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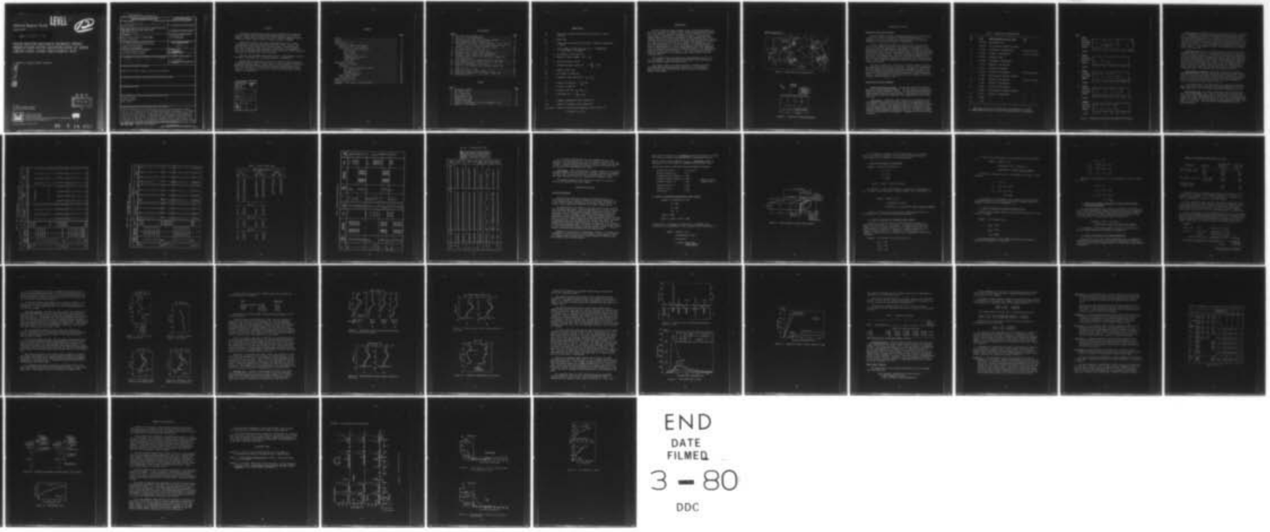

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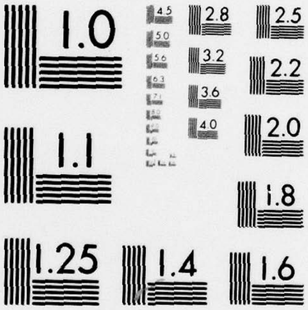
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Special Report 79-29

August 1979

MASS WATER BALANCE DURING SPRAY IRRIGATION WITH WASTEWATER AT DEER CREEK LAKE LAND TREATMENT SITE

G. Abele, H.L. McKim and B.E. Brockett

Prepared for
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The water budget for a 3.6-ha test area was calculated during and two days after a 2.7-cm (equivalent to 991,000 ℓ) application of wastewater. By computing the water remaining in the soil from soil sample water content data, calculating the amount lost to evapotranspiration and measuring the underdrain flow rate, it was possible to calculate the water budget to within 95% of the actual amount applied. The accuracy in computing the soil water content is critical. In this case, a 1% variation of error in the volumetric water content is equivalent to nearly one third of the total water applied.

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PREFACE

This study was conducted by Gunars Abele, Research Civil Engineer, Applied Research Branch, Experimental Engineering Division, and by Dr. Harlan L. McKim, Soils Scientist and Bruce E. Brockett, Physical Science Technician, Earth Sciences Branch, Research Division, USACRREL.

Applying wastewater, monitoring climatological and soil tension instrumentation, obtaining underdrain flow data (after 4 August), and sampling water quality were done by Richard Cantor, Graduate Student, Ohio State University, under the general supervision of Dr. Shamsher S. Brar, Post Doctoral Research Associate, and Dr. Robert H. Miller, Professor, Department of Agronomy, Ohio State University.

This work was performed during 1978 under U.S. Army Engineer District-Huntington, Huntington, WV, Intra-Army Order No. E 8678ED-03.

Appreciation is expressed to the staff of the Deer Creek Lake Corps of Engineers Office at Mt. Sterling, Ohio, for their support and assistance during the 1978 test season. Appreciation is also expressed to Carolyn Merry and James Martel of CRREL and to Professor William Larson of the University of Minnesota for the review of this report and their valuable comments and suggestions.

CONTENTS

ILLUSTRATIONS

TABLES

NOMENCLATURE

A_T = Total area of spray field (three 3-acre plots = 9 acres = 3.64 ha)

h = Depth (cm)

h_T = Total effective depth of spray fields $\approx$ depth of underdrains $\approx$ $\approx$ 80 cm

V_T = Total volume of spray field$_3$ ($A_T \times h_T \approx$ 7,700,000 gal $\approx$ $\approx$ 29,145,000 ℓ $\approx$ 29,000 m^3)

γ = Dry density of soil (g cm^{-3})

γ_w = Density of water (assume 1 cm^3 = 1 g)

G_s = Specific gravity of soil

w = Gravimetric water content (%) $w = \frac{W_w}{W_s} \times 100$

W_w = Weight of water (g)

W_s = Dry weight of solids (g)

V_w = Volumetric water content (%) $V_w = w \frac{\gamma}{\gamma_w}$

V_s = Volume of solids (%) $= \frac{\gamma}{G_s} \times 100$

V_v = Volume of voids (%)

V_a = Volume of air (%) $V_w + V_a = V_v$

S = Saturation (%) $S = \frac{V_w}{V_v} \times 100$

Δw = Change in gravimetric water content (%)

ΔV_w = Change in volumetric water content (%)

V_w (soil) = Amount of applied water remaining in soil (gal or ℓ)

$$V_w \text{ (soil)} = \Delta V_w \times V_T$$

INTRODUCTION

The Deer Creek Lake land treatment system, located approximately 48 km (30 mi) southwest of Columbus, Ohio, treats wastewater from a camping site. The facility, designed to handle a flow of 174,000 ℓ per day (46,000 gpd) is composed of a stabilization lagoon, a holding lagoon, a pumping system that transports wastewater to the treatment site, and a rotating nozzle spray distribution system that applies wastewater uniformly over four 1.21 ha (3-acre) test plots, using nozzle spacing of 12 m (40 ft) longitudinally and 18 m (60 ft) laterally. An underdrain system with a lateral spacing of 9 m (30 ft) collects the percolate water at a depth of approximately 75 to 80 cm (approximately 30 in) and terminates at a point where the discharge can be diverted either to the stabilization lagoon or to Deer Creek Lake (Fig. 1). The 4 test plots were planted with reed canarygrass, an oat-soybean double crop, alfalfa, and tree seedlings (Fig. 2).

The treatment system was designed by the Huntington District, U.S. Corps of Engineers. The operation and performance of the system have been described by Lambert and McKim (1977).

The primary objective of this study was to determine the total water mass balance during wastewater application. The parameters measured under field conditions will serve as input for available moisture flow models.

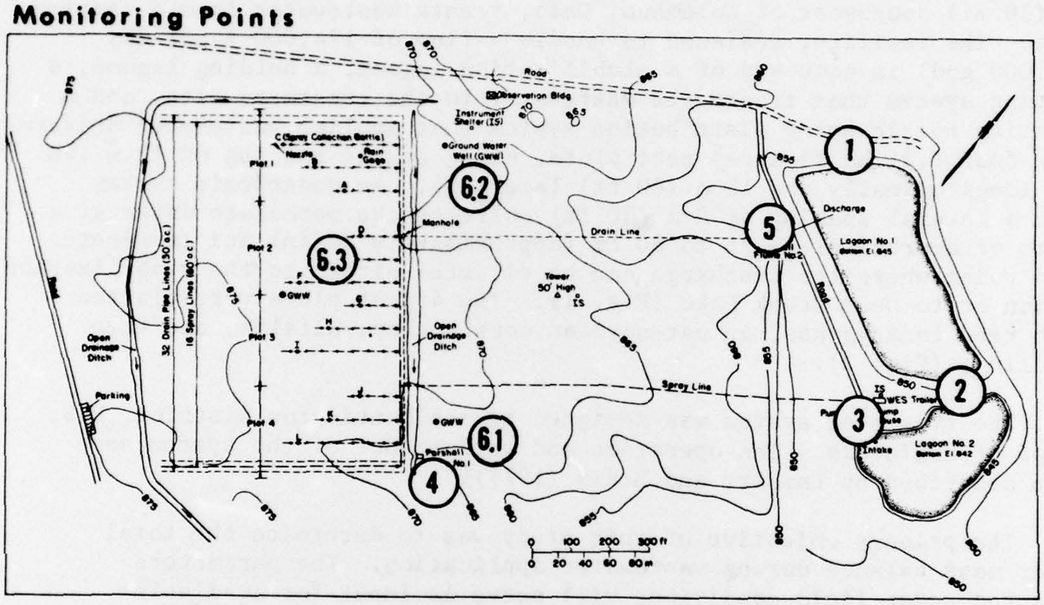


Figure 1. Deer Creek land treatment site.

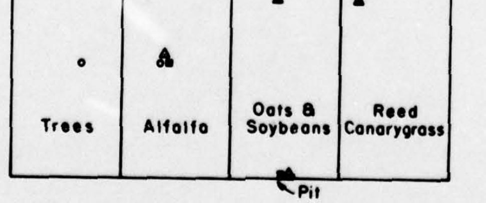


Figure 2. Location of field measurements.

DESCRIPTION OF STUDY

Wastewater Application Schedule

During the summer of 1978, wastewater was applied to the test area a total of 11 times. The amount of application was usually 2.6 cm (slightly over 1 in) of water; for a 3.64-ha (9-acre) area this was equivalent to approximately 946,300 ℓ (250,000 gal).

The first application included all four 1.21-ha (3-acre) plots (grass, oats, alfalfa, and trees). No wastewater was applied to the tree plot during the remaining 10 applications. During the first two applications, the double crop plot contained oats. During the third and fourth applications, the plot contained no crops; the oats were harvested before the third application. The fifth application, immediately after planting of the soybeans, was limited to the grass and alfalfa plots. The last six applications included all three plots with the agricultural crops. Table 1 shows the application schedule, as well as the planting and harvesting dates.

The rate of application, dictated by the spray system's capacity, was approximately 0.5 cm (0.2 in) per hour. The first six applications were done without interruptions, requiring approximately 5 hours. The last five applications included several 15 to 30 min. interruptions to permit soil tension and water content observations during the spraying process. Applications Nos. 9 and 10 were done on a regular 1/2 hour on, 1/2 hour off basis (refer to Fig. 3).

Observation and Test Schedules

Density and specific gravity. The dry soil density and specific gravity G_s data are listed in Table 2. The 1974 data are from the Ohio State Soil Testing Laboratory records. All other data were obtained by CRREL personnel during the last two years. The specific gravity data from the alfalfa plot are considered to be representative of the entire test area.

Soil tension. Tensiometers were installed at four depths in each of the grass, oat-soybean, and alfalfa plots at the beginning of the test season. Readings were taken daily (with a few exceptions) throughout the season, from 14 June through 15 Sep 1978. During four of the last five applications, soil tension data were also obtained at several intervals during wastewater application (Fig. 3). The data are listed in Table 3 and plotted in the Appendix. Tensiometer locations are shown in Figure 2.

Table 1. Application schedule (1978)

No.	Date	Amount applied and crop stage	Area
	18 April	Planting of oats	
	10 June	1st cutting of alfalfa and grass	
1.	14 June	1,283,100 ℓ (339,000 gal)	4.86 ha (12 acres)
2.	22 June	957,600 ℓ (253,000 gal)	3.64 ha (9 acres)
	27 June	Cutting of oats	
3.	29 June	1,067,000 ℓ (281,900 gal)	" "
4.	5 July	962,100 ℓ (254,200 gal)	" "
	11 July	Planting of soybeans	
5.	12 July	657,100 ℓ (173,600 gal)	2.43 ha (6 acres)
	17 July	2nd cutting of alfalfa and grass	
6.	25 July	970,900 ℓ (256,500 gal)	3.64 ha (9 acres)
7.	2 Aug	990,900 ℓ (261,800 gal)	" "
8.	10 Aug	615,100 ℓ (162,500 gal)	" "
	12 Aug	3rd cutting of alfalfa and grass	
9.	15 Aug	946,300 ℓ (250,000 gal)	" "
10.	22 Aug	" "	" "
11.	7 Sep	" "	" "

Beginning with the third application, the wastewater was spiked by adding ammonium nitrate at a rate of 20 mg/liter prior to spraying.

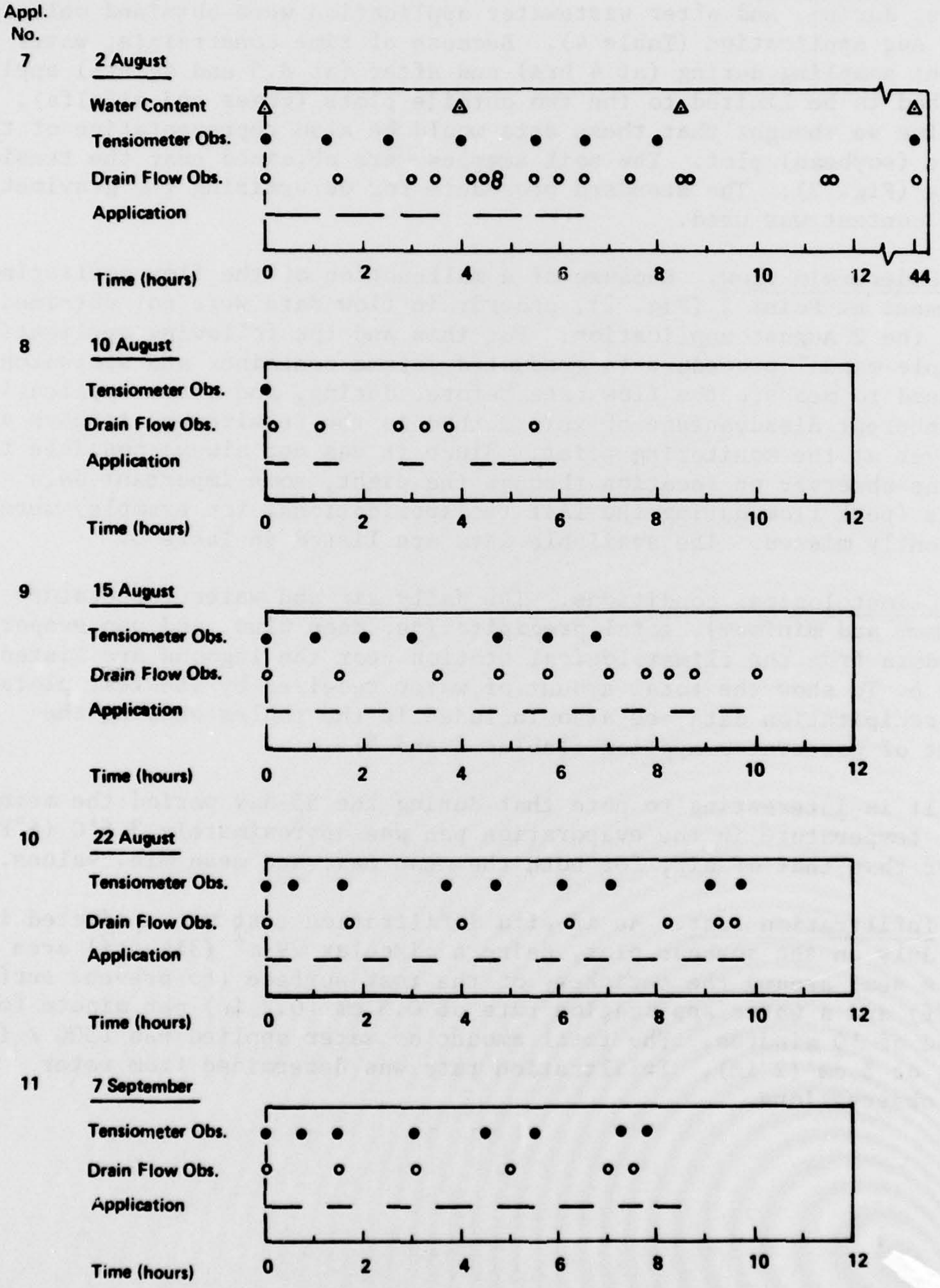


Figure 3. Wastewater application and observation schedule.

Water content. Gravimetric water content data from soil core samples before, during, and after wastewater application were obtained only for the 2 Aug application (Table 4). Because of time constraints, water content sampling during (at 4 hrs) and after (at 8.5 and 44 hrs) application had to be limited to the two outside plots (grass and alfalfa). At the time we thought that these data would be also representative of the middle (soybean) plot. The soil samples were obtained near the tensiometers (Fig. 2). The standard procedure for determining the gravimetric water content was used.

Underdrain flow. Because of a malfunction of the flow monitoring equipment at Point 5 (Fig. 2), underdrain flow data were not obtained until the 2 August application. For this and the following applications, a simple manual procedure (a graduated volume container and stopwatch) was used to measure the flow rate before, during, and after application. The inherent disadvantage of this method is the requirement to have an observer at the monitoring point. Since it was not always possible to have an observer on location through the night, some important data points (peak flow during the last two applications, for example) were apparently missed. The available data are listed in Table 5.

Climatological conditions. The daily air and water temperature (maximum and minimum), total precipitation, mean wind, and pan evaporation data from the climatological station near the lagoons are listed in Table 6. To show the total amount of water received by the test plots, the precipitation data are also included in the tables showing the amount of wastewater applied (Tables 3 and 5).

It is interesting to note that during the 55-day period the mean water temperature in the evaporation pan was approximately 3.5°C (6°F) higher than that of air, for both the mean max. and mean min. values.

Infiltration test. An in-situ infiltration test was conducted in late July on the soybean plot, using a circular 29-m^2 (314-ft^2) area with a seal around the periphery of the test surface (to prevent surface runoff) and a water application rate of 0.5 cm (0.2 in) per minute for a period of 10 minutes. The total amount of water applied was 1500 ℓ (400 gal), or 5 cm (2 in). Infiltration rate was determined from water head observations.

Table 2. Dry Soil Density and Specific Gravity Data

Grass		Soybeans		Alfalfa		
Depth (cm)	Density (g cm^{-3})	Depth (cm)	Density (g cm^{-3})	Depth (cm)	Density (g cm^{-3})	G_s
June 1977		May 1974		May 1974		
10	1.71	10	1.56	9	1.69	
22	1.68	52	1.68	25	1.62	
39	1.40	122	1.93	55	1.69	
74	1.51	160	1.86	127	1.81	
April 1978		April 1978		April 1978		
30	1.41	42	1.41	4	1.53	
		67	1.76	19	1.51	
		111	1.71	39	1.63	
				65	1.92	
				93	1.95	
		July 1978		June 1978		
		2.5	1.42	19	1.55	2.67
		7.5	1.53	39	1.67	2.73
		12.5	1.75	65	1.77	2.74
		17.5	1.72	90	1.87	2.76
		22.5	1.53			
		27.5	1.66			
		34	1.48			
		50	1.58			
		62	1.64			
		72	1.60			
		82	1.52			
		88.5	2.02			
		93.5	1.94			
		98.5	1.72			
		103.5	1.74			
		108.5	1.90			
		113.5	1.88			

Table 3. Soil Tension Data
(Tensiometer gage readings, cm of water)

Date	Water applied (gal)	Water applied in (cm)	Rain* in (cm)	Depth, in (cm)											
				Reed Canarygrass				**Oats - Soybeans**				**Alfalfa**			
				5(13)	10(25)	18(46)	30(76)	5(13)	10(25)	25(64)	.35(89)	5(13)	10(25)	22(56)	30(76)
14 June	339,015	1.05(2.67)	-	810	490	810	-	810	580	610	300	260	220	62	-
15 "			.01 (.03)	102	370	80	-	140	120	80	20	20	40	20	-
16 "			.01 (.03)	160	320	80	-	120	120	80	25	40	42	40	-
17 "			0 (0)	-	-	-	-	-	-	-	-	-	-	-	-
18 "			0 (0)	70	410	100	-	77	360	90	40	250	170	60	-
19 "			1.05 (2.67)	60	100	40	-	20	50	80	-	20	50	80	-
20 "			.05 (.13)	-	-	-	-	-	-	-	-	-	-	-	-
21 "			.20 (.51)	-	-	-	-	-	-	-	-	-	-	-	-
22 "	252,960	1.04(2.64)	.30 (.76)	120	120	60	-	210	180	70	10	60	50	20	-
23 "			.02 (.05)	30	30	20	-	40	40	40	0	0	0	0	-
24 "			0 (0)	150	100	70	-	170	100	70	0	20	40	80	-
25 "			0 (0)	230	100	50	-	480	160	80	0	140	80	20	-
26 "			.12 (.30)	380	140	60	-	750	340	60	20	290	120	40	-
27 "			.12 (.30)	610	220	80	-	820	580	90	-	520	220	80	-
28 "			.17 (.43)	610	300	80	20	(Oats cut previous day)				380	260	70	-
29 "	281,860	1.16(2.95)	0 (0)	780	400	80	40	-	840	80	40	50	380	60	-
30 "			0 (0)	60	150	60	20	20	480	60	10	20	40	0	-
1 July			0 (0)	180	190	60	20	20	240	70	20	100	70	30	-
2 "			.74 (1.88)	-	-	-	-	-	-	-	-	-	-	-	-
3 "			.29 (.74)	30	40	40	0	0	40	60	0	0	0	0	-
4 "			0 (0)	60	60	40	0	30	60	40	0	20	10	0	-
5 "	254,220	1.05(2.67)	.01 (.03)	100	80	50	0	70	100	60	0	60	30	20	-
6 "			.02 (.05)	30	40	20	0	0	0	0	0	0	0	0	-
7 "			.01 (.03)	-	70	50	0	60	60	40	0	40	20	0	-
8 "			0 (0)	160	100	60	20	60	120	50	0	120	60	20	-
9 "			0 (0)	320	120	60	20	70	340	60	0	350	100	30	-
10 "			.01 (.03)	580	200	80	20	0	620	70	0	580	160	40	-
11 "			.01 (.03)	760	360	80	40	(Soybeans planted)				700	340	60	-
12 "	173,580	1.07(2.72)	0 (0)	840	620	60	40	(No application)				780	520	50	-
13 "			.09 (.23)	-	-	-	-					-	-	-	-
14 "			.20 (.51)	-	-	-	-					-	-	-	-
15 "			.01 (.03)	120	100	80	20					60	80	100	-
16 "			0 (0)	-	-	-	-					330	160	40	-
17 "			0 (0)		Grass cut								Alfalfa cut		
24 "			.54 (1.37)	-	-	-	-	-	-	-	-	-	-	-	-
25 "	256,480	1.05(2.67)	.15 (.38)	0	820	200	40	0	0	160	20	0	760	80	40
26 "			.07 (.18)	-	-	-	-	-	-	-	-	-	-	-	-
27 "			0 (0)	0	770	80	40	0	0	80	20	0	580	60	20

* Precipitation since previous observation.

Table 3 (cont). Soil Tension Data
(Tensiometer gage readings, cm of water)

Date	Time Since Start of Applic. (hrs)	Water Applied, Cummulative		Rain in (cm)	Depth, in (cm)											
		(Gal)	in (cm)		Reed Canarygrass				Soybeans				Alfalfa			
					5(13)	10(25)	18(46)	30(76)	5(13)	10(25)	25(64)	35(89)	5(13)	10(25)	22(56)	30(76)
28 July				0 (0)												
29 "				0 (0)												
30 "				.27(.69)												
31 "				.37(.94)												
1 Aug.				.02(.05)												
2 "	0			0 (0)	175	385	85	45	(No data obtained)				255	200	65	35
"		61,100	.25(.64)													
"	1.25				20	385	110	65					295	220	80	42
"		114,900	.47(1.19)													
"	2.5				15	385	105	55					310	230	80	50
"		156,400	.64(1.63)													
"	4.0				15	375	100	40					320	230	80	50
"		210,200	.86(2.18)													
"	5.5				15	305	50	30					350	275	80	42
"		261,800	1.07(2.72)													
"	6.5				0	120	10	0					0	260	20	0
"	8.0				5	55	10	0					0	210	5	<0
3 "	19.0			.01(.03)	15	45	25	0					0	10	0	<0
"	21.0				20	45	30	0					0	10	0	<0
"	23.5				35	50	40	10					15	5	15	<0
4 "	44.0			.05(.13)	40	90	55	20					20	20	20	<0
5 "				— —	120	100	60	30	140	110	50	0	0	70	40	0
6 "				0 (0)	100	40	40	0	20	40	60	0	0	0	0	0
7 "				1.5 (3.81)	0	0	0	0	0	0	0	0	0	0	0	0
8 "				.01(.03)	80	80	60	10	50	60	40	0	30	20	20	0
9 "				0 (0)	100	80	50	20	80	60	40	0	40	20	20	0
10 "	0	162,500	.65(1.65)	.46(1.17)	30	20	40	0	20	50	40	0	0	0	0	0
11 "	24			.30(.76)	0	0	0	0	0	0	0	0	0	0	0	0
12 "	48			.05(.13)	20	50	30	0	0	0	0	0	0	0	0	0
13 "				.01(.03)	80	80	50	10	0	0	0	0	0	0	0	0
14 "				0 (0)	120	80	60	30	10	80	60	0	0	40	40	10
15 "	0			0 (0)	180	90	70	30	260	100	40	0	200	60	40	0
"		25,000	.10(.26)													
"	1				180	100	60	30	230	100	60	0	200	60	40	0
"		50,000	.20(.51)													
"	2				60	100	70	20	200	100	60	0	220	60	40	10
"		75,000	.31(.80)													
"	3				40	80	80	30	120	100	60	0	240	80	40	10
"		100,000	.41(1.04)		-	-	-	-	-	-	-	-	-	-	-	-
"		125,000	.51(1.30)													
"	4.75				20	60	60	30	40	30	60	0	20	20	20	0
"		150,000	.61(1.55)													
"	5.75				0	40	40	20	30	30	40	0	0	0	0	0
"		175,000	.72(1.83)													
"	6.75				0	20	20	0	20	20	20	0	0	0	0	0
"		200,000	.82(2.08)													
"		225,000	.92(2.34)		-	-	-	-	-	-	-	-	-	-	-	-
"	9.7	250,000	1.02(2.59)		-	-	-	-	-	-	-	-	-	-	-	-
16 "	26.5			.05(.13)	0	0	0	0	0	0	0	0	0	0	0	0
17 "	49.5			.01(.03)	100	80	60	20	80	80	40	0	40	20	20	0

Table 3 (cont.) Soil Tension Data
(Tensiometer gage readings, cm of water)

Date	Time Since Start of Applic. (hrs)	Water Applied, Cumulative		Rain in (cm)	Depth, in (cm)											
					Reed Canarygrass				Soybeans				Alfalfa			
		(Gal)	in (cm)		5(13)	10(25)	18(46)	30(76)	5(13)	10(25)	25(64)	35(89)	5(13)	10(25)	22(56)	30(76)
18 Aug.				0 (0)	120	80	60	20	120	60	40	0	20	60	20	0
19 "				0 (0)	220	100	60	20	320	100	60	0	150	40	40	10
20 "				.17(.43)	350	200	-	40	560	180	70	0	360	130	30	20
21 "				.01(.03)	-	-	-	-	-	-	-	-	-	-	-	-
22 "	0			.01(.03)	590	240	60	50	-	360	40	0	560	180	60	20
"		25,000	.1 (.25)													
"	0.6				600	260	80	60	-.	360	60	0	580	180	60	20
"		50,000	.2 (.51)													
"	1.6				600	260	80	60	-	380	60	0	580	280	60	20
"		100,000	.4 (1.02)													
"	3.7				140	280	80	60	-	380	60	0	560	220	60	20
"		125,000	.5 (1.27)													
"	4.7				40	240	80	60	-	320	60	0	20	220	50	0
"		150,000	.6 (1.52)													
"	6.1				20	220	80	60	-	380	60	0	0	160	0	0
"		175,000	.7 (1.78)													
"	7.1				0	220	80	40	-	340	60	0	0	100	0	0
"		225,000	.9 (2.29)													
"	9.1				0	160	80	0	-	150	40	0	0	0	0	0
"		250,000	1.0 (2.54)													
"	9.7				0	140	60	0	-	-	-	-	0	0	20	0
23 "	24			.01(.03)	30	60	60	30	20	40	30	0	0	0	0	0
24 "	48			0 (0)	30	80	60	20	80	60	40	0	0	0	0	0
28 "	144			- -	0	120	60	20	100	360	60	0	20	40	40	0
29 "				.38(.97)	20	40	40	20	20	40	40	0	0	0	0	0
30 "				.30(.76)	-	-	-	-	-	-	-	-	-	-	-	-
31 "				1.52(3.86)	-	-	-	-	-	-	-	-	-	-	-	-
1 Sep.				.06(.15)	-	-	-	-	-	-	-	-	-	-	-	-
2 "				.03(.08)	80	80	60	20	60	60	20	0	0	20	20	0
3 "				.01(.03)	-	-	-	-	-	-	-	-	-	-	-	-
4 "				.06(.15)	120	100	60	20	140	100	60	0	180	40	40	0
5 "				.01(.03)	200	100	60	20	260	100	60	0	220	40	40	0
6 "				0 (0)	360	140	80	40	460	160	60	0	380	60	40	20
7 "	0			0 (0)	570	200	60	40	580	220	60	0	560	60	40	20
"		37,500	.15(.38)													
"	0.8				600	220	80	60	560	220	80	0	300	80	50	0
"		50,000	.2 (.51)													
"	1.5				600	220	80	40	570	220	80	0	320	80	60	20
"		87,500	.35(.89)													
"	3.1				600	220	80	60	560	220	80	0	20	70	50	0
"		125,000	.5 (1.27)													
"	4.5				580	240	80	50	510	230	70	10	20	80	60	0
"		162,500	.65(1.65)													
"	5.5				220	240	80	40	480	220	70	0	20	80	60	0
"		200,000	.8 (2.03)													
"	7.3				50	170	80	120	-	150	70	0	20	60	60	0
"		225,000	.9 (2.29)													
"	7.8				0	220	80	40	-	70	60	0	0	40	60	0
"		250,000	1.0 (2.54)													
"	8.5				-	-	-	-	-	-	-	-	-	-	-	-
8 "	24			.01(.03)	30	140	60	20	70	50	40	0	20	40	20	0
9 "	48			.01(.03)	90	140	60	30	120	70	50	0	80	30	30	0
10 "	72			.01(.03)	200	220	90	50	300	120	80	0	210	60	60	30
11 "				-	320	220	60	30	360	100	60	0	230	40	20	0
12 "				-	440	300	30	10	530	130	60	0	540	-	70	40
13 "				-	670	380	80	40	600	180	10	70	550	70	50	20
14 "				-	760	450	70	40	720	240	80	0	640	70	50	20
15 "				-	800	520	80	40	740	290	60	0	680	60	40	20

Table 4. Water content data.

Before application (2 Aug)					
Grass		Alfalfa		Soybeans	
h Depth (cm)	w Water Cont. (%)	h Depth (cm)	w Water Cont. (%)	h Depth (cm)	w Water Cont. (%)
3.5	19.0	4	18.3	2.5	14.8
3.5	15.9	5	19.6	7.5	14.2
10.5	17.7	10	15.9	12.5	11.9
11	16.2	14	15.9	17.5	12.2
17	15.9	15.5	16.7	22.5	22.1
17	15.9	18.5	16.1	27.5	18.0
22	15.6	24	21.6	34	26.2
25	20.4	26	22.4	50	25.1
27	21.0	32	25.3	62	22.6
33	21.0	35	23.9	72	24.6
34.5	23.4	42	21.1	82	26.6
40	17.0	51.5	17.1	88.5	11.4
40.5	21.1	51.5	16.6	93.5	12.3
47	19.9	60.5	13.9		
54.5	14.1	73.5	10.8		
63.5	15.3	81.5	11.8		
73	13.4				
76	11.3				
79	11.5				
After 4 hrs					
7	22.0	7	19.7		
22	17.5	22	21.2		
37	21.3	37	25.4		
53	18.0	53	14.6		
68	15.5	68	12.5		
82	13.0	80	14.7		
After 8.5 hrs					
7	19.1	7	16.6		
22	18.4	22	13.7		
37	21.1	36	15.5		
52	15.6	45	17.1		
65	12.2	50	12.4		
After 44 hrs					
7	20.9	7	19.4		
22	20.7	22	17.4		
37	22.3	37	22.0		
52	16.3	52	16.0		
68	16.5	67	15.4		
81	14.6	81	11.2		

Table 5. Underdrain flow data (Point 5)

Date	Time Since Start of Applic. (hrs)	Water Applied, Cummulative		Rain in (cm)	Flow Rate (gal/min)
		(gal)	in (cm)		
2 Aug.	0			0 (0)	0.3
"	1.5	66,000	.27(.69)		0.4
"	3.0	127,100	.52(1.32)		9.7
"	3.5	151,500	.62(1.57)		9.7
"	4.2	156,400	.64(1.63)		8.9
"	4.5	168,600	.69(1.75)		8.9
"	4.7	183,300	.75(1.91)		11.2
"	4.8	183,300	.75(1.91)		12.9
"	5.5	210,200	.86(2.18)		23.8
"	6.0	237,100	.97(2.46)		27.6
"	6.5	261,800	1.07(2.72)		48.3
"	7.4				58.0
"	8.5				43.3
"	8.7				43.3
"	11.4				23.8
"	11.5				25.7
3 "	19.8			.01(.03)	12.5
"	20				12.5
"	30				7.4
"	33				5.5
4 "	44			.05(.13)	6.3
"	46				3.6
5 "				-	-
6 "				0 (0)	-
7 "				1.5 (3.81)	58
" (PM)					29
8 "				.01(.03)	12
9 "				0 (0)	6.7
" (PM)					4.5
10 "	0			.46(1.17)	-
"	0.2				7.3
"	1.1	25,000	.10(.26)		10.1
"	2.8	50,000	.20(.51)		22.3
"	3.2	75,000	.31(.79)		38.7
"	3.8	75,000	.31(.79)		223
"	5.5	137,500	.56(1.42)		362
"		162,500	.66(1.68)		-
11 "	22			.30(.76)	36.2
12 "	44			.05(.13)	12.7
"	45.6				13.4
13 "	69			.01(.03)	5.8
14 "				0 (0)	3.4
15 "	0			0 (0)	1.6
"	1.5	50,000	.20(.51)		2.4
"	3.5	100,000	.41(1.04)		3.1
"	4.8	125,000	.51(1.30)		7.0
"	5.8	150,000	.61(1.55)		11.8
"	7.0	175,000	.72(1.83)		31.5
"	7.8	200,000	.82(2.08)		42.6
"	8.2	200,000	.82(2.08)		60.4
"	8.9	225,000	.92(2.34)		78.4
"	10.0	250,000	1.02(2.59)		116
16 Aug.	25.2			.05(.13)	18.4
"	26.5				22.3
"	30.5				13.3
17 "	48			.01(.03)	6.6
18 "	72			0 (0)	3.2
19 "				0 (0)	2.1
20 "				.17(.43)	0.9
21 "				.01(.03)	0.8
22 "	0			.01(.03)	0.5
"	1.6	50,000	.20(.51)		0.5
"	3.9	100,000	.41(1.04)		1.2
"	6.1	150,000	.61(1.55)		2.1
"	8.1	200,000	.82(2.08)		3.0
"	9.2	225,000	.92(2.34)		6.6
"	9.5	237,500	.97(2.46)		8.1
"		250,000	1.02(2.59)		-
23 "	24			.01(.03)	-
24 "	47			0	2.5
25 "				-	-
26 "				-	-
27 "				-	-
28 "				-	0.4
29 "				.38(.97)	1.5
30 "				.30(.76)	145
31 "				1.52(3.86)	72
1 Sep.				.06(.15)	29
2 "				.03(.08)	7.8
3 "				.01(.03)	3.1
4 "				.06(.15)	2.0
5 "				.01(.03)	1.3
6 "				0 (0)	0.9
7 "	0			0 (0)	0.4
"	1.5	50,000	.20(.51)		0.5
"	3.1	87,500	.36(.91)		1.0
"	5.0	137,500	.56(1.42)		1.3
"	7.0	200,000	.82(2.08)		3.6
"	7.5	212,500	.87(2.21)		11.2
"		250,000	1.02(2.59)		-
8 "	23			.01(.03)	6.9
9 "	46			.01(.03)	2.0
10 "	70			.01(.03)	0.7
11 "				-	0.6
12 "				-	0.5
13 "				-	-
14 "				-	-
15 "				-	0.3

Table 6. Climatological data

Note: Data shown below were obtained each day at approx. 9 am. Therefore, the data obtained on a particular date actually represent the climatological conditions for the 24-hour period prior to observation. (Net evaporation = evaporation + precipitation; negative pan evap. indicates evap.< precip.)

Date of observ.	Air temp. (°F) max.	min.	Water temp. (°F) max.	min.	Wind Mean (mph)	Precipitation (in)	Pan evaporation (in)	Net evaporation (in)
June								
14	83	42	95	50	-	-	-	
15	82	43	87	55	-	.01	.31	.32
16	72	43	76	58	-	.01	.47	.48
17	86	43	85	58	-	0	.22	.22
18	81	61	88	62	-	0	.34	.34
19	89	61	92	66	4.2	1.05	(-.60)	.45
20	81	55	93	65	0.3	.05	.22	.27
21	82	62	93	67	1.0	.20	.05	.25
22	80	77	88	57	1.3	.30	.18	.48
23	74	48	89	56	0.6	.03	.25	.28
24	80	55	93	60	0.5	0	.23	.23
25	87	52	94	60	0.8	0	.18	.18
26	84	52	91	67	2.7	.12	.16	.28
27	88	65	90	68	4.7	.12	.31	.43
28	94	63	97	70	3.9	.17	.31	.48
29	87	69	99	73	1.0	.01	.23	.24
30	90	61	97	69	1.3	0	.44	.44
Mean:	84	56	91	62	1.9	.13	.21	.34
July								
1	87	61	94	68	1.3	0	.24	.24
2	88	63	86	67	1.2	.74	(-.46)	.28
3	74	63	76	65	0.4	.29	(-.26)	.03
4	71	60	75	64	0.6	0	.07	.07
5	76	54	86	63	0.6	.01	.17	.18
6	76	55	87	63	0.4	.02	.03	.05
7	85	60	94	64	1.2	.01	.35	.36
8	87	65	94	67	3.5	0	.21	.21
9	87	55	91	65	1.8	0	.24	.24
10	87	64	93	66	2.4	0	.25	.25
11	81	48	87	57	2.8	0	.19	.19
12	76	46	88	56	1.3	0	.33	.33
13	79	55	91	57	1.2	.09	.10	.19
14	81	57	86	63	2.4	.20	(-.06)	.14
15	89	61	94	67	1.2	.01	.37	.38
16	84	56	90	66	2.2	0	.20	.20
17	80	49	89	58	2.5	0	.29	.29
18	83	51	93	62	1.0	0	.31	.31
19	85	55	93	64	1.0	.01	.23	.24
20	90	63	96	66	1.1	0	.26	.26
21	93	68	99	72	1.2	0	.28	.28
22	99	67	93	73	3.8	0	.24	.24
23	93	65	94	71	3.9	0	.38	.38
24	92	64	92	69	3.8	.54	(-.08)	.46
25	77	60	80	69	0.3	.15	(-.05)	.10
26	77	64	80	70	1.6	.07	.01	.08
27	88	56	93	69	4.0	0	.29	.29
28	83	56	97	64	4.0	0	-	-
29	82	58	92	64	0.8	0	.14	.14
30	83	60	93	64	3.4	.27	(-.27)	0
31	76	59	92	64	0.1	.37	(-.28)	.09
Mean	83.5	59	90	65	1.8	.09	.13	.22
Aug								
1	79	55	80	60	0.8	.02	-	-
2	84	56	87	61	2.2	0	.15	.15
3	86	64	90	69	2.1	.01	.25	.26
4	88	54	85	60	2.3	.05	.24	.29
5	78	55	85	59	2.0	0	.17	.17
6	69	54	85	59	0.4	.58	-	-
7	78	53	85	60	0.1	1.5	-	-
8	81	56	83	61	3.6	.01	.18	.19
Mean	80	56	85	61	1.7	.27		.18
Total (55 days)						7.02		12.93
Mean	83.2	57.7	89.6	63.5		.13		.25

A 1.2 m high, 46-cm-diameter core was obtained from the area adjacent to the infiltration test site for further laboratory tests and analyses. The pit which was excavated to obtain the large core was used to make a detailed description of the soil profile, particularly soil structure and root distribution with depth.

Other tests. Water quality tests, including chemical and biological analyses, analyses of plant samples for nitrogen, phosphorus, potassium and heavy metal content and crop yield determinations were conducted by Ohio State University and will be discussed in a separate report.

The Surgeon General's Office conducted a "virus in, virus out" study in the lagoons during early August.

DISCUSSION OF RESULTS

Sensitivity Analysis

During the data reduction and water mass budget analysis, it became obvious that very small variations in the field measurements or in the computed values, depending on the method of data analysis, can result in very significant variations in the water budget values.

The computation of the changes in the soil water content resulting from wastewater application, and the computation of the amount of percolation into the underdrain system requires integration of areas under irregular curves or a sequence of straight lines connecting discrete data points. Since the applied water volume is relatively small in comparison with the total soil volume of the spray fields and the existing water in the soil, a small change in the soil moisture content represents a significant portion of the applied water volume. Therefore, the computation of the water budget values is very sensitive to the accuracy of the field measurements and to the manner in which the data representing the soil characteristics (density, specific gravity, volume of water and solids) are plotted and interpolated during computations.

Examples of the influence of measurement, analysis, or computational variations (or errors) in the 1) water content, 2) dry density of soil, 3) volumetric water content, and 4) specific gravity of solids on the water budget values are shown below.

Total volume of field, $V_T \approx$ 7,700,000 gal (three 3-acre plots = 3.64 ha, 80 cm deep; the depth of the underdrains was approximately 80 cm)

Typical volume of water applied, $V_{w(appl)} \approx$ 250,000 gal (which is equivalent to 2.6 cm of water on a 3.64 ha area, or 3.25% of V_T)

Typical mean values of the spray field soil profile (2 Aug 78):

Dry density of soil, γ	$\approx$ 1.6 g cm^{-3}	
Specific gravity, G_s	$\approx$ 2.7	
Gravimetric water content, w	$\approx$ 18%	
Volumetric water content, V_w	$\approx$ 29%	(Refer to block diagram, Fig. 4)
Volume of solids, V_s	$\approx$ 60%	
Volume of voids, V_v	$\approx$ 40%	
Volume of air, V_a	$\approx$ 11%	
Saturation, S	$\approx$ 73%	

1. Effect of variation in gravimetric water content

Example: 1% variation in w(%)

$w_1 = 18\%$

$w_2 = 19\%$

$\Delta w = 1\%$

$V_w(\%) = \gamma\, w(\%)$

$\Delta V_w(\%) = \gamma\, \Delta w(\%) = 1.6 \times 1 = \underline{1.6\%}$

In this case, a 1% change in w results in a 1.6% change in V_w. In terms of the total amount of water applied, this is equivalent to:

$$V_w(\text{gal}) = V_T(\text{gal}) \times \Delta V_w =$$

$$= 7{,}700{,}000 \text{ gal} \times 0.016 =$$

$$= 123{,}200 \text{ gal},$$

or approx. 49% of the water applied.

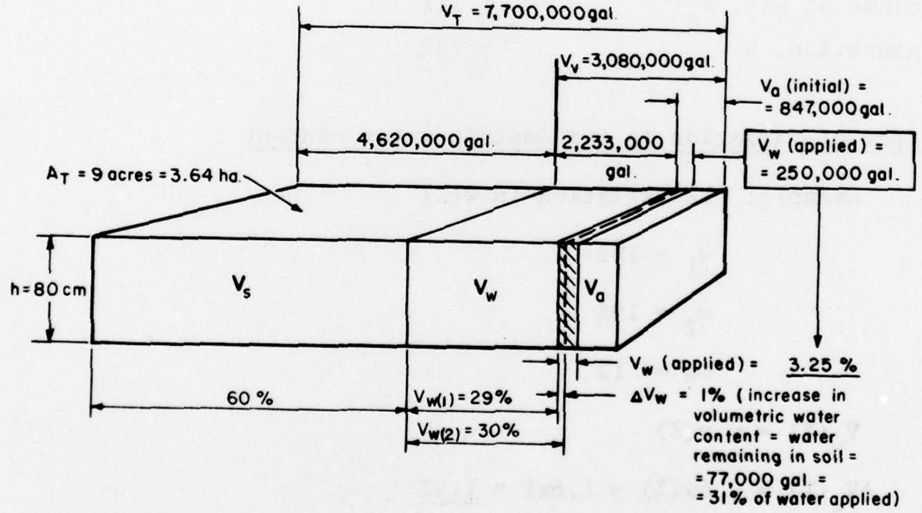


Figure 4. Block diagram of volume relationships.

A 0.5% change in w would result in a 0.8% change in V_w, or almost 25% of the total water applied. A 0.1% change in w would represent a 0.16% change in V_w, or almost 5% of the water applied.

2. Effect of variation in dry density

Example: 0.05 g cm^{-3} variation in γ

$$\gamma_1 = 1.55$$

$$\gamma_2 = 1.60$$

$$\Delta\gamma = \underline{0.05}$$

$$\Delta V_w(\%) = \Delta\gamma w(\%) = 0.05 \times 18 = \underline{0.9\%}$$

In this case, a 0.05 g cm^{-3} change in γ results in a 0.9% change in V_w. In terms of the total amount of water applied, this is equivalent to:

$$V_w(\text{gal}) = V_T(\text{gal}) \times \Delta V_w =$$

$$= 7{,}700{,}000 \text{ gal} \times 0.009 =$$

$$= 69{,}300 \text{ gal, or approximately } \underline{28\% \text{ of the water applied}}$$

A 0.01 g cm^{-3} change in the mean profile density would result in a 0.18% change in V_w, or 5.6% of the total water applied.

3. Effect of variation in volumetric water content

The mean V_w values for the soil profile during the 2 August 78 application were in the 27 to 33% range. It has been shown above that a change of 0.5% in the water content (w) or a change of 0.05 g cm^{-3} in the dry density of the soil (γ) results in a change of almost 1% in the volumetric water content (V_w). Therefore, a 1% variation in V_w is probably a realistic error to be expected due to measurement and analysis techniques.

Example: 1% variation in V_w (refer to Fig. 4)

$$V_{w(1)} = 29\%$$

$$V_{w(2)} = 30\%$$

$$\Delta V_w = \underline{1\%}$$

In terms of the total amount of water applied, this is equivalent to:

$$V_w(\text{gal}) = V_T(\text{gal}) \times \Delta V_w =$$

$$= 7{,}700{,}000 \times 0.01 = 77{,}000 \text{ gal, or}$$

approximately <u>31% of the water applied</u>

The effect on saturation due to a 1% change in V_w, using $V_v = 40\%$, would be:

$$S = V_w \div V_v$$

$$S_1 = 29 \div 40 = 72.5\%$$

$$S_2 = 30 \div 40 = 75\%$$

$$\Delta S = \underline{2.5\%}$$

A 0.5% change in the volumetric water content would be equivalent to approximately 15% of the total water applied, and would result in a change of a little over 1% in saturation.

<u>4. Effect of variation in specific gravity of soil</u>

Typical specific gravity values of the soil at this site are in the 2.66 to 2.76 range.

Example: 0.05 variation in G_s

$$G_{s(1)} = 2.66$$

$$G_{s(2)} = 2.71$$

$$\Delta G_s = \underline{0.05}$$

The resulting effect on the volume of solids (or the volume of voids) would be (using $\gamma = 1.6 \text{ g cm}^{-3}$):

$$V_s = \gamma \div G_s$$

$$V_{s(1)} \approx 60\%; \; V_{v(1)} \approx 40\%$$

$$V_{s(2)} \approx 59\%; \; V_{v(2)} \approx 41\%$$

$$\Delta V_s \approx \underline{1\%} \qquad \Delta V_v \approx \underline{1\%}$$

The effect on saturation due to a 0.05 change in G_s would be (using $V_w = 29\%$):

$$S = V_w \div V_v$$

$$S_1 = 29 \div 40 = 72.5\%$$

$$S_2 = 29 \div 41 = 70.7\%$$

$$\Delta S = \underline{1.8\%}$$

5. Effect of variation in the amount of water drained through the underdrain system

The estimated maximum error caused by the method of monitoring the flow at Point 5 during the 2 August 1978 application and the integration of the area under the flow rate versus time curve would not ordinarily exceed 5%. The amount of water drained off after 44 hrs was, in this case, 35,500 gal. A 5% error would cause a variation of:

35,500 gal x 0.05 = 1,775 gal, or

approximately <u>0.7% of the total water applied</u>

In computing the water mass balance, an error of less than 1% of the total water volume can be considered insignificant.

6. Effect of variation in the evapotranspiration

Since the ET value is not a direct measurement, but is computed or estimated from pan evaporation data based on climatological conditions, it is felt that an error as high as 10% of the total water volume applied is possible.

Summary (for wastewater application of 2.6 cm)

Parameters	Variation (Δ)	Resulting variation in V_w (ΔV_w)	% of total water applied
Water content, w(%)	0.1%	0.16%	5%
	0.5%	0.8 %	25%
	1.0%	1.6%	49%
Dry density, γ(g cm^{-3})	0.01 g cm^{-3}	0.18%	5.6%
	0.05 g cm^{-3}	0.9 %	28%
Volumetric water content, V_w(%)		0.5%	15%
		1.0%	31%

Therefore, for a 2.6-cm water application on a 3.64-ha area, a 1% change in the volumetric water content is equivalent to almost 1/3 of the total water applied. For a 5.2-cm application, a 1% change in V_w would be equivalent to only 1/6 of the water applied.

If it is desired to keep the water mass budget computations within a 20% error (10% due to errors in each, w and γ), the volumetric water content data have to be kept to within a 0.65% error, requiring the water content (w) data to be within a 0.2% error and the dry density data within a 0.02 g cm^{-3} error, not considering errors in computing ET.

If the contributing error from estimating the ET is 10%, the drainage amount error is considered insignificant, and the error in computing the amount of applied water remaining in soil is to be kept at 10% (in order for the cumulative error not to exceed 20%), the water content and dry density errors have to be limited to half of the values shown above.

Example:

Error in w: 0.1% = 0.16% error in V_w(%)

Error in γ: 0.01% g cm^{-3} = 0.18% error in V_w(%)

Total: 0.34% error in V_w(%)

0.34% error in V_w(%) = 7,700,000 gal x 0.0034 = 26,180 gal

10% error in computing ET = 250,000 gal x 0.1 = 25,000 gal

Total: 51,180 gal $\approx$

$\approx$ 20% of total water applied

Therefore, great care has to be exercised in the field measurements, data plotting and analysis, if the desired accuracy of the mean water content profile is to be kept to ± 0.1%, and that of the dry density profile to ± 0.01 g cm^{-3}, in order to stay within a 10% error of the total water volume applied. This degree of accuracy may, however, be difficult to achieve in field measurements.

The relationship between dry density of soil, gravimetric water content, volumetric water content and the resulting total volume of water for the 3.64-ha (9-acre) test field is shown in the nomogram (Fig. 5).

The example shown in the nomogram is as follows: for a dry density of 1.6 g cm^{-3} and a gravimetric water content of 18%, the resulting volumetric water content is 28.8%, representing a total volume of water of 8.37 Mℓ (2.21 Mgal) in the test field. An increase in the gravimetric water content to 19% corresponds to a volumetric water content of 30.4% (an increase of 1.6%), representing a water volume of approximately 8.82 Mℓ (2.33 Mgal), or an increase of approximately 0.45 Mℓ (0.12 Mgal). The increase in the volumetric water content (%) in terms of the actual volume of water (ℓ or gal) or the equivalent percentage of total water applied, is shown in Figure 6.

It should be pointed out that in this case an error or variation of only 0.33% in the volumetric water content is just as serious as a 10% error in ET.

Field Data

Soil density and specific gravity. The dry density profile data (Table 2) obtained from the three test sites are plotted in Figure 7. The scatter of data is quite significant, indicating that the soil density profile varies considerably throughout the test area. The scatter may also be caused by different measurement techniques or by differences in the water content during density measurements due to shrinkage or swelling of the soil because of its high clay content. The dashed line, constructed by computing the mean density at the various depths where data were available, represents the mean dry density profile of the test area. The mean density for the 0 to 80 cm depth of soil, integrated at 5-cm increments, is 1.59 g cm^{-3}. The mean density values for the individual test plots are as follows:

Grass plot:	1.58 g cm^{-3}
Soybean plot:	1.58 g cm^{-3}
Alfalfa plot:	1.60 g cm^{-3}

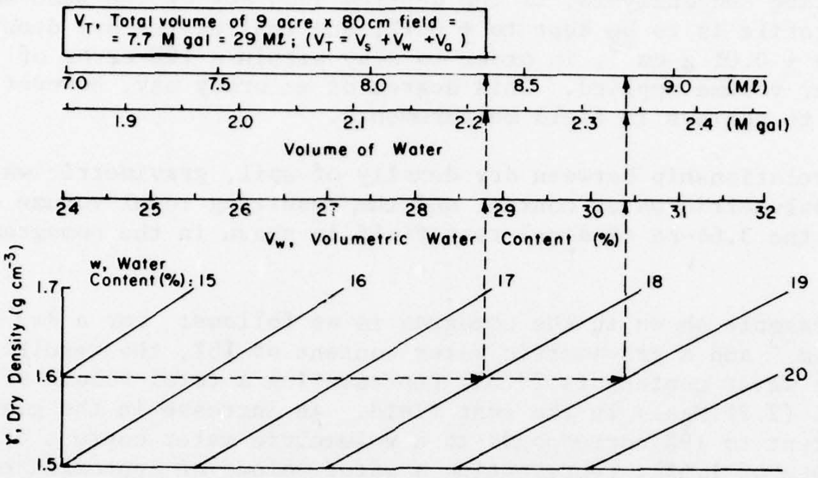


Figure 5. Relationship between dry density, gravimetric water content, volumetric water content, and volume of water in soil.

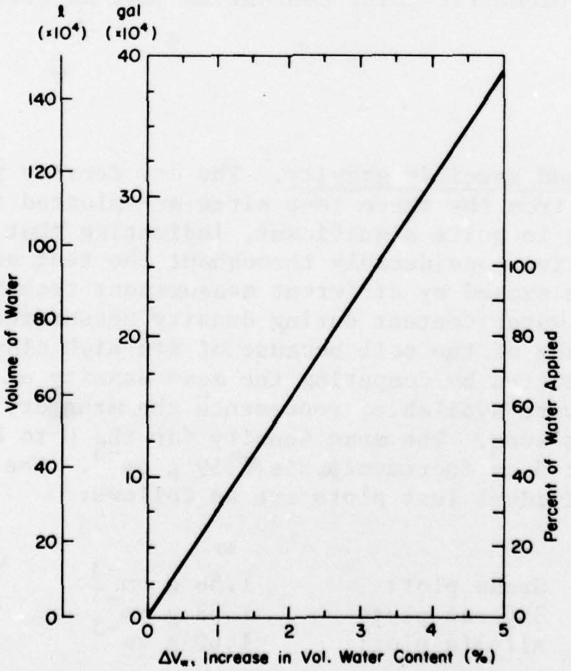


Figure 6. Volume of water vs increase in water content.

It is interesting to note that, although the variation in data (width of the data envelope in Fig. 7) at any particular depth is, for the most part, greater than 0.2 g cm^{-3}, the variation between the 0 to 80-cm mean density values for the three test plots is only 0.02 g cm^{-3} (two of the mean values being identical).

The specific gravity data (Table 2) are plotted in Figure 8. The mean G_s value for the 0 to 80-cm depth is 2.71 (integrated at 5-cm increments). It was assumed that the 20-cm value is representative of the 0 to 20-cm depth.

Soil water content. The mean soil water content (w) profiles for the three test plots prior to the 2 August wastewater application are shown in Figure 9. The profiles of the grass and alfalfa test plots are reasonably similar. The soybean plot data were obtained from the pit at one end of the test plot (refer to Fig. 2) slightly outside the spray area. The soybean plot water content profile below 35 cm is significantly different from the profiles of the grass and alfalfa plots. (The initial saturation values for 0 to 80-cm depth were: grass plot: 65%; alfalfa plot: 68%; soybean plot at pit site: 80%.)

The corresponding volumetric water content (V_w) profiles are plotted in Figure 10. The V_w values were computed by using the density data for each individual test plot (Table 2), not the mean density profile shown in Figure 7.

For the water budget analysis, only the water content data from the grass and alfalfa plots were used as representative of the 3.64-ha (9-acre) test area, since 1) no water content data were obtained in the soybean plot during or after the wastewater application because of time constraints, and 2) the data from the pit may not have been representative of the initial (before application) water content profile of the soybean plot.

The actual data points of the initial water content in the grass and alfalfa plots (Table 4) on 2 Aug are plotted in Figure 11a; Figures 11b through 11d show the water content during and after the wastewater application. The lines in Fig. 11 represent the mean profiles from the combined grass and alfalfa data.

It is apparent that the 8.5 hour water content data (2 hrs after end of application) are lower than those before, during, or 2 days after application. The available data are not adequate to explain this.

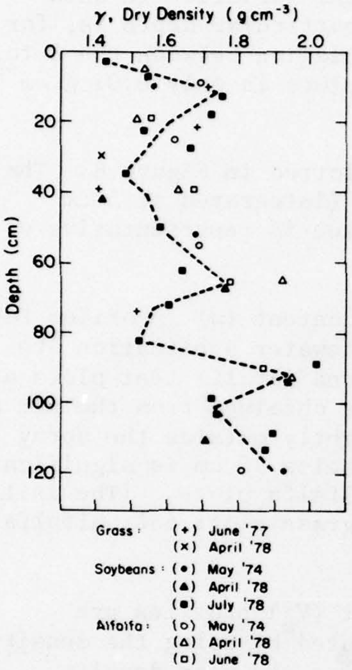


Figure 7. Dry density profile of test area.

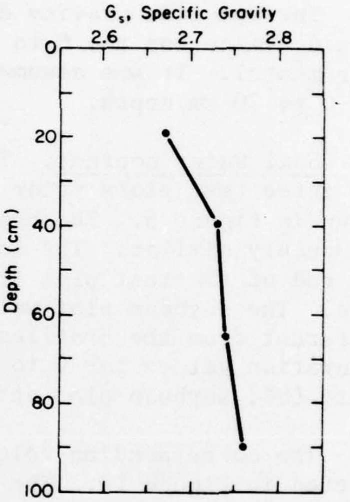


Figure 8. Specific gravity profile of test area.

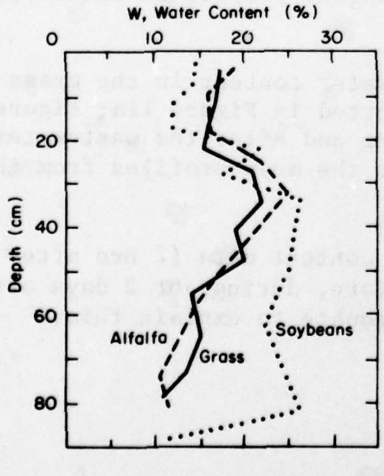


Figure 9. Gravimetric water content before application.

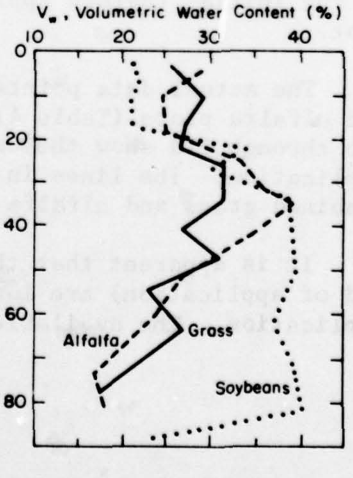


Figure 10. Volumetric water content before application.

The mean water content values (combined data from the grass and alfalfa plots) are as follows:

Time			Mean w(%)
Before	application	(0 hrs)	17.18
During	"	(4 hrs)	18.30
After	"	(8.5 hrs)	16.35
"	"	(44 hrs)	17.94

Consequently, the water budget calculations were limited to the 4- and 44-hour data.

The water content (w) profiles for 0 and 4 hrs are compared in Figure 12a, and for 0 and 44 hrs in Figure 12b. The corresponding volumetric water content (V_w) profile comparison is shown in Figure 13. It appears that the depth increments for the 4 and 44-hr water content data (approximately 15 cm between samples) may have been too large, possibly causing some of the high water content locations to be missed (at 25, 35, and 45 cm, for example). This problem is even more apparent in Figure 14, where all three components of the soil profile (volume of solids, volume of water, and volume of air) are shown.

If $V_s + V_w$ profile lines were plotted from the available data for 4 and 44 hours and compared with the $V_s + V_w$ profile before application, it would appear that at certain depths (at 10 to 15 cm and at 25 to 30 cm, in particular) the volume of water had decreased after application. This impression is due to the lack of data for the 4 and 44-hour water content conditions at certain specific depths where the before-application data (obtained at approximately 5-cm increments) indicate noticeable peaks in the $V_s + V_w$ profile (refer to Fig. 14).

Therefore, it is evident that water content data obtained at 15-cm increments with depth may not be sufficient to provide accuracy of the $V_s + V_w$ profile to a 5% level. Data obtained at 5-cm increments would increase the profile accuracy. Also, it is very important that the data at the various time intervals be obtained at the same depth in order to permit a reliable comparison of the "before" and "after" water content conditions. The question still remains whether or not the sampling done at one location in each plot is representative of the entire plot.

Drainage rate. A record of the drainage flow rate at the underdrain discharge point (Point 5; refer to Fig. 2) and the wastewater application and precipitation data are shown in Figure 15. A total of almost 2 cm of rainfall occurred shortly prior to and during the 10 August application, resulting in an exceptionally high peak flow.

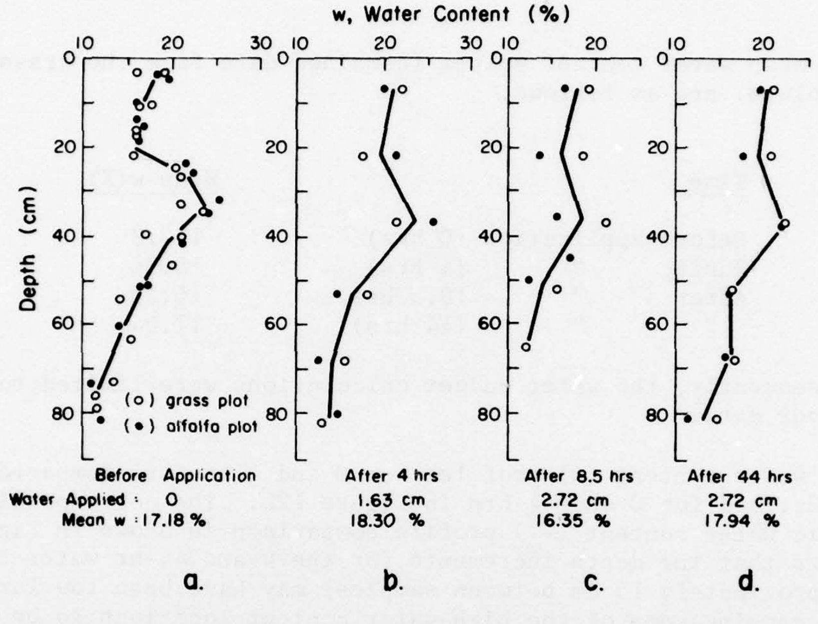


Figure 11. Gravimetric water content profiles before, during, and after application.

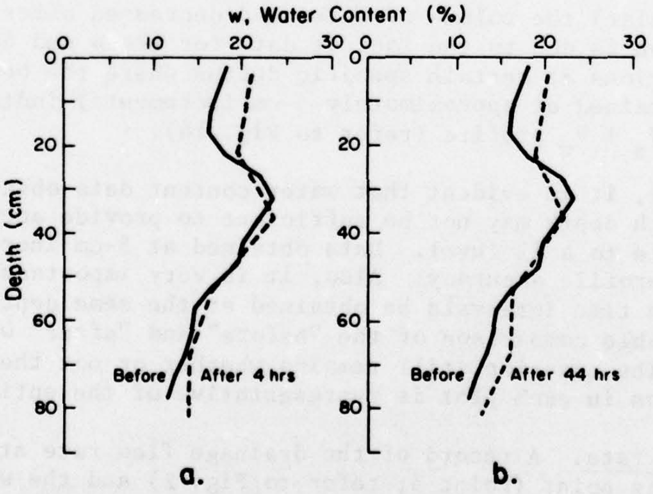


Figure 12. Mean gravimetric water content profiles of test area.

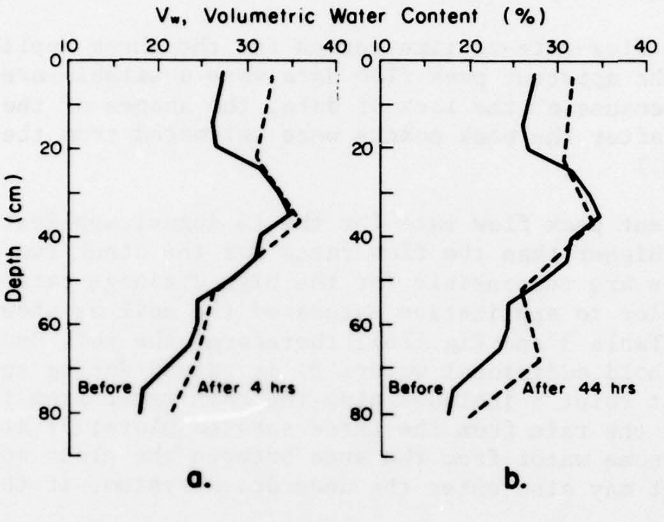


Figure 13. Mean volumetric water content profiles of test area.

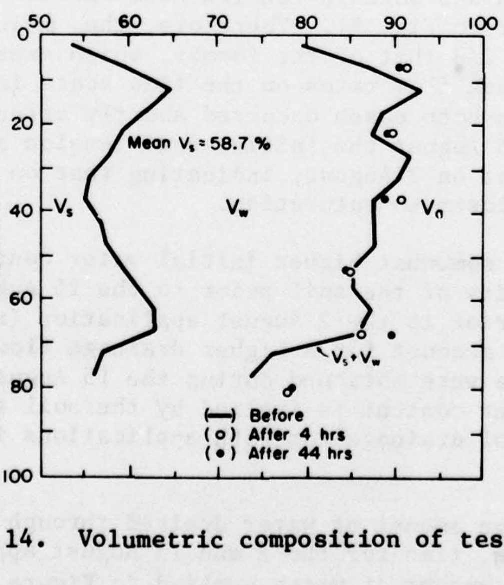


Figure 14. Volumetric composition of test area.

During the 22 August and 7 September applications, the peak flow points were apparently missed.

The drain flow-rate-vs-time curves for the three applications during which the apparent peak flow data were available are plotted in Figure 16. (Because of the lack of data, the shapes of the 10 and 15 August curves after the peak points were estimated from the shape of the 2 August curve.)

The apparent peak flow rate for the 10 August application is significantly higher than the flow rates for the other two applications. Several factors are responsible for the high drainage rate in this case: 1) rainfall prior to application saturated the soil as shown by the soil tension data (Table 3 and Fig. 16); therefore, the soil had very little capability to hold additional water; 2) it rained during application and the drainage at Point 5 includes also the rain water from the tree plot, in addition to the rain from the three sprayed plots; 3) it may be possible that some water from the area between the plots and the drainage discharge point may also enter the underdrain system, if the drain pipes are cracked.

It is not completely clear why the peak flow rate for the 15 August application is twice as high as that for the 2 August application. The amount of wastewater applied in both cases was approximately the same, and rainfall was not a factor. The rate of application and the initial water content were the principal differences the 2 August application was done in 5 increments during a 6.5-hour time period, while the 15 August application was done in ten 1/2 hour increments during a 9.7-hour time period (refer to Fig. 3). Therefore, the mean rate of application of the latter was 2/3 that of the former, which explains the relative location of the peak flow rates on the time scale in Figure 16. The peak flow rates in both cases occurred shortly after the end of application. Also, on 15 August the initial soil tension at the 25 cm depth was lower than that on 2 August, indicating that on 15 August the soil below 25 cm was closer to saturation.

Because of a somewhat higher initial water content, the water retention capability of the soil prior to the 15 August application was lower than that prior to the 2 August application (refer to soil tension data) which would account for a higher drainage flow rate. No direct water content data were obtained during the 15 August application; the difference in water content is implied by the soil tension data. After 2 days, the rate of drainage for both applications is approximately the same.

The cumulative amount of water drained through the underdrain system, plotted vs. time for the 2 and 15 August applications, is compared with the amount of water applied in Figure 17. After 1 day,

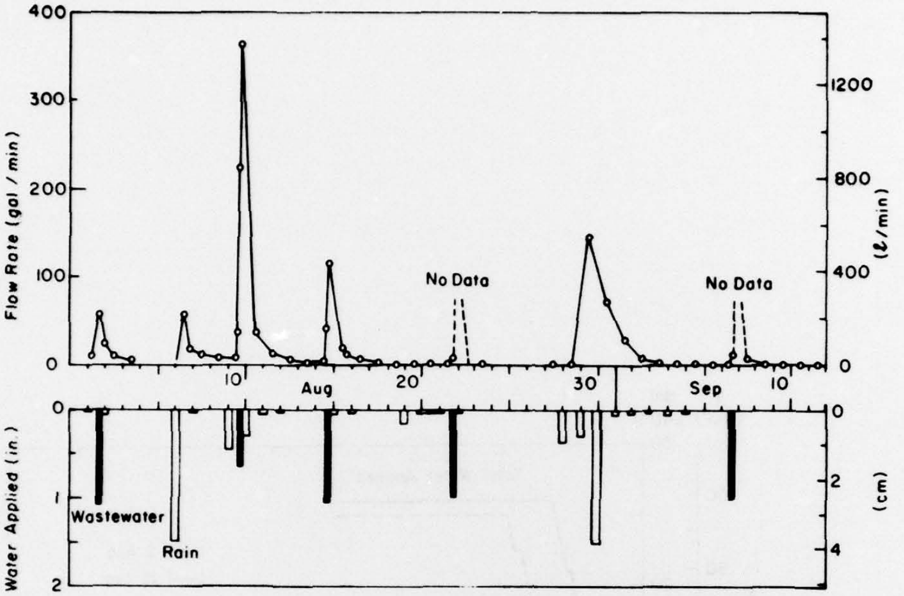
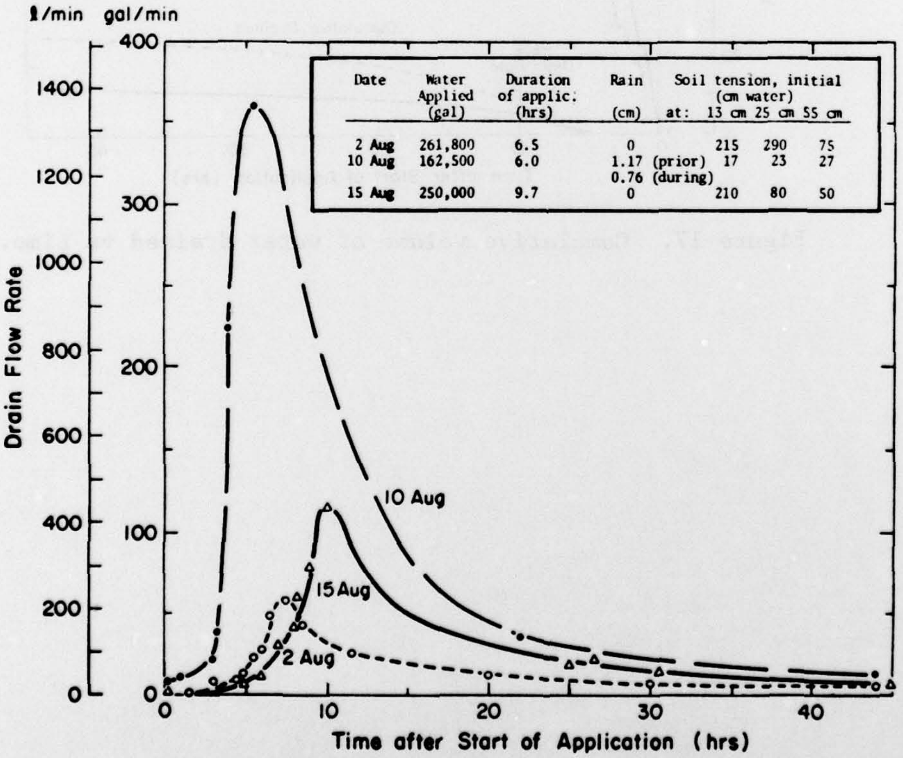


Figure 15. Drain flow rate compared with wastewater applied and rain.



Date	Water Applied (gal)	Duration of applic. (hrs)	Rain (cm)	Soil tension, initial (cm water) at: 13 cm	25 cm	55 cm
2 Aug	261,800	6.5	0	215	290	75
10 Aug	162,500	6.0	1.17 (prior) 0.76 (during)	17	23	27
15 Aug	250,000	9.7	0	210	80	50

Figure 16. Drain flow rate vs time.

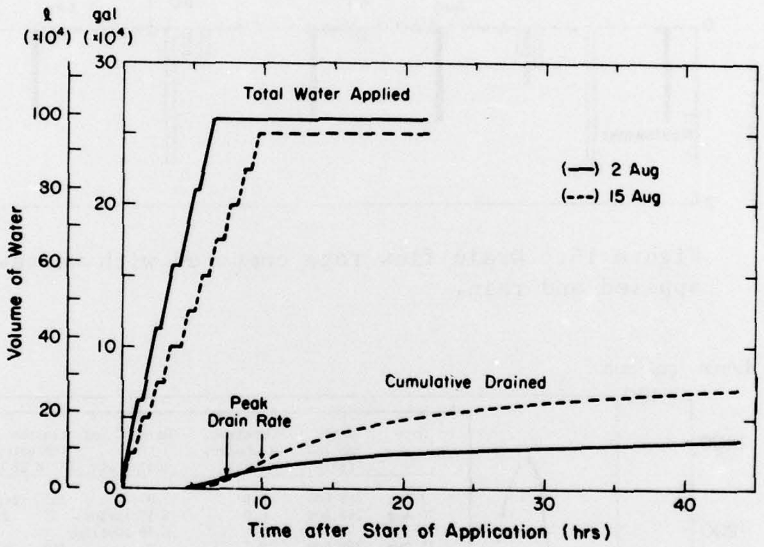


Figure 17. Cumulative volume of water drained vs time.

the cumulative drainage for the 15 August application is approximately twice that of the 2 Aug application.

The vertical distance between "total water applied" and "cumulative drained" lines in Fig. 17 indicates the amount of water remaining in the soil and lost due to evaporation and transpiration.

The cumulative drainage figures for the 2, 10, and 15 August applications at various times after the start of application are compared in Table 7.

Table 7. Cumulative drainage

Date	Time (hrs): 4	8	12	24	44	% of applied (44 hrs)
	Amount of water drained (gal)					
2 Aug	1,400	10,740	17,940	28,350	35,350	13.6%
10 Aug	18,480	92,280	133,080	174,180	197,340	*
15 Aug	600	6,960	29,160	55,680	70,320	28.1%

*Not determined due to uncertain amount of rain.

Evapotranspiration. The percentage of water lost to ET during the 2 August application was estimated from methods discussed in literature (Chang, 1968; Bilello and Bates, 1978). The usual method for estimating ET (80% of pan evaporation during the day of application) resulted in a value of approximately 0.5 cm (80% x 0.26 in; refer to Table 6), or approximately 18% of the water applied. The ET during the next day was estimated from transpiration vs. volumetric water content relationship (Chang, 1968), resulting in a value of less than 0.25 cm, or approximately 10% of the water applied. Therefore, the total estimated ET after 44 hours was 28% of the water applied. During application (after 4 hours) the ET was estimated to be 1%.

Water Budget Analysis

The relationship of the principal components in the water budget can be expressed by:

Water applied + precipitation = water drained +
+ water remaining in soil +
+ water lost due to evapotranspiration

Other components, such as water in the drainage and spray systems and in the soil below the drains were considered insignificant for calculating the total budget.

The amount of water drained through the underdrain system, obtained by integrating the area under the 2 August curve in Figure 16 (the curve was replotted on an expanded scale for area integration), was:

After 4 hrs: 1,400 gal
After 44 hrs: 35,500 gal

The estimated amount of water lost to evapotranspiration was:

After 4 hrs: 1% x 156,900 (gal applied) = 1,600 gal
After 44 hrs: 28% x 261,800 (gal applied) = 73,300 gal

Therefore, the total amount of water lost due to drainage and evapotranspiration (D + ET) was:

After 4 hrs: 3,000 gal
After 44 hrs: 108,800 gal

The amount of water remaining in soil was computed by a number of methods, depending on the procedure used for calculating the water content from the data available. Although the variations in the water content values between the results of the various computation methods appear to be very small numerically, their effect on the total water budget can be quite significant, as discussed previously under "Sensitivity analysis."

Six methods of computation were used for determining the amount of water remaining in the soil after 4 and 44 hours. The first three methods used the gravimetric water content profiles and the mean dry density values, while the other three methods used the volumetric water content profiles. The results are listed in Table 8.

Method No. 1: The gravimetric water content profiles were plotted separately for the grass, alfalfa, and soybean plots (Fig. 9); the mean value of each profile was calculated by using values from each profile at 5-cm depth increments and then multiplied by the corresponding mean dry density profile value (Fig. 7) to obtain the mean volumetric water content value. Since water content data during and after application were obtained only on the grass and alfalfa plots, the mean of these two profiles at 0, 4, and 44 hrs was used as the mean water content in the 3.64-ha (9-acre) test field.

Method No. 2: One gravimetric water content profile was plotted using the combined grass and alfalfa data for each observation time (Fig. 11) and the mean value for each profile computed as in Method No. 1, using 5-cm-depth increments and the mean dry density profile value.

Theoretically, both methods would give the same results, if the same number of data points were obtained at the same depth for both test plots. Since this was not the case, there is some variation between the results from the two methods.

Method No. 3: The areas between the mean 0-hr and 4-hr and between the 0-hr and 44-hr gravimetric water content profiles (Fig. 12) were integrated by measurement at 2-cm-depth increments, and these values were multiplied by the mean dry density to obtain the corresponding difference in the volumetric water content.

Method No. 4: The gravimetric water content values were taken at 5-cm increments from the mean water content profiles (Fig. 11) and multiplied by the corresponding dry density values, resulting in a volumetric water content profile for each of the 0, 4, and 44-hr observation times (Fig. 13). The mean value of each profile was then calculated, using the values at 5-cm-depth increments.

Method No. 5: Comparisons between the mean initial volumetric water content profile and those of 4 and 44 hours were made at those depths where actual data were obtained after 4 and 44 hours; i.e., the mean value of each profile was calculated using approximately 15-cm-depth increments.

Method No. 6: Same procedure as in Method No. 3, except the areas integrated (measured) were from the volumetric water content graphs (Fig. 13), instead of the gravimetric water content graphs.

The values representing the amount of water remaining in soil after 4 and 44 hours, computed by using the six analysis methods, are summarized in Table 8.

The area integration methods (Nos. 3 and 6) resulted in values that are too high at 4 hours; i.e., the amount of water remaining in soil was greater than the amount applied during the first 4 hours of spraying. This was also the case with Method No. 4. In general, calculations using the volumetric water content data (Methods 4 through 6) resulted

Table 8. Results of calculations for water remaining in soil.

Analysis	Time	w(%)	γ(g cm^{-3})	V_w(%)	Water remaining in soil		D+ET (gal)	Total (gal)	% of applied
					ΔV_w(%)	ΔV_w(gal)			
(Grass)	Before	17.03	1.58	26.91	-				
	4 hrs	18.47	1.58	29.18	2.27				
	44 hrs	19.00	1.58	30.02	3.11				
(Alfalfa)	Before	17.53	1.60	28.05	-				
	4 hrs	18.34	1.60	29.34	1.29				
	44 hrs	17.66	1.60	28.26	0.21				
No. 1 (Mean)	Before	17.28	1.59	27.48	-	-			
	4 hrs	18.41	1.59	29.27	1.79	137,800	3,000	140,800	89.7
	44 hrs	18.33	1.59	29.14	1.66	127,800	108,800	236,600	90.4
No. 2	Before	17.18	1.59	27.32	-	-			
	4 hrs	18.30	1.59	29.10	1.78	137,000	3,000	140,000	89.2
	44 hrs	17.94	1.59	28.52	1.20	92,400	108,800	201,200	76.9
No. 3	Before	-	1.59	-	-	-			
	4 hrs	Δ_w=1.35	1.59	-	2.15	165,500	3,000	168,500	107.4
	44 hrs	Δ_w=1.25	1.59	-	1.99	153,200	108,800	262,000	100
No. 4	Before	-	-	27.25	-	-			
	4 hrs	-	-	29.30	2.05	157,800	3,000	160,800	102.5
	44 hrs	-	-	29.23	1.98	152,500	108,800	261,300	99.8
No. 5	Before	-	-	26.84	-	-			
	4 hrs	-	-	28.62	1.78	137,000	3,000	140,000	89.2
	44 hrs	-	-	28.56	1.72	132,400	108,800	241,200	92.1
No. 6	Before	-	-	-	-				
	4 hrs	-	-	-	2.45	188,600	3,000	191,600	122.1
	44 hrs	-	-	-	2.30	177,100	108,800	285,900	109.2
Mean	Before			27.2*	-				
	4 hrs			29.1*	2.00	154,000	3,000	157,000	100
	44 hrs			28.9*	1.81	139,200	108,800	248,000	94.8

* Mean of 4 analyses only

in higher values than those using the gravimetric water content and mean dry density data (Methods 1 through 3).

Assuming that the measurement as well as the analysis errors are as likely to be positive as negative, the logical approach for computing the most realistic value of the amount of water remaining in soil appeared to be the use of the mean value from the six separate analysis methods. By doing that, it was possible to account for all of the water applied at 4 hours and approximately 95% of the water two days after application (Table 9).

These results illustrate the great sensitivity of the results to the method of analysis or computation procedure used. At 4 hours after the beginning of application, for example, three analysis methods result in values that are too low, and the other three methods give values that are too high, but the mean value of all six corresponds to the exact theoretical value of the amount of water remaining in the soil (i.e., water in soil = water applied - water drained - water lost to ET).

At 44 hours after the beginning of application, the amount of water unaccounted for is approximately 5%. The values for the percentage of water accounted range from approximately 77% to approximately 109% from the six analyses, the mean being 94.8% (refer to Table 8).

The volumetric water budget values for the 2 Aug wastewater application are summarized in Figure 18. The bar graph on the left shows the volumetric composition of the test field during (at 4 hrs) the wastewater application. The one on the right shows the volumetric composition after 44 hours. The applied water volume is also illustrated on an expanded scale to show the distribution of the applied water.

Infiltration Rate

Results of the infiltration test conducted near the pit at one end of the soybean plot are shown in Figure 19. A total of approx. 5.1 cm of water was applied to the test area. It is estimated from evaporation data that approximately 0.5 cm of water was lost to evapotranspiration. After 24 hours, there was no free water (ponding) on the soil surface. The saturation of the soil prior to application was approximately 80%. The initial water content profiles at this site are shown in Figures 9 and 10.

During the first hour after application, the rate of infiltration (determined from the slope of the curve in Fig. 19) was approximately 1 cm per hour. After 6 hours, the rate was approx. 0.2 cm per hour, decreasing eventually to approx. 0.1 cm per hour. According to the USDA-SCS permeability classification for saturated soils, these rates would be comparable to a range from moderately slow (1 cm hr^{-1}) to very slow (0.1 cm hr^{-1}) infiltration.

Table 9. Summary of water budget.

	After 4 hours			After 44 hours		
	ΔV_w(%)	V_w(gal)	% of applied	ΔV_w(%)	V_w(gal)	% of applied
Water applied (during 6.5 hours)		156,900			261,800	
Water remaining in soil						
Analysis No: 1	1.79			1.66		
2	1.78			1.20		
3	2.15			1.99		
4	2.05			1.98		
5	1.78			1.72		
6	2.45			2.30		
Mean:	2.00	154,000	98%	1.81	139,200	53.2%
Water drained:		1,400	1%		35,500	13.6%
Evaportranspiration:		1,600	1%		73,300	28%
Total:		157,000	100%		248,000	94.8%
Unaccounted:		-	-		13,800	5.2%

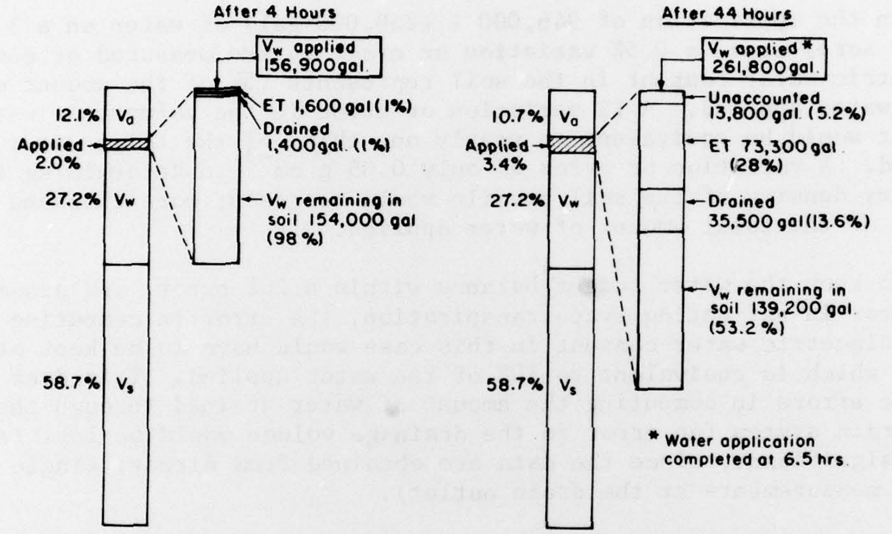


Figure 18. Volume relationships and water budget (2 Aug 1978).

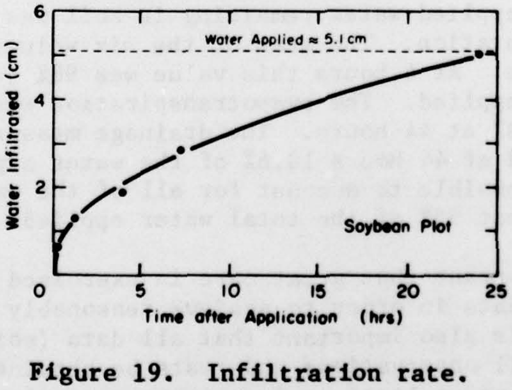


Figure 19. Infiltration rate.

SUMMARY AND CONCLUSIONS

Computation of the water budget values during and after water application is very sensitive to the accuracy and variations in the field measurements of water content and physical soil properties and to the method used in data analysis and calculations.

In the application of 946,000 ℓ (250,000 gal) of water on a 3.64-ha (9- acre) area, a 0.5% variation or error in the measured or computed volumetric water content in the soil represents 15% of the amount of total water applied. A 1% variation or error in the volumetric water content would be equivalent to nearly one third of the total water applied. A variation or error of only 0.05 g cm^{-3} in determining the mean dry density of the soil profile would represent more than one fourth of the total amount of water applied.

To keep the water budget balance within a 20% error, and assuming a 10% error in estimating evapotranspiration, the error in computing the soil volumetric water content in this case would have to be kept at 0.32%, which is equivalent to 10% of the water applied. This does not include errors in computing the amount of water drained through the underdrain system (an error in the drainage volume would be less likely to be significant, since the data are obtained from direct, single source measurements at the drain outlet).

The water budget in the test area was calculated for the wastewater applied on 2 August. A total of 991,000 ℓ (261,800 gal) equivalent to 2.72 cm (1.07 in) on a 3.64-ha (9-acre) area, were applied during a period of 6.5 hours. The calculations were done for the water budget at 4 hours (during application) and at 44 hours (almost 2 days after application).

The volume of applied water remaining in soil was calculated using six methods of computation. The mean of the six values was used as the representative value. At 4 hours this value was 98% and at 44 hours 53.2% of the water applied. The evapotranspiration was estimated to be 1% at 4 hours and 28% at 44 hours. The drainage measured at 4 hours was approximately 1% and at 44 hours 13.6% of the water applied. Therefore, at 4 hours it was possible to account for all of the water applied and at 44 hours for almost 95% of the total water applied.

It is very important that great care is exercised in obtaining the soil water content data in order to achieve reasonably accurate water budget values. It is also important that all data (soil density and water content) in all observations and tests be obtained at the same depth to permit a more realistic and accurate comparison of the soil characteristics before, during and after water application.

The accuracy in computing the water mass balance would increase proportionally with an increase in the amount of water applied.

An in-situ infiltration test conducted on the soybean plot indicated that on the day of the test (31 July 1978) the infiltration rate at this site (initial saturation approximately 80%), ranged from approximately 1 cm per hour during the first hour after application to approximately 0.1 cm per hour 1 day after application.

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APPENDIX: SOIL TENSION VS TIME AND DEPTH

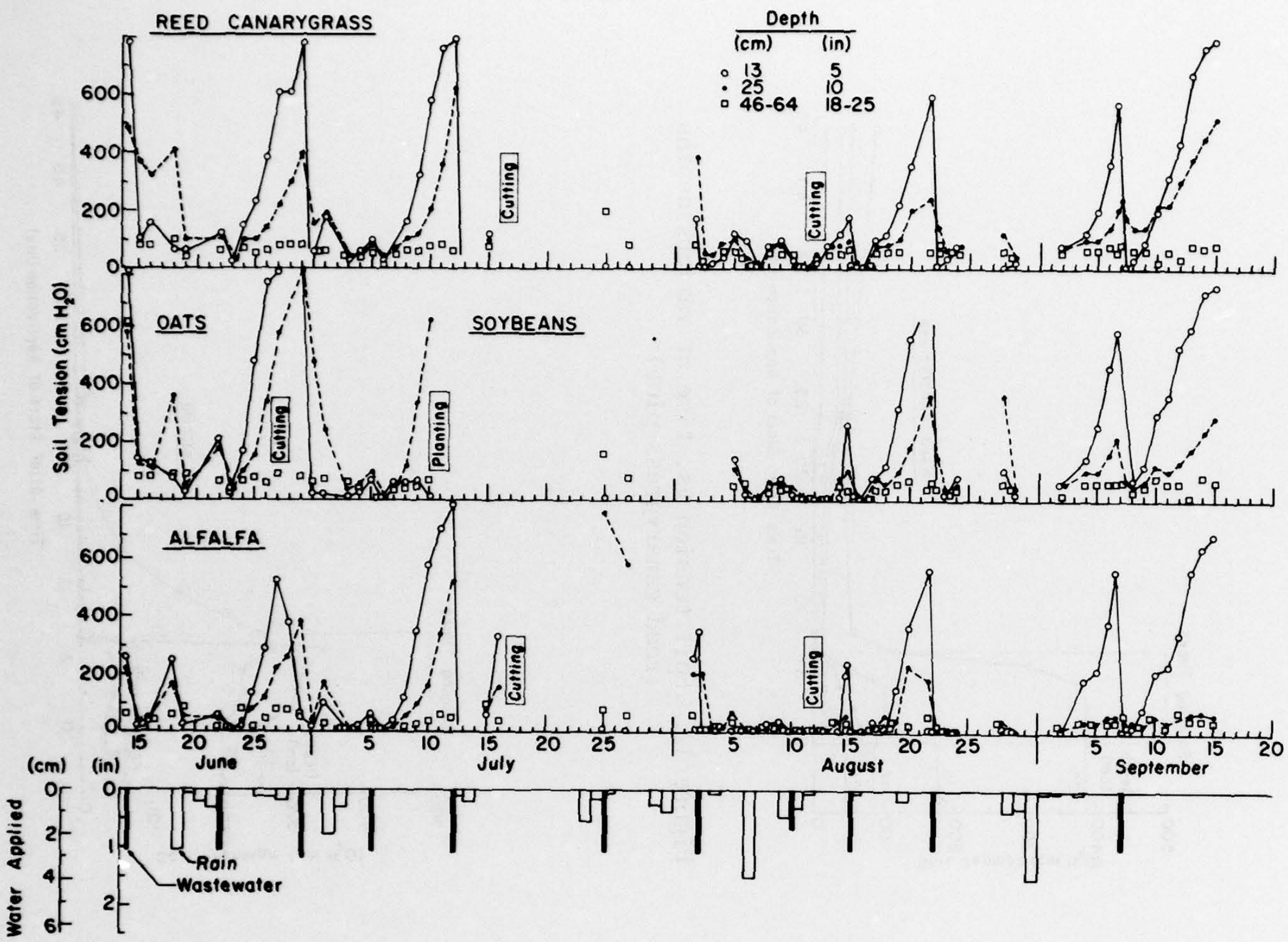

Figure A1. Soil tension vs. time.

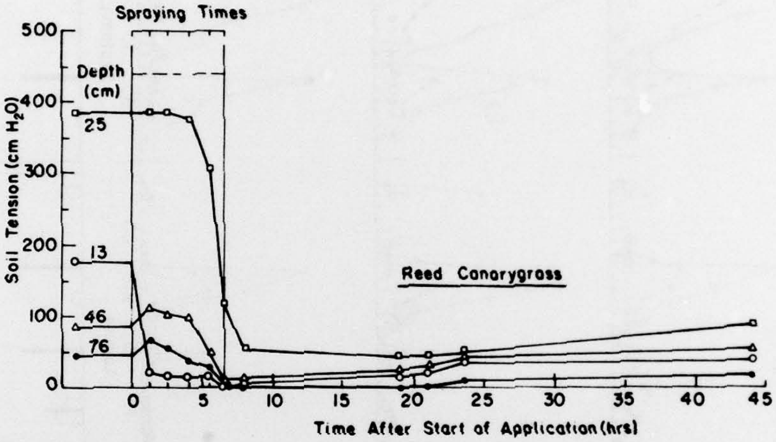

Figure A2. Soil tension vs. time at various depths (reed canarygrass plot)

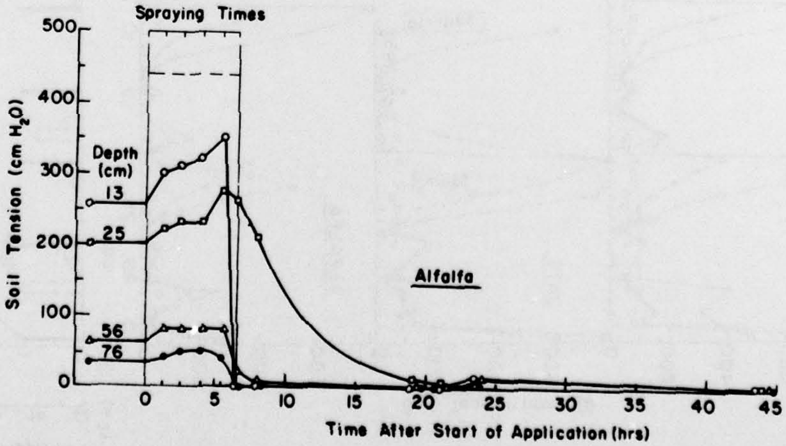

Figure A3. Soil tension vs. time at various depths (alfalfa plot)

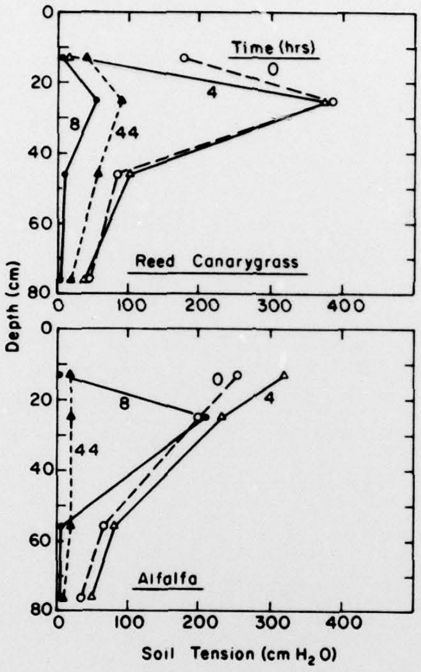

Figure A4. Soil tension vs. depth.