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MEASUREMENT OF CANAL SEEPAGE

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WITH DISCUSSION BY MESSRS. RAYMOND A. HILL; DEAN C. MUCKEL; CALVIN C. WARNICK; N. SZALAY; CYRIL W. LAURITZEN; AND AUGUST R. ROBINSON, JR., AND CARL ROHWER

SYNOPSIS

Existing methods of measuring seepage have been investigated by the authors in an effort to develop new methods and to study the factors affecting seepage. Special studies include the effect of depth of water on seepage, the effect of the depth to ground water, and the effect of temperature on the seepage rate. Seepage meters were found to indicate the order of magnitude of loss, although they do not provide accurate measurement. A method of analysis was developed for using the well-permeameter test results in forecasting seepage.

INTRODUCTION

Of the water diverted for irrigation in the seventeen western states of the United States, nearly 35,000,000 acre-ft, or approximately 40%, is lost before it reaches the farms. On forty-six operating projects constructed by the Bureau of Reclamation, United States Department of the Interior, it was determined that approximately 25% of the water was lost in transit. This loss consists of seepage, evaporation, transpiration, and leakage. The greatest amount of water is lost by seepage. This seepage water is not only lost to the canal to which it is appropriated but may also cause considerable damage to lands as a result of high water-table conditions and excess salts in the soil. Although the water is lost to the canal, it is not totally lost, as a considerable amount may go to replenish ground-water supplies or to increase the return flow to streams.

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Methods of measuring seepage are necessary in order to determine the magnitude of the losses and also to isolate reaches of canals where high losses are occurring. Water is becoming increasingly valuable and it is necessary to determine whether the economic value of the water saved and the land reclaimed, plus the savings in cost of operation and maintenance, will exceed the cost of lining. It is also desirable to determine whether a new canal should be lined before construction is started.

Many factors have a definite effect on the seepage rate, but the permeability of the material forming the bed of the canal is the most important one. Other factors that influence the seepage rate are: (1) The depth of water in the canal,

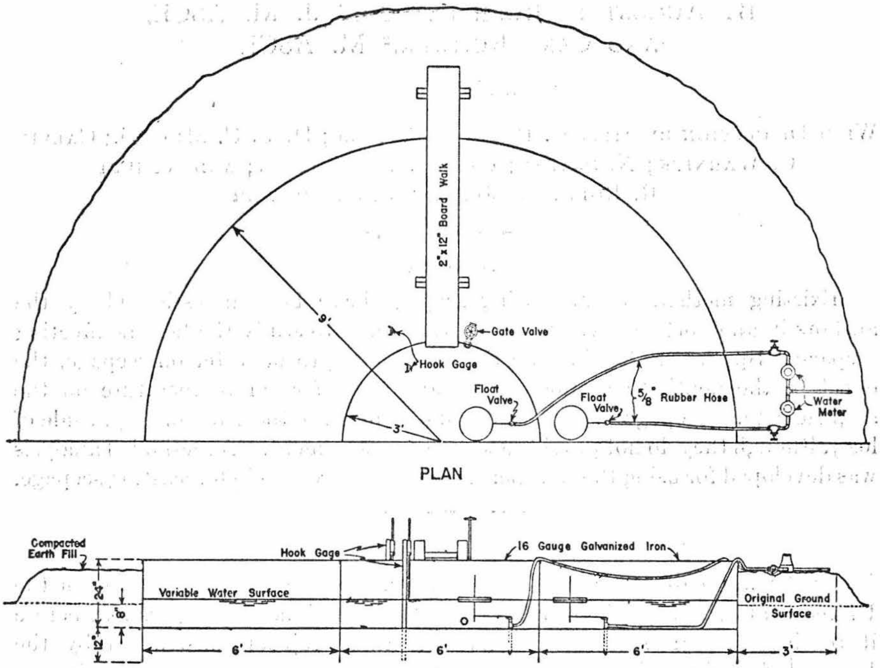

FIG. 1.—SEEPAGE RINGS

(2) the length of time the canal has been in operation, (3) the depth to ground water, (4) the temperature of the water and the soil, (5) the percentage of entrained air in the soil, (6) the soil-moisture tension, (7) the salt content of the soil or water, and (8) the volume of silt carried by the canal. Biological factors and the barometric pressure may affect the seepage rate, to a degree dependent on conditions. Because all these factors may act simultaneously and may, in some cases, counteract each other, it is difficult to segregate the effect of any one of them.

Various methods of measuring seepage have been devised which are adaptable for use in the field or in the laboratory. Some of these methods yield results which are the average seepage for a section of a canal, whereas others give the seepage rate for a small area or merely furnish information as to the permeability of a sample of the canal bed material, either in its undisturbed state or in a crushed, screened, and compacted condition. If methods are used that yield only the permeability, additional observation must be made to determine the hydraulic gradient.

The principal methods of measuring seepage now in use are: (1) Ponding, (2) inflow-outflow, (3) use of the seepage meter, (4) use of the well permeameter, (5) laboratory permeability measurements, and (6) special methods such as measuring electrical resistance in the areas where seepage is occurring or tracing radioactive material in the seepage water. Seepage rates based on the ponding tests are the most reliable but the cost of these tests frequently

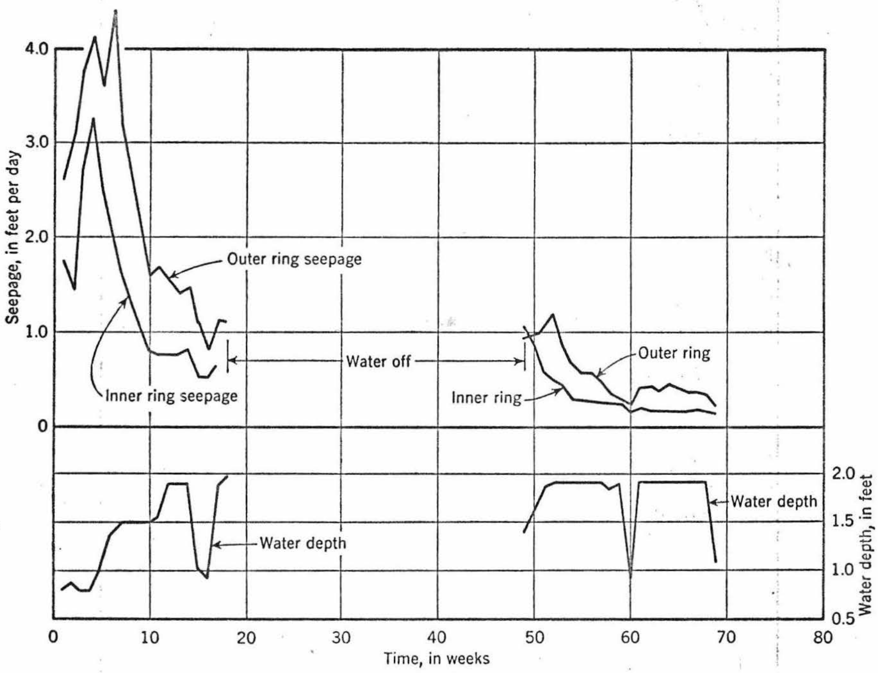

FIG. 2.—EFFECT OF ELAPSED TIME ON THE SEEPAGE RATE FROM SEEPAGE RINGS IN SANDY LOAM

precludes the use of this method. For this reason, other methods must usually be adopted.

The project being reported on was initiated to (*a*) study the existing methods of measuring seepage, (*b*) develop new methods of measuring seepage, and (*c*) study the factors that affect seepage.

MEASUREMENT OF SEEPAGE LOSSES

Seepage Rings.—Because of the limitations of the customary methods of measuring seepage, such as inflow-outflow and ponding methods, it was decided in the present study that some of the experiments would be conducted in artificial pools where the measurements and factors involved could be accurately determined. These pools were formed by concentric metal rings as shown in Fig. 1. The rings could accommodate a 2-ft depth of water, and the inflow necessary to maintain a constant depth of water could be accurately measured. The seepage meter was calibrated by using these rings with the meters installed in the outer ring and then by comparing the rate from the seepage meter with the seepage-ring rate. The rings were installed in several

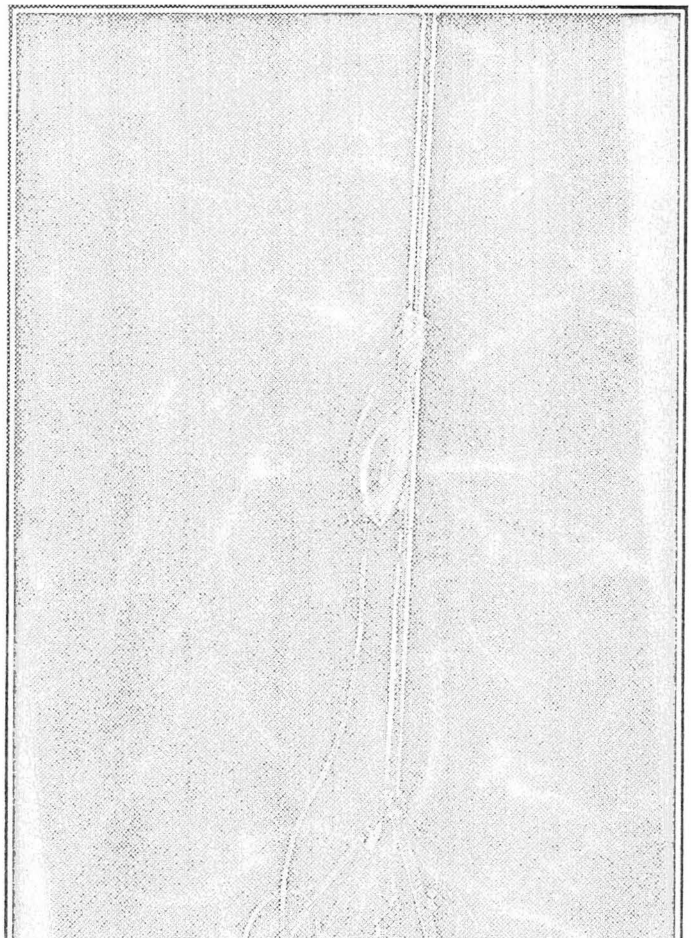

FIG. 3.—A SEEPAGE METER, WITH PLASTIC BAG

locations in soils ranging from clay to sand. These rings were operated continuously in each location for periods of approximately six months. The rings also provided facilities for studying the effect of depth of water, time, temperature, and other related factors on the rate of seepage through soils of different types.

In long-term seepage tests, it is significant to note the effect of time and its related factors on the seepage rates. Generally, the seepage rate decreases with time after the water is first introduced. Fig. 2 shows the seepage rate determined from use of rings installed in sandy loam during a period of two years. The seepage rates continued to decrease throughout the entire period although no silting occurred. This decrease was probably due to microbiological action, the decomposition of soil aggregates, and possibly the clogging of pores.

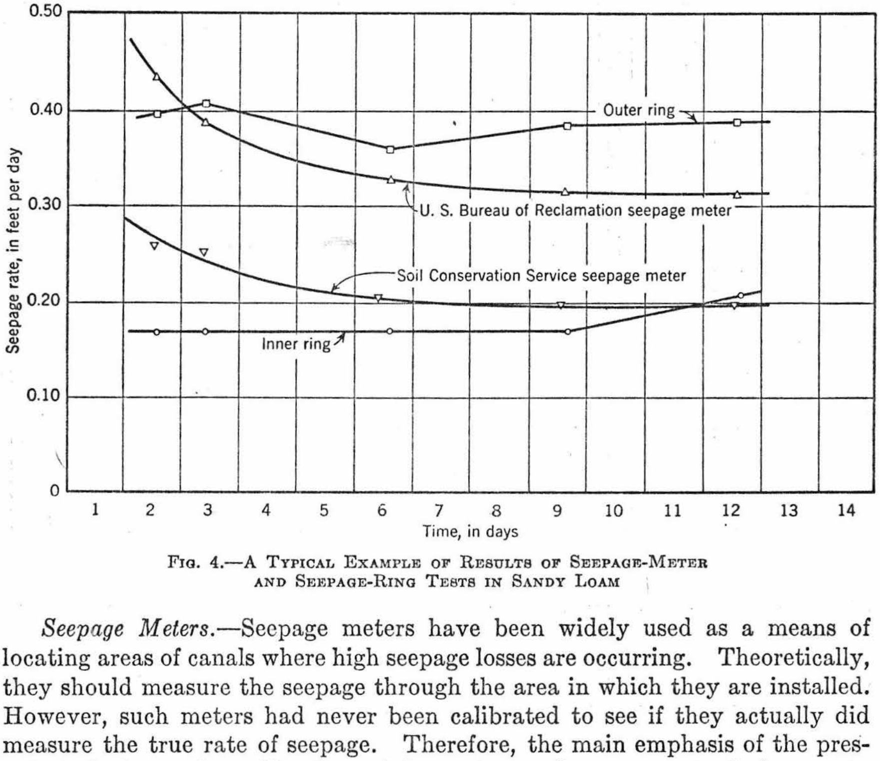

FIG. 4.—A TYPICAL EXAMPLE OF RESULTS OF SEEPAGE-METER AND SEEPAGE-RING TESTS IN SANDY LOAM

Seepage Meters.—Seepage meters have been widely used as a means of locating areas of canals where high seepage losses are occurring. Theoretically, they should measure the seepage through the area in which they are installed. However, such meters had never been calibrated to see if they actually did measure the true rate of seepage. Therefore, the main emphasis of the present study is on the calibration of the meters and on recommendations as to the best method of installation.

Fig. 3 shows one type of seepage meter which was adapted by the Bureau of Reclamation from the meter developed by the Regional Salinity Laboratory, Soil Conservation Service, United States Department of Agriculture (Riverside, Calif.), and used in this study. The bell of the meter is pressed into the canal bottom or side in order to isolate a small area. The meter is installed under water but the area under the bell is isolated so that water is fed into the bell from the plastic bag, which is submerged in the canal. A seepage rate can then be determined from the volume of water drawn from the bag during a certain period of time.

Several hundred tests were made with the seepage meter in the seepage rings. In some types of soil the initial rates measured by the meters were much higher than those indicated by the seepage rings. An example of this is shown in Fig. 4. In other cases the seepage-meter rates were lower than the seepage-ring rate. The method of installation seemed to affect the results. Hammering or jarring the meters during installation tended to influence the results in that the measured rates were much lower than the seepage-ring rates.

A calibration curve for the seepage meter is shown in Fig. 5. The rates measured by the seepage meter and those determined in the rings agree fairly

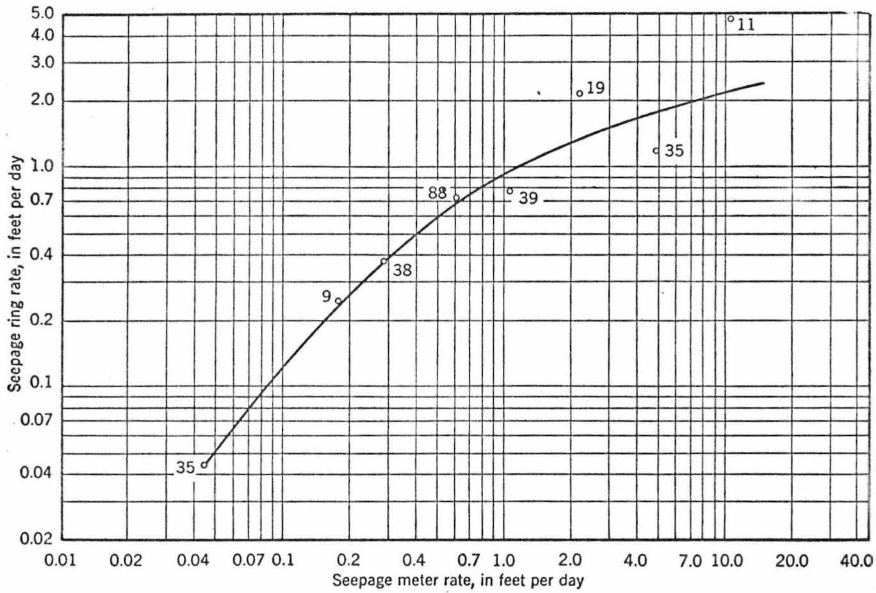

FIG. 5.—THE RELATIONSHIP BETWEEN SEEPAGE RATES FROM SEEPAGE RINGS AND SEEPAGE METERS (NUMBERS ON POINTS ARE NUMBER OF SINGLE DETERMINATIONS AVERAGED TO DETERMINE POINT)

well up to a rate of 1.0 ft per day (cubic feet per square foot per day). However, beyond this point the seepage-meter rates are greater than the seepage-ring rates.

Seepage-meter tests in canals which were checked by ponding tests yielded discouraging results. The seepage-meter tests were made only in the canal bottoms and at great distances apart. It is believed that the discrepancy in the results was due to the possibility that the seepage was greater through the sides than through the bottom of canals. In order for satisfactory results to be obtained with seepage meters in canals, the meters should be installed on the sides as well as on the bottom of canals. The measurements should be made at points as close together as possible.

Well Permeameters.—Whenever the feasibility of a new irrigation project is being investigated, there is need for information on the probable seepage loss from proposed canals. The well permeameter was developed by the Bureau of Reclamation for this purpose. This device measures the rate at which water seeps from a small well drilled in the soil on the center line of the proposed canal. After observations have been made on seepage from wells at intervals along the canal, an estimate of probable seepage loss can be made.

The well permeameter is shown in Fig. 6. This permeameter consists of a calibrated supply tank equipped with an indicator glass and an outlet pipe equipped with a float mechanism. The float maintains a constant water level in an uncased hole. This hole varies in depth but is usually drilled to the same elevation as the proposed canal invert.

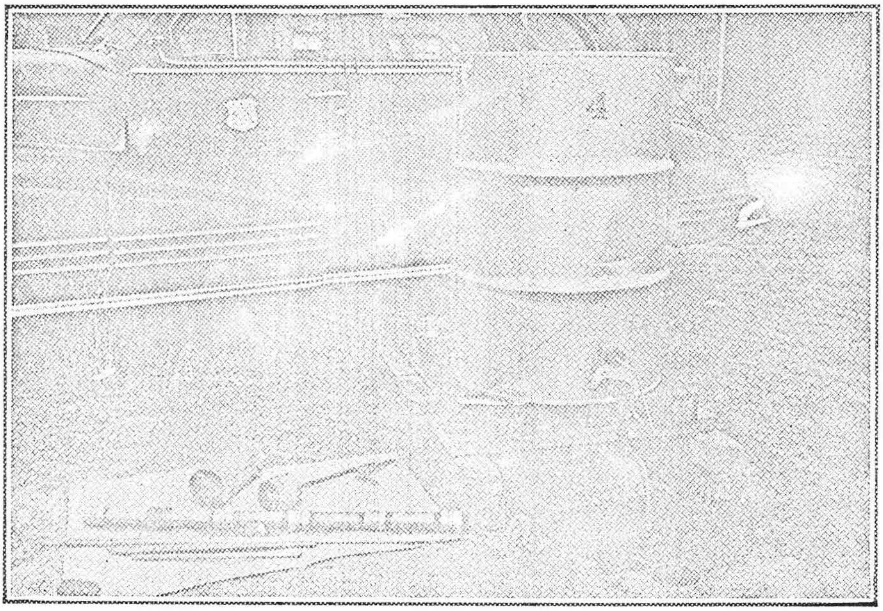

Fig. 6.—Equipment for the Well-Permeameter Test

A calibration curve for the well permeameter is shown in Fig. 7. The results of the well-permeameter tests have been compared to those from ponding tests on the canal after completion. The permeameter test results were computed on the basis of the outflow from the well converted to a unit seepage rate over the wetted area of the well. From Fig. 7 it can be seen that the correlation is not definite for line A. For this relationship the seepage from the ponding test was considered to be through the sides and bottom of the canal. From previous tests it had been determined that most of the seepage occurs through the sides of a canal in many instances. For this reason the data from the ponding tests were recomputed so that all the seepage was considered as passing through the canal sides. This relationship is shown as Line B in Fig. 7.

Special Studies

Effect of Depth of Water on Seepage.—Seepage measurements made by the ponding method during previous investigations of seepage have shown that the seepage rate increases as the depth of water in the canal increases. In some instances the sides of the canal are more permeable than the bottom, which results in an increased seepage rate as the depth of water is increased. In order to study the effect of water depth on seepage through the canal

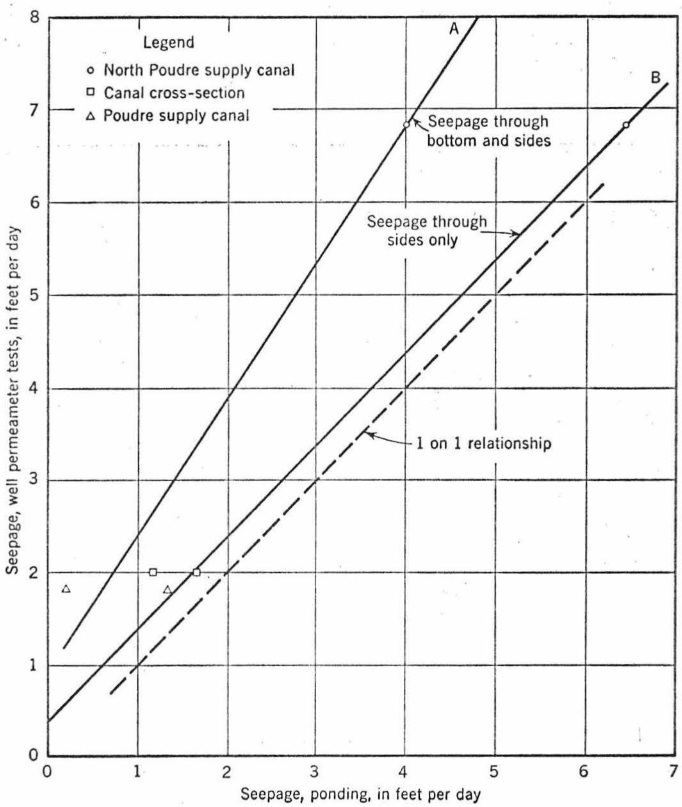

Fig. 7.—The Relationship Between Seepage Data from Ponding Tests and Those From Well-Permeameter Tests (All Rates Corrected to 60° F)

bottom, seepage rings were used in which all the seepage would occur through the bottom under a wide range in depths.

In order to determine the effect of depth on the seepage rate the water levels were allowed to drop in the seepage rings and every two hours readings were taken of the water depth, seepage rate, and water temperature. Fig. 8 shows the effect of depth on the seepage rate for sandy loam. The seepage rate always decreased as the depth decreased but seepage was indicated even as the depth approached zero. This shows that the seepage rate is not directly proportional to the depth of water but is proportional to this depth plus some distance below the surface. In all cases it should be noted that the seepage

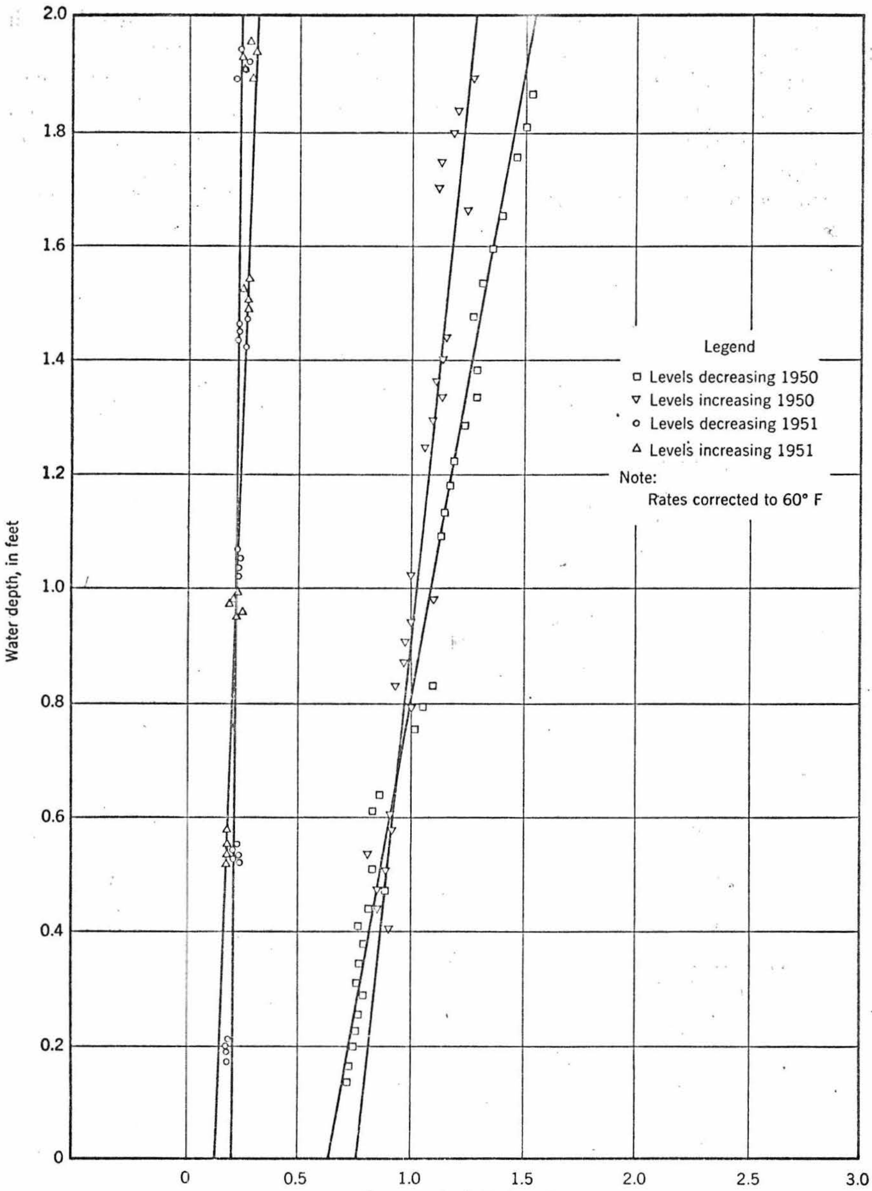

FIG. 8.—THE EFFECT OF WATER-DEPTH VARIATION ON THE SEEPAGE RATE IN SANDY LOAM, MEASURED IN THE OUTER SEEPAGE RING

rate did vary in a straight-line relationship and the rate increased with depth. Fig. 8 shows that the effect of depth on the seepage is greater as the permeability of the soil increases.

The results of several ponding tests on canals revealed, however, that the depth-seepage relationship was not linear, but that the slope usually increased with depth. This effect was probably due to the fact that the seepage through the sides was much greater than through the bottom of the canal.

A method of solving for the permeability, k, for the seepage rings was developed. This method is based on the results of the effect of depth study. The data for the inner ring were used. By projecting the lines representing the depth-seepage relationship until zero depth was reached, a value was determined for the seepage rate when the water level and the ground surface

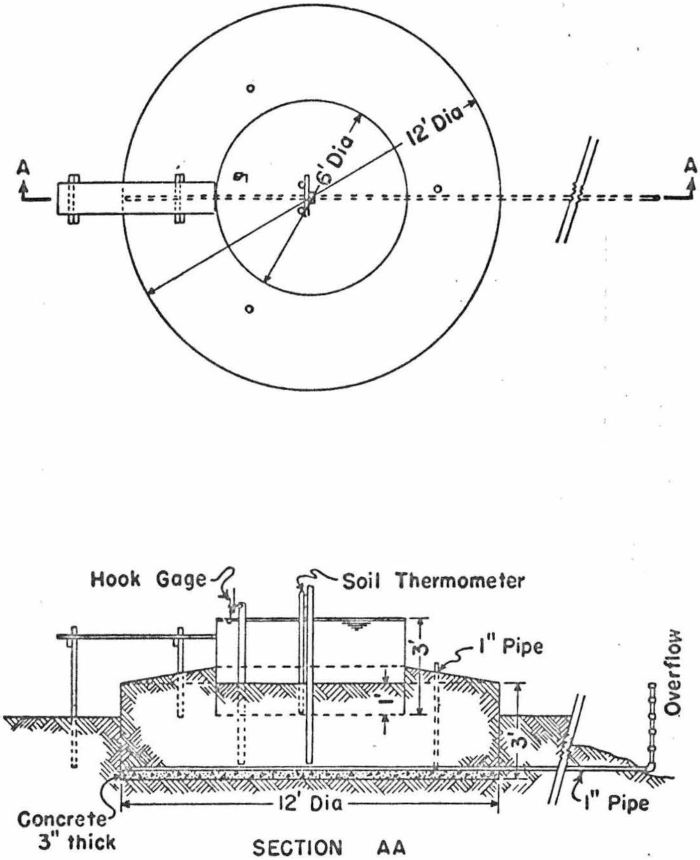

FIG. 9.—DETAILS OF THE SEEPAGE RING USED FOR A STUDY OF THE EFFECT OF GROUND-WATER FLUCTUATION ON THE SEEPAGE RATE

coincide. According to the Darcy equation, $q = k(h/l)$, in which q is the rate of flow per unit area, k is the permeability, h is the hydraulic head, and l is the length of the soil column. At zero depth of water, h and l are equal so that h/l equals unity, and q equals k at this point. It should be pointed out that this is true only if a negative head caused by soil-moisture tension does not exist or is negligible. This development may prove useful in other studies for determining the permeability of soils.

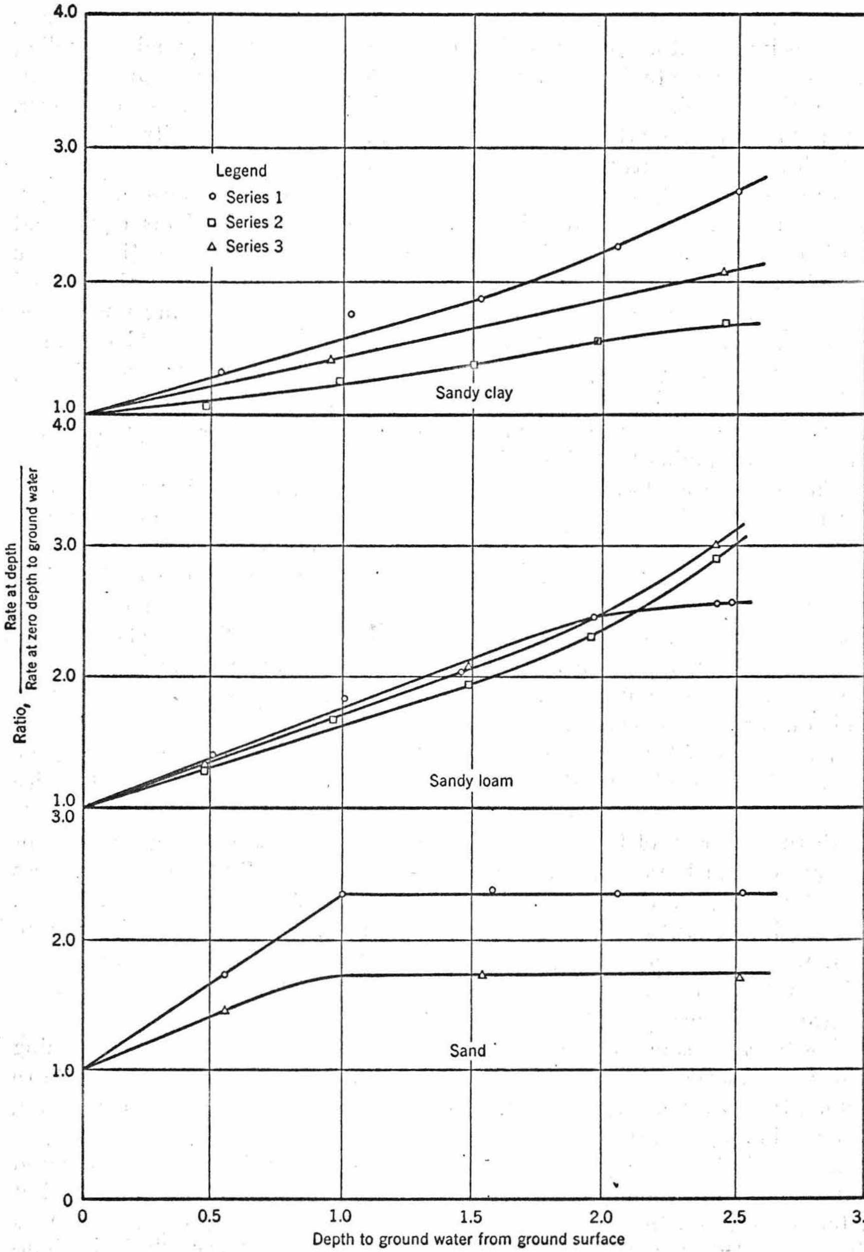

Fig. 10.—Effect of Variation of Water-Table Elevation on the Seepage Rate

Effect of Depth to Ground Water.—One of the problems encountered in the study of seepage is the effect of depth to ground water on the seepage rate. Previous investigators[3] have noted, in connection with water spreading studies, that the seepage rate decreases as the ground-water level approaches the surface of the ground. The problem was investigated by the writers to discover, if possible, how important this factor is and within what limits of ground-water levels it is effective.

In order to study the effect of depth to ground water on the seepage rate, the special equipment shown in Fig. 9 was constructed. This equipment consisted of two concentric rings with the larger ring sealed on the bottom and filled with soil. This ring had an adjustable outlet so that the ground water could be maintained at any desired level. The inner ring was placed to accommodate a maximum 2-ft depth of water, which was held constant. The inflow necessary to maintain this constant level was measured accurately. Soil thermometers were placed in the inner ring in order to determine the soil temperature at various depths. Tensiometers were also placed in the rings for determining the soil tension.

These rings were located in different types of soils, and continuous operation was maintained during a period of several months. The ground water was held at constant level for a period of approximately five days. After this time the level was changed by adjusting the elevation of the outlet pipe. The elevations were changed in sequence starting at maximum depth and proceeding by 6-in. increments until zero depth was reached. The ground-water elevations were then lowered by the same increments until maximum depth was again maintained. Approximately three complete cycles were made during the test period.

The results of tests on the effect of depth to ground water on the seepage rate are shown in Fig. 10. The rate for sand increased to approximately twice that at zero depth when the ground water was lowered 1 ft. Below this 1-ft depth the lowering of the water table did not change the seepage rate. For the sandy loam the seepage rate had increased to approximately three times that at zero depth, when the depth to ground water had been lowered to 2.5 ft. The maximum depth to ground water that could be produced with the equipment was 2.75 ft. For the sandy clay the rates had increased an average of twice the rate at zero depth when the ground water was lowered 2.5 ft below the ground surface.

For both the sandy clay and sandy loam the seepage rates were continuing to decrease at the 2.5-ft depth to ground water. From this fact, it is safe to assume that a further lowering of ground water would result in a continuing decrease in seepage rates.

Effect of Temperature on the Seepage Rate.—It has long been recognized that temperature should affect the seepage rate because of the known effect of temperature on the viscosity of water. Because the viscosity increases as the temperature decreases, the seepage rate should decrease when the temperature drops. However, continuous tests with well permeameters on the line of the proposed North Poudre Supply Canal (Colorado-Big Thompson

[3] "Spreading Water for Underground Storage," by A. T. Mitchelson and D. C. Muckel, *Technical Bulletin 578*, U. S. Dept. of Agriculture, Washington, D. C., 1937.

Project in Colorado) showed that the loss from the permeameters increased as the temperature decreased (Fig. 11) and that the maximum losses occurred when the temperature was a minimum. Readings twice daily of the seepage loss from the seepage rings in various types of soil had failed to disclose this tendency. For this reason several series of continuous observations for periods of three days were made on the seepage rings to determine whether temperature affected the seepage readings in the same way. The readings were taken at 2-hr intervals.

These tests were made on several different types of soil. The rings were refilled between readings to minimize the effect of the drop in the water level. These observations on the seepage rate also showed that it decreased as the temperature of the water increased.

There was considerable variation in the amount of the decrease in different types of soil, but the trend was unmistakable. The maximum variation in the seepage rates due to temperature occurred in the sandy soil. When the seepage

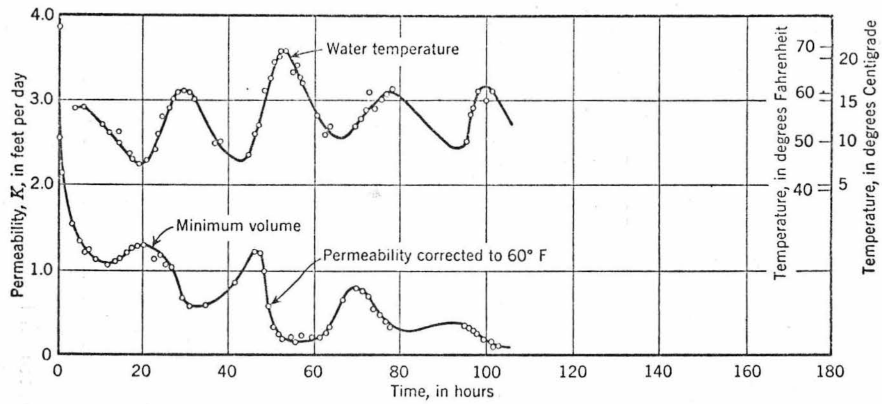

FIG. 11.—EFFECT OF TEMPERATURE VARIATION ON PERMEABILITY—WELL-PERMEAMETER TEST

rates were corrected for viscosity to the standard temperature of 60°F, the trend was made more noticeable. The results of typical series of observations in 1952 and 1953 are shown in Fig. 12.

Attempts were made to explain this phenomenon on the basis of the expansion and contraction of the bubbles of air trapped in the soil as the temperature changed, but the change in volume of the air was too small to account for the difference in the seepage rate. The effect of the variation in solubility of air in water with variation in temperature was also investigated. Although this is a logical approach to the problem, the temperature gradient between the water and the soil was usually too small to account for the observed differences.

Apparently some other factor, dependent on temperature, was causing the variation in the seepage rate. Because the air that remains in the soil even after long periods of saturation would change in volume with changes in the vapor pressure of the saturated air in the bubbles, the effect of these changes was also investigated. Vapor pressure changes rapidly with an increase in

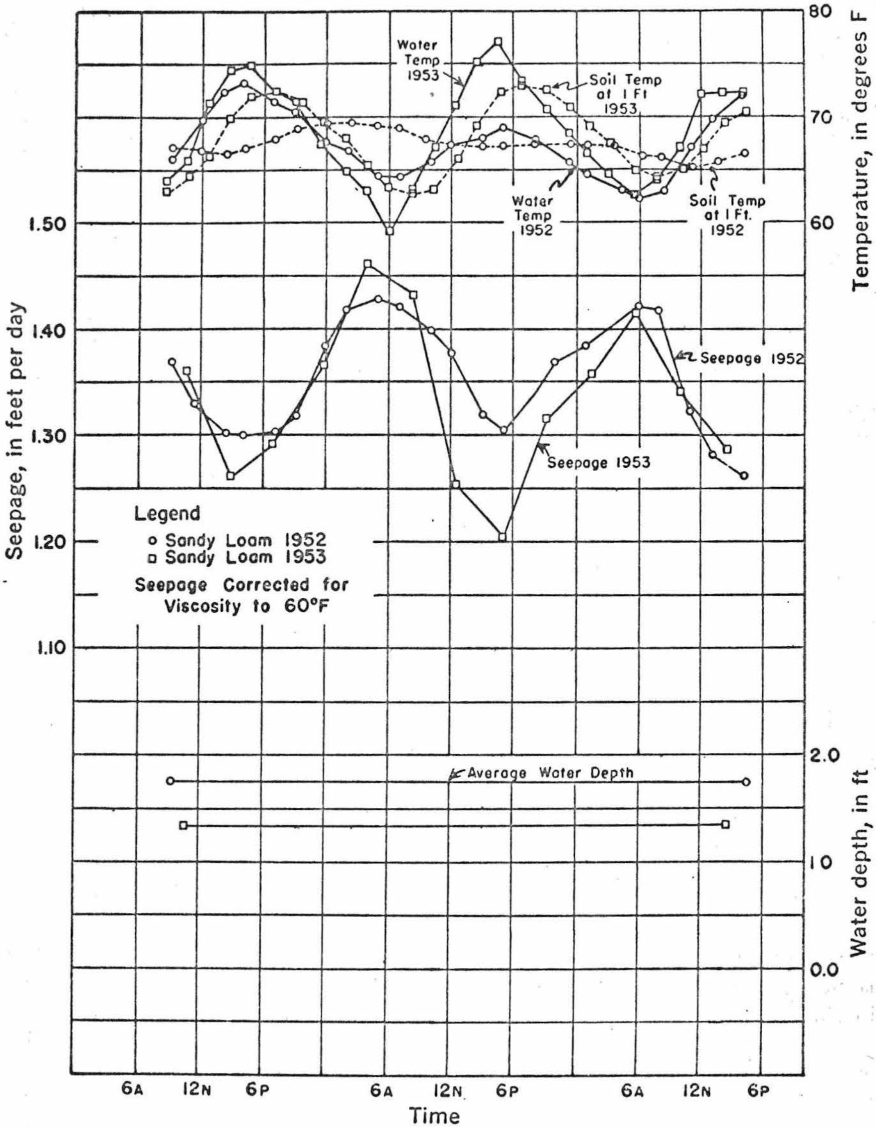

Fig. 12.—Effect of Temperature Variation on the Seepage Rate—Sandy Loam

temperature and, for this reason, the expansion of the bubbles which reduces the permeability of the soil should decrease the seepage rate as was found by the tests.

The effect of change in porosity on the permeability of granular material has been shown by G. M. Fair, M. ASCE, and L. P. Hatch[4] to be proportional

[4] "Porosity Factor for Case of Laminar Flow Through Granular Media," by J. B. Franzine, *Transactions*, Am. Geophysical Union, Vol. 32, 1951, pp. 443–446.

to $n^3/(1-n)^2$, in which n is the porosity of the material. Small changes i porosity produce large changes in the permeability, and consequently in th seepage rate, because seepage is directly proportional to permeability. Ur fortunately, the percentage of air bubbles in the soil was unknown but b assuming various percentages of air the effect of changes in vapor pressur could be determined.

Seepage rates corrected in this manner for assumed values of 10% air an 15% air are shown in Fig. 13. The corrected seepage rates for 15% air an standard viscosity have a considerable variation, whereas if the assumptio were correct the seepage rate should be constant. When the corrections ar made on the assumption that the soil contains 10% air, the seepage rat approaches the observed rate. For this condition the correction for change i viscosity appears to balance approximately the correction for change i permeability due to the variation in vapor pressure with temperature. A though the vapor pressure of the entrapped air seems to have a definite effec on the seepage rate, the precise relationship of the factors to the seepage rat could not be determined from the available data.

In the study of the effect of temperature on the seepage rate it was observe that the seepage rate was small when the difference between the temperatu of the water and that of the soil was large, and that the reverse was true whe the temperature difference was small. This relationship was particularl noticeable when the temperature of the water was at the maximum during th day. This phenomenon can be explained by the fact that the temperature c the soil is soon raised to that of the water when the seepage rate is high, wherea the soil temperature is not greatly affected by the seepage if the rate is smal Preliminary studies indicate that the temperature difference might be used a the basis for determining the relative seepage rates from different parts c a canal.

Summary

The seepage rings provide an accurate method of measuring seepage rate in small, isolated areas. For this study the seepage rings were used as standard for the calibration of seepage meters. Additional factors whic affect seepage, such as time, temperature, and depth of water, were also studie using the seepage rings. The study demonstrated the fact that there ar many other factors besides the soil type which determine the seepage rate.

The calibration of seepage meters showed that, although the meters do nc provide an accurate method of measuring seepage, they do indicate the orde of magnitude of the loss. For losses less than 1.0 ft per day the meters provid a fairly accurate measurement, but for greater rates the meters definitel overregister. Care must be exercised in installing the meters because hamme ing or jarring the meter was likely to affect the results. It was found that period of from two days to a week should elapse after the meters are installe before reliable readings could be obtained. The plastic-bag seepage mete was the simplest type to operate and the results seemed to be reliable. I was concluded that seepage-meter measurements must be made both in th sides and in the bottom of canals in order to obtain reliable estimates of seepag

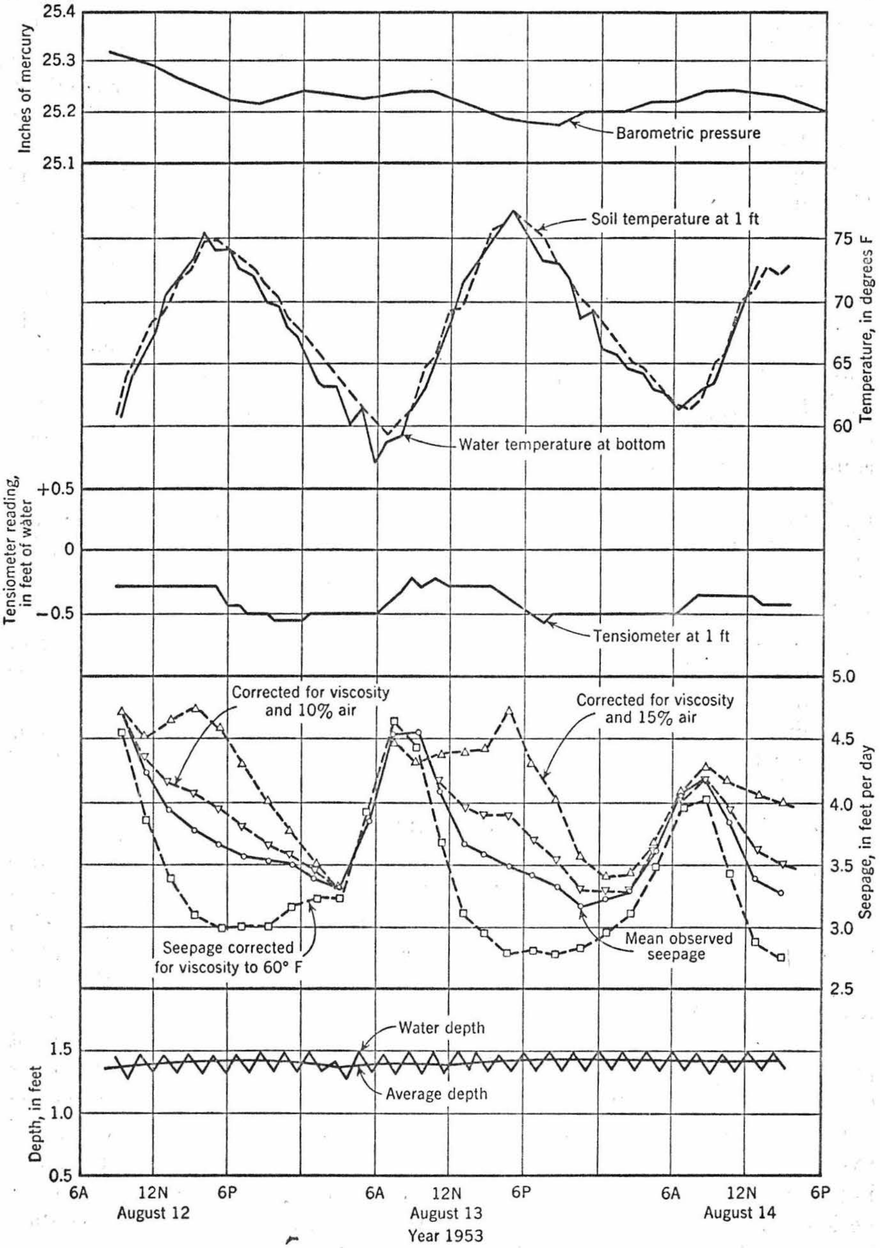

Fig. 13.—Effect of Temperature on the Seepage Rate in Sand; The Seepage Rate Is Shown Corrected for Viscosity and Porosity

A method of analysis was developed for using the well-permeameter test results in forecasting the seepage from proposed canals. A further study of this method is needed before its use can be recommended.

Studies of the effect of depth of water on seepage show that the rate increases as the depth increases but not in direct proportion to the increase in depth. For a high seepage rate, an increase in depth produced a proportionally greater increase in rate than it did for a low rate.

Variation of the depth to ground water had a definite effect on the seepage rate. The tests showed that the seepage rate increased as the depth to ground water increased within the range of depths tested, except in a sandy material. The tests on sand showed that increasing the depth beyond 1 ft did not further increase the seepage rate. At maximum depth to ground water (2.75 ft) the seepage rate in other types of soil was several times that when the ground-water level was at the ground surface.

In several tests it was found that the seepage rate is not a constant but may vary over wide ranges for periods of a few hours. In some cases, the highest seepage rates occurred at the lowest water temperatures and the lower rates at the higher temperatures. Because this phenomenon was contrary to present concepts of the influence of the factors involved, a detailed study was made to determine the cause of the fluctuations. These studies, however, have not been successful in explaining the variations.

Although much has been learned about seepage as a result of this study, many questions still remain unanswered and, because of the economic importance of seepage losses, the study of the problem should be continued.

Acknowledgment

This study was conducted by the Agricultural Research Service, United States Department of Agriculture, in cooperation with the Experiment Station of the Colorado Agricultural and Mechanical College and the Irrigation Operations Division, Region VII, Bureau of Reclamation.

DISCUSSION

RAYMOND A. HILL,[5] M. ASCE.—In the "Introduction," the following statement appears, to which exception must be taken:

> "Of the water diverted for irrigation in the seventeen western states of the United States, nearly 35,000,000 acre-ft, or approximately 40%, is lost before it reaches the farms. On forty-six operating projects constructed by the Bureau of Reclamation, United States Department of the Interior, it was determined that approximately 25% of the water was lost in transit."

The writer questions the validity of these figures, believing that the indicated losses are much greater than the actual losses on these projects. The quantities reported as lost in transit are merely differences between water that is diverted and that presumed to have been delivered to farms.

The quantity of water diverted from a river into a canal system is usually known within reasonable limits. The quantities of water delivered to individual farms, however, are not known accurately, even on extremely well-managed projects; they are only approximated on most irrigation projects. Overdeliveries to farms are the rule rather than the exception. Furthermore, the quantities of water reported as having been returned to the river through wasteways are too frequently no more than guesses by gate tenders.

In brief, the quantities of water reported by the Bureau of Reclamation and others as lost in transit represent only water not accounted for by measurements. Such measurements are generally inadequate and tend to exaggerate the apparent loss of water due to seepage.

DEAN C. MUCKEL[6].—The measurement of canal seepage presents problems similar to those encountered in measuring infiltration on water-spreading areas for ground-water replenishment. The data presented by the authors are helpful in understanding some of the factors affecting this rate—whether it is called seepage or infiltration. In the case of canal seepage the desired end result will be to reduce the rate; in water spreading the aim is to increase it. In either case a thorough understanding of the factors involved will be necessary in order to reach a final solution.

The writer has made numerous measurements of infiltration on water-spreading areas in California, and it is noteworthy that the results obtained agree in general with those given in the paper. The shape of the curve in Fig. 2 is typical of an infiltration curve over the period of time shown. A suggested explanation of the variation in rate was presented in an earlier work by the writer[7] and agrees with the conclusions reached by the authors.

The use of seepage rings (commonly called infiltrometers in irrigation and water-spreading studies) is widespread. However, rarely does one find different workers using the same sizes of rings, depth of setting, or techniques of operation. Also, there is no general agreement as to the use of a buffer. Con-

[5] Cons. Engr., Leeds, Hill & Jewett, Los Angeles, Calif.

[6] Irrig. Engr., Soil and Water Conservation Branch, Agri. Research Service, U. S. Dept. of Agriculture, Washington, D. C.

[7] "Research in Water Spreading," by Dean C. Muckel, *Transactions*, ASCE, Vol. 118, 1953, p. 209.

sequently, the results are not comparable and even results obtained by the same operator are often erratic. Standardization is needed for most effective use of the data being obtained throughout the irrigated western United States. The seepage ring used by the authors has a disadvantage because of its large size and the amount of water required to operate it, particularly if many isolated sites are to be investigated. In water-spreading investigations the writer was asked to determine infiltration rates at locations remote from any water supply so that water had to be transported by truck. A much smaller unit under these conditions would have a distinct advantage over that used by the authors.

The depth of setting of a seepage ring or infiltrometer is important, and the 1-ft depth used by the authors may not be sufficient in all cases to obtain the desired result. The fact that the curves for seepage through sand in Fig. 10 break at a depth to ground water of approximately 1.0 ft raises the question as to whether the same results would have been obtained if a different depth of setting has been used for the rings. In connection with water-spreading studies,[8] it was found that a saturated soil column extends below the soil surface during prolonged submergence. The length of this saturated soil column will vary with permeability and depth of water on the surface. For soils with low permeability the head loss in the soil is high and the column will be short. In soils with high permeabilities the column will be longer because the head losses per unit of length are less. If the depth of setting of a seepage ring is less than the length of the saturated soil column, lateral percolation will occur whereas if the depth of setting is greater than the length of the soil column, no lateral percolation should occur (except for a small capillary movement) and buffering should have no effect. It would be interesting to know whether the authors performed tests with the equipment shown in Fig. 1 while the buffering rings were not in operation and, if so, what the results were.

The effect of depth to ground water on the seepage rate also involves the saturated column. It is difficult to understand how ground water can affect the seepage rate unless the ground water rises and comes in actual contact with the saturated soil immediately below the surface. Possibly over the range tested the soil between the surface and the water table was saturated, or nearly so. A five-day period seems rather short for the time interval between changing of the depths to ground water. Stabilization may not have occurred in the heavier soils.

As to the effect of head on seepage rate, the authors correlated seepage rate with depth of water on the soil surface. Actually the total effective head is the depth of water on the surface plus the length of the saturated soil column immediately below the surface. In terms of the Darcy equation,

$$q = k \frac{d + l}{l}$$

in which d is the depth of water on the surface and l is the length of the saturated column. For the ranges in water depth used, the value of l is probably small in comparison to d.

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[8] "The Effect of Surface Head on Infiltration Rates Based on the Performance of Ring Infiltrometers and Ponds," by Leonard Schiff, *Transactions*, Am. Geophysical Union, Vol. 34, 1953, pp. 257–266.

In connection with the authors' attempt to explain the effect of temperature on the basis of air entrapment, it might be mentioned that in water-spreading studies it was found that gases other than air were generated within a soil during a prolonged run. This was noticed particularly in laboratory experiments with soils containing quantities of organic matter and after anaerobic conditions developed. This information is not offered here as an explanation of temperature effects but merely to add another perplexity to the problem of measuring seepage over a prolonged period and to emphasize the difficulties involved in measuring an item affected by so many changing factors.

The authors cite the discouraging results in checking seepage-meter tests with actual canal losses determined by ponding. Similar discouraging results have been obtained in experiments with small ponds, 0.005 acre in size, located within a few feet of each other on soils supposedly uniform. Seepage rates ranging from the equivalent of that in adjacent ponds to several times that rate were obtained without apparent reason. The question is raised as to whether the authors reproduced their tests at a particular site with two or more seepage rings or accepted the results from an individual seepage ring.

The authors are to be congratulated on their work in dealing with a difficult problem, and the continuance of the study should be encouraged. The results will have widespread use not necessarily confined to canal seepage.

CALVIN C. WARNICK,[9] J. M. ASCE.—The authors have presented their investigation of the measurement of canal seepage in a very concise and interesting manner. The enumeration of eight principal factors that influence seepage rates and the presentation of data covering these factors shows a genuine thoroughness of the study.

The writer concurs in the opinion that the ponding method is the most reliable test for determining the average seepage loss from a given section. In the study of seepage meters it has been the writer's experience that the seepage meter shown in Fig. 3 is difficult to operate because the seepage bag is not always capable of transmitting the same pressure to the meter supply source as that outside the bag in the water surrounding the meter. Likewise, the operator cannot watch what is happening to be sure the meter is functioning properly. A meter adapted by Lloyd E. Meyers from the laboratory seepage meter and used on the Weber Basin Project of Utah has merit for canal seepage studies. The sketch of this meter is shown in Fig. 14. In order to maintain a constant head of water on the confined area of canal perimeter within the seepage meter cup, the principle of the Mariotte siphon is used. Water is supplied to the cup from the 500-milliliter burette as a reservoir. Atmospheric pressure exists at the lower end of the air inlet tube and the water in the burette above the end of the tube is actually under a pressure less than atmospheric. By setting the air inlet tube at the water surface in the canal, the water flowing into the soil from the seepage cup is actually under the same hydrostatic head as the water entering the canal perimeter outside the seepage meter. Actually, for operation, the end of the air inlet tube is set $\frac{1}{3}$ in. above the water surface in order to allow the bubbles of air to escape and rise to the vacuum zone of the

[9] Associate Research Prof., Eng. Experiment Station, Univ. of Idaho, Moscow, Idaho.

burette. This type of meter has been used extensively in canal seepage studies conducted by the Engineering Experiment Station of the University of Idaho at Moscow. A number of these meters have been operated in test sections of irrigation laterals at the same time ponding tests were in progress. In an uncompacted silt section a rather consistent relationship has been developed by averaging the readings of numerous seepage-meter tests with the data from ponding tests. For three years of record the loss measured by seepage meter

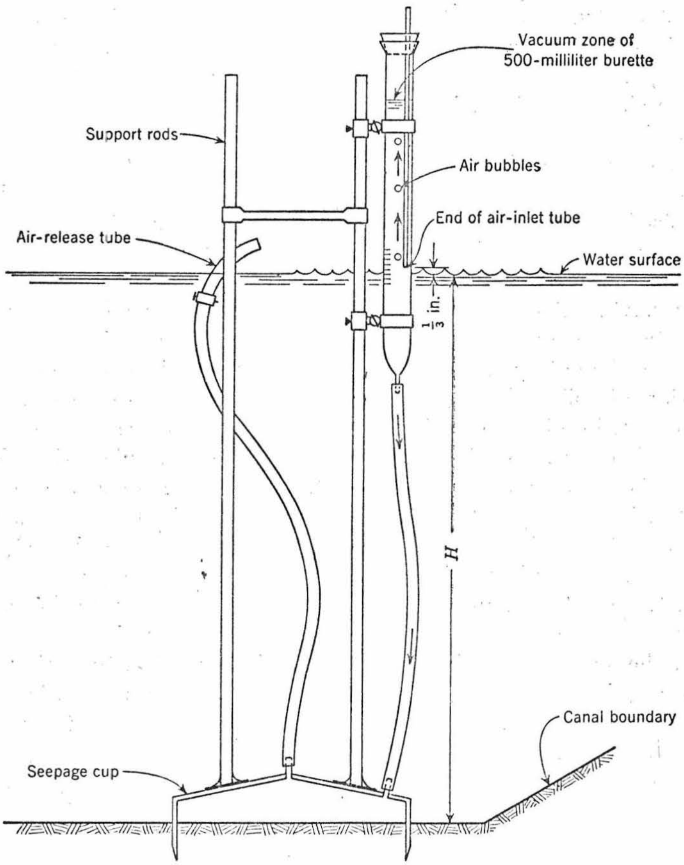

FIG. 14.—WEBER BASIN STORAGE METER

was 57%, 67%, and 69% of the loss measured by ponding. The writer agrees that this percentage will vary with the shape of section, degree of silting, and ground-water condition. However, if these can be standardized, a relationship can be established that should permit evaluation of an approximate rate of loss from a canal.

The writer questions whether the comparison of seepage-meter rates with the rates from the seepage rings represents the measurement of an identical flow rate. From Fig. 4 it appears that the seepage rate from the inner ring approaches that rate measured by the seepage meter after a few days, yet the meter represented a localized area whereas the inner ring data represented a composite of a considerably greater area. Inserting the meter more than two or three times, it appears, would naturally change that composite figure by disturbing the soil. The fact that a seepage meter measures a localized area definitely limits the meter's value and, because of silting in the bottom, lack of homogeneity of soil strata through which a canal perimeter cuts makes the data of a single seepage-meter measurement of little real value. However, a series of careful measurements can provide data on relative loss that is valuable in indicating where high-loss sections are. The writer is confident that seepage meters have a place in canal seepage measurements because they represent a cheap, quick, and convenient method of measurement.

The well permeameter described in the paper presents a possible device for predicting seepage loss from proposed canals, but each test takes considerable time and also represents a very localized area. If data on loss at a localized area are used, many measurements must be taken. In this respect, the well permeameter does not seem to fill this need efficiently.

N. SZALAY[10].—The measurements of canal seepage made by the authors show a rate of seepage which decreases with time when using seepage rings. According to the authors this decrease is due to microbiological action, the decomposition of soil aggregates, and possibly the clogging of pores. It must be added that, in addition to the factors mentioned, decrease of seepage rate with time also has an explanation based on pure hydraulic principles. According to the Darcy equation, $q = k(h/l)$. However, if a canal becomes filled with water, infiltrating water fills the soil pores within a distance always increasing with time. Therefore, the value of l cannot be considered constant but is instead a value increasing with time. Thus, assuming a constant head of water, h, the rate of flow should decrease with time because the same head is used to overcome a continuously increasing frictional resistance.

As for the mathematical interpretation of the foregoing, the writer presents the following simple application.[11] A constant head of water, h, is applied to a horizontal soil surface. The seepage velocity will be $v_s = k(h/z)$, in which $z = z(t)$ and is the instantaneous depth of infiltration, as a function of time, t. The true infiltration velocity will be $v_i = e\, v_s$, in which e is the void ratio. The function, $z = z(t)$, can be determined from two equations,

$$v_i = n\,K\,\frac{h}{z}$$

and

$$v_i = \frac{dz}{dt}.$$

By setting equal the two expressions for v_i and separating the variables, one determines the basic differential equation for nonpermanent seepage flow—

[10] Associate Prof. of Hydr. Eng., Technical Univ. of Budapest, Budapest, Hungary.

[11] "Determination of the Permeability of Soil Layers Lying Above Groundwater Table," by N. Szalay, *Hidrologiai Közlöny*, November-December, 1954.

$z\,dz = n\,K\,h\,dt$. After integration,

$$z = \sqrt{2}\,n\,K\,h\,t - C.$$

In order to determine the rate of flow, the Darcy equation is used again:

$$q = K\frac{h}{z} = \sqrt{\frac{K\,h}{2\,n\,t}} = \frac{c}{\sqrt{t}}.$$

That is, the rate of flow is inversely proportional to the square root of the time.

The accuracy of rate-of-flow measurements depends on the infiltration area as lateral infiltration has greater influence on the pure vertical infiltration in small areas than in large areas. This fact was proved by the experiments of L. Szabo[12] who found that, under the foregoing conditions, the measured rate of infiltration depends on the infiltration area as follows:

Infiltration area, in square meters	Rate of seepage, q, in meters per second
0.01	$c_1\ t^{-0.45}$
0.02	$c_2\ t^{-0.45}$
0.25	$c_3\ t^{-0.46}$
16.00	$c_4\ t^{-0.48}$
100.00	$c_5\ t^{-0.48}$
Theoretically	$c\ t^{-0.50}$

The values of c_1 through c_5, experimentally determined, show a tendency to decrease with increasing infiltration area.

Finally, it may be mentioned that the basic principles of the foregoing theory of nonsteady seepage were also applied to pure horizontal seepage flow, approximately as it occurs when using well permeameters[11] and when infiltration develops through flood-control levees. In both cases the results computed theoretically were in satisfactory agreement with experimental data.[13]

CYRIL W. LAURITZEN[14].—The ever-increasing demand for water in arid countries has focused attention on losses sustained in the conveyance of irrigation water. One of the most perplexing problems encountered has been the accurate determination of these losses. A few methods have been used for measuring seepage losses, but all have had their limitations and none has been entirely satisfactory. As pointed out by the authors, the results obtained from ponding measurements are probably the most reliable. However, ponding measurements can lead to erroneous conclusions unless one considers antecedent conditions as well as conditions at the time of measurement.

The extreme variability in seepage-meter measurements made in operating canals coincides with the results obtained by the writer and his associates.[15]

[12] "Influence of Lateral Seepage Upon Rate-of-Flow Standards of Surface Irrigations," by L. Szabo, *Hidrologiai Közlöny*, July–August, 1954.

[13] "Design of Flood-Control Levees with Special Regard to Seepage," by N. Szalay, *ibid.*, March–April, 1953.

[14] Project Supervisor, Agri. Research Service, U. S. Dept. of Agriculture, Logan, Utah.

[15] "Measuring Seepage from Irrigation Canals," by W. W. Rasmussen and C. W. Lauritzen, *Journal*, Am. Soc. of Agri. Engrs., Vol. 34, 1951, p. 326.

It has been their experience that, frequently, the difference between measurements made with meters set side by side is as great or greater than measurements made by the ponding method in canals of widely different subgrade material. The closer agreement between measurements with seepage rings in uniform material would seem to indicate that part of the variability is actual. Possibly this should be anticipated even though the material appears to be uniform. It is known, for example, that stratification of the material in a soil sample can greatly alter the permeability of the material as a whole. The fact that some variability persists in the measurements made in seepage rings may indicate that there is an inherent error in the results due to installation and operation of the meters. The consistent overregistration of the seepage rate, as indicated by the seepage rings, suggests the possibility of applying a correction factor to seepage-meter measurements. Correction factors, based on the relationship between seepage-meter measurements and ponding measurements, have been developed and used by Mr. Warnick[16] in an attempt to determine a better index of seepage losses. In developing a correction factor based on a comparison with ponding tests one must, of course, take into account the difference in seepage loss between the bottom and the sides of the canal.

At first, such a procedure might appear to be a solution to the problem and under certain circumstances might provide a reasonably accurate index of seepage losses. However, when one considers the fact that the relationship between the seepage from the bottom and sides of the canal may differ widely among canals and from one season to the next, the value of such an approach must be re-examined. Possibly a permeability measurement on disturbed samples of bed material would provide an equally accurate index of losses.

The authors have pointed out that there are other factors in addition to soil type which influence seepage losses; among those mentioned is temperature. Permeability measurements are commonly corrected for temperature in order to take into account the change in viscosity of water with temperature. It has been the writer's experience that corrections applied to permeability measurements as mentioned by the authors give contradictory results. Apparently, some factor other than the change in viscosity of water is operating. The authors seemed to have ruled out the possibility that the reduction in porosity is due to an increase in the size of air bubbles. The fact that a correction for viscosity seems to compensate more for temperature changes with coarse-textured material than with fine-textured material indicates that the discrepancy may be associated with the fine fraction. Possibly the reduction in permeability which sometimes accompanies an increase in the temperature during a measurement can be explained as resulting from a reduction in porosity due to greater hydration of the clay minerals at higher temperatures. This theory, at least, might well be explored. If this should be the situation, the greater transmission of water, which would be expected to accompany an increase in temperature and the corresponding decrease in viscosity of the water would tend to be compensated for by the reduced porosity of the profile due to swelling of the constituent material.

[16] "A Study of Canal Linings for Controlling Seepage Losses," by C. C. Warnick, *Progress Report No. 3*, Eng. Experiment Station, Univ. of Idaho, Moscow, Idaho.

The depth of water in the canal and the distance to the ground-water table have long been known to be important factors contributing to seepage losses. Engineers have generally attributed the increased seepage rate which accompanies an increased depth of water in the canal to the difference in permeability of the material constituting the upper side slopes, as compared to the lower side slopes and bottom of the canal. If only the bottom of a canal is being considered, corresponding to measurements in seepage rings, seepage should be proportional to the hydraulic gradient as the authors have shown. The problem has been to establish the value of the hydraulic gradient. It is of interest to note that as the seepage rate increases the effect of water depth on seepage increases. This might be explained by the steeper hydraulic gradient associated with coarse-textured material, which in effect, disproportionately increases water transmission as the water depth is increased. Additional information on this point would be valuable. The fact that the influence of water-table depth was restricted to 1 ft for sand as compared to a greater distance for fine-textured material supports this reasoning.

It is evident from the paper that all the questions related to seepage measurement have not been answered. The investigation has, however, done much to clarify certain aspects of the problem and the authors are to be commended for their careful work and the contribution they have made.

August R. Robinson, Jr.,[17] J. M. ASCE, and Carl Rohwer,[18] M. ASCE. —Seepage measurements, even when made under carefully controlled conditions, yield rates that are correct only at a specific place at the time of the tests. It does not necessarily follow that the same results should be obtained in the same area at a different time under different conditions. For this reason, widely divergent results are frequently obtained when seepage measurements are extended over a considerable period of time. This fact makes the solution of the seepage problem especially difficult.

Mr. Hill has taken exception to the total seepage losses reported by the writers for the seventeen western states because more water is delivered to farmers than is ordinarily shown by the records. This is probably true, but it should be pointed out that more water is frequently available for delivery than is shown by the diversions from streams and reservoirs at the canal intake, because many canals receive waste water from higher irrigated land and intercept runoff from rainfall. This inflow cannot be accurately measured and, although it is probably less than the excess deliveries to farmers, it is a compensating factor. Also, water records of the Turlock Irrigation District in California indicate a loss of water from diversion to irrigator of 27.2%. This record is for an irrigated area of 168,000 acres and is an average loss for the five-year period from 1950 to 1954. Whether the seepage losses for the seventeen western states quoted in the paper are correct or not is probably not important to the paper because they were cited merely to show the magnitude of the seepage problem.

[17] Agri. Engr., Agri. Research Service, U. S. Dept. of Agriculture, Colorado Agri. and Mech. College, Fort Collins, Colo.

[18] Senior Irrig. Engr. (Retired) Agri. Research Service, U. S. Dept. of Agriculture, Fort Collins, Colo.

The comments by Mr. Muckel, based on his extensive experience with ground-water recharge by water spreading, show that the difficulties encountered by the writers in the study of seepage are not unique. With reference to Mr. Muckel's question as to the effect of operating the inner ring when no water was in the buffer ring, this condition was not investigated by the writers. Mr. Muckel found that gases other than air were released in the soil under certain conditions. When this occurs, the seepage rate is reduced.

The fact that the depth of water in the rings is not the true head was recognized in the study of effect of depth of water on the seepage rate. By projecting the curves downward until they intersect the vertical axis, a head is determined which makes the seepage rate directly proportional to the depth, as should be the case according to the Darcy law. Since the seepage rings were used primarily for checking seepage meters, a single installation was used in each type of soil. However, many seepage-meter measurements were made in each seepage ring. Observations of seepage were made at intervals during a period of approximately two weeks for each setting of the seepage meter. At the end of the period, the seepage meter was installed at a new location inside the ring and the procedure repeated. As a result of this procedure, many replications of seepage-meter measurements in different soils were obtained where the seepage rate was accurately known.

An ingenious method of keeping the pressure inside the seepage meter equal to the head on the canal bed is described by Mr. Warnick. By using the Mariotte siphon principle, the reservoir of water for the seepage meter can be placed above the water surface in the canal. This equipment permits the observer to see whether the seepage meter is functioning properly and to note the rate at which water is seeping away through the cup of the meter. Mariotte controls were tried by the writers on well permeameters but the equipment did not prove satisfactory because it was affected by temperature. Furthermore, the surface tension at the bottom end of the air inlet tube affected the sensitivity of the device because the water level had to drop appreciably before the air bubble could break loose from the tube. A simple float control was found to be more sensitive and it was not affected by temperature.

It is difficult to understand why the plastic seepage bag is not capable of transmitting pressure at the same magnitude as that due to the water surrounding the bag, as indicated by Mr. Warnick. The writers had occasion to try different measuring devices on the meters at the same installations without finding any difference in the measured rate. The burette on the Weber Basin seepage meter is considered by many technicians to be too fragile for field use.

The tests reported by Mr. Warnick, which extended over a period of three years, showed that the losses measured by the seepage meter were 57%, 67%, and 69% of the losses measured by ponding. The writers found, however, that seepage meters installed in the seepage rings usually indicated a higher rather than a lower rate. This difference is probably due to the fact that all the seepage from the seepage rings had to pass through the bottom, whereas in the experiments reported by Mr. Warnick a large portion of the seepage probably occurred through the side slopes of the canals where it is difficult to install the seepage meters.

The development by Mr. Szalay is interesting but several inconsistencies should be pointed out. The true infiltration velocity is $v_i = v_s/n$, in which n is the porosity and v_s is the bulk velocity. The interpretation by Mr. Szalay is applicable only to the case of flow through a horizontal section on which the gravitational forces would be constant. For the case of a constant depth of water on a horizontal soil surface the hydraulic head would be $h + z$, so that the Darcy equation would be $v_s = K\ (h + z)/z$. In terms of infiltration velocity through the pores:

$$v_i = \frac{K}{n}\frac{h + z}{z}$$

and

$$v_i = \frac{dz}{dt}.$$

By eliminating v_i from these equations, the basic differential equation results:

$$\frac{z\,dz}{h + z} = \frac{K}{n}\,dt.$$

Integration of this equation results in

$$z = \frac{K\,t}{n} + h \log \frac{h + z}{h}.$$

In view of the foregoing analysis, it is difficult to understand how Mr. Szalay determined the relationship which he has tabulated from data on infiltration.

The possibility of utilizing permeability measurements on disturbed samples of bed material in determining seepage losses is mentioned by Mr. Lauritzen. It is believed that this method would not be an indication of a true seepage rate from a canal, owing to the difference in seepage rates on the sides and bottom. In many cases the sides have a higher seepage rate due to stratification and secondary structure—that is, cracks, root channels, and holes dug by rodents. The effect of these factors would be eliminated in disturbed soil samples.

In order for the greater hydration of clay minerals at a higher temperature to be a factor in a reduction of permeability at these temperatures, the process would have to be reversible. Referring to Fig. 12, it is noted that there is a cyclic variation so that when the water temperature decreases the seepage rate increases.

The comments of the discussers of the paper have emphasized the complexities of the seepage problem. Many uncertainties still exist and because of the importance of seepage the study of the problem should be continued.