UNITED STATES DEPARTMENT OF AGRICULTURE

Miscellaneous Publication No. 372

Washington, D. C. May 1940

A SURVEY AND DISCUSSION OF LYSIMETERS

AND

A BIBLIOGRAPHY ON THEIR CONSTRUCTION AND PERFORMANCE

By

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Superintendent of Documents, Washington, D. C. Price 10 cents

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LYSIMETERS: A SURVEY AND DISCUSSION

By HELMUT KOHNKE and F. R. DREIBELBIS [1]

INTRODUCTION

With the great impetus that soil conservation and flood-control work have given to the study of the relations of water to soil, lysimeters have received wider attention during the past decade than at any previous time. They have been used for at least two and a half centuries in studies of the percolation of water through soil. The purpose of such studies may be strictly hydrological, attention being given only to the rate and amount of the percolate. In most of the more recent investigations the chemical composition of the percolate is analyzed, generally as a part of the study of the fertility balance of the soil, but, in some cases, in connection with studies of the genesis and development of soils.

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[1] The authors wish to express their appreciation to W. U. Garstka, Hydrologic Division, Soil Conservation Service, for guidance and valuable assistance given in the development of this publication.

CLASSIFICATION OF LYSIMETERS

Lysimeters, classified according to the principles of construction, are of three major types: (1) Monolith, or undisturbed soil-block; (2) Ebermayer, and (3) Filled-in.

In the first type, a case is built around the sides of a block of soil as it is found in the field, a partly open bottom is attached, and the percolate is conducted to receiver tanks. In the Ebermayer type, the soil is left in situ and a percolate collecting funnel is placed under it, but no side walls separate a definite soil block from the adjoining soil. A tube attached to the funnel conveys the percolate into a receptacle. The filled-in type consists of a container, which has vertical walls, an open top, and a bottom that provides for percolation and is filled with soil that has been removed from its original location and that usually has been screened and mixed in order to make it uniform. In some lysimeters of this type the tops of the side walls are completely covered with soil so that the ground is level with the surrounding soil. This construction permits natural run-off and eliminates the border effect resulting from the unplanted area along the rim of the lysimeter. In these lysimeters an attempt is made to combine the advantages of both the filled-in and the Ebermayer types. A special kind of the filled-in type can be called the laboratory lysimeter, which is usually small in size and artificially supplied with water or a solution. It is used to study specific problems; and experiments with it are usually restricted to short periods because the rather unnatural conditions tend quickly to deteriorate the soil.

Lysimeters may also be classified according to the type of provision made for the run-off of rain water that falls in excess of the infiltration rate. The following classes are in use:

(1) Unlimited run-off: The Ebermayer lysimeters allow unrestricted run-off, since they have no side walls. A number of the more recent lysimeters of the soil-block type (table 1) are constructed to permit run-off, as are also the filled-in types at San Dimas and Berkeley, Calif. (4, *8, 10)*,[2] and at La Crosse, Wis. *(205)*.

(2) Run-off through overflow pipes: Some lysimeters are provided with overflow pipes a short distance above the soil surface. This permits the water of very large rainstorms to run off, but a certain amount of water will remain standing on the soil surface. Dalton *(211)* recognized the necessity of natural run-off and installed a vertical overflow pipe in his first lysimeter. The soil soon settled below the level of the pipe opening, however, making the device ineffective. Among the more recent installations only the two sets of lysimeters in India are equipped with horizontal overflow pipes, which are about 3 inches above the ground. No run-off: The great majority of the lysimeters of the filled-in type (and a number of the soil-block type) are encased with walls that extend above the soil surface on all sides. Such lysimeters dispose of the rainfall entirely through percolation, evaporation, or transpiration. The absence of provision for outflow of run-off results in a stagnation of water on the top of the soil after nearly every rain, particularly on heavy soils.

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[2] Italic numbers in parentheses refer to Bibliography, p. 32.

TABLE 1. *—Data on soil-block and Ebermayer lysimeters with undisturbed soils*

SOIL-BLOCK LYSIMETERS

Investigator and citation number in bibliography, or footnote	Location	Year of installation	Precipitation	Drainage as percentage of precipitation	Provision for run-off	Remarks
			Inches	*Percent*		
Lawes and Gilbert (early work) Miller (later work) *(224, 227, 242,252).*	Rothamsted, England.	1870	29.0	47. 1 to 53.2	No	
E. L. Sturtevant (*77, 84, 111)*	Massachusetts	1875	---		No	
Sturtevant and Babcock *(93,122).*	Geneva, N. Y	1882	---	[1] 37.6 [2] 41. 5; [3] 43.8	No	
Babcock and Goff *(99)*	--- do ---	1887	---		No	
J. W. Sanborn *(85)*	Columbia, Mo	1888	---		No	
Burt and Leather *(290)*	Cawnpore, India	1903	31.5	44.3 to 48.9	Yes	
R. E. Horton *(103)*	Grafenburg, N. Y.	1904	---		No	
Weibel (463, 474, 476)	Ploti, Soviet Union	1905	16.0	9.6 to 11.4	No	
Arnott and Leather (284)	Pusa, India	1906	40.0	25.0	Yes	
Hendrick and Welsh *(263, 267, 271, 272, 276,278)*	Aberdeen, Scotland	1914	34.6	52 to 55	No	
Miller and Duley (86)	Columbia, Mo	1918	---		Yes	
Weaver and Crist [4]	Lincoln, Nebr	1923	([5])		Yes	With weighing mechanism.
Duley *(87)*	Columbia, Mo	1925	---		No	
Winnik *(308)*	Palestine	1925	20.0	17.0	No	
Harper [8]	Oklahoma	1927			Yes	
F. Shreve *(2)*	Tucson, Ariz	1929				
Musgrave *(65)*	Temple, Tex	1931			Yes	
California Forest and Range Experiment Station. [7]	Berkeley, Calif	1932			Yes	
Southwestern Forest and Range Experiment Station. [7]	Sierra Ancha Experimental Forest,Globe, Ariz.	1932	---	---	Yes	
Musgrave *(65, 69)*	Clarinda, Iowa	1933	[8]25. 6	[8] 5.6 to 22.9	Yes	With tensiometers for measuring capillary tension of soil moisture.
Lake States Forest Experiment Station *(205).*	Upper Mississippi Valley Soil & Water Conservation Experiment Station, La Crosse, Wis.	1934	---		Yes	
Southwestern Forest and Range Experiment Station.[7]	Sierra Ancha Experimental Forest, Globe, Ariz.	1934			Yes	
Musgrave [9]	Statesville, N. C.	1934			Yes	
Southwestern Forest and Range Experiment Station.[7]	Fort Valley Branch Station, Fort Valley, Ariz.	1935			Yes	
Osugi *(313)*	Kyoto, Japan	1935[10]			No	
Stauffer and Smith *(59)*	Urbana, Ill.	1935			Yes	
North Appalachian Experimental Watershed, Soil Conservation Service *(138, 139, 140).*	Coshocton, Ohio		[11]45.0	[11] 60. 5	Yes	With self-recording weighing mechanism.
Southwestern Forest and Range Experiment Station.[7]	Sierra Ancha Experimental Forest, Globe, Ariz.	1937			Yes	
Southwestern Forest and Range Experiment Station.[7]	--- do ---	1938			Yes	

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[1] Surface of the lysimeter sodded.

[2] Surface of the lysimeter bare.

[3] Surface of the lysimeter cultivated.

[4] WEAVER, J. E., and CRIST, J. W. DIRECT MEASUREMENT OF WATER LOSS FROM VEGETATION WITHOUT DISTURBING THE NORMAL STRUCTURE OF THE SOIL. Ecology 5: 153-170. 1924.

[5] Irrigated.

[6] HARPER, H. J. A STUDY OF LYSIMETER INSTALLATIONS FOR THE MEASUREMENT OF GRAVITATIONAL WATER. Unpublished paper presented before the meeting of the Amer. Soc. Agron., November 1937.

[7] Unpublished data through courtesy of U. S. Forest Service.

[8] Musgrave and Neal (68).

[9] Private communication.

[10] Year published.

[11] Data for 1 year only.

TABLE 1.—Data on soil-block and Ebermayer lysimeters with undisturbed soils- Continued

EBERMAYER LYSIMETERS

Investigator and citation number in bibliography, or footnote	Location	Year of installation	Precipi-tation	Drainage as percentage of precipitation	Provision for run-off	Remarks
			Inches	*Percent*		
Weibel *(463, 474, 476)*	Ploti, Soviet Union.	1903	16.0	1.9 to 11.4	Yes	
W. W. Gemmerling*(481)*	Moscow, Soviet Union	1922		---	*Yes*	
V. P. Popov *(485)*	Soviet Union	1928		---	Yes	
J. *S.* Joffe *(88, 89, 90, 91)*	New Brunswick, N. J.	1929	35.8	0.3 to 37.6	Yes	
R. C. Collison (131)	Geneva, N. Y	1932		4.0 to 18.8	Yes	
H. A. Lunt *(19, 53)*	New Haven, Conn	1933		11.1 to 85.8	Yes	
H. J. Harper [6]	Oklahoma			---	Yes	
University of Pretoria *(489)*	Pretoria, South Africa	1934		---	Yes	

[6] HARPER, H. J. A STUDY OF LYSIMETER INSTALLATIONS FOR THE MEASUREMENT OF GRAVITATIONAL WATER. Unpublished paper presented before the meeting of the Amer. Soc. Agron., November 1937.

Lysimeters may also be classified in two groups: Those that are and those that are not weighed. The very nature of the Ebermayer lysimeters prohibits any weighing, whereas both the soil-block and the filled-in types can be weighed. Because the weighing of a large mass of soil in a heavy container is a cumbersome task, not many lysimeters have been installed with weighing mechanisms. Investigators interested in studying only the fertility balance of soils can easily dispense with such installations. Some lysimeters *(351, 357)* [3] are so arranged that scales can be rolled underneath them. In only two cases, so far as the authors know, is a set of scales placed permanently under the lysimeter *(139, 140, 396, 397).*

In a great majority of experiments the moisture content of lysimeter soils has not been recorded. This is due to the difficulties connected with such determinations and also to the lack of appreciation of the importance of information on moisture content. A number of investigators determine the moisture content of the soil by weighing the whole lysimeter. This gives accurate data only where the dry weight of the original soil is available, as it may be in refilled lysimeters; for soil-block lysimeters the data will at best be approximate. The weighing method can give only the average moisture content of the total soil and does not indicate the distribution of the moisture. Weighing of lysimeters containing soil on top and sand on the bottom does not yield any direct data with respect to soil moisture. A similar objection can be raised against weighing soil-block lysimeters, since the natural soil profile tends to distribute soil moisture unevenly. Lysimeters filled with only one type of uniformly mixed soil may have different moisture contents at various depths. It should be kept in mind that the purpose of weighing lysimeters usually is not the determination of soil moisture but the tracing of evaporation and transpiration, for which purpose information regarding the distribution of soil moisture may not be necessary.

The direct determination of soil moisture in lysimeters might be carried out by removing soil samples and making a gravimetric determination. This technique, however, would destroy the lysimeter, since the openings left in the soil would permit excessive percolation. Under special circumstances destruction of the lysimeter would not be objectionable, as, for instance, when the exact soil moisture in a lysimeter at a definite time is the object of research. For the ordinary type of lysimeter installation a direct measurement

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[3] Personal communication from H. Baumann, concerning Berlin-Dahlem lysimeters, March 1938.

of soil moisture throughout the profile without disturbing the soil should be considered a prerequisite. Tensiometers have recently been used successfully *(69)* for this purpose. The effective range of tensiometers in indicating soil moisture, however, is not wide enough for all lysimeter investigations. The development of a reliable in situ soil-moisture meter is urgently needed.

Two main types of lysimeters can be distinguished with respect to the method by which the percolating water is conducted from the soil to the receiver tanks. In one, the soil (or in the deeper soil-block type lysimeters, the parent material) rests immediately on the funnel or perforated bottom plate; in the other, a layer of sand or gravel is placed between the soil and the lysimeter bottom. The percolating water on its way to the receivers is always protected from evaporation, and in some lysimeters *(152)* it is protected also from oxidation.

HISTORY OF LYSIMETER STUDIES

It probably will never be known who was the first to study the percolation of water through soil, but it seems likely that such experiments were carried out by the natural philosophers of the Classical Age. The first actual lysimeter investigation, the report of which the writers have been able to study, was started in 1688 in Paris, by De la Hire[4] *(402)*, who was interested in determining the origin of springs. At that time and for almost two centuries later the belief was held by some scientists that springs were entirely unrelated to rainfall, but originated from huge underground reservoirs that were replenished by the condensation of moist air or by ocean water entering through large crevasses. Others thought that springs represented that part of the precipitation that percolated through the soil and reappeared where a ground-water horizon cropped out. De la Hire used leaden vessels of three different depths (8 inches, 16 inches, and 8 feet), which he filled with sandy loam from the park of the castle of Louis XIV, whom he served as mathematician and meteorologist. He found that the lysimeters in grass evaporated more water than the ones in fallow, and he noticed a number of other phenomena that have been verified by many later lysimeter investigations. His findings with respect to the origin of springs, however, were not conclusive enough to convince the scientific world of that period.

Also of the filled-in type were the lysimeters of Maurice[5] *(223)*, in Switzerland, and of Dalton *(211)*, in England, both of whom started their experiments in 1796. Dalton, though commonly credited with being the first one to install lysimeters, acknowledges the inspiration he received from De la Hire.

In table 2 is given a record of lysimeter installations beginning with that of De la Hire in 1688 and continuing to those of the present. Data pertaining to the soil used, as well as to the type of construction, are given insofar as they are available in the literature. While an attempt was made to make a complete survey of the literature, it is most likely that there are some omissions. The historic references and discussions of findings are based entirely on the literature cited. The Forest Service supplied information concerning a number of their lysimeters for which no published references are available.

Table 3 gives the chronology of the development of lysimeters.

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[4] DE LA HIRE, PHILIPPE. SUR L'ORIGINE DES RIVIÈRES. list. de l'Acad. Roy. des Sei., pp. 1-a. 1703.

[5] MAURICE. BIBLIOGRAPHIE UNIVERSELLE DE GENÈVE SCIENCES ET ARTS. V. 1. No date. [Original not seen.]

TABLE 2 . – *Lysimeter installations 1688-1939*

Investigator and citation number in bibliography, or footnote	Location	Year of instal-lation	Soil		Lysimeter construction								
			Texture	Other characteristics	Type	Shape of surface	Dimensions				Material		Foreign substance in bottom layer
							Area		Depth		Walls	Bottom	
							Sq. meters	*Sq feet*	Meters	*Feet*			
De la Hire [1] *(402)*	Rungis, near Paris, France	1688	Sand, loam		Filled-in	Round			0.19; 0.38 2.43	0.62; 1.25 7.97	Lead		
John Dalton *(211)*	Manchester, England	1795	"Good fresh soil"		do	do	0.051	0.545	0.91	3.00	Tinned iron	Tinned iron	Gravel and sand.
Maurice [2]	Geneva, Switzerland	1796			do	do							
Gasparin [3]	Orange, France	1821			do								
Dickinson and Evans *(223)*	Nash Mills, England	1836	"Surface soil"		do	Round	0.165	1.77	0.91	3.00	Cast iron		
John Dickinson *(214, 215)*	Abbottshill, England	1836-43	Sandy loam		do	do	0.073	0.79	0.91	3.00			
J. Thomas Way [4]	England	1850 [5]			do	do	0.0003	0.003	0.38; 0 .46	1.25; 1.50			
Greaves *(223, 330)*	Lee Bridge, England	1851	Mixture of loamy soil with sand and gravel		do	Square	0.836	9.0	0.91	3.00	Slate		
G. von Mullendorf *(330, v. 11).*	Goerlitz, Germany	1853	Clay, loam, sand	Residual	do	do	0.093	1.0	1.30	4.25			
E. Pfaff *(330)*	Erlangen, Germany	1867	Poor sandy soil		do	Round	0.018	0.20	0.15; 0.30 0.61; 1.22	0.50; 1.00 2.00; 4.00	Tin		
E. Ebermayer [6] *(325; 330,* r. *13, pp. 1-15).*	Munich, Germany	1868	Gravelly sand, fine sand loessal loam, limestone sand muck, humous garden soil.		do	Square	4.0	43.0	1.00 1.20	3.28 3.94	Concrete	Concrete, funnel -shaped.	
J. N. Woldrich *(330)*	Salzburg, Austria	Before 1870	Sandy loam, loam, sand		do	Round	0.018	0.20	0.15; 0.30 0.61; 1.22	0.50; 1.00 2.00 ; 4.00	Tin		
Do (330)	Oberdöbling, Austria	Before 1870	do		do	do	0.018	0.20	0.15; 0.30 0.61; 1.22	0.50; 1.00 2.00; 4.00	do		
J. B. Lawes and J. H. Gilbert (early work); N. H. J . Miller (later work) *(225, 223, 242, 252)*	Rothamsted, England	1870		Glacial, 8" cultivated soil over 10" friable clay over clay subsoil of rather stiff clay	Soil block	Rectangular	4.05	43.56	0.51; 1.02 1.52	1.67; 3.34 5.00	4 ½ brick coated with cement.	Cast-iron plates perforated.	None
E. L. Sturtevant (77, *84, 111).*	Waushakum Farm near South Framingham, Mass.	1875		Glacial	do	do	20.234	218.0	0.67	2.18			Do
Levi Stockbridge *(82, 83).*	Amherst, Mass	1876-77		do	Filled-in		1.35	14.50	0.91	3.00			

B. Latham (247)	Croydon, England	1878	Gravelly	Chalk soil, upland, alluvial.	do	Square	0.837	9.0					
E. Wollny *(330)*	Munich, Germany	1880	Sand, clay loam, humous sandy loam mixture of sand and peat.		do	do	0.04 0.10	0.43 1.08	0.30 0.50	0.98 1.64	Zinc	Perforated zinc	
Blucharov *(82)*	Moscow, Soviet Union				Round				0.20	0.66	Metal cylin-ders.		
A. Petermann *(401)*	Gemblout, Belgium	1881	Sandy loam		Filled-in	Square	1.0	10.76	1.00	3.28	Masonry		Gravel.
Sturtevant and Babcock *(93, 122).*	Geneva, N. Y	1882	Dark clay loam	Glacial	Soil block	do	0.404	4.34	0.91	3.00	Oak plank lined with heavy copper	Sheet metal and copper.	None.
Babcock and Goff *(93, 99).*	do	1887		do	do	Round	0 404 0.404	4.34 4.34	0.91 1.83	3.00 6.00	White - oak staves.	White-oak plank with copper.	
Do	do	1887		do	Filled-in	do	0.404 0.404	4.34 4.34	0.91 1.83	3.00 6.00	do	do	
M. P. E. Berthelot	France	1887[5]			do		0.152	1.64			Glazed earthen ware pot.		
P .*P. D*ehérain (405)	Grignon, France	1888			do		4.0	43.0	1.00	3.28	Concrete		
J. W. Sanborn (85)	Missouri Agricultural Experiment Station, Columbia, Mo.	1888	Clay loam		Soil block...	Rectangular	40.46	435.6	1.30	4.26	Tarred fence	None except for drain tiles 7 ft. apart	None.
B. Tacke et al. *(347)*	Ottersburg, Germany	1894	Peat	Peat	Filled-in	Round	0.049	0.529	0.35	1.15	Glass		Broken glass.
J. Hanamann *(346, 349)*	Lobositz, Austria	1896			do		0.10	1.08	0.50; 1.00	1.64; 3.28	Metal container		

See footnotes at end of table.

TABLE 2. - *Lysimeter installations* 1688-1939 - Continued

Investigator and citation number in bibliography, or footnote	Location	Year of installation	Soil		Lysimeter construction								
			Texture	Other characteristics	Type	Shape of surface	Dimensions				Material		Foreign substance in bottom layer
							Area		Depth		Walls	Bottom	
							Square meters	Square feet	*Meters*	*Feet*			
B. Welbel (*463, 474, 476*)	Ploti, Soviet Union	1899		Chernozem	Filled-in	Square	0.05	0.538	0.30; 0.45 1.00	0.98; 1.48 3. 28	Zinc		
Do	do.	1903		do		Ebermayer	0. 1	1.08	0.25; 0.50 0.75 1.00	0.82; 1.64 2.46; 3.28	None		
Burt and Leather *(290)*	Cawnpore, India	1903	Loam, sand	Alluvium of Ganges River.	Soil block		4.05	43. 56	0.91; 1.83	3.00; 6.00			None
R. E. Horton *(103)*	Grafenburg, N. Y	1904	Clay, loam, sand.	Clay from residual shale.	do	Round	0.164	1.767	0.91	3.00	Galvanized iron.	Galvanized iron on wooden rack	Do.
B. Weibel (463,474, 476).	Ploti, Soviet Union	1905		Chernozem		do			0.20; 0.25 0.40; 0.50 1.00	0.66; 0.82 1.31; 1.64 3. 28			
Arnott and Leather 0(*284, 290)*	Pusa, India	1906	Loam, sand	Alluvium; contains 40 percent chalk.	do	Rectangular	4.05	43.56	0.91; 1.83	3.00; 6.00	Masonry plastered with cement.	Galvanized sheetmetal.	None.
Von Seelhorst *(351)*	Goettingen, Germany	1906 [5]	do		Filled-in		1. 0	10.76	1.25	4. 10	Iron	Iron	
Gerlach *(359,378,386)*	Bromberg, Germany		Peat ,loamy sand, sandy loam, humous sand.		do	Square	4.0	43.0	1.10	3.61	Masonry lined with Dutch tile.	Galvanized iron with 0.5 - cm. holes.	None.
E. Krüger *(357-358)*	do	1908	Sandy soil	35 cm. surface soil, 85 em. subsoil.	do	do	1. 0	10.76	1.37	4.49	with rein forcements. Protected with asphalt tar.	Iron sheets	10 cm. gravel.
T. L. Lyon and J. A. Bissell *(109,133).*	Ithaca, N. Y	1910	Silty clay loam Silt loam Sandy loam	Dunkirk;[7] glacial Volusia,[7] glacial Petoskey[7], glacial	do	do	1. 619	17.4	1.30	4.25	Asphalt over concrete		Sand and gravel.

G. S. Fraps *(194)*	College Station, Tex	1910	Sand Fine sandy loam Clay Loam Clay Fine sandy loam Clay Fine sandy loam	Norfolk[8], coastal plain. Orangeburg[8], coastal plain. Houston[8], coastal plain. do Yazoo, bottom land Miller (flood plain) Crawford [8] Lufkin [8]	do	Round	0.073	0.79	0.61	2.00	Galvanized iron.	Galvanized iron.	
S. Collison and Seth Walker (31)	Gainesville, Fla	1910	Sand	Norfolk, coastal plain	do	do	2.024	21.78	1. 22	4. 00	Steel		
C.A. Mooers and W.H. MacIntire *(152, 173).*	Knoxville, Tenn	1911	Loam Clay loam Silt loam.	Hagsertown.[7] Limestone residual. Cumberland Memphis [7]		do	0.810	8.71	0.31; 0.61 1.22; 1.83	1.00; 2.00 4.00; 6.00	Heavy galvanized iron parafined inside.	Block tin outlet.	1-inch sand over glass wool
S. S. Peck (55)	Honolulu, H. I	1911 [5]		Upland Lowland	do	do	0.032	0.35	0.61	2.00	Galvanized iron painted with asphalt.	Perforated galvanized iron.	3-inch washed black lava sand.
Von Feilitzen, Lugner, and Hjerstedt*(19,456)*	Jonkoping, Sweden	1912	Muck		do	Square	0.64	6.87	0.50	1.64			
J. Hendrick and H. D. Welsh *(263, 267, 271, 272,276,278).*	Aberdeen, Scotland	1914	Light	Glacial (granitic)	Soil block	Rectangular.	4.05	43.56	0.99	3.25	Slate slabs	Perforated slate	None
R. C. Collison, et al. *(108 122, 125, 128).*	Geneva, N. Y	1914	Loam	Ontario [7] glacial	Filled-in	Round	1.619	17.4	0.61; 1.22 2. 44	2.00; 4.00 8. 00	Steel tanks lined with pitch..	Perforated metal disk	Quartz over glass wool.
C. A. Mooers and W. H. MacIntire *(152).*	Knoxville, Tenn.	1914	Same as 1911		do	do	0. 202	2. 17	0.30 0.61	1.00 2.00	14-gage galvanized iron painted with asphalt.		1-inch layer sandover glass wool.

See footnotes at end of table.

TABLE 2.- *Lysimeter installations* 1688-1939 - Continued

Investigator and citation number in bibliography, or footnote	Location	Year of installation	Soil		Lysimeter construction								
							Dimensions				Material		Foreign substance in bottom layer
			Texture	Other characteristics	Type	Shape of surface	Area		Depth		Walls	Bottom	
							Square meters	Square feet	*Meters*	*Feet*			
H. K. Dean (145)	Umtilla, Oreg	1915	Medium sand, fine sand, coarse sand, silt, silt loam.		Filled-in	Square	1.03	11. 1	1.83	6.00	Concrete	Concrete	
E. E. Deturk[9]	Urbana, Ill	1916			do	do	25.29	272. 25	2. 51	8. 25	do	do	
Miller and Duley *(86)*	Columbia, Mo	1918			Soil block				1. 22	4.00			
W. Geilmann (371)	University Goettingen, Germany.	Before 1920		Mild loam, yellow sand.	Filled-in	Round			1.30	4.26	Galvanized iron		
C. A. Mooers and W.H. MacIntire *(158).*	Knoxville, Tenn	1921[5]			do	do	0.073	0.785	1.83 2.14	6.00 7.00	Galvanized ingot from tanks.	Conical shaped at bottom.	Coarse sand.
V.V.Gemmerling *(481).*	Moscow, Soviet Union	1922[5]		Podzol	Ebermayer						None		
E. E. Deturk[9]	Urbana, Ill	1922-23			Filled-in	Rectangular	3.55	38.2	1. 73	5.67	Concrete lined with asphalt.	Concrete	One-fourth inch crushed quartz.
W. B. Ellet and H. H. Hill *(198, 203).*	Blacksburg, Va	1922		Limestone soil	do				0.20 to 0.71	0.67 to 2.33	Iron		Quartz pebbles.
Do	do	1922 1924	Silt loam Sand	Frederick[7] Hagerstown series[7] Norfolk series[8]	do		.245	2.64	0.20 to 0.71	0.67 to 2.33			
J. E. Weaver and J. W. Crist[10]	Lincoln, Nebr	1923		Fine sandy loam	Soil block	Round	0.093	1.0	0.91	3.00	Heavy galvanized iron cylinder.		None
F. L. Duley *(87)*	Columbia, Mo	1925[5]			do	do	0.186	2.0	1.22	4.00	Asphalt between soil and cylinder.	Perforated copper plate.	Lead shot.
E. Krüger[9]	Berlin-Dahlem, Germany.	1925	Sandy	Glacial	Filled-in		1.0	10.76	1.50	4.92	Masonry	Masonry	
M. Winnek *(308)*	Mikveli-Israel Experiment Station Palestine.	1925	Clay, loamy sand	Alluvial, glacial	do Soil block								
H. H. Nicholson and B. Pantin *(256).*	Reading, England	1926	Loam		Filled-in		0.0506	0.545	0.32	1.05	Glazed earthenware.		1-inch coarse washed gravel.
H. J. Harper[11]	Stillwater, Okla	1927			do								

W.N.C. Belgrave *(309).*	Kuala, Lumpur, Fed-crated Malay States.	1927	Sandy	Quartzite, eroded; laterite, good crumb structure.	Soil block Ebermayer Filled-in	Round	0.067	0.721	0.43	1.41	None Glazed earthen-ware.		
A.W.R. Joachim *(301,* 1928: 3).	Peradeniya, Ceylon	1927											
W. C. Lowdermilk (4)	Berkeley, Calif	1927	Sandy loam Sandy clay loam Clay loam	Holland Aiken Altamont	do	Rectangular.	0.929	10.00	0.76	2.50	Galvanized iron.	Galvanized iron.	Gravel and sand.
V. P. Popov *(482)*	Soviet Union	1928[5]			Ebermayer						None		
H. C. Hendericksen *(147).*	Mayaguez, Porto Rico	1928	Sandy clay	Practically devoid of organic matter and nutrients.	Filled-in	Round	(12)				Iron	Iron	
Niklas and W. Schropp (382).	Weihenstephan, Germany.	1928[5]			do								
C. Pfaff *(398, 400)*	Limburgerhof, Germany.	1928	Alkaline, humous sandy soil, alkaline loam, acid slightly humous sandy soil, acid sandy loam.		do	Square	1.0	10. 76	1.0	3. 28	Concrete	Concrete	10 cm. gravel, 50 cm. sand.
California Forest and Range Experiment Station.[13]	Devil Canyon Branch, San Bernardino, Calif.	1929	Gravelly loam	Of granitic origin		Circular	0.45	4.91	1.14	3.75	Galvanized iron.	Galvanized iron.	
F. Shreve *(2)*	Tucson, Ariz	1929	Adobe clay	Alluvial	Soil Block	Round	0.067	0.72	0.43	1.41			
M. F. Morgan *(14, 21)* .	Windsor, Conn	1929	Loamy sand Sandy loam Loam Very fine sandy loam	Merrimac,[7] glacial do Wethersfeld[7], glacial Enfield.[7], glacial	Filled-in do do do	do do do do	0.206	2.22	0.23 0.51 0.76	0.75 1.67 2.50	Metal cylinders		Pure quartz sand.

See footnotes at end of table.

TABLE 2.- *Lysimeter installations 1688-1939 - Continued*

Investigator and citation number in bibliography, or footnote.	Location	Year of installation	Soil		Lysimeter construction								
			Texture	Other characteristics	Type	Shape of surface	Dimensions				Material		Foreign sustance in bottom layer
							Area		Depth		Walls	Bottom	
							Square meters	Square feet	*Meters*	*Feet*			
J. S. Joffe *(88, 89, 90, 91)*	New Brunswick, N. J	1929	Sandy loam	Sassafras [7]	Ebermayer	Round	0.073	0.79	0.18; 0.42 0.58; 0.80	0.6; 1.4 1.9; 2.6	None	Funnel	Quartz pebbles
J. Bartels and W. Friedrich *(896, 397).*	Eberswalde, Germany	1929	Yellow fine sand	Glacial	Filled-in	Square	1.0	10. 76	1.50	4.9	Iron	Iron	10 cm. gravel.
California Forest and Range Experiment Station.[13]	Berkeley, Calif	1929	Sandy clay loam Clay loam	Aiken Altamont	do	Rectangular	1.858	20.00	0.91	3.00	Redwood	Redwood	Gravel and sand.
University of Pretoria (489).	Pretoria, South Africa	1930	Sandy loam		do	Round	2.63	28.27	1.22 1.68	4.0 5.5	Pitch & tar mixture over cement plaster.		
A. Demolon and E. Bastisse (419,*425, 427, 458).*	Versailles, France	1930	Loam	Upland	do	Square	1.0	10.76	0.60	2.0			
Arizona Agricultural Experiment Station	Tucson, Ariz	1930	Clay	Gila (alluvial) Mohave (pedocal)	do	do	1.49	16.0	1.53	5.00	Concrete	Concrete	
G. *W.* Musgrave (65)	Temple, Tex	1931			Soil block	Round	0.648	7.0	0.91	3 .00			Coarse gravel.
California Forest and Range Experiment Station.[13]	Berkeley, Calif	1931	Sandy clay loam Clay loam	Sierra Altamont	Filled-in	Rectangular	7.432	80.00	1.27	4.17	Iron (painted).	Iron (painted) on concrete foundation.	Gravel and sand.
R. C. Collison (/3/)	N. Y	1932	Loam	Ontario,[7] glacial	Ebermayer	Round	0. 073	0.79	0.30; 0.58 0 .89; 1.19	1.0; 1.9 2.9; 3.9	None	Funnel	
H. A. Lunt *(19, 23)*	New Haven, Conn	1932	Gravelly fine sandy .loam.	Hartford, glacial	Filled-in Ebermayer	Round Square	0.206 0.103	2.22 1. 11	0.10 0.50	0.33 1.64	Galvanized iron. None	Square funnel.	
California Forest and Range Experiment Station. [13]	Berkeley, Calif	1932	Clay loam	Altamont	Soil block	Circular	0.650	7.0	1. 27	4.17	Galvanized iron.	Galvanized iron.	None.
Southwestern Forest and Range Experiment Station. [13]	Sierra Ancha Experimental Forest, Globe, Ariz.	1932	Sandy clay do Clay loam	Quartzite Granite Basalt	do		0.322	3.47	0.56	1.83	Steel		Do.
California Forest and Range Experiment Station. [13]	North Fork Branch Station, North Fork, Calif.	1932	Sandy clay loam	Sierra	Filled-in	Rectangular	0.646	6.95	0.53	1.75	Galvanized iron.	Galvanized iron.	Fine gravel and sand.
G. W. Musgrave (65, 69).	Clarinda, Iowa	1933	Silt loam	Marshall, prairie soils Shelby, prairie soils	Soil block	Round	0. 648	7.00	0.91	3.00	Metal		Coarse gravel.

P. E. Karraker and C.E. Bortner (71).	Lexington, Ky	1933	do	Maury [8]	Filled-in	do	0. 256	2. 761	0.61	2.00	Steel		
J. E. Adams (148)	South Carolina Experiment Station, Clemson College, S. C.	1933			do	do	2.023	21.8	1.22	4.00	do		
California Forest and Range Experiment Station. [13]	North Fork Branch Station, North Fork, Calif.	1933	Sandy clay loam	Sierra	do	Circular	0.455 0.646	4. 90 6.95	0.91	3.00	Galvanized iron	Galvanized iron.	Fine gravel and sand.
Do. [13]	San Dimas Experimental Forest, Glendora, Calif.	1934	Sandy loam	Holland (Pacific coast)	do	Rectangular	20.234	217.8	1.83	6.00	Concrete	Concrete	None.
G. W. Musgrave [9]	Statesville, N. C	1934		Cecil, Red soil of Piedmont.	Soil block	Round			1.22	4.00	Metal		
F. Boeuf and V. Novikoff *(486).*	Ariana, Tunis	1934	Clay	Calcareous	Filled-in	Square	4.0	43.0	2.0	6.56	Reinforced concrete.	Concrete	
E. Miege (487)	Rabat, Morocco	1934	4 soil types.		do								
University of Pretoria *(489).*	Pretoria, South Africa.	1934			Ebermayer	Round	0. 552	5.94	1. 22	4.00	None	Copper funnels	
Intermountain Forest and Range Experiment Station. [13]	Boise Basin Experimental Forest, Idaho city, Idaho.	1934	Sandy	Granitic	Filled-in	Rectangular	8.093	87.12	1.22	4.00	5/16-inch steel plate.	Concrete	Gravel.
Lake States Forest Experiment Station *(205).*	Upper Mississippi Valley Soil and Water Conservation Experiment Station La Crosse, Wis.	1934	Silt loam	Clinton	Soil block	do	18.58	200.00	1.22	4.00	Asphalt-lined concrete.		Sand.

See footnotes at end of table.

TABLE 2. *-Lysimeter installations 1688-1939 - Continued*

Investigator and citation number in bibliography, or footnote	Location	Year o installation	Soil		Lysimeter construction								
			Texture	Other characteristics	Type	Shape of surface	Dimensions				Material		Foreign substance in bottom layer
							Area		Depth		Walls	Bottom	
							Square meters	Square feet	*Meters*	*Feet*			
Southwestern Forest and Range Experiment Station. [13]	Sierra Ancha Experimental Forest, Globe, Ariz.	1934	Clay		Filled-in	Rectangular	9.29	100.00	2.44	8.00	Concrete	Concrete	Sand
Do. [13]	do	1934	Stony sandy clay	Quartzite	Soil block	do	83.61	900.00	0. 91 to 1.83	3 to 6	do		None
Do.[13]	Fort Valley Branch Station, Fort Valley, Ariz.	1935	Clay loam	Basalt	do	do	0. 312	3.47	0.56	1.83	Steel		Do
S. Osugi *(313)*	Kyoto, Japan	1935[5]	Sandy loam, clay soil with gravel.		do	do	0. 83	8.9					Do
R. S. Stauffer and R. S. Smith (59).	Urbana, Ill	1935	8 silt loams	Prairie soils	do	Round	0. 648	7.0	1.02	3.3	Galvanized iron.		Crushed quartz
North Appalachian Experimental Watershed, Soil Conservation Service *(138, 139, 140).*	Coshocton, Ohio	1936	Silt loam	Muskingum.[7] Residual from sandstone and shale.	do	Rectangular	8.089	87.08	2.44	8.00	Concrete lined with asphalt.	Perforated steel plate	None
Alabama Experiment Station.	Auburn, Ala	1936	Sandy loam, fine sandy loam, clay loam.	Norfolk[8] Hartsells[8] Decatur[8]	Filled-in	Round	0.455	4.9	0.30 0.91	1.00 3.00	Galvanized iron painted with asphalt.	Galvanized iron	Gravel and sand
Southwestern Forest and Range Experiment Station. [13]	Sierra Anche Experimental Forest, Globe, Ariz.	1937	Sandy clay loam		Soil block		0. 646	6.95	0.71	2.33	Steel		None
Rocky Mountain Forest and Range Experiment Station [13]	Manitou Experimental Forest, Colorado Springs, Colo.	1937	Gravelly	Granitic	Filled-in	Rectangular	0.405	4.36	0.46 0.91	1.50 3.00	do	Steel	Gravel
California Forest and California Forest & Range Experiment Station. [13]	San Dimas Experimental Forest, Glendora, Calif.	1937	Sandy loam	Holland (Pacific coast).	do	Circular	0.484	5.21	1.01	3.33	Galvanized iron.	Galvanized iron	None
Do. [13-]	do	1937	do	do	do	do	0.161	1.73	0.61	2.00	do	do	Do
Do. [13]	do	1937	do	do	Filled-in, unconfined.	Rectangular	28.451	306. 25	2.13	7.00	Soil		Do
Do. [13]	do	1938	do	do	Filled-in	Rectangular	2.230	24.00	1.83	6.00	Concrete	Concrete	Do

Do.[13]	do	1938	do	do	do	Circular	0.161	1.73	0.61	2.00	Galvanized iron.	Galvanized iron.	Do
North Appalachian Experimental Watershed, Soil Conservation Service. [14]	Coshocton, Ohio	1938	Silt loam	Subsoils used: Loam, silt loam, silty clay.	do	Round	0.032	0.349	1.04	3.42	Glazed tile	Wire screen over sheet metal.	Washed sand
Southwestern Forest and Range Experiment Station. [13]	Sierra Ancha Experimental Forest, Globe, Ariz.	1938			Soil block		0.646	6.95	0. 71	2.33	Steel	Steel	None
Do. [13]	do	1939		Sandy loam	Filled-in		41.80	450.00	1.22	4.00	Concrete	Concrete	Sand

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[1] DE LA HIRE, PHILIPPE. See footnote 4, p. 9.

[2] MAURICE. See footnote 5, p. 9.

[3] GASPARIN. In Cours d'Agriculture, v. 2, p. 116. No date. [Original not seen.]

[4] WAY, J. T. ON THE POWER OF SOILS TO ABSORB MANURE. Roy. Agr. Soc. England Jour. 11: 313-379. 1850.ã5

[5] Year published.

[6] EBERMAYER, ERNST. UNTERSUCHUNGS-ERGEBNISSE UBER DIE MENGE UND VERTEILUNG DER NIEDERSCHLAGE IN DEN WALDERN. Forstl. Naturw. Ztschr. 6: 283-301. 1897.

[7] Gray-Brown Podzolic soils.

[8] “Red and yellow" soils.

[9] Private communication.

[10] WEAVER, J. E., and CRIST, J. W. See footnote 4, table I.

[11] HARPER, H. J. See footnote 6, table 1.

[12] 30-gallon capacity.

[13] Unpublished data through courtesy of U. S. Forest Service.

[14] Unpublished date.

TABLE *3.* *— Chronology of the development of lysimeters, 1688-1937*

Type of lysimeter	Investigator	Location	Year of construction
First lysimeter	De la Hire	Paris, France	1688
First lysimeter with run-off provision	Dalton	Manchester, England	1796
First extensive use of lysimeters for the study of soil chemistry.	Way	England	1850
First soil-block lysimeter	Lawes and Gilbert	Rothamsted, England	1870
First (soil-block) lysimeter in the United States.	Sturtevant	Framingham, Mass.	1875
First large comparative lysimeter study	Wollny	Munich, Germany	1880
First lysimeter in natural contact with substrata drained by tiles.	Sanborn	Columbia, Mo	1888
First Ebermayer lysimeter	Welbel	Ploti, Soviet Union	1903
First soil-block lysimeter with run-off provision.	Leather	Cawnpore, India	1903
First lysimeter, with weighing mechanism	V. Seelhorst	Goettingen, Germany	1906
First soil-block lysimeter with weighing mechanism.	Weaver and Crist	Lincoln, Nebr.	1923
First Ebermayer lysimeter in the United States.	Joffe	New Brunswick, N.	1929
First soil-block lysimeter with self-recording weighing mechanism.	Research Division, Soil Conservation Service.	Coshocton, Ohio	1936
First lysimeter with tensiometers for measuring capillary tension of soil moisture.	Iowa State College and Soil Conservation Service.	Clarinda, Iowa	1937

During the nineteenth century lysimeter investigations became more frequent. All investigations conducted before 1870 were with filled-in lysimeters. This is what should be expected, since pedology was in its infancy; and, in general, only the surface soil was subjected to research by the pioneers of soil science. The plow layer is disturbed regularly through cultivation, and therefore it seemed unobjectionable to remove it from its original site and place it in lysimeters. At that time the significance of the soil profile as a nonseparable unit was not understood. De la Hire, Dalton, and Maurice, as well as a number of other investigators in England, Germany, Austria, and France, used lysimeters of the filled-in type merely for the study of the rate and amount of the percolate. They did not pay much attention to the chemical composition of the percolate, and most of them did not seem to care greatly whether the soil in the lysimeters was covered with vegetation or not.

In 1850 Way,[6] in England, reported his fundamental studies on the chemical changes of solutions percolating through soil. He used a number of laboratory lysimeters, filled them with different types of soils, and found that bases of the sprinkling solution were exchanged against the calcium of the soil and that the power of soils to absorb fertilizing elements depends on its clay content. He also noticed that burning destroyed this capacity of the clay. Through this work, Way laid the foundation for further base-exchange studies. He was the first to carry out extensive lysimeter investigations to clarify the problem of soil fertility. The influence of his studies is noticeable in the work begun 20 years later at Rothamsted.

Lysimeter investigations took a great step forward in 1870, when Lawes, Gilbert, and Warington established three "drain-gauges" at Rothamsted, England. These men recognized that basic information concerning the natural rate and chemical composition of drainage water could be obtained only from natural, undisturbed soils. In stead of filling soil into tanks they left the soil intact and placed a perforated iron

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[6] See footnote 4, table 2.

bottom under it and masonry walls around it. These lysimeters exceeded all preceding installations in area five times, and they are responsible for a great many findings concerning the percolation rate of rain water and the leaching of plant nutrients from soil. After 68 years of successful operations, these lysimeters are still in use. It is not surprising that the construction of these first soil-block lysimeters met with some difficulties and that leakage through the side walls could be stopped only after repeated repairs. As in all early installations, run-off is not allowed to occur from the Rothamsted lysimeters. Under English climatic conditions, this may not be a great handicap, since the rainfall is generally much more gentle than in this country. The depth of each of these "drain gauges" is different; therefore, no replicate exists to check directly the results obtained. However, a comparison of the data from these lysimeters with those from later installations indicates a high degree of reliability of the Rothamsted work. While the construction of these lysimeters was very satisfactory, the fact that only three of them exist and that these three are located on the same soil type and are otherwise under identical conditions, makes it impossible to interpret the effect of soil type, vegetation, and various other factors on the rate and amount of percolation.

Research to investigate such effects was started by Wollny *(330)* in Munich, Germany, in 1880. In his very elaborate set-up he studied the following problems:

(1) Influence of soil structure on the rate and amount of percolate.
(2) Effect of soil type on the rate and amount of percolate. (Sand, clay loam, humous sandy loam, peat, a mixture of sand and peat, stony sand, stony humus and sandy loam were used.)
(3) Effect of soil depth on the rate and amount of percolate.
(4) Effect of soil surface cover on the rate and amount of percolate. (Sand, loam, dead vegetable mulch, and growing vegetation were compared.)
(5) Effect of the distribution of precipitation on the amount and rate of percolate and on the ratio of percolate to precipitation.

This study, continued through almost a decade, was carried out with a large number of lysimeters of the filled-in type. Wollny was a very thorough worker who studied many questions of agricultural meteorology and soil physics, and it is not surprising that the majority of his lysimeter findings have been verified by later workers. The great number of phenomena that he subjected to research excluded for him the use of soil-block lysimeters, which would have been altogether too costly. The use of the filled-in type cannot be considered very objectionable for the study he carried out, since he wanted to obtain comparative information concerning natural percolation. It is to be noted that Wollny did not include any analyses of the leachate in his research.

For many purposes the filled-in type of lysimeters proved to be inadequate, as, for instance, the study of the moisture relationships in forests. Ebermayer[7] *(325, 330)* carried out such studies in numerous meteorologic stations in the forests of Bavaria. He found that filled-in lysimeters could not depict natural conditions, since the tree roots did not reach into the lysimeters and hence could not remove water from the soil. Within a few seasons the lysimeter soil became so waterlogged that the experiment had to be

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[7] See footnote 6, table 2.

discontinued. This may have been due not only to the lack of tree roots, but also to the poor under-drainage inherent in most lysimeters. This phenomenon is discussed in detail on pages 19-22. In order to overcome the obstacles encountered in the study of hydrologic conditions of forests, Ebermayer suggested a rather unique scheme. A large area of the forest, about one-fourth hectare, was to be undermined about 1.5 meters below the soil surface so that the soil and trees would remain undisturbed. The roof of this wide tunnel would consist of impervious material and would slant to one point where the percolate could be measured. This project evidently did not materialize, owing to the technical and financial difficulties involved in such a huge undertaking.

A number of years later, Russian investigators modified this plan of collecting percolate from undisturbed, unencased soil. In particular, the size of the collecting funnel was considerably reduced and thus construction problems were simplified. From Russia *(463, 474, 476, 481, 482)* this funnel-type lysimeter came to the United States *(88, 89,),* and it has, therefore, frequently been called a Russian lysimeter, although a Russian investigator, Katchinsky,[8] was among the first to call it the Ebermayer type.

The first lysimeter in the United States was built by Sturtevant on his farm in Massachusetts in 1875, and it is interesting to note that this was of the soil-block type. In 1882 Sturtevant installed another set of three lysimeters at the experiment station at Geneva, N. Y. These lysimeters were also of the soil-block type and, were transported from the original location to the lysimeter pit. They were constructed of white oak planks lined with heavy sheet copper and had a bottom made of a heavy flat section of "boiler iron." After a number of years, Babcock and Goff, who continued this work, believed that the lysimeters dried out too readily, and they therefore built four additional lysimeters with an artificially maintained ground-water table. Two of these lysimeters were of the soil-block type and two were filled with soil that was previously sifted and dried. The records obtained from this research do not seem to have been very convincing; for the installation was abandoned in 1890.

None of the earlier lysimeters was provided with run-off facilities, except, of course, the Ebermayer lysimeters, whose lack of side walls allows free run-off. It is significant that the first large lysimeter with run-off provision was constructed in India *(284, 290),* where dry periods alternate with seasons of intense storms. This installation was made in 1903 and has been followed by numerous others, particularly in the United States, where intense rainfall frequently causes large quantities and high rates of run-off.

Direct information can be obtained on only percolation and run-off from stationary lysimeters. The sum of evaporation and transpiration can be calculated for longer periods by differences if precipitation data are available, but accurate evapotranspirational data for short-time intervals can be obtained only if the lysimeters are weighed, as only then will the change of soil-moisture content be known. Von Seelhorst *(351)* was the first to equip lysimeters with weighing devices (1906). Other German investigators *(357, 396, 397)*[9] used similar installations for the study of transpirational losses of various crops and the evaporation

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[8] KATCHINSEY, N. A. METHODES POUR DETERMINER LA PERMÉABILITÉ DU SOL À L'EAU EN VUE D'UNE IRRIGATION. 1st Comn. Internatl. Soc. Soil Sci. Trans., section Soviet, Moscow, A, 2: 79-99. 1934.

[9] See also footnote 3, p. 4.

from bare soil. Weaver and Crist[10] weighed soil-block lysimeters in this country (1923), and the first soil-block lysimeters with self-recording weighing mechanism were built in 1937 by the Soil Conservation Service at Coshocton, Ohio.

These large lysimeters (one five-hundredths of an acre) at Coshocton, in the planning of which the writers took part, embody numerous features recognized as essential for a study of true natural percolation and other hydrologic factors. In order to illustrate how some of these features have been incorporated, a short description of these lysimeters will be given. (Details of design and construction have been reported by other members of the Research Division, Soil Conservation Service *(138, 139, 140).* Figure 1 shows a schematic cross section through an entire lysimeter installation. The lysimeter is 8 feet deep; the soil extends merely 2 to 3 feet; disintegrated rock extends another 2 to 3 feet; and the lowest 3 to 4 feet contains undecomposed parent rock. All these layers are left in their natural structure, and the rock rests immediately on the percolate sieves. Water reaching these strata can fairly be called percolation, and relative assurance is given that no plant roots reach this depth. It seems probable that water passes with little difficulty from the rock fissures into the multiple percolate collectors. In figure 1 are shown cross sections of steel strips that serve to prevent fictitious percolation from descending in the space that may at times exist between the soil block and the side walls of the lysimeter.

Provision is made for the collection of run-off, and the amounts of water and soil in the run-off tank are recorded. Conditions with respect to run-off in the lysimeter are not representative of field conditions because the vertical side walls cut off overland flow. To date, however, no method that permits overland flow to occur on a lysimeter has been found to give an accurate knowledge of the amount of water that infiltrates into the soil mass. The side walls have another disadvantage, that of creating a border effect, which is due both to the lack of vegetation on a strip about 15 inches wide and also to cutting off the soil from its surroundings. The necessity of isolating a soil block for the study of its percolation and its weight changes requires such a procedure. An attempt is made to keep the temperature in the subsoil somewhat the same as it would be in nature by keeping the service tunnel closed as well as possible. Grease seals (fig. 1) are placed between the top of the lysimeter walls and the outside retaining wall to keep the atmospheric air from descending into the tunnel and at the same time to allow for free play of the lysimeter on the scales. These record weight changes accurately to the nearest 5 pounds, which is equivalent to approximately one one-hundredth of an inch of rainfall.

DISCUSSION

The purpose of lysimeter investigations is twofold; the measurement of the hydrologic balance of the soil, in which the amount and rate of percolation is the primary consideration, and the determination of the chemical losses accompanying percolation. Omitting laboratory lysimeters, which are used to study special

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[10] See footnote 4, table 1.

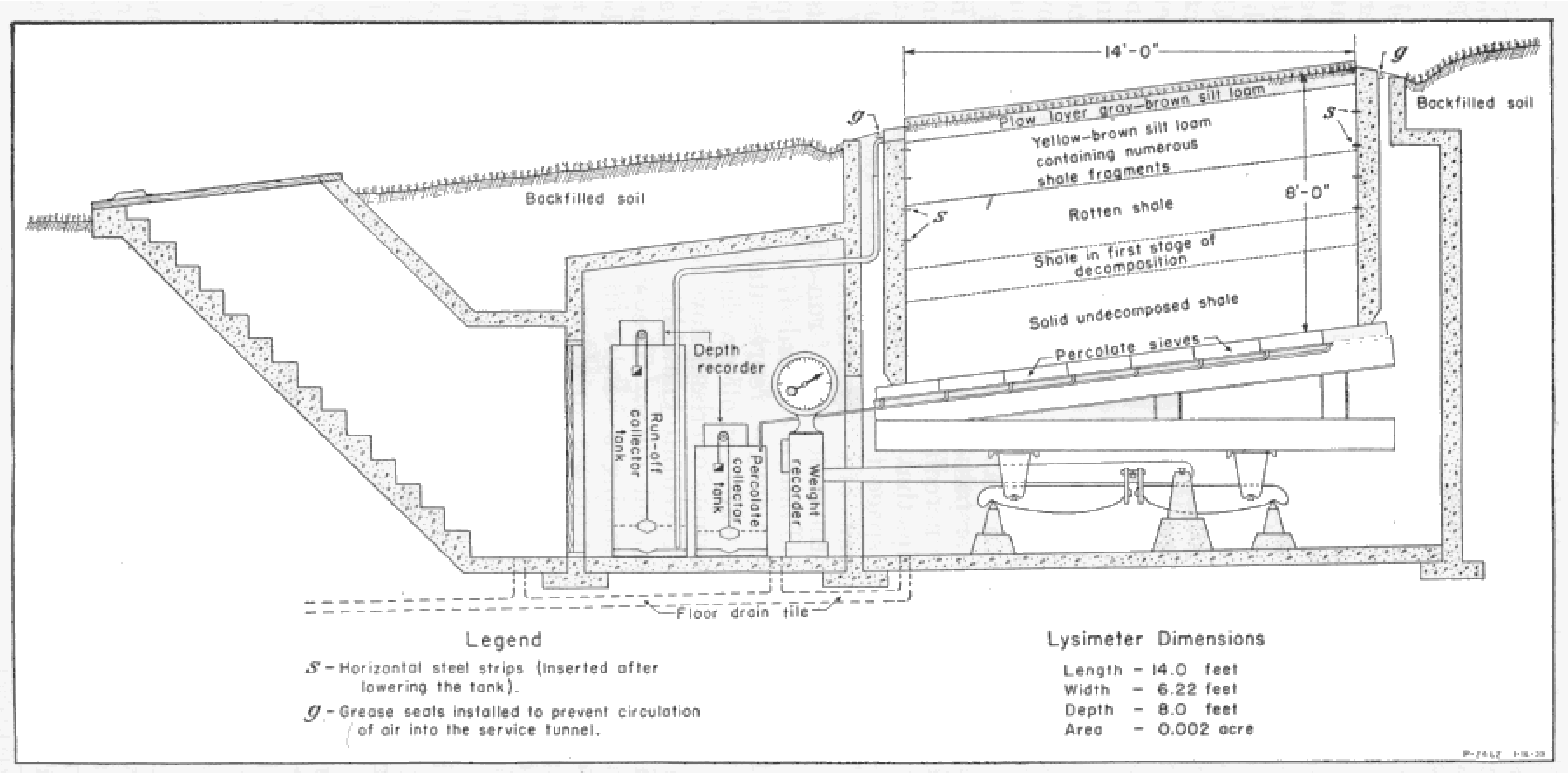

FIGURE 1.— Schematic cross-sectional diagram. A soil-block lysimeter with self-recording weighing mechanism used at the North Appalachian Experimental Watershed, Coshocton, Ohio.

percolation problems and which are sometimes sprinkled artificially, lysimeters are set up to supply data that correspond closely to those that would be obtained under natural conditions. It is surprising to note that in the majority of the lysimeters soil and percolation conditions prevail that are far from natural, and to sanction the use of such lysimeters by declaring very shallow filled-in lysimeters without run-off provision to be standard *(210)* appears to be unjustified. The removal of soil from its original site, and the process of sifting, mixing, and replacing it in a container is bound to change the resulting soil climate considerably. If this mixing is restricted to the plow layer, it does not seem to be so objectionable, since it is this part of the soil that is likewise disturbed in the field by agricultural implements. The mixing of the plow soil in itself cannot adversely affect the results, but its separation from the underlying soil layers is apt to change the percolation rate. To overcome this objection, some investigators have filled lysimeter tanks with a number of soil horizons in the same sequence as they occur in the natural profile, but in this way it frequently happens that soil that was on the upper side of a certain horizon will be placed in the lower part of the same horizon when filled into the lysimeter tank. This will result in a change of chemical, physical, and biological conditions and is apt to influence the rate of percolation and its chemical composition.

The change of the original soil structure, the obviation of root channels and of soil fissures in the lower horizons are apt to decrease greatly the rate of percolation, particularly in heavy subsoils; but the changes of percolation from natural conditions are not restricted to filled-in lysimeters. The greatest functional error in all three types of lysimeters probably occurs at the boundary of the lysimeter soil and the air beneath it. When the gravitational water reaches this point it will have to overcome the resistance set up by surface tension before it can leave the soil. This phenomenon has been studied by various soil investigators and has been described particularly well by Lebedev[11] and by Zunker[12] *(389)*, but it appears that many lysimeter installations have been planned without a complete comprehension of this drainage-impeding effect of the soil-air boundary at the bottom of the lysimeter.

Frequently sand or gravel is placed below the soil to keep it from washing out through the drain pipe. This practice is also followed in an attempt to provide for better drainage. The writers have investigated the effect on drainage by covering the bottom of lysimeters with 6-inch layers of washed sand and placing various layers of soil above them. At the end of the dry season (October) these layers of soil and sand were removed and the soil-moisture content of numerous samples determined gravimetrically. An accumulation of soil moisture was found above the soil-sand boundary as well as above each boundary between soil layers of different texture and a particularly great accumulation of water was present in the lower part of the sand just above the bottom screen.

In very humid climates where percolation rates are high the percolate restriction at the soil-air boundary will not be very serious, because enough water percolates to overcome the surface-tension impediment and

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[11] LEBEDEFF, A. F. THE MOVEMENT OF GROUND AND SOIL WATERS. 1st Internatl. Cong. Soil Sci., Washington, 1928. Proc. 1: 459-494. 1928.

[12] ZUNKER, F. DAS VERHALTEN DES WASSERS ZUM BODEN. Blank's Iiandbuch der Bodenlehre 6:125. 1930.

because the natural soils are moist most of the time. In drier climates, however, the soils in lysimeters will have a tendency to contain much more moisture in the bottom layer than they contain in this layer in the undisturbed profile. Unless lysimeters are very deep, the roots of the plants growing on them will reach this excess water and hence will supply the plants with more water for transpiration and more nutrients than they would under natural conditions. In this way the rate and amount of percolation and the chemical composition of the percolate are changed. Frequently, this accumulation of water together with the prevention of run-off, produces such an unhealthful condition that plant growth suffers, and the rate of transpiration is reduced below normal. Some investigators even aggravate this objectionable waterlogged condition of lysimeter soils by preventing the growth of higher plants and thus eliminating the natural disposal of water through transpiration. After a few seasons, moss and algae take the site, which has been made unsuitable for agricultural crops.

It is a well-known fact that waterlogging of soils is accompanied by many changes, such as lowering of the oxidation-reduction potential, denitrification, dissolving of iron and titanium, formation of hydrogen sulfide, raising of the partial pressure of carbon dioxide, all of which will tend to alter the chemical composition of the percolate. Where side walls do not permit the horizontal flow of water in lysimeters, as in the monolith and filled-in types, the water will be forced to escape through the open bottom after sufficient hydrostatic head has been developed to overcome the drainage-impeding effect of surface tension. In Ebermayer lysimeters it may frequently happen that the water, when encountering the obstacle to percolation set up by the soil-air interface, follows the path of least resistance and flows around the funnel. This may explain the extremely low percolation rates reported by Joffe *(90)* in the lower soil horizons. Harper[13] found that under certain soil conditions Ebermayer lysimeters did not yield any percolate, whereas under other conditions the same lysimeters acted as drains and therefore produced excessively high percolation rates. It is doubtful whether Ebermayer lysimeters will yield reliable data for the study of the composition of the percolate, but it seems certain that they cannot yield quantitative hydrologic data.

While this impeding effect will be operative in a greater degree in dry seasons and climates, the large amounts of gravitational water that percolate in times of excessive precipitation or after the thawing out of the soil in the spring will find less resistance at the soil-air boundary than they would in passing downward through an almost saturated subsoil. After such excessive drainage has taken place, no ground water is at the disposition of the lysimeter soil; and this soil may dry out considerably, whereas natural soil would have been kept moist for a much longer period. It is these two opposing factors, the impediment of percolation by the surface tension operative at the soil-air interface and the lack of resistance to percolation below the lysimeter, that frequently give percolation data of apparently satisfactory agreement with natural conditions, when only the amount of percolation of longer periods is considered. But data, obtained through compensation of two large errors, are of little value.

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[13] HARPER, HORACE J. A STUDY OF LYSIMETER INSTALLATIONS FOR THE MEASUREMENT OF GRAVITATIONAL WATER. Unpublished paper presented before the meeting of the Amer. Soc. Agron., November 1937.

One of the greatest objections to lysimeter investigations is that, generally, measurements of the moisture content of the various soil layers are not made, and therefore no knowledge can be obtained of the movement of the water within the lysimeter and no comparisons made with the moisture content of similar soils in natural surroundings. Determinations of gravitational soil moisture are normally out of the question in a lysimeter. Recently, however, tensiometers have been used *(69)* to study soil-moisture conditions in lysimeters, and other work is under way on this problem.

It is probable that air-pressure conditions in most lysimeters are different from those in the undisturbed soil, since so many factors occur in lysimeters that are likely to change soil-air pressure. The most important of these factors are probably the open bottom and the side walls. That such pressure changes influence percolation rates cannot be doubted, but it is likely that their magnitude is much smaller than the changes due to the factors mentioned above. Some careful research will be necessary to clarify this problem.

Soils containing a fair percentage of clay shrink on drying. When they are contained in a lysimeter it frequently happens that fissures appear between the soil and the side walls, and precipitation often results in direct percolation along the side walls before the soil has had time to swell and fill these openings. The amount of such "fictitious" percolation can be very large, and precautions should be taken to prevent it. Precipitation is not the only source of soil water; condensation and absorption of water vapor also contribute a significant share, and equipment should be installed to ascertain the magnitude of these accretions. If only chemical phenomena are investigated, such information is not particularly important. Wherever possible, provision should be made for weighing the lysimeter. Scales with weight recorders are to be preferred, since they permit the study of diurnal moisture fluctuations in the soil body. The following equations show how the data from a weighing lysimeter can be used.

Water addition	=	Water loss	+	Water storage
Precipitation (direct measurement)		Run-off (direct measurement)		Direct measurements by weight [14]
Rain		Percolation (direct measurement)		
Snow				
Hail		Evapo-transpiration [15]		
Sleet		Evaporation		
Fog		Transpiration		
Condensation				
Dew (plants)				
Condensation (soil)				
Adsorption (soil)				

Precipitation + condensation = run-off + percolation + evapo-transpiration + storage [16]

Precipitation - run-off - percolation - storage = evapo-transpiration - condensation

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[14] Weight changes of a lysimeter may be caused by other factors besides water. Most of these are insignificant, but such factors as application of manure, soil erosion, growth, and harvest of plants have to be included in the calculation.

[15] Evaporation and transpiration cannot be separated accurately in a single lysimeter experiment.

[16] Storage may be positive or negative (loss of weight). If it is negative, the opposite sign should be used.

These equations are applicable to any period of time studied. All factors on the left-hand side of equation (3) can be determined directly, while only the difference between evapo-transpiration and condensation can be obtained with this equation from the data of a weighing lysimeter. A rather close separation between condensation and evapo-transpiration can be obtained by plotting accumulated evapotranspiration minus condensation against time, wherever accurate weights are recorded for 30-minute intervals or less.

ESTABLISHED LYSIMETER FINDINGS

A critical review of the literature on lysimeters reveals that some authors have studied phenomena that have been satisfactorily investigated by others at previous times. All the factors that depend on purely local conditions obviously have to be studied at each given location. This is true of the determination of the magnitude of data obtained through lysimeter research. But since many lysimeters are constructed that cannot possibly represent natural hydrologic conditions, their data will yield at best only generalizations, and of these a good many are already known. A summary of those fundamental facts that have been established through the lysimeter research of two and a half centuries is presented.

FINDINGS WITH RESPECT TO THE MOISTURE RELATIONSHIPS OF SOILS [17]

TEXTURE

Percolation is more rapid through light soils than through heavy soils. Percolation is more continuous through heavy soils than through light soils. The total amount of percolation per year is greater through light soils than through heavy soils.

Heavy soils lose more water through evaporation and run-off than light soils.

STRUCTURE

Porous crumb structure favors percolation, whereas single-grain structure tends to decrease percolation. Exchangeable cations affect the percolate indirectly as they affect structure and swelling. Calcium and hydrogen soils have a higher rate of percolation than the same soils when treated with sodium salts, because the deflocculation of the clay brought about by the sodium ion results in the elimination of many of the larger pore spaces.

OTHER SOIL CHARACTERISTICS

Natural fissures, worm holes, and channels of dead roots increase percolation. Virgin forest soils allow a much greater percolation to occur than the same soils after they have been cleared and cultivated.

The amount of drainage is largely a reflection of the amount of precipitation and of the total amount of dry matter removed in crops, being increased by increases in precipitation and decreased by increases in the amount of dry matter removed. The influence of the depth of the soil column on percolation is largely determined by soil type. Since various investigators have reported entirely different correlations of soil depth with percolation, no general statement can be made.

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[17] The presentation of lysimeter findings is based on a comparative study of the data cited in this discussion of lysimeters.

Fertility affects the amount and rate of percolation only indirectly through the growth of plants. In general, high fertility is associated with increased transpiration and decreased percolation.

SOIL COVER

When a lysimeter soil is covered with coarse sand or gravel, infiltration is increased and evaporation decreased, and hence percolation is increased; this relationship might be obscured or changed by plant growth if the plants take up the greater amount of available water.

A mulch of dead vegetal material shows an effect very similar to a mulch of sand or gravel. The beneficial effect of a dead vegetal mulch on the moisture relationships of soils increases with increases in the thickness of the mulch to about 3 inches; but when the mulch gets much thicker the amount of water intercepted and directly evaporated surpasses the amount of water that is saved from evaporation, and hence percolation decreases.

Owing to transpirational losses, lysimeters covered with living vegetation usually show less percolation than those without vegetation. This difference is more or less proportional to the rate of growth, increasing during the summer and becoming negligible during the winter.

WEATHER AND CLIMATE

An annual cycle of percolation rates is frequently observed. In the Temperate Zone, percolation is greatest in the latter part of the winter and in the early spring and decreases rapidly with the growth of plants in the summer. In many installations percolation ceases entirely in midsummer and does not begin until late in the autumn.

The amount of annual percolation from any given lysimeter generally fluctuates approximately to the same extent as precipitation, whereas evapo-transpiration remains rather uniform under similar conditions of plant cover. The amount of percolation is affected after extremely dry or extremely wet years in proportion to the change of the soil-moisture storage from normal.

As is consistent with the genesis of soils, percolation occurs freely through Pedalfers, whereas through Pedocals it occurs only occasionally and in small quantities, unless the soils have been irrigated heavily.

FINDINGS WITH RESPECT TO THE CHEMICAL CONSTITUENTS OF THE PERCOLATE

The rate of loss of chemical constitutents from lysimeter soils is dependent on the amount of percolating water. During the summer, when the rate of percolation becomes very low, the rate of loss of chemical constitutents also drops considerably, but the total concentration normally increases with the decrease of the percolation rate. This, however, is not true of all individual elements. The amounts in which the various substances occur in the percolate depend on their abundance, their affinity to the soil, their solubility, the temperature, and the rate of percolation.

In general, the amount of chemical constituents lost is greater from bare soils than from soils supporting a vegetation, because the plant roots take up a considerable part of the dissolved chemicals.

The difference of concentration is particularly great in easily leachable materials, such as nitrate, chloride, and sulfate, whereas phosphate, usually in low concentration, is leached in about the same small quantities from fallow lysimeters as from vegetated lysimeters. The exchangeable bases take up an intermediate position in this respect.

EXCHANGEABLE BASES

In every lysimeter installation of which the writers have studied percolate analyses, calcium is leached out in much greater quantities than the other bases. Magnesium, potassium, and sodium usually follow in the order named. It is probable that in saline soils sodium would be lost to a greater extent than calcium, but lysimeter experiments on such soils are rather uncommon, probably because of the very nature of Pedocal soils, in which percolation is very low.

NITROGEN

Nitrogen occurs in the percolate mainly in the form of nitrate, A part of the ammoniacal nitrogen is utilized by plants, and the remainder is held largely in the exchange complex. Any ammonia released from these sources is normally oxidized before leaving the soil, and hence little ammonia appears in the percolate. In peat soils, because of their reducing power, a great deal of the nitrogen in the percolate appears in ammoniacal form. Under conditions favorable for denitrification, nitrates are found in the percolate. In filled-in lysimeters it is frequently noticed that in the first year or two the nitrate content of the percolate is rather high, but afterwards it decreases to very low rates. This decrease is due to aeration caused by stirring and mixing the soil before it bas settled and to the larger pore spaces remaining in the soil, which tend to make conditions favorable for nitrification. Later on, these spaces close up; and since the natural fissures and cracks have been destroyed by the sifting and filling process, aeration conditions, and hence nitrification, become poorer, particularly if drainage in the soil is impeded, as it is in numerous lysimeters.

PHOSPHATE

Phosphate is found only in traces in the percolate from most lysimeters irrespective of the fertility status of the soil and regardless of whether plants are growing on it. Only in case of high application of phosphate to a very light soil is the phosphate content of the percolate somewhat higher.

SULFATE

Rain water in practically every locality contains appreciable quantities of sulfate, particularly in the vicinity of cities and industrial plants, and it seems that the amount of sulfate in the percolate is somewhat dependent on the amount of sulfur in the rain. Other important sources of sulfur are commercial fertilizer and manure. Sulfate occurs in the soil in various compounds, some of which are not easily soluble, but there is usually an abundance of bases with which it can form soluble compounds, and, consequently, percolation waters are almost always relatively rich in sulfate. The amount of sulfate percolation, as well as nitrate percolation, is greatly affected by plant growth. The rate at which mineralization of organic matter takes place is another factor affecting the amounts of sulfate in the percolate.

CHLORINE

Chlorine is supplied to the soil mainly through precipitation and fertilizers, and since most chlorides are very readily soluble, they are leached out of the soil in about the same quantities in which they are supplied. If lysimeters are cropped, some chlorine is retained by the plants. This, however, does not greatly change the amount of chlorides in the percolate, since plants absorb very little of this ion. The concentration of chlorides in percolating waters of any given soil does not change very greatly during the season if no fertilizer containing chlorides is added. The rate at which chlorides are lost from the soil is almost proportional to the rate of percolation. In any one year the amount of chlorides in the percolate may be smaller or larger than the amount added to the soil through precipitation and fertilizers, depending on the amount of percolating water, which in turn depends largely on the rainfall.

SILICA

Only a few investigators have analyzed silica in lysimeter leachings, and little is known m this regard. Silica is lost in great quantities from most soils. Low concentrations of electrolytes in the soil solution seem to encourage the percolation of silica, because under such conditions the inorganic soil colloids become easily peptized and comparatively mobile, which results in a greater loss of silica in the winter than in the summer.

OTHER ELEMENTS OR COMPOUNDS

Iron, aluminum, titanium, manganese, carbonate, bicarbonate, and organic carbon have been determined in lysimeter leachates by a few investigators, but in the authors' opinion no general conclusions drawn from the data published to date are warranted.

REACTION OF THE PERCOLATE

In general, the pH value of the percolate from an unfertilized soil is higher than that of the soil itself. This is due probably to the presence of basic carbonate or bicarbonate salts in the percolate. When fertilizers are applied to the soil the pH value of the percolate may be either higher or lower than that of the soil, depending on the physiologic reaction of the fertilizer. The reaction of leachings from soils treated with sodium nitrate is near the neutral point, whereas leachings from soils treated with ammonium sulfate are distinctly acid.

SUGGESTIONS FOR FUTURE LYSIMETER STUDIES CONSTRUCTION OF LYSIMETERS

Two and a half centuries of lysimeter studies have greatly helped to promote the knowledge of the phenomena of the movement of water through soil and the leaching of chemicals from soils. Not in every case, however, does the yield of information obtained from a lysimeter investigation seem to correspond to the effort put into it. This is not surprising if one considers the many difficulties encountered in the construction and operation of lysimeters. In the following pages an attempt is made to enumerate the factors that are of primary importance m the construction of lysimeters.

In general, lysimeters should be constructed in such a way that their moisture relationships correspond closely to those of soils under natural conditions. (In some instances, special features that require a somewhat artificial environment have to be studied. The laboratory lysimeters will not be discussed here.) It should be considered ' essential that the soil in a lysimeter be in its original undisturbed condition. This is true regardless of whether the main purpose of the study relates to questions concerning hydrology or fertility. After the soil has once lost its identity by mixing, sifting, and packing, it is futile to hope that it will be restored to its original composition and structure by allowing it to settle for a few years. Flodkvist[18] found an increased permeability in soil that had been allowed to settle for 48 years. Nitrification is a very sensitive index of soil conditions. The percolate of freshly filled lysimeters, as has been mentioned, usually contains large quantities of nitrates, since the soil was aerated when it was handled and its pore space is greater than it was when the soil was in its original position.

After a few years the yield of nitrates in the leachate rapidly decreases to a point below that which would be obtained from the natural soil. The soil has then become so packed and dense that aeration proceeds only with difficulty. The cracks that provide air circulation in a natural soil have not had time to form. The change in nitrification can be very readily observed. There is no doubt that most of the other physical, chemical, and biological soil reactions are seriously affected by filling the soil into lysimeter boxes. The heavier the soil and the more mature its profile the greater will be the disturbance created by digging and replacing, even if an attempt be made to keep the horizons in their original sequence. It can be assumed that a sandy soil, particularly if its profile is rather undeveloped, will be little affected by removal from its original site and replacement in a lysimeter. In general, however, a soil should be left unmolested and the lysimeter built around it if data are to be obtained that will serve to answer the intricate problems of the moisture relationships of natural soils.

It can hardly be doubted that the separation of the soil profile from the substrata and the placing of a perforated bottom under it will affect the rate of percolation. The reasons for this have been discussed. It would appear reasonable to follow the example of Sanborn (85), who in 1888 built large lysimeters merely by encasing one one-hundredths of an acre of natural soil in impermeable vertical walls and placing drain tiles at a 4-foot depth in the ground to collect the percolate. It seems that no other investigator has employed this type of lysimeter, probably because of the uncertainty of all the percolate being collected in the tiles and the probability of obtaining data that are not quantitative. The excessive drainage caused by the drain tiles can hardly be considered a valid argument against the Sanborn lysimeter, since some other lysimeters also are defective in this respect, at least during the wet season.

In the authors' opinion, it would be worth while to make a study of the usefulness of Sanborn lysimeters; for they permit a study of percolate obtained from soil with a minimum of disturbance of the profile.

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[18] Flodkvist, H. AGRONOMISCH-HVDROTECHNISCHE ERGEBNISSE VON DRÄNUNGSVERSUCHEN AUF TONBODEN. 3rd Internatl. Cong. Soil Soi., Oxford, Trans. 3: 164-168. 1936.

Sanborn was not able to make such a study, because he left the Missouri Agricultural Experiment Station shortly after completing the lysimeters. As all other lysimeters are constructed with an artificial bottom and as percolation of water through soil cannot be studied at present without lysimeters, it seems best to place this bottom as deep as possible. This is particularly important if plants grow on the lysimeters. The bottom of a lysimeter should be so deep that only very few roots can reach it, because then the water removed by plants from the soil at the bottom will be negligible. In a rather shallow lysimeter (3 to 4 feet) many roots penetrate to the bottom layer, which is frequently better supplied with water than soil of the same depth that is in contact with strata underneath. The drier the climate, the more serious is this factor.

The movement of gravitational water through soil is not exclusively perpendicular, but frequently follows fissures, old root channels, and the like, in a slanting direction. The lysimeter walls will act as an insurmountable obstacle to such percolation. The ideal would be to construct lysimeters without side walls (Ebermayer lysimeters), but it is impossible to obtain quantitative data with them since the soil area drained is not definitely known. A practical approach to the ideal is to decrease this border effect of the side walls by building lysimeters of rather large area (one one-thousandth to one one-hundredth of an acre).

Soils containing an appreciable amount of clay have a tendency to shrink on drying, and cracks are therefore very likely to be formed between the soil block and the lysimeter walls. Precautions should be taken to avoid drainage along such cracks. Horizontal steel strips extending 1 to 2 inches into the soil and roughened side walls have been found useful in this respect. Not only will standing water alter the immediate moisture conditions of a soil, but, after some time, it will actually alter the very nature of the soil itself. It is obvious that after such a change has occurred, the data from a lysimeter lose their significance. Soils that have in nature free surface drainage should be provided with the same drainage in the lysimeter. It is obvious that the amount of run-off water should be recorded.

The writers believe that no one construction should be regarded as standard in a lysimeter and that a proper design can be made only by having an accurate knowledge of both the purpose of the experiment and of the pedologic, geologic, and climatic conditions.

EXPERIMENTAL PLAN

To avoid drawing conclusions from inadequate information, investigators should not carry out lysimeter studies without replicating each individual treatment. The number of replicates needed depends largely on the nature of the investigation and the type of lysimeters used. If the soil is left in its natural condition, no assurance is given of its uniformity; therefore, at least triplicates should be used to represent any one condition studied. The frequent practice of attempting to study too many factors with too few lysimeters should be avoided. As soil in all existing types of lysimeters may be subject to deterioration, it is necessary to continue the study of a given installation at least throughout a decade in order to determine whether such deterioration has occurred and to judge the value of the data. It may be advisable to install a number of extra lysimeters and to remove the soil from one of them every 2 or 3 years so that its chemical, physical, and biological properties may be determined. If pronounced changes of soil properties are found, the potential future usefulness of the installation for attaining the original objective should be carefully considered.

Lysimeter installations are normally supplemented with precipitation gages and other meteorological measuring devices. For the selection of adequate equipment the investigator should get the advice of a professional meteorologist. An accurate knowledge of hydrologic factors is needed regardless of whether the main object of the investigation is the study of the rate and amount of the percolate or of its composition.

PUBLICATION OF DATA

Lysimeter investigations could be made more useful by describing the installations more completely and recording the data in a uniform manner. The soils are usually, though not always, described in detail, but information concerning soil changes during the investigation is seldom included. Any chemical, physical, and biological change should be noted, since it might give an important clue to the nature of the percolation. All hydrologic data should be expressed as inches depth (or centimeters depth) and the chemical constituents as pounds per acre (or kilograms per hectare), so that any lysimeter investigation may be easily compared with another or with related studies. It is very confusing to read lysimeter reports in which precipitation is recorded as inches depth, percolate as cubic centimeters per lysimeter, and the chemical constituents as parts per million of the percolate.

"Lysimeter" is an accepted term for a device to study the rate, amount, and composition of natural precipitation percolating through soil and it should be used wherever reference is made to such an instrument. Such terms as "culture pot," "rim," "percolator," "percolimeter," and "drain-gauge" are ambiguous and should be avoided.

SUPPLEMENTARY STUDIES

In many instances a knowledge of the amount, rate, and composition of the percolate can well be obtained by the study of water flowing from springs or field drain tiles. This information may not be quantitatively correct, because the drainage area is not definitely known and not all the percolation water may be caught. The great value of such studies lies in the fact that the data are acquired from a percolate obtained without any interference with natural soil conditions. " A combination of such studies and lysimeter research appears to be advisable.

CONCLUSION

Lysimeters have distinct limitations, as has been pointed out; but without doubt many questions concerning pedology, soil fertility, and hydrology can be answered by the correct use of lysimeters. Filled-in lysimeters may fulfill useful tasks in fertility investigations if a sound water balance is maintained in the soil; but for pedologic and hydrologic studies carefully designed monolith lysimeters seem to be indispensable.

BIBLIOGRAPHY ON LYSIMETERS

Compiled by J. M. DAVIDSON [19]

CONTENT AND ORGANIZATION

This bibliography lists publications that refer to the design or construction of lysimeters, the method of filling and the type of soil used, the treatment and cropping of the soil, the amount of leaching and the loss of plant nutrients, the analysis of the soil and the leachate, or the discussion of some phase of lysimeter investigations. For the purpose of this bibliography a lysimeter is defined as an instrument that contains soil and receives natural rainfall or irrigation and is provided with an arrangement for collecting and measuring the percolate. Literature on natural lysimeters, such as small watersheds, having no apparent supply of moisture other than that from the atmosphere and provided with either natural drainage or tile-drainage systems, is not included. In most entries the pagination refers to that part of a publication that treats of lysimeters. No reference is included that does not deal directly with the subject of lysimeters.

The following letters are used to indicate the content of any entry:

A. Information on the size, design, construction, installation of the lysimeter.
B. Data on the amount of leaching or quantity of leachate from the lysimeter.
C. Data on the quantity of plant nutrients lost from the soil or the chemical analysis of either the leachate or the soil.
D. A comparison with other investigators' work or inclusion of data from such reports.
E. Only a general statement or discussion with no data included unless otherwise indicated.

The letter or letters directly opposite an author's name indicate those subjects discussed in the material cited in the entry. Letters within the body of the entry indicate the subject treated in particular citations.

The entries are made according to the geographical distribution of the lysimeters. The arrangement of references in chronological order under the geographical divisions indicates the historic development of lysimeter research in each. No special significance is attached to the order in which the countries are listed. Entries of the studies in the States and Territories of the United States are first; next in order are those for Great Britain, Asia, continental Europe, and Africa.

The author index (pp. 65-67) is arranged alphabetically. The numbers following each author's name provide a ready reference to the entry in the bibliography in which his work is cited.

It was the aim of the compiler of this bibliography to set up an arrangement that would permit the selection of references for any period, location, author, or specific type of subject matter without the necessity of reviewing the entire field of literature on the general subject of lysimeters. This type of bibliography reduces the time necessary for the selection of references on a particular phase of lysimeter investigation. For example, the preparation of a report on the amount of nitrogen lost by leaching from soils in lysimeters in Europe would necessitate the review of only those entries denoted by C and listed under European countries.

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[19] The compiler wishes to express his gratitude for the advice and cooperation of his associates in the Soil Conservation Service, and for the excellent assistance of Robert Jones, Ann Goodwin. and others of the Works Progress Administration in the preparation of the bibliography.

Titles of publications are given in the language in which they were published, except those in Russian. These are transliterated. If a work has appeared in more than one language the languages in which it has been published are named.

All translations by the compiler and additions to the references are in brackets. Citations to abstracts have not been made unless so stated; however, abstracts of many of the works cited appear in the Experiment Station Record and Chemical Abstracts. All the publications in this bibliography, with the exception of entry 456, which is not obtainable in this country, have been examined by the compiler in the libraries in Washington, D. C.

If omissions have been made of lysimeter investigations that are within the limitations set up for this bibliography, the librarian of the Soil Conservation Service would appreciate receiving such information. The exact title, author, publication, and date should be given. There are several lysimeter studies that have been or are being conducted in various parts of the world for which no published reports have been made.

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U.S. GOVERNMENT PRINTING OFFICE: 1940