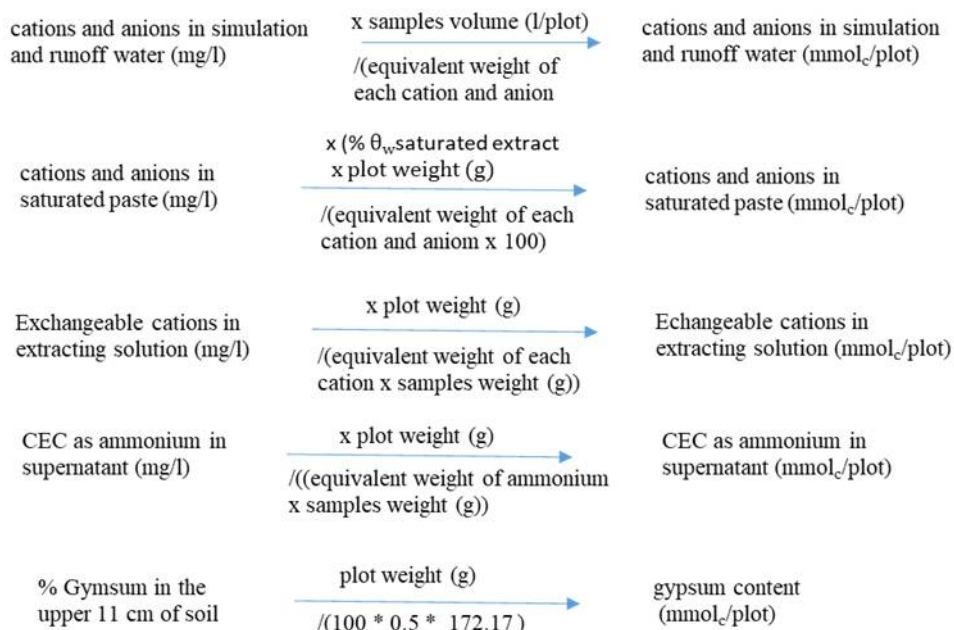


Fig. 3 Calculations sequence for final unit of cations and anions balance calculation (mmol_c/plot).

Table 1 Site vegetation and soil surface characteristics for rainfall simulation intensities, standard deviation and coefficient of variation (CV%).

Intensity (mm/h)	Slope %	Rock %	Litter %	Bare %	Canopy %	Shrub %
50.8	26.77	69.00	0.45	31.36	0.45	0.45
76.2	20.39	54.00	0.00	45.91	0.00	0.00
101.6	22.00	60.00	1.36	30.91	11.36	11.36
127	28.21	60.00	0.45	36.36	3.18	3.18
50.8	23.55	57.00	7.27	35.45	9.55	9.55
76.2	15.65	59.00	1.36	30.45	12.73	12.73
101.6	20.63	64.00	3.64	29.55	14.09	14.09
127	27.64	72.00	0.00	27.27	0.00	0.00
50.8	19.73	50.00	0.00	48.64	0.91	0.91
76.2	14.23	88.00	0.00	10.91	0.45	0.45
101.6	14.74	56.00	1.82	38.64	4.09	4.09
127	18.15	75.00	0.00	25.91	0.91	0.91
Average	20.97	63.67	1.36	32.61	4.81	4.81
CV%	23.22	16.75	158.41	30.03	114.23	114.23

Table 2 Site vegetation and soil characteristics for rainfall simulation intensities averages and CV%.

	Intensity (mm/h)	Slope %	Rock %	Litter %	Bare %	Canopy %	Shrub %
	50.80	26.77	69.00	0.45	31.36	0.45	0.45
	50.80	23.55	57.00	7.27	35.45	9.55	9.55
	50.80	19.73	50.00	0.00	48.64	0.91	0.91
Average		23.35	58.67	2.57	38.48	3.64	3.64
CV%		15.09	16.38	158.30	23.47	140.96	140.96
	76.20	20.39	54.00	0.00	45.91	0.00	0.00
	76.20	15.65	59.00	1.36	30.45	12.73	12.73
	76.20	14.23	88.00	0.00	10.91	0.45	0.45

Table 2 to be continued

Average		16.76	67.00	0.45	29.09	4.39	4.39
CV%		19.26	27.40	173.21	60.29	164.41	164.41
	101.60	22.00	60.00	1.36	30.91	11.36	11.36
	101.60	20.63	64.00	3.64	29.55	14.09	14.09
	101.60	14.74	56.00	1.82	38.64	4.09	4.09
Average		19.12	60.00	2.27	33.03	9.85	9.85
CV%		20.18	6.67	53.04	14.84	52.49	52.49
	127.00	27.64	72.00	0.00	27.27	0.00	0.00
	127.00	28.21	60.00	0.45	36.36	3.18	3.18
	127.00	18.15	75.00	0.00	25.91	0.91	0.91
Average		24.67	69.00	0.15	29.85	1.36	1.36
CV%		22.90	11.50	173.21	19.04	120.13	120.13
	50.80	23.35	58.67	2.57	38.48	3.64	3.64
	76.20	16.76	67.00	0.45	29.09	4.39	4.39
	101.60	19.12	60.00	2.27	33.03	9.85	9.85
	127.00	24.67	69.00	0.15	29.85	1.36	1.36
Average		88.90	20.97	63.67	1.36	32.61	4.81
CV%		36.89	17.52	8.01	90.81	13.09	74.76

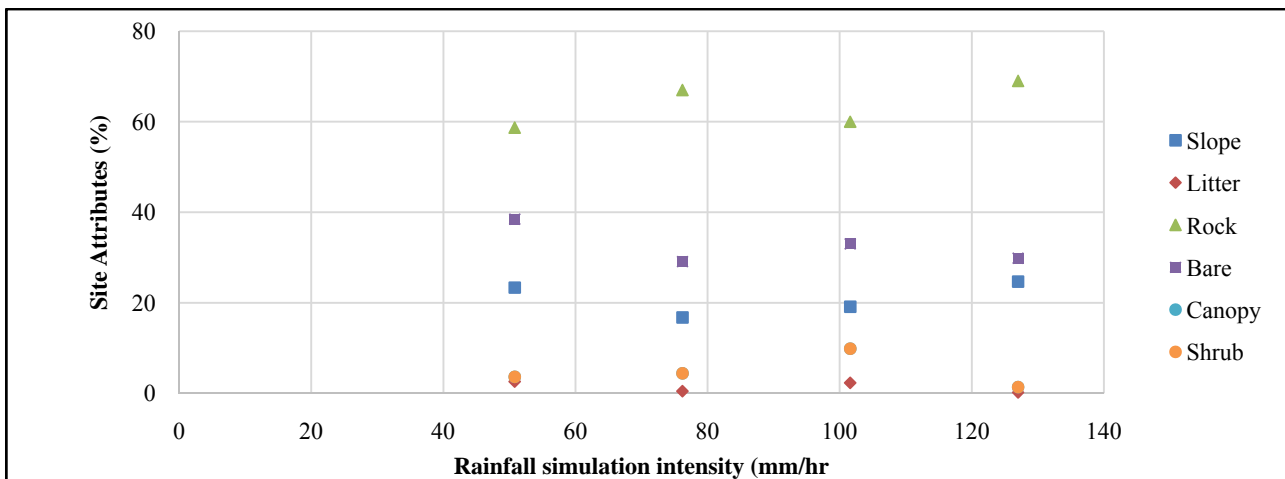


Fig. 4 Scatter plot of average rainfall simulation intensity soil and canopy measured attributes.

3.2 Water Balance

3.2.1 Soil Moisture

Average pre-simulation soil moisture (Fig. 5) was low at the surface (0-1 cm), higher in the second layer (1-6 cm), and in the third layer (6-11 cm) which can be attributed to the history before simulation. The moisture content under both canopy and interspace had the same trend with lower under-canopy values in the second and third layers. The correlation coefficient between interspace moisture and under-canopy was high ($r = 0.91$). Simulations increased soil moisture from the surface crust and moved downwards

increasing the moisture content of the lower depths. The moisture content of the interspace surface crust increased more than under-canopy (Figs. 5 and 6), which can be attributed to canopy, litter, basal cover absorption of a part of simulation water [34]. The low intensity runs had higher moisture content at the surface because the simulations run for longer period to reach study state runoff condition.

Fig. 6a shows the average pre-simulation (average 3 replicates) and post-simulation (12 runs) moisture content and Fig. 6b shows the increase in moisture content resulting from simulations. The increase in

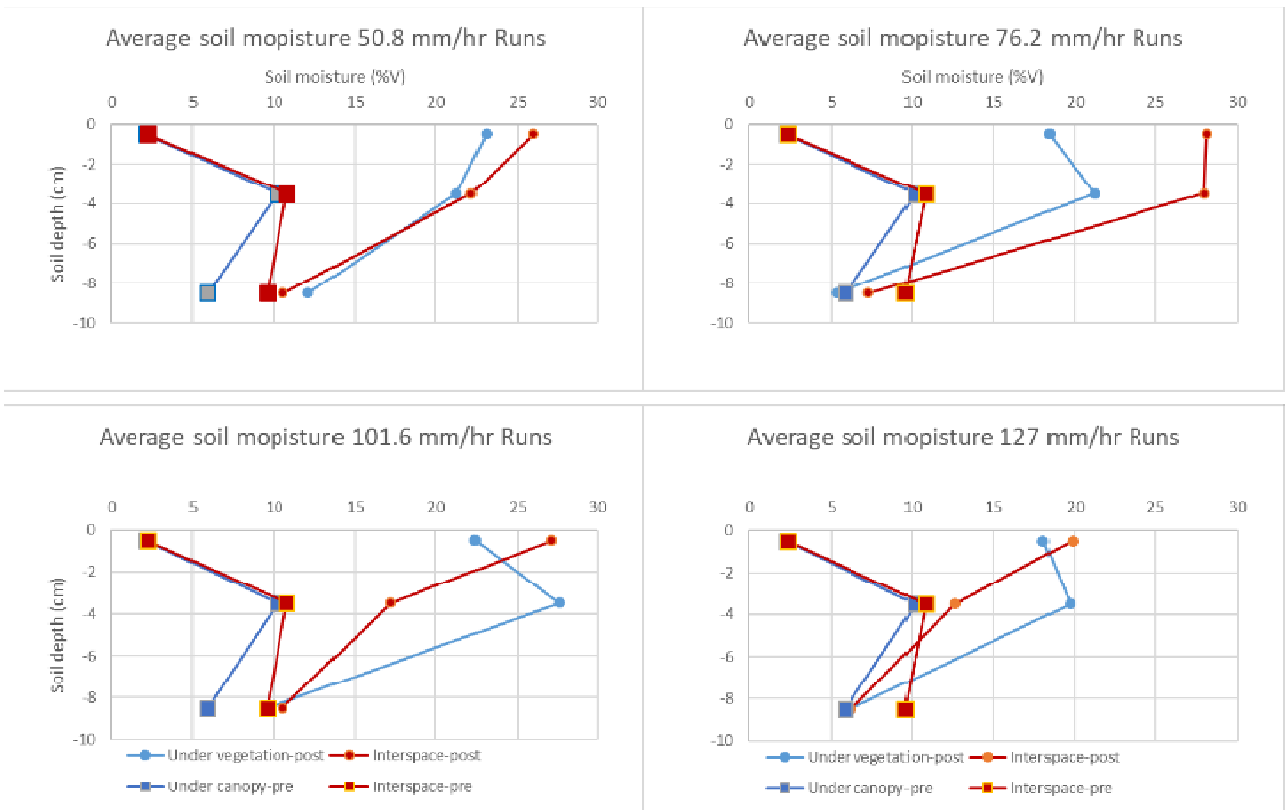


Fig. 5 Pre and post-simulation average percent soil moisture on volume basis under canopy and interspace.

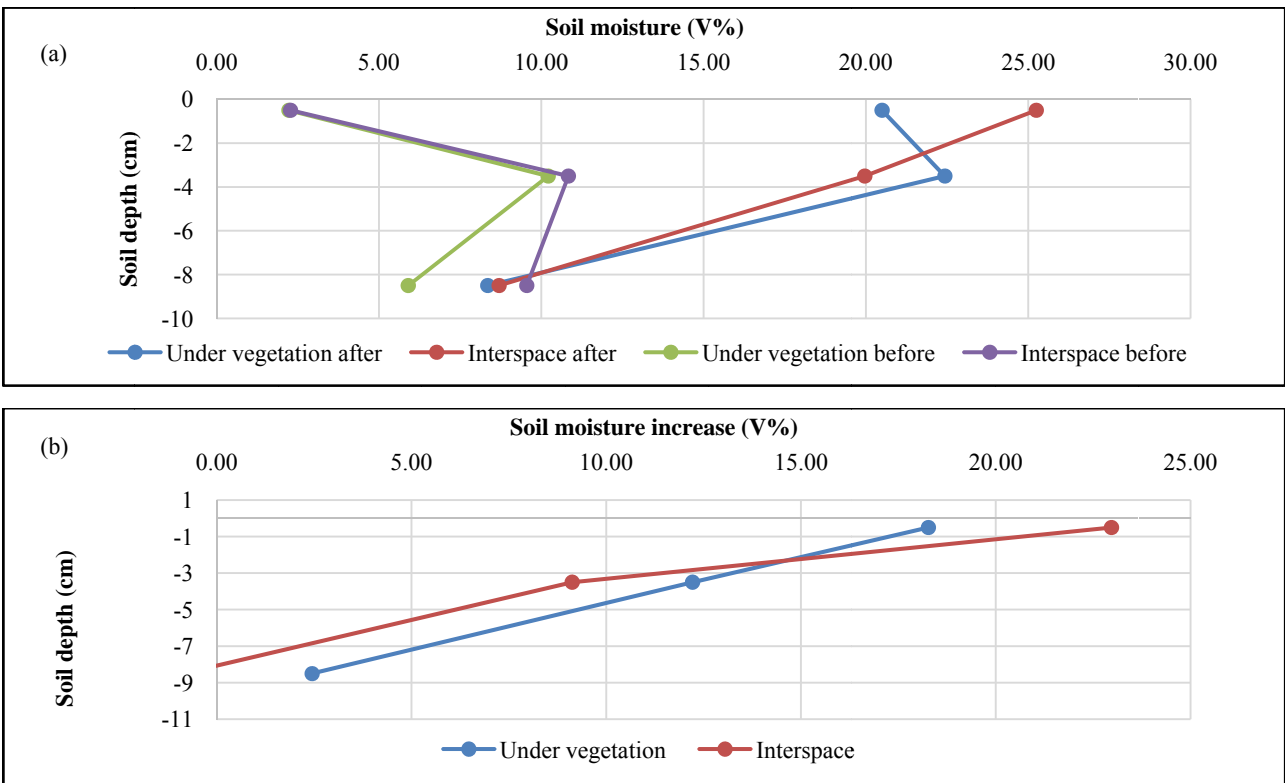


Fig. 6 (a) Average soil moisture (volume %) for three depths under canopy and interspace before (average 3 replicates) and after simulations (average 12 runs), (b) the increase in moisture content after the rainfall simulation (volume %).

Table 3 The major components of the water balance before and after rainfall simulation.

Simulation intensity	Applied water		Cumulative runoff	Moisture before		Moisture after	
(mm/h)	(L/plot)	% of soil moisture before	(L/plot)	% of soil moisture before	(L/plot)	(L/plot)	% of soil moisture before
50.8	472.17	420.83	156.3	139.3	112.20	227.9	203.19
76.2	798.73	711.88	393.1	350.4	112.20	250.1	222.91
101.6	785.16	699.79	401.2	357.6	112.20	224.6	200.20
127.0	814.75	726.16	512.4	456.7	112.20	157.3	140.20
Average	717.70	639.66	365.8	325.0	112.20	215.0	191.62
CV%	22.87	22.87	40.97	41.10	0.00	18.64	18.65

Table 4 Average rainfall simulations intensities physical attributes, average response, and CV%.

Intensity (mm/h)	Duration (min)	Applied water (L/plot)	Cumulative runoff (L/plot)	Calculated infiltration (L/plot)	Infiltration rate (L/min)	Moisture increase (L/plot)	Infiltrated-moisture increase (L/plot)
50.8	46.5	472.2	156.3	315.9	6.8	115.8	200.1
76.2	52.4	798.7	393.1	405.6	7.7	137.9	267.7
101.6	38.6	785.2	401.2	384.0	9.9	112.4	271.6
127.0	32.1	814.8	512.4	302.3	9.4	45.1	257.2
Average	42.4	717.7	365.8	351.9	8.4	102.8	249.1
CV%	21.0	22.9	41.0	14.4	17.1	39.0	13.3

soil moisture decreased with depth, with larger increase in soil moisture at the surface (0-1 cm) of the interspace. The increase in soil moisture of the second (1-6 cm) and third depth (6-11 cm) was higher under canopy.

The major components of the simulation process and the resulting effects are presented in Table 3 using the same unit to show the magnitude of each component by itself and relative to the moisture content of the studied plot before simulation. In average, the amount of applied simulation water was 6.4 times the amount

of soil moisture of the studied plot before simulation and runoff represented 3.26 times the amount of soil moisture. Simulations increased the moisture content from 112.2 to 215.0 L/plot.

3.2.2 Simulation and Runoff Water Hydrologic Parameters

Average and CV% of the simulations physical parameters for simulation intensities are presented in Table 4. The infiltrated-moisture increase (L/plot) column in Table 4 represents the unmeasured parameters such as increasing the moisture content of

Table 5 Correlation matrix and two tail significance of the average simulations' intensities physical parameters.

	Simulation intensity (mm/h)	Simulation duration (min)	Applied water (L/plot)	Cumulative runoff (L/plot)	Infiltrated water (L/plot)	Infiltration rate (L/min)	Soil moisture Increase (L/plot)	Infiltrated - moisture increase (L/plot)
Simulation intensity	1.00							
Simulation duration	-0.83*	1.00						
Applied water	0.80**	-0.33**	1.00					
Cumulative runoff	0.93**	-0.56*	0.95***	1.00				
Infiltrated water	-0.16**	0.58***	0.42*	0.13	1.00			
Infiltration rate	0.89*	-0.75**	0.76**	0.80*	0.10***	1.00		
Soil moisture increase	-0.76	0.90*	-0.27**	-0.55*	0.75***	-0.50*	1.00	
Infiltrated - moisture increase	0.68***	-0.20***	0.97 (0.006)	0.85	0.61*	0.76***	-0.06*	1.00

* Significant at $p \leq 0.05$, ** significant at $p \leq 0.01$, *** significant at $p \leq 0.001$.

the above ground vegetation, litter moisture content increase, direct evaporation of simulation water, evaporation from the plant canopy cover, possible deep percolation below the measured soil moisture depth, and errors. It has the lowest CV% value (13.34) because it is almost the same for all simulation intensities.

The correlation matrix of the average simulations' intensities physical parameters and two-tail significance are presented in Table 5. Larger amounts of applied simulation water are associated with increasing intensity ($r = 0.80^{**}$), while duration generally decreases with increasing intensity ($r = -0.83^*$).

Cumulative runoff increases with increasing intensity with high CV%. The calculated infiltrated water (applied-runoff) does not have a clear trend and has a small CV% value of 14.36, while the infiltration rate (L/min) has a higher CV% and increases with increasing intensity ($r = 0.89^*$). Cumulative runoff increased with increasing intensity ($r = 0.93$). The increase in soil moisture decreased with intensity ($r = -0.76$) while it increased with simulation duration ($r = 0.90^*$).

3.3 Chemistry Balance

3.3.1 Simulation and Runoff Water Quality

The simulation water and time-stamped runoff water analysis of Cl^- , SO_4^{2-} , Ca^{2+} , Mg^{2+} , Na^+ and SAR are presented in Fig. 7. The following points can be extracted by comparing the concentration of ions in simulation water with runoff samples:

- The concentration of all ions in the runoff water is higher than simulation water except Mg^{2+} ;
- The difference in ions concentration between runoff and simulation water decreases with simulation run time for all ions;
- The monovalent ions move with runoff water faster than divalent ions [35];
- Faster movement of anions in runoff water than cations;
- The differences in Cl^- , NO_3^- , SO_4^{2-} anions concentrations between the runoff water and

simulation water start high and decrease quickly to get close to zero during the simulation period;

- The concentration of Ca^{2+} and Mg^{2+} in the runoff water increases during the simulation and reaches asymptotic values close to the concentration of in simulation water;
- The sodium absorption ratio (SAR) of runoff water starts high and decreases quickly and approaches the SAR of the simulation water;
- High coefficient of determinations was obtained in all ions and SAR in runoff water vs. time by fitting fourth order polynomial.

3.3.2 Simulation Intensity and Applied Water vs. Runoff Water Ions Correlations

Averaging the amounts of SO_4^{2-} , NO_3^- , sum of anions (mmol/plot) in runoff water for amounts of applied simulation water showed increasing their amounts with increasing the applied simulation water (Table 6). The Cl^- started to decrease after reaching a peak value of 113.2 at 785.7 L of simulation water. The increase in the average amounts of the measured anions with the average amounts of applied simulation water had the same trend. All correlation coefficient values between the applied simulation water (L) and the amounts of Cl^- , SO_4^{2-} , NO_3^- and sum of anions in runoff water were positive and ranged between 0.922 and 0.999 (Table 7).

The average amounts of cations removed from the plot decrease with time during the runoff event. The specific decay rate is varied by cation (Table 8). All correlation coefficient values between the applied simulation water and the amounts of Ca^{2+} , Mg^{2+} , Na^+ , K^+ and sum of cations in runoff water (mmol/plot) ranged between 0.784 and 0.983 (Table 9).

3.3.3 Exchangeable Cation, Soluble and Slightly Soluble Salts

The average sum of the exchangeable (EX) cations before simulation was 33.0 cmol/kg, increased after runs by 28.3% to average 42.3 cmol/kg as a result of exchanges between the soluble part and the

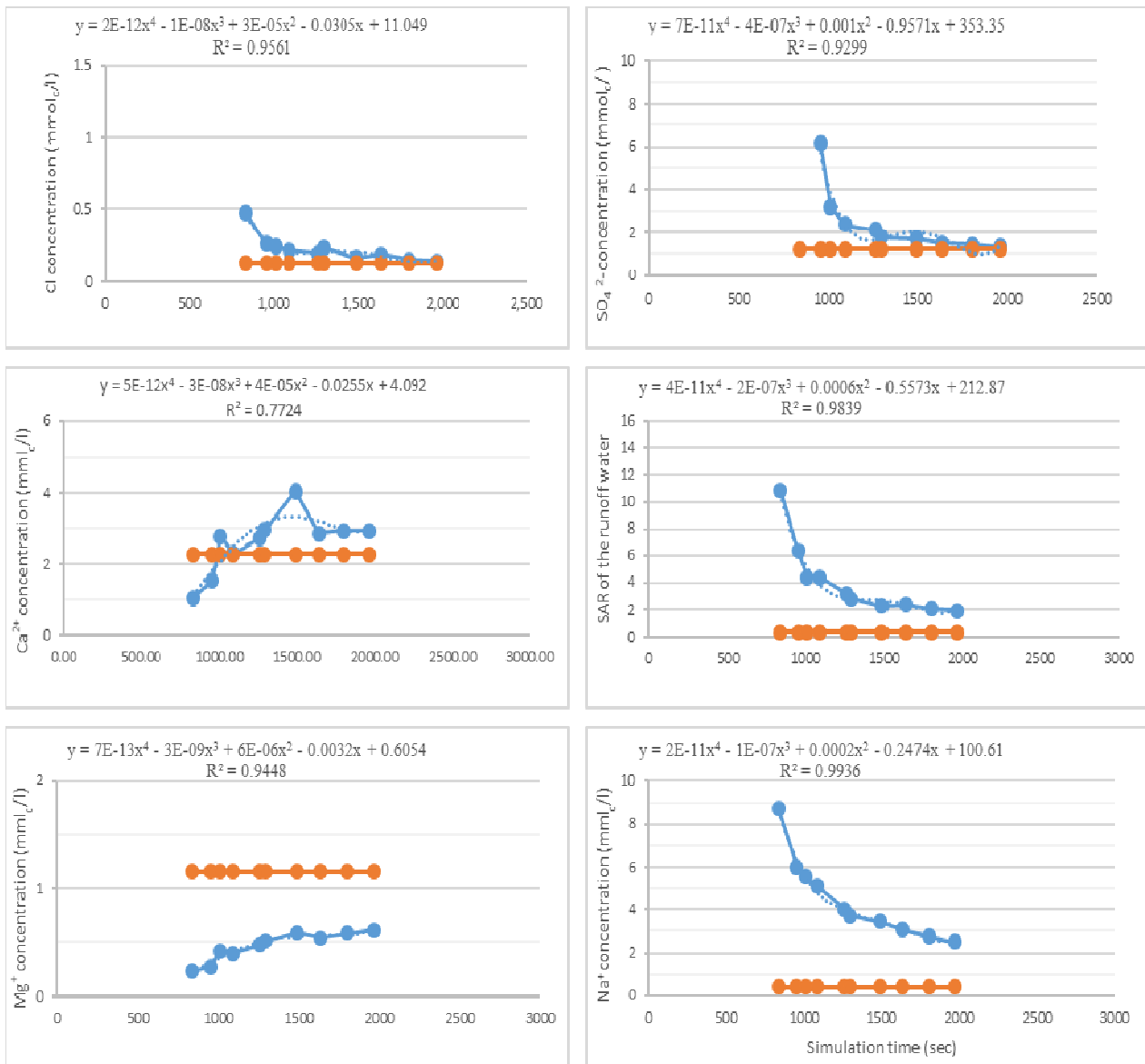


Fig. 7 The concentration of ions and sodium adsorption ratio (SAR) of simulation (red line) and time-stamped runoff water (blue line) with the average amount of applied simulation water.

Table 6 Amounts of anions removed from the plot (mmol_c/plot) as a function of simulation intensities (mm/h) and amounts of the applied simulation water (L).

Treatments	Simulation intensity (mm/h)	Simulation water (L)	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻	Sum anions
			(mmol _c /plot)			
1	50.8	472.2	59.9	295.6	15.9	371.5
2	76.2	798.7	133.3	889.6	24.8	1,047.6
3	101.6	785.2	113.2	873.4	26.1	1,012.8
4	127.0	814.8	106.9	906.4	26.9	1,040.2
Average	88.9	717.7	103.3	741.3	23.4	868
CV%	36.9	22.9	30.1	40.1	21.8	38.2

Table 7 The correlation matrix and two tail significance of the average amounts of anions (mmol_c/plot) in the applied simulated rainfall and runoff water (L).

	Simulation water	Ions (mmol _c /plot) in runoff water			
	(L)	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻	sum ⁻
Simulation water	1				
Cl ⁻ runoff	0.922**	1			
SO ₄ ²⁻ runoff	0.999	0.927*	1		
NO ₃ ⁻ runoff	0.987**	0.856**	0.987*	1	
sum ⁻ runoff	0.999	0.939*	0.999**	0.981*	1

Table 8 Amounts of cations removed from the plot (mmol_c/plot) as a function of rainfall simulation intensities (mm/h) and the amount of the applied simulation water (L).

	Simulation intensity	Simulation water	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Sum cations
	(mm/h)	(L)					
	50.8	472.2	314.6	52.0	888.1	24.3	1,278.9
	76.2	798.7	1,476.7	275.1	1,690.9	69.6	3,512.3
	101.6	785.2	1,372.5	303.2	1,118.5	57.1	2,851.3
	127.0	814.8	1,212.9	273.3	1,755.8	69.9	3,311.8
Average	88.9	717.7	1,094.2	225.9	1,363.3	55.2	2,738.6

Table 9 The correlation matrix of the average amounts of cations in the runoff water for average applied simulation water (L/plot).

	Water	Ca RO	Mg RO	Na RO	K RO	Sum + RO
Water	1.000					
Ca RO	0.967*	1.000				
Mg RO	0.983***	0.976*	1.000			
Na RO	0.784*	0.697	0.658**	1.000		
K RO	0.975**	0.933*	0.921*	0.898**	1.000	
Sum + RO	0.972*	0.952**	0.925*	0.883*	0.996*	1.000

exchangeable part, keeping in mind the mixing between the cations in the simulation water and the soil-water (Fig. 8a). The precipitated salts on the plant canopy are another possible source of the cations that can be dissolved in the simulation water and transported to the soil-water system. The average sum of the exchangeable cations under canopy before simulation 29.7 cmol_c/kg, increased after runs by 29.5% to average 38.4 cmol_c/kg (Fig. 8b), and the average interspace sum of the exchangeable cation before simulation 36.31 cmol_c/kg increased after runs by 24.8% to 45.3 cmol_c/kg (Fig. 8c).

The sum of EX-cations in all depths of the interspace before simulation was higher than under canopy (Fig. 9). Despite the low concentration of ions in the simulation water (126.9 mg/L), the sum of

EX-cations increased after simulation in all depths. The increases in the first and second measured depths under canopy 5.6 and 7.5 cmol_c/kg respectively were larger than the interspace 4.3 and 5.2 cmol_c/kg respectively. However, the increase was larger in the third depth of the interspace (13.8 cmol_c/kg) compared with under canopy (10.6 cmol_c/kg).

Although simulations increased the values of EX-cations under canopy and interspace for all depths, they were associated with decreases in ESP values (Fig. 10). The decrease in ESP under canopy was 7.8% and interspace 2.9%.

3.3.4 Soluble Ions in the Saturated Paste Extract

The concentration of cations and anions in the saturated extract before simulation increases with depth, except for NO₃⁻, Mg²⁺ and K⁺ (3.91%, 0.75%

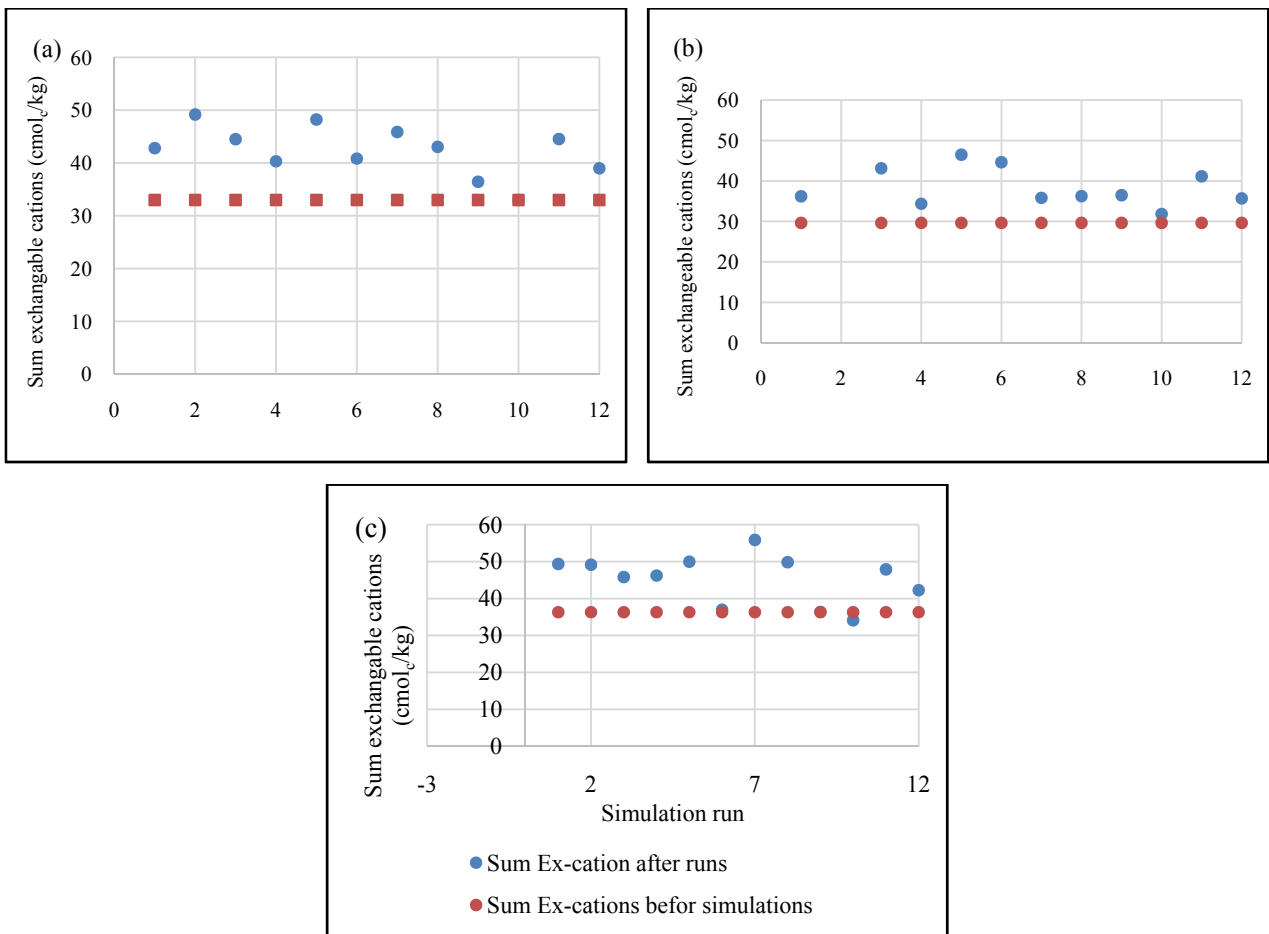


Fig. 8 (a) Average, (b) under canopy, and (c) interspace sum of exchangeable (EX) cations before rainfall simulation and after simulation runs.

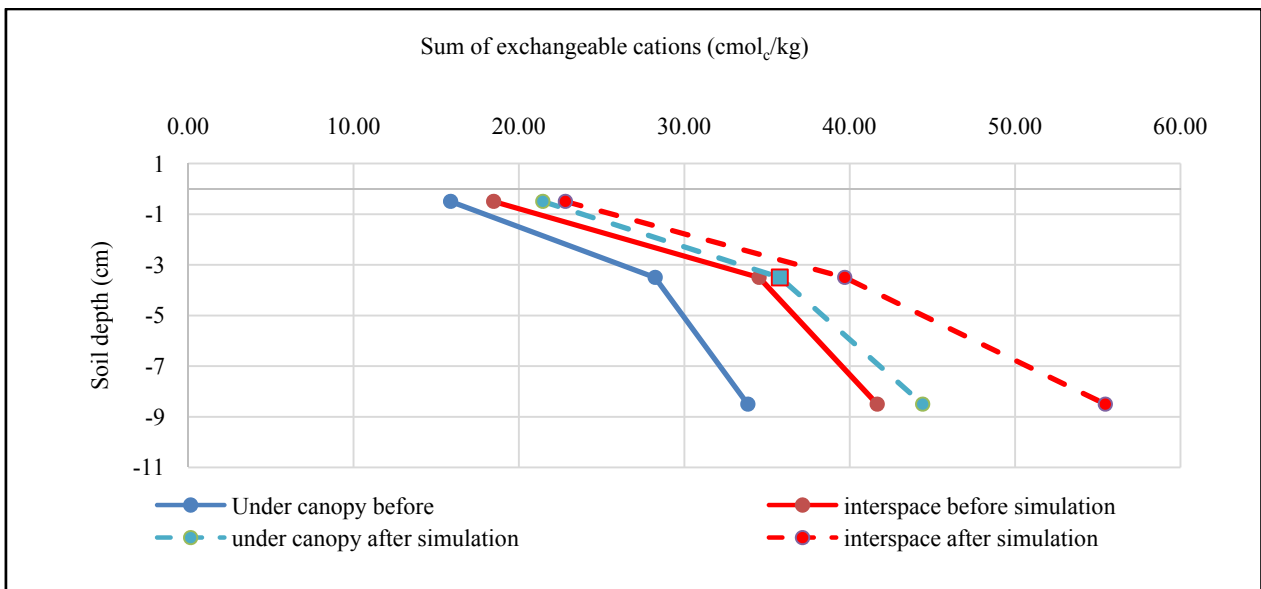


Fig. 9 Sum of exchangeable cations under canopy and in the interspace before and after rainfall simulations.

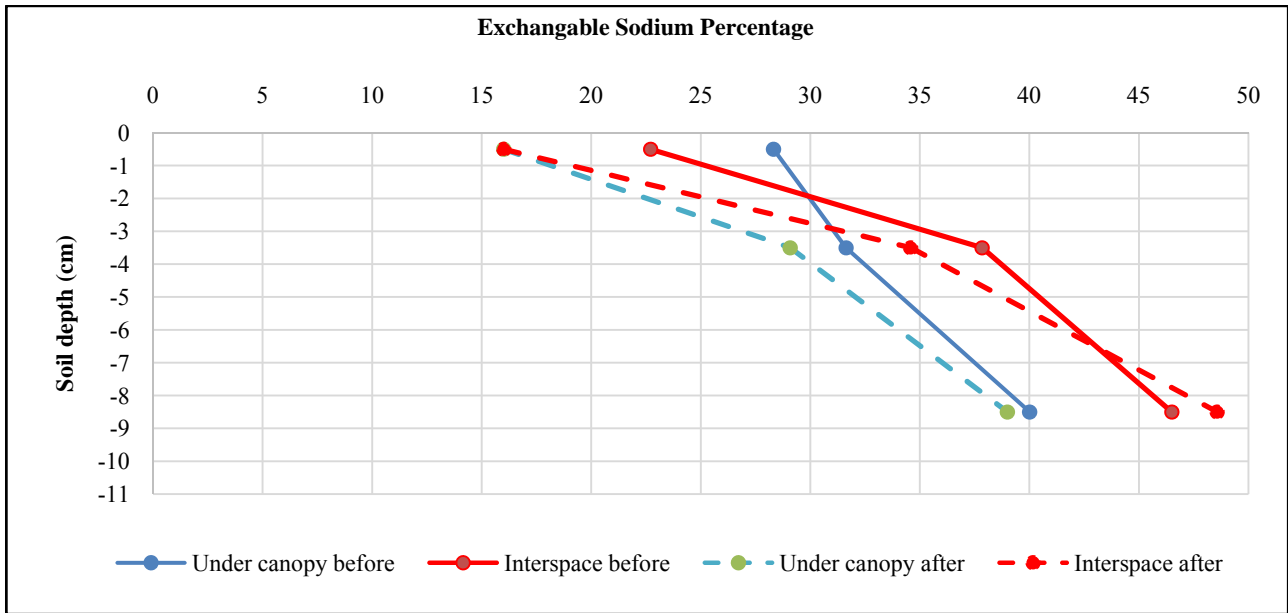


Fig. 10 Interspace and under canopy exchangeable sodium percentage values before and after rainfall simulations.

Table 10 Concentration of ions in the saturated paste extract of the soil before and after simulations.

Average depth (cm)	Concentration (mmol _e /L) before simulation								
	Cl ⁻	NO ₃ ⁻	SO ₄ ²⁻	Sum ⁻	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Sum ⁺
0 to 1	3.0	2.5	29.5	35.0	5.2	0.5	34.1	0.3	39.9
1 to 6	16.5	5.8	74.0	96.3	11.5	1.1	90.5	0.4	103.4
6 to 11	21.6	4.1	136.1	161.8	17.0	1.0	156.9	0.4	175.3
0 to 11	17.6	4.7	98.2	120.5	13.4	1.0	115.5	0.4	130.3
Average depth (cm)	Concentration (mmol _e /L) after simulation								
	Cl ⁻	NO ₃ ⁻	SO ₄ ²⁻	Sum ⁻	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Sum ⁺
0 to 1	0.8	0.4	5.9	7.0	2.2	0.4	19.2	0.3	22.1
1 to 6	11.5	10.8	72.6	93.0	6.8	0.4	90.1	0.3	97.6
6 to 11	23.3	22.3	182.3	219.7	16.0	0.6	222.4	0.4	39.3
0 to 11	15.9	15.1	116.4	142.8	10.5	0.5	143.8	0.3	155.1

and 0.230% of the sum of cations respectively) which have small percentages. After simulation all cations and anions in the saturated paste extract show increases with depth resulting from solute movement downwards, in addition to salt transport with runoff water which extracts more ions from the surface soil compared with deep soil (Table 10). The sum of cations is larger than the sum of anions in the saturated paste extract, because bicarbonate was not measured due to technical difficulties. The simulation processes decreased the sum of cations and anions at the crust and 1 to 6 cm depth, and it increased the sum in the 6 to 11 cm depth. The sum of cations and anions in the whole studied depths (0 to 11 cm) increased after simulations.

4. Discussion

4.1 The Variation in Plots Characteristics

On rangeland, it is difficult to select plots having similar soil and vegetation characteristics to follow the effects of different simulation intensities on runoff water. The difficulties increase under salt affected soils, where the variation in soil properties and canopy cover increase [36, 37]. Averaging soil and vegetation parameters of each simulation intensity improved the average CV% of the parameters for each intensity but remained high and ranged between 8.01 and 90.81% (Table 2). The high coefficient of variation between the plots of each

intensity treatment did not allow treating them as replicates and analyzing data with ANOVA analysis. Therefore, all measured simulations, soil, and cover parameters were considered independent variables of single run which will require large data sets for the prediction purpose.

In this study we determined the CV% and the correlation matrices with two tail significance to identify the suitable independent variable for the derivation of pedotransfer functions or incorporation in existing models such as RHEM in process based theoretical and physical chemistry subroutines. The selected parameters ought to have:

- High CV% as a function of intensities/simulation water;
- High positive or negative correlation coefficient values and significance as a function of intensities/simulation water;
- Show a trend with simulation intensities/applied simulation water.

The data in this study were suitable for obtaining significant correlation coefficient functions for soil and vegetation cover parameters on runoff and erosion. Although the obtained correlation coefficients are significant, they may have limited application to other saline soils due to limited range in soil, cover, slope, and aspect values evaluated in this study.

4.2 Soil Moisture, Simulation and Runoff Water Hydrologic Parameters

The small increase in soil moisture compared with the difference between the applied simulation water and runoff (calculated infiltration) suggests other unmeasured sources of loss of simulation water such as increasing the moisture content of the above ground vegetation and litter, direct evaporation of simulation water, deep percolation below the measured depth as preferential flow, and evaporation from the plant canopy cover [13-15]. Stopping the simulation when trendless real-time hydrograph was observed for 10 minutes marks steady state conditions produced

increasing the amounts of applied simulate water with increasing intensity and decreasing simulation duration leading to increase in cumulative runoff with increasing intensity. The infiltration rate (L/min) is a better candidate than the calculated infiltrated water (applied-runoff) because it has higher CV% and it increases with increasing intensity ($r = 0.89^*$), while the calculated infiltration does not have a trend with increasing intensity (Tables 4 and 5).

The high positive and negative correlation coefficients with simulation intensities such as simulation duration, applied simulation water, cumulative runoff, infiltration rate, and moisture increase values in Table 5 are good parameters to derive equations describing the ongoing processes. However, these results are considered provisional pending additional research that includes more variations in rangelands soil types, slope, simulation intensity, and vegetation communities under saline-alkaline conditions before a global solution to predict runoff, erosion, and changes in soil water content can be identified. The infiltrated-moisture increase column in Table 4 represents the unmeasured parameter has the lowest CV% value because it is almost the same for all simulation intensities.

4.3 Simulation and Runoff Water Quality

Pre-simulation average water total dissolved solid (TDS) measured from the sum of Ca^{2+} , Mg^{2+} , Na^+ K^+ , Cl^- , SO_4^{2-} and NO_3^- ions concentration is low 126.9 (mg/L) with a low CV% of 3.6 owing to using the same source of simulation water. The HCO_3^- concentration calculated from subtracting the sum of anions from the sum of cations had an average value of 2.3 mmol/L and CV% of 4.0. The small values of CV% are indications of the good sampling, analysis procedures, instrumentation performance which justifies adopting the calculated value of bicarbonate from the difference between the sum of measured cations and anions.

The higher concentration of ions in runoff than simulation water at the start of runoff is the result of

the exchange between the simulation water ions with the ions in soil (soluble and exchangeable in addition to a very small amount of slightly soluble salts such as gypsum). It is clear:

- The exchange reactions are fast, and their effects appear even in the first runoff sample;
- The monovalent ions concentrations in runoff water appear faster than divalent ions which follow the general order of preference for electrostatic adsorption of the common cations;
- The anions move faster than cations in runoff water, which can be explained by the effect of negative cation exchange sites on the soil colloids.
- The concentration of Ca^{2+} and Mg^{2+} in the runoff water increases during the simulation to reach asymptotic values close to that of simulation water, while the monovalent cations such as Na^+ and K^+ start with high concentration in runoff water and decrease with time to get close to the concentration in simulation water;
- All reactions start from the soil surface and move downwards in the soil and tend towards equilibrium between liquid and solid phases in the system;
- There are differences in cations and anions concentration between runs that can be attributed to differences in the salinity and alkalinity of the spatially variable soil, simulation intensities.

The above changes in ions concentration might be different with the use of different simulation water quality, intensity, and soil. Although correlation functions with high coefficients were obtained in most cases of runoff water vs. time, these functions are site specific and better predictions of runoff water quality can be obtained by incorporating these processes in models such as RHEM.

4.4 Changes in the Soluble and Exchangeable Ions during the Simulation Process

The increases of exchangeable cations under canopy and interspace in all depths after simulation propose additional sources of cations, rather than

simulation water contributing to the sum of exchangeable cations. The canopy is a possible candidate especially in this site where *Halogeton glomeratus* (saltlover) dominates, which is characterized by high concentrations sodium oxalates on the leaves. The small decreases in ESP values between before and after simulation resulted from:

- The increase of ESP in the third depth in interspace is smaller than the decrease in first and second depths;
- The involvement of all exchangeable cations (sum of exchangeable) in calculating ESP values;
- In our case, where the exchangeable cations were determined without washing salts before exchangeable cations determination, the soluble and slightly soluble cations are part of the exchangeable cations;
- In our experiment, the ESP values before and after simulation under canopy and interspace increase with depth. The canopy itself might be the reason of having a higher under canopy ESP value at the surface than interspace before and after simulation [20].

The simulation process decreased the sum of soluble cations and anions at the crust and 1 to 6 cm depth and increased the sum in the 6 to 11 cm depth as a result of downward transport process of ions in the soil with simulation water application to the soil surface and mixing, convection, diffusion in the liquid phase, dissolution, precipitation, exchange reactions in the soil liquid-solid phases. The concentration of soluble cations and anions after simulations is larger than before simulation, mainly due to the increase in Na^+ , Cl^- and SO_4^{2-} . Other increases and decreases in concentration during the simulation are negligible compared with Na^+ , Cl^- and SO_4^{2-} . Converting the measured soluble concentration of cations and anions in the saturated paste extract to mmol/plot helped compare the values of ions in the soluble form with other forms such as exchangeable, simulation water, and runoff water. The large increase in soluble Na^+ concentration (amount) as a result of simulation, and the high concentration of Na^+ in runoff water

compared with simulation water can be attributed to dissolution of salts from the canopy leaf surface of halophytic shrubs, and Na^+ release from the soil which decreased the SAR with time.

5. Conclusion

Gypsum content in the soil before simulation to a depth of 11 cm was 0.27% on weight basis (58,913 $\text{mmol}_c/\text{plot}$). This very small percentage of gypsum contains what is equivalent to 52.06 % of the sum of saturated extract soluble anions on the studied plot before simulation (113,159 $\text{mmol}_c/\text{plot}$) which is a considerable contribution to total solute transport in addition to its positive effect on the quality of the transported salts.

The average amount of simulation water (717.7 L/plot) is about 1.96 times the average amount of runoff water (365.76 L/plot). The average concentration of anions in runoff water (2.53 mmol_c/L) is 2.09 times the simulation water (1.21 mmol_c/L). This means 870 $\text{mmol}_c/\text{plot}$ was added through the simulation water and 925 $\text{mmol}_c/\text{plot}$ was removed with runoff water. Runoff water removed 56.96 $\text{mmol}_c/\text{plot}$ of soil anions during the simulation.

The calculations show that the amounts of anions in simulation water and runoff water are about 0.77 and 0.82% of the sum of soluble anions in the studied plot before simulation which are very small. Comparing these contributing percentages with that of the 0.27% gypsum content, we find that the very small amount of gypsum contributes about 65 times the contribution of simulation water and runoff water. The average amount of ions in runoff water appears small but it represents average intensity of one simulation run. Therefore, we did not determine gypsum % after simulation because the amount of Ca^{2+} and SO_4^{2-} removed from the studied plot is negligible compared with the soluble and the amount of gypsum present in the soil before simulation.

Relating the cations contents of different components on plot basis to the sum of soluble cations

in the saturated paste shows the relative importance of each form. We had to separate anions from cations in our discussion because the EX-anions are negligible compared with EX-cations. Under moderately saline-alkaline soil:

- The amounts of cations in simulation water and runoff water are about the same and very small;
- The CEC contained about 2.5 times the sum of the saturated extract cations;
- The very small amount of gypsum contained half the sum of saturated extract cations and anions.

This means that special attention should be paid to them in the management of such soils. Moreover, the modelers need to include subroutines using physical chemistry approach or suitable pedotransfer functions containing gypsum and CEC of the soil for a better prediction of runoff water quality and the changes in soil properties after rainfall or simulation.

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