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Tucson, Arizona 85721

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I. INTRODUCTION

The movement of moisture and the simultaneous transfer of water and solutes in unsaturated porous media are problems of practical interest in ground water hydrology and soil physics. A large fraction of the water falling as rain on the land surfaces of the earth moves through unsaturated zone of soil during the subsequent processes of infiltration, drainage, evaporation, and absorption of soil-water by plant roots. A soil profile is characteristically nonuniform in its properties, nonisothermal, and may be nonrigid. Microorganisms and the roots of higher plants are a part of the system. This region is characterized by cylic fluctuation of water content as water is removed from the soil profile by evaportranspiration and replenished by recharge, irrigation, or rainfall.

In unsaturated porous media the problem of movement and retention of water may be approached from (1) the molecular, (2) the microscopic, or (3) the macroscopic standpoint. In the molecular viewpoint theories of the mechanisms of flow and retention in terms of the behavior of water molecules are devised. At microscopic level a theory of flow treating the fluid in pores as a continuum and applying the principles of continuum mechanics to understand the detailed behavior of fluid within the pores is developed. The complicated pore geometry and consequent impossibility of specifying the boundary conditions on flow, preclude any practical progress by this appraoch. Since the behavior of individual molecules and the distributions of fluid velocity and pressure cannot be observed in porous media, a macroscopic theory of flow is needed.

In the macroscopic approach, all variables are treated continuous functions of time and space. Velocity, pressure, and other variables are assumed as point functions. Thus, any theory of water transport to be useful must be developed to the point of describing the transfer of water on the macroscopic level. The coefficients of transport such as permeability and diffusivity can be defined microscopically.

In many investigations which involve the transport of pesticides and fertilizes along with water , the simultaneous movement of water and solutes is of primary concern. These pollutants when mixed with water move in the unsaturated soil and finally join the region of saturated soil or water table, resulting in the contamination of fresh water existing below the water table.

The scope of this report is to review the available literature, that may be categorized into two parts; one, the movement of water in unsaturated soil, and the other, the simultaneous movement of water and solutes in unsaturated soil. The papers, reviewed in this report, pertain to the theoretical study, laboratory study and field study on the two problems. At the end, an appendix appears which lists the references, categorizing the kind of study by various investigators.

II. REVIEW OF LITERATURE

Abaza and Clyde (1) in 1969 developed an analytic relationship that related the rate of flow through porous media to the streaming current and streaming potential induced by the flow. Laboratory experiments were conducted to test the analytic relationship. The effects of the concentration of dissolved salt in the percolating solutions, the grain size of porous medium, and the temperature of the solution on the streaming current and the streaming potential were determined.

Abd-el-Aziz and Taylor (2) in 1965 used the thermodynamic theory of irreversible processes to develop two rate equations for the simultaneous movement of potassium chloride and water through unsaturated porous media under isothermal conditions.

Alfaro (3) in 1971 applied a physical model theory to predict salt displacement in soils. The theory that used physical scaled soil profile models was reviewed and tested. Uniform and stratified soil profiles were built according to the design conditions specified by the theory. Uniform soil profiles were constructed of artificially salinized Glendale silty clay loam soil and Blue Point sandy loam soil. The stratified profiles were built, using salinized Glendale silty clay loam soil over salinized Rio Grande sand and salinized Blue Point over nonsalinized Rio Grande sand. Water was applied to the surface of each prototype and model at a rate of 0.64 cm/hr by means of a water applicator apparatus. Unsaturated soil moisture conditions were maintained during the experiment. Salt concentration curves were presented for each profile under experiment. Dimensionless plots of the relative effluent salt concentration C/Co versus the parameter $\frac{Dw}{Ds}$ suggested that physical scaled models built to meet the theoretical requirements could be used to predict salt displacement from uniform and stratified soil profiles, in which C/Co may be defined as the relative concentration, D_s as the volume of soil, and D_w as the volume of effluent.

Arbhabhirama and Kridakorn (4) in 1968 presented from theoretical considerations the distribution of capillary pressure above the water table during steady downward flow. Experiments were conducted, using water as the wetting fluid and air as the non-wetting fluid, for both homogeneous and stratified media.

Arend and Horton (5) in 1942 investigated the effects of rain intensity, erosion, and sedimentation on infiltration capacity. Experiments, while carried out on smaller plots, showed results of the same character as those obtained from larger plots. The mode of conducting the experiment led to the following results:

(i) The experiments showed no evidence of significant change in the constant infiltration capacity (f_c) due to rain intensity when the intensity was increased from 3 to 6 inches per hour on the three vegetal covers sampled.

(ii) Although a significant decrease in f_c resulted when the rain intensity was decreased from 6 to 3 inches per hour, the change was not due directly to rain intensity but was attributed to the deposition of sediment from residual runoff of the higher rain intensity preceding the lower rain intensity.

(iii) If the rain that follows produces runoff that is sufficiently intense, sheet erosion may occur, keeping soil pores continually exposed to infiltration. Under these conditions the infiltration capacity may remain substantially unchanged.

(iv) Excessively high rain intensities may induce higher values of the initial infiltration capacity (f_o) than would prevail with natural rain intensities and smaller drop sizes.

(v) Unless prevented either by adequate vegetal cover or by excessive erosion, the time required for infiltration capacity to become sensibly constant varies in an inverse ratio to the rain intensity.

(vi) The use of rather high, constant rain intensities in infiltrometer experiments tends to produce (1) abnormally high apparent values of f_o, (2) the reduction of f from f_o to f_c in an abnormally short interval, (3) the formation of wave trains and the formation of marked initial runoff surge similar to that occurring on natural areas only in cloudburst storms, (4) the production of initial surges and wave trains with erosion in excess of that obtained on the same area in natural storms, and (5) distortion and irregularities of the runoff hydrographs, making their analysis and determination of infiltration capacities difficult and unreliable.

Ashcroft et al. (6) in 1962 solved the diffusion equation for one-dimensional case using an implicit difference scheme. The study was limited to horizontal flow in a uniform, semi-infinite porous medium. The results of the study indicated that the numerical solutions were similar to those from Boltzman transformation and experimental results.

Bally (7) in 1969 discussed the differential equations for one-dimensional vertical and horizontal flow in the soil and the use of these equations for the determination of hydraulic conductivity and suction in relation to the soil moisture content. The study resulted into two differential equations which included the functions - soil moisture content as a function of distance and time, hydraulic conductivity as a function of soil moisture content, and suction as a function of soil moisture content. This method determined these functions. A verification of the proposed method was given with data from laboratory experiments.

Behnke and Bianchi (8) in 1965 conducted experiments on pressure distributions in layered sand columns during transient and steady-state flows. The pressure distributions were similar to layered sand systems composed of different grain sizes during steady-state flow at different surface heads. Positive pressures occurred near the top of the layered column and negative pressures developed with depth, reaching a maximum at or near the layer interface. There was no significant head loss at the layer interfaces for the grain sizes studied. Pressure distribution profiles in layered sands during transient flow (drainage conditions) prior to air entry were similar to those described for steady-state flow. Drainage rate curves for the layered systems studied were not continuous power functions when entrapped air was in the sands.

Behnke (9) in 1969 developed an empirical equation which predicts accumulated water quantity versus time relationships for several concentrations of a specific turbidity.

Beskin and Kondratyev (10) in 1969 reported on the neutron moisture meter for saline soils. The principle of neutron moisture meter is based on detecting the thermal neutrons which appear when rapid neutrons are being slowed down by hydrogen nuclei. However, such detectors are sensible to changes in the percentage of chloride, boron, lithium and other excessive absorbers of neutrons which may result in considerable errors in measuring the moisture of soils containing these elements. It is possible to reduce the action of the strong absorbers by detecting the epithermal neutrons, but this would deteriorate sensitivity of the moisture meters. Thus, best suited for this purpose is the method of measuring the moisture by total density of thermal neutrons and the gamma photons in a cadmium screen. This method is practically insensitive to any changes in percentage of chloride and other strong absorbers. It was proven that when moisture is measured by such a moisture meter, a single calibration can be used on all types of soils of nonorganic origin, provided the error is $\pm$ 2%.

Bhuiyan et al. (11) in 1971 developed a computer model that simulated the vertical infiltration of water into unsaturated soil. The modeling concept consisted of dividing the soil into a large number of layers of equal thickness. The net flux of water through each layer at any perticular time was established by using the principles of conservation of mass and Darcy's law. The ensuing water content was then calculated by integrating the net flux by means of the fourth order Runge-Kutta method with suitable error criteria. The cumulative infiltration was calculated from the instantaneous infiltration rates by using the same integration technique. Water content profiles with time were obtained for three different soils: (1) Yolo light clay, (2) Adelanto loam, and (3) Pachappa loam. The infiltration rate and cumulative amount were also calculated with time. The simulation results for Yolo light clay were compared with those obtained by Philip (165) under identical initial and boundary conditions.

Biswas, Nielsen, and Biggar (12) in 1966 analyzed the redistribution of soil water after the cessation of infiltration in three agricultural soils experimentally in the laboratory. It was found that the rate of redistribution within the soil profiles depended upon the initial depth of wetting and the soil water content-soil water pressure conductivity relations. The results were discussed in relation to measured and predicted profiles of porous media.

Black, Gardner, and Thurtell (13) in 1969 measured evaporation, drainage, and changes in storage for a bare mainfield sand in a lysimeter during June, July, and August, 1967, under natural rainfall conditions. Cumulative evaporation at any stage was proportional to the square root of time following each rainfall. The drainage rate was found to be an exponential function of water storage. Both relations can be predicted from flow theory with knowledge of soil capillary conductivity, diffusivity, and moisture retention characteristics. Using these two relations and daily rainfall data, the water storage in the top 150 cm. was predicted over the season to within 0.3 cm.

Bodman and Colman (14) in 1943 described a laboratory study of the infiltration of water into columns of air-dry soil in which the impact effects of water drops falling on the soil surface, in-washing of colloids, and compression of air ahead of the wetting front, were excluded, and in which clay migration was probably negligible. The diminishing infiltration rate versus time relation was of the same type as that so frequently observed in both field and laboratory. The soil moisture distribution, moisture-potential conditions, and permeabilities observed within the infiltration zone have made it possible to explain the changes in infiltration rate on the basis of physical laws governing the flow of water through soils. These analyses strongly suggest that infiltration rates approach a final constant value. This final rate is determined by a total potential gradient within the upper part of the wet soil equal to that of the gravitational potential, and a permeability at 30°C corresponding to a pressure potential of about -2.8×10^4 ergs per gram.

Although the two soils, Yolo sandy loam and Yolo silt loam, studied differed widely in texture, maximum moistures in the upper wet zone, and infiltration rates, yet the same types of conditions accompanied the infiltration process in both cases.

Bouwer (15) in 1962 applied and tested the theory and principles in laboratory and field studies. It was shown how sufficient depth of saturation and corresponding consistency in resulting hydraulic conductivity values can be ascertained in the field without calculating the hydraulic conductivity after each set of measurements. The double-tube method appeared to be a suitable tool for *in situ* measurement of hydraulic conductivity of soil that was not saturated prior to the time of measurement.

Bouwer (16) in 1964 presented the double-tube method by which horizontal and vertical hydraulic conductivity of anisotropic soils can be measured. The principle was based on manipulation of flow direction in the artificially saturated soil region below the auger hole. The presence of water table was not required. Laboratory studies on artificial anisotropic soil consisting of alternating 0.5 cm layers of coarse and fine soil were performed to verify and exemplify the method.

Bouwer (17) in 1964 reviewed the methods of obtaining the hydraulic conductivity for unsaturated media (K_u) versus pressure head of soil water (p) relationship and presented curves for this relationship for 28 soils. These curves were sigmoid, showing unsaturated hydraulic conductivity close to saturated hydraulic conductivity (K_s) when pressure head was not much below zero and an abrupt reduction in K_u with further decreasing p to values that were eventually only a small fraction of K_s. Coarse-textured soils showed a reduction in K_u that was more abrupt and that occurred at higher values of p that did structureless fine-textured soils.

Simpler solutions were obtained by replacing the sigmoid relationships between K_u and p by a step function through the integrated center of the pressure head range over which the reduction in K_u occurred. This integrated center, called the critical pressure head p_c, was calculated as

$$p_c = \frac{1}{K_s} \int Ku \; dp$$

To include the flow at negative pressures in the solution of flow system, the systems were analyzed on the basis of K_s, with p_c as the pressure head condition at the free boundary. Values of p_c, calculated for 28 different soils, indicated that p_c might vary from 10 cm of water for coarse material to 10 cm or less for fine soils.

It was shown that the use of p_c accurately accounts for the flow in negative pressure regions in such cases as: (1) Flow above mildly sloping water tables; (2) Flow below seeping streams in uniform soils with deep water tables or drainage layers; and (3) downward flow in unsaturated, well drained relatively coarse material that receives water from less permeable overlaying soils.

Bouwer (18) in 1968 presented a technique for evaluating local channel seepage rates from the rate of advance of a salt wave in the bottom material. The salt wave was created by applying a layer of salt crystals to selected areas of wetted perimeter of the channel. Sufficient salt could be applied to create a well defined, easily detected electrical-conductivity wave in porous media. The salt penetration method appeared to be an accurate as well as a convenient tool for local seepage measurement in channels.

Bresler and Hanks (19) in 1969 presented a numerical solution of noninteracting salt flow simultaneously with water in unsaturated soil. The finite difference scheme was utilized to solve one-dimensional flow equations. Solutions were obtained for infiltration, redistribution, and evaporation under different wetting and boundary conditions. The effect of diffusion on salt distribution was neglected. The method gave satisfactory results for noninteracting solutes. When compared with measured total salt distribution after one wetting and drying cycle, the model gave fairly good results when a source term was added to the computations.

Bresler, Kemper, and Hanks (20) in 1969 conducted experiments on soil columns at three different rates which caused unequal water content profiles during infiltration. Water content profiles during infiltration, redistribution, and evaporation were observed experimentally and computed using a numerical solution of the isothermal flow equation. Each wetting rate resulted in a different drying water retention curve. The hysteresis in the soil water content-water pressure relationships had a large influence as the wetting rate increased. Hysteresis effects tended to keep the water content higher and the zone of wetting shallower during the redistribution stage when rates of wetting were faster. Higher water content and lower wetting depth at any redistribution time caused subsequent evaporation to be greater. Evaporation was directly related to the previous wetting rate, when the soil was subjected to evaporation after redistribution for 4 days. The differences in evaporation between the three wetting treatments were significant at the 90% probability level. Allowing time for redistribution decreased evaporation compared to evaporation and redistribution occurring simultaneously. The effects of wetting rates and hysteresis on water content profiles and evaporation were similar in the experimental and computed results.

Brooks and Corey (21) in 1966 extended theories found in the literature of petroleum technology to derive empirical equations among pressure, saturation, and permeability for two-phase flow in isotropic media. Experiments conducted on unconsolidated and consolidated media verified the empirical relationship between pressure and saturation.

Bruce and Klute (22) in 1956 presented a flow equation for water in unsaturated porous media from Darcy's law and the equation of continuity. The equation for horizontal flow was similar to nonlinear diffusion equation. Boltzmann transformation was utilized in the equation which allowed the diffusivity-moisture content function to be calculated from a moisture content distribution curve.

Four types of porous materials, namely, 75 μ glass beads , 50 to 250 μ Bloomfield sand, Bloomfield sand, and a very fine sand from Mason county, Illinois, were used in the experiments. Columns of sand at a constant moisture content throughout their length were prepared. Water was applied at one end of the columns and allowed to move into them for a measured period of time. The distribution of moisture content in the columns was then determined and calculations of the diffusivity-moisture content function were made. Data from one column gave moisture diffusivity values representing the entire moisture range of that column. The results indicated that there might be a maximum in the diffusivity-moisture content function at a moisture content less than saturation.

Brustkern and Morel-Seytoux (23) in 1970 devised a numeric procedure. Two equations were derived with two unknowns: water saturation and total velocity. One equation was a partial differential equation, the other one an algebraic equation referred to as the integral equation. Infiltration rates predicted by this analysis were in good agreement with those predicted by a finite difference solution.

Brutsaert (24) in 1968 derived an equation for the permeability of a porous medium based on the general principles of the series-parallel model which contained a double integral. It was solved for several continuous probability laws describing the distribution of the sizes of the interstices of porous medium. Satisfactory agreement was obtained between calculated results and available experimental data.

Brutsaert (25) in 1968 derived a solution for one-dimensional equation describing vertical flow in a partly saturated porous medium, using series expansion originally developed for Philip's (164) numerical method of solution of diffusion equation with diffusivity concentration dependent. The solution for horizontal infiltration proved to be an adequate solution for vertical infiltration.

Brutsaert (26) in 1971 developed a fully implicit scheme along with a functional iteration method for solving the system of nonlinear difference equations. Newton's iteration technique was mathematically the most preferable of all functional iteration methods because of its quadratic convergence. The Richards equation, Newton - linearlized with respect to relative permeability and saturation as functions of capillary pressure, was particularly aided by this new approach for problems in which saturations vary rapidly with time. Although the computing time was almost twice as long for a time step with Newton's iteration scheme, the smaller time truncation than that of classical implicit schemes and the stability in cases in which classical schemes were unstable permitted the use of much larger time steps. To demonstrate the method, layered soil systems were used to simulate sharp infiltration fronts caused by ponding at the soil surface.

Bybordi (27) in 1969 derived an equation to describe the yield of water at a given time for freely draining composite column of initially saturated porous materials in a gravitational field. The equation was supported by experimental results, predicting the cumulative outflow in time.

Byrne, Drummond, and Rose (28) in 1967 presented a method based on theoretical analysis and laboratory calibration of a sensor to measure fluid flux in porous medium which showed that a flow velocity of 10^{-4} cm sec^{-1} can be readily measured and that sensor output is uniquely related to flux.

Byrne, Drummond, and Rose (29) in 1968 gave a theoretical analysis of the temperature field for boundary conditions appropriate to each type of sensor. Theoretical and experimental calibrations agreed closely when assumptions in the theory were realized experimentally. The analysis was used to elucidate design principles and their effect on instrument performance.

Canarache, Motoe, and Dumitriu (30) in 1969 studied infiltration rate and its relationship with hydraulic conductivity, moisture deficit, and other soil properties. Correlation and regression analyses using data for 150 soil profiles of different genetic and textural types were performed. Soil properties involved in the calculations were infiltration rate, clay content, porosity, hydraulic conductivity, and moisture content. Positive coefficients of correlation existed between rate of infiltration and percent of water free pores at field capacity, as well as between infiltration rate and hydraulic conductivity. Negative coefficients of correlation were found between infiltration rate and moisture deficit. No correlations were observed between infiltration rate and moisture content at the beginning.

Cary (31) in 1968 built and tested a soil moisture flux transducer in the laboratory under steady-state conditions in a column of Portneuf silt loam soil. The principal advantage is that measurements of moisture flow may be made without any prior information concerning the unsaturated hydraulic conductivity of the soil. Rather, one needs to know only a soil moisture convergence factor which is dependent on the state of the soil and the design of the transducer. While this convergence factor is dependent upon the soil moisture content, the dependence appears to be nearly an order of magnitude less than the dependence of hydraulic conductivity on soil moisture content.

Cassel et al. (32) in 1968 presented a laborabory method based upon time dependent soil-water content distributions for calculating isothermal soil-water diffusivity values for soils at 5 to 15 volume percent water. The redistribution of water within sealed soil columns was monitored by gamma radiation attenuation at approximately 100 to 1000 hour intervals over a period exceeding 3 months. Diffusivity values from numerical intergration of the diffusion equation were obtained and were expressed in terms of the polynomial. However, the scatter between the fitted curve and the experimental data was large.

Cassel, Nielsen, and Biggar (33) in 1969 studied redistribution of soil-water within insulated, uniformly packed, horizontal samples of unsaturated Columbia fine sandy loam at several soil-water contents in response to imposed temperature gradients ranging from 0.5 to 1.0 C/cm. Soil bulk density and initial, transient, and final soil-water content distributions were determined each 0.5 cm along the column by gamma ray attenuation. Initial, transient, and final soil temperature distributions were monitored by glass-encased thermistors at 2 cm intervals both at the center and 0.3 cm from the column wall. Apparent thermal and isothermal soil-water diffusivity values were calculated using transient water content data. The observed net water flux was found to increase with decreasing water content throughout the 0.077 - 0.274 cm^3/cm^3 range. For Columbia soil at 0.077 cm^3/cm^3 the observed mean net water flux across 1 cm sections of the soil showed acceptable agreement with that predicted by the theory of Philip and de Vries (166); Fick's law and the modified Taylor-Cary (214) irreversible thermodynamic equation both underpredicted the observed fluxes.

Cassel and Nielsen (34) in 1971 designed a gamma radiation attenuation unit to monitor water content of large cores of natural soil. A logistic system was developed that allows one person easily to maneuver and monitor soil cores as large as 1 foot in diameter and 3 feet in height.

Childs and Collis-George (35) in 1950 investigated on permeability of porous materials. A simple statistical theory, based upon the calculation of the probability of occurrence of sequences of pairs of pores of all the possible sizes, and of the contribution to the permeability made by each such pair, led to an expression of the permeability as the sum of a series of terms. The summation at a selected upper limit of pore size may evaluate the permeability at any moisture content and permeability may be plotted as a function of soil moisture. An example was presented, using a coarse graded sand specified by its moisture characteristic. To check these calculations, experimental determinations of the permeabilities of unsaturated materials were presented, using two different grades of sand and a sample of slate dust. The agreement was good.

Childs (36) in 1960 showed an assumption implicit in works of Maasland (137) and Isherwood (98) on the nonsteady state of the water table. The assumption was that there is such a quantity as a constant specific yield f, defined as the volume of soil moisture released for unit surface area per unit fall of the water table. This case was examined together with errors associated with the assumption of constant specific yield.

Childs and Poulovassilis (37) in 1962 showed from theoretical considertations that the shape of the moisture profile about a moving water table depends upon both the rate of infiltration at the soil surface and the rate of rise or fall of the water table. The profile shape may be computed provided that the moisture characteristic and the dependence of the hydraulic conductivity of the material on moisture content are known, and also provided that if the water table should be falling, its velocity should not exceed the value of $\frac{dK}{d\theta}$ (where K is the hydraulic conductivity and θ is the moisture content) at the moisture content θ_u prevailing at the surface of infiltration, where the hydraulic conductivity is equal to the infiltration rate. Experiments are described and the results are presented to show agreement between observed and computed profiles when the limiting condition is satisfied, for various combinations of rate of infiltration and rate of fall of water table.

Childs and Bybordi (38) in 1969 extended the infiltration law of Green and Ampt to include heterogeneous profiles. Formulas were developed to express three relationships. The infiltration law was derived for a profile consisting of a succession of different layers with conductivity decreasing from surface. An expression was derived for the conductivity profile that would give a specified infiltration law, and in particular, a linear infiltration law with specified parameters. This expression served to determine the conductivity when the infiltration law was observed. Experiments were described to measure the infiltration rates into layered columns, the results of which confirmed the theory.

Christensen (39) in 1943 investigated the permeability-capillary potential relationship for three Prairie soils. The experiments were discussed to obtain the permeability versus potential relations for other soils and to compare the permeability of soil having disturbed structure with that of the same soil having natural field structure. Data from all of the unsaturated flow experiments were summarized graphically.

Cole and Green (40) in 1969 reported on measuring soil moisture in the Brenig Catchment. As part of a water balance study over the 2020 ha catchment area, soil moisture profiles were measured with the 356 neutron scatter equipment in 15 sites. The selection of an appropriate calibration curve for each horizon of the soil, relating neutron count to soil moisture, with due allowance for soil density, and content of iron or organic hydrogen were described. The correction of field observations for interface effects was discussed on the basis of laboratory measurement of interfaces with various moisture contents. After considering the total change in moisture contents at each node in the Brenig Catchment, the variance of these changes during 1965 was found to be greater than would be explained by the individual errors of measurement.

Coleman and Bodman (41) in 1944 investigated the soil moisture and energy conditions during water entry into moist and texturally layered columns of laboratory packed soil. The decreased rate of water infiltration which resulted from moistening the soil column prior to the infiltration trials was apparently the result of the dominating influence of the decreased pressure potential gradient against the wet front. In texturally layered columns the less permeable layer limited water entry into the soil surface regardless of whether it lay above or below the more permeable one. If the less permeable layer occupied the upper position, the water entry characteristics of the column were very much like those of a uniform column of the same soil. If the layer occupied the lower position, a positive hydrostatic pressure developed in the layer above. This pressure increased with time but showed no influence upon the rate of water entry into the lower layer. If this sequence of layers occurred in a sloping field soil, lateral subsurface flow would take place within the upper layer when the rainfall rate exceeded the infiltration rate of the lower, less permeable, layer.

Corey (42) in 1957 used the equipment developed for the measurement of oil and gas flow in oil producing sands to study unsaturated permeability in a soil. The method employed the simultaneous flow of air and water under the same pressure gradient to maintain a uniform tension and, as a consequence, a uniform saturation within the sample during permeability measurements. The saturation was reduced in increments by reducing the water pressure with respect to the air pressure.

Results of unsaturated permeability measurements on two relatively undisturbed samples of a sandy soil were presented. The interrelationship between gas and liquid permeabilities as a function of saturation was discussed, and a method of calculating the unsaturated water permeability from the more easily measured air permeabilities was suggested. The magnitude in gas slippage in a dry soil sample was determined by measuring the air permeability at several mean pressure function to an infinite pressure. The permeability of water of the saturated soil was only about half the permeability to air of the dry soil even when the air permeability was corrected for slippage.

Corey and Corey (43) in 1967 described a theory of similitude based on Richards equation and its applicability to model studies of soil drainage systems. An equation was derived combining Darcy's law with the continuity equation as it applied to flow in a porous medium in which the gas phase was everywhere at atmoshperic pressure. Two drainage systems would be essentially similar provided that the following criteria of similitudes were satisfied: (a) macroscopic geometric similarity existed; (b) the initial and boundary conditions in terms of scaled variables were the same for both systems; and (c) the value of pore size distribution index was nearly the same for both media.

Corey, Boulogne, and Horton (44) in 1970 used sequential measurements of gamma and fast neutron attenuation for determination of both soil density and water content of soil samples. Soils containing known amounts of water were packed into 22.5 cm diameter cylinders to a depth of about 9.0 cm. Measurements were made of attenuation of fast neutrons from a 3 μg ^{252}Cf source and attenuation of gamma rays in a collimated beam from a ^{137}Cs source. The attenuation was used to calculate the soil density and water content of these samples. Calculations based only on counting statistics showed that an attenuation method using a combination of gamma and fast neutrons was better than a method of two gamma energies.

Cotecchia et al. (45) in 1968 used the multigroup transport theory to study the influence of the physical and chemical properties of soil on the measurement of the water content by means of neutron probes. It was concluded that interpretation of the values obtained was not reliable, and the measurement of the water content by thermal neutron counts did not provide a sufficient degree of accuracy.

Danfors (46) in 1969 studied changes in the moisture content of the top soil as measured with a neutron moisture gage. A neutron surface gage was calibrated to register the moisture content in soils to a depth of 10 cm. Intermittent moisture measurements were made with a few hours to a few days time spacing. The fluctuations observed were related to several factors such as soil texture and structure, composition, and weather conditions. The neutron surface gage was found to be a very efficient and reliable tool in this investigation.

Davidson, Nielsen, and Biggar (47) described a laboratory method, based on gamma radiation, for studying transient water flow in packed soil columns. The gamma rays from a 200 millicurie source of Cs^{137} are collimated through a narrow slit, and the beam is then focused on a soil column. A radiation analyzer in the circuit allows only primary rays of energy 0.66 ± 0.15 Mev to be recorded. Both bulk density and water content of the soil can be calculated using an absorption equation. This method makes possible the rapid and frequent measurement of the water content of soil as a function of time and position without disturbing the soil-water system. Experimental results for water moving into a uniformly packed air-dry soil are presented.

Davidson et al.(48) in 1969 measured the hydraulic conductivity versus soil-water content relation for different depths in the field for three soil profiles. Soil properties varied from homogeneous to heterogeneous with depth and from loamy sand to silty clay in surface soil texture. Hydraulic conductivity values calculated from drainage data taken during different time intervals compared favorably with each other and showed no measurable hysteresis. The soil-water flux at various soil depths with and without evaporation at the soil surface was measured. The rate at which water drained from each of the profiles was predicted using Darcy's law.

The objective of the study by Davidson et al.(49) in 1969 was to calculate the soil water diffusivity and examine the water content distribution at specific depths within the samples during outflow experiments. Two experiments were reported and analyzed for the variation of the diffusivity as a function of soil moisture and for water content distribution in time for the Oakley and Columbia soils. The experiments included the pressure outflow determinations of soil water diffusivity using both small and large pressure increments and the soil water diffusivity determinations using the classical 2 half-cell method.

Day and Luthin (50) in 1956 described Richards equation for one-dimensional vertical drainage in unsaturated porous media. A finite difference scheme was employed and the equation was solved when the hydraulic conductivity and the water content have been determined for various values of the soil moisture tension. An illustration and experimental test of the method were given for the drainage of a column of fine sand.

Day and Forsythe (51) in 1957 dealt with hydrodynamic dispersion of solutes in the soil moisture stream. The soil moisture stream was characterized by a heterogeneous velocity pattern that affected the movement of dissolved solutes. The solutes were carried by the moving stream at diverse rates, causing a spreading action whose amount depended upon the detailed pattern of the flow. The amount of dispersion in unidirectional flow was proportional to the square root of the linear displacement of fluid. The proportionality constant was a characteristic of the flow system and could be determined experimentally. The amount of dispersion obtained for a given amount of linear displacement was theoretically independent of the velocity of flow. Experiments supporting this conclusion were cited. The experiments with ion exchange resin indicated that the free ions are translocated in accordance with Scheidegger's probability theory. It was concluded that the movement of dissolved solutes in the soil moisture stream cannot be determined adequately from the average fluid velocity unless the hydrodynamic dispersion effect is taken into account.

De Boodt, Moerman, and De Boever (52) in 1969 studied the water balance in the aerated zones with radioactive methods and weighable lysimeter. For practical reasons as well as for accuracy, aluminum access tubes were preferred. The well type gamma ray density meter in its actual state of development seemed unsuitable for water balance studies. It was concluded that the neutron moisture meter yielded good results when readings were made in a freshly drilled borehole. When old auger holes were used the results obtained might not be accurate as a preferential pathway existed along the access tube for water movement.

De Vries (53) in 1958 developed differential equations for the simultaneous transfer of heat and moisture in porous media under the combined influence of gravity and gradients of temperature and moisture content. A consistent distinction was made between changes of moisture content in the liquid and the vapor phase. The interaction between heat and moisture transfer in steady-state heat conduction was discussed in detail using numerical values for two soils - a clay loam and a medium sand. The behavior was found to be dependent on the boundary conditions for moisture transfer, on the direction of the temperature gradient, and on the ratio of two moisture diffusivities entering the analysis.

Drake and Peterson (54) in 1971 described a technique for solving the vertical subsurface flow problem through the application of similarity transformations. The problems discussed in this paper included certain previously published results and some new results obtained for the nonlinear Fokker-Planck equation.

Duley (55) in 1939 reported the surface factors affecting the rate of intake of water by soils. The effect of different soils, varying rather widely in texture and profile characteristics, on total intake of water and infiltration rates was considered. In order to determine the rate at which the soil pores may become congested, a number of studies were conducted in the laboratory and field with a special laboratory sprinkler. Comparisons of straw mulch and cultivated bare soil on intake of water by different soils were presented.

Eagleman and Jamison (56) in 1962 obtained measurements of the velocity of flow and hydraulic gradient in the suction range of 0 to 700 cm of water across the plane of contact for three different soil textural pairs, two of which were sampled from naturally occurring textural breaks in alluvial soil profiles. The hydraulic conductivity values across the textural breaks indicated that the soil properties were favorable for moisture transfer from large pores to smaller pores, but a barrier existed for water movement from smaller pores to large pores. In the naturally occurring breaks in soil texture, the compaction of the different soil layers determined the degree of expression of the barrier to water movement.

Elrick, Erh, and Krupp (57) in 1966 described an apparatus for studying miscible displacement process in soils. Also, the experimental results for the relative concentration versus pore volume of effluent were presented for different flow velocities of tracers.

Elrick (58) in 1969 presented a brief review of some methods and procedures that can be used to determine capillary conductivity and capillary diffusivity. Two relationships between soil-water content versus soil-water pressure and between capillary conductivity versus soil-water content were used to characterize the soils. Data on these hydrologic properties of a soil were reported and the effects of air-drying and sieving on these properties were discussed.

Feodoroff (59) in 1969 described experiments in which the water movement during redistribution had to proceed either downwards or upwards. It was shown that the orientation of the soil column had no influence on moisture distribution after 24 hours, except in coarse sandy soil. Thus, redistribution was mainly due to attractive forces of the dry soil in the wetting zone.

Ferguson and Gardner (60) in 1963 obtained the solution of one-dimensional flow equation in unsaturated porous media utilizing the Boltzmann transformation. Unsaturated water flow data using gamma ray equipment were collected. The theoretical solution did not fit the data satisfactorily. However, the data did indicate that diffusivity was a function of water content alone over much of the time of water flow. The relationship between diffusivity and water content followed a non-exponential, curvilinear relation. The data also suggested that a minimum gradient might be essential in order for unsaturated flow to occur.

Filipkowska (61) in 1969 described the Polish isotope apparatus manufactured by the Bureau for Nuclear Technique Installation. This apparatus determined the water content in the surface layer and at the vertical level. The basic part of each probe was the source of fast neutrons and the Geiger-Müller Counter covered with cadmium tin. To detect the neutron, the reaction which occurred between the moderated thermal neutrons and the cadmium covering the counter was used. Since the number of detector counts depended on the quantity of emmitted gamma photons, those in turn depended on the moderated neutrons. Measuring the number of pulses, the moisture content in the soil could be determined. When the probe calibration was performed, the influence of bulk density of the ground on moisture and the eventual errors due to contents of elements which strongly absorb neutrons in the ground mixtures must be considered. Soil moisture measurements could be performed within the range of 0-45% of volume moisture with the accuracy of water content from 0.3 to 1.5.

Fok and Bishop (62) in 1965 developed a relationship that expressed the length covered by the advancing water as a function of application time, inflow rates, width, normal depth, and empirical constants. The advance equation yielded good results when compared with field data.

Fok (63) in 1967 developed an empirical relationship for infiltration, utilizing two dimensionless parameters, namely, $\frac{y}{h}$ and $\frac{kt}{nsh}$; where y is the length of wetting from soil surface to wetting front during infiltration; h, the constant head loss in tramsmission zone extrapolated to the wetting front; k, the constant hydraulic conductivity of the transmission zone; t, the time of infiltration; n, the constant porosity of soil profile; and s, the net increment of the degree of saturation after infiltration of the transmission zone. Four power equations were obtained from an evaluation of the four straight lines fitted in different regions of time.

Földi and Szőnyi (64) in 1969 described a method for measuring soil moisture from the temperature gradient. In the surroundings of a heat transmitter with stabilized heat flux, thermal conductivity of the soil can be determined and recorded from the temperature gradient. Using a corrosion resistant transmitter introduced into the soil and ensuring constant calibration conditions, soil moisture can be measured. For determining soil moisture a new electric method was developed, which is independent from the concentration of the soil solution. The measuring probe was weather proof, resistant to mechanical effects during installation into the soil and to influences of temperature for extended periods.

Freeze and Witherspoon (65) in 1966 derived the two-dimensional Richard's equation for steady-state flow in saturated porous media. Comparison of analytic solution and numeric solution to a hypothetical three layered aquifer was presented.

Freeze (66) in 1969 presented a mathematical model for one-dimensional unsaturated flow above a recharging or discharging ground water flow system. The unsaturated flow processes of infiltration and evaporation were described in physical and mathematical continuity with the parallel saturated processes of recharge and discharge. Water table fluctuations resulted when the rate of ground water recharge or discharge was not matched by the unsaturated flow rate created by infiltration or evaporation. A water table rise provided the source of replenishment to the ground water zone that allowed the prevailing rate of recharge to continue. This dynamic behavior of water table was simulated by a one-dimensional, numerical mathematical model involving transient flow through an integrated saturated-unsaturated system. The flow equations were solved using an implicit finite difference scheme. The solutions were applicable to homogeneous, isotropic soils in which the functional relationships showed hysteresis properties. The model allowed upper boundary conditions of constant rainfall, ponded water, evaporation and redistribution. It can be used to determine the water table fluctuation that will rise from a given set of initial conditions, boundary conditions, and soil type.

Freeze (67) in 1971 described a three-dimensional finite difference model for the treatment of saturated-unsaturated transient flow in ground water basins. The integrated equation of flow was solved by the line successive overrelaxation (LSOR) technique. The model allowed any generalized region shape and any configuration of time variant boundary conditions. Results of simulations for hypothetical basins were presented. Application of the model to developed basins could allow to simulate not only the manner in which ground water withdrawals were transmitted through the aquifers, but also the changes in the rates of ground water recharge and discharge induced by the withdrawals. For any proposed pumping pattern, it may be possible to predict the maximum basin yield that could be sustained by a flow system in equilibrium with the recharge-discharge characteristics of the basin. An example was given on the application of the model to a three-dimensional saturated-unsaturated flow system in a two-layer basin to ground water withdrawals from a single well.

Freeze and Banner (68) in 1970 conducted column experiments in laboratory using a tensionmeter-transducer system. The results were compared with the mathematical model of Freeze (66) which simulated one dimensional, vertical, unsteady, unsaturated flow above a recharging ground water flow system. Field measurements were discussed. On the Canadian prairies, cases of recharge-sustaining infiltration to the water table were isolated in time and space. Only spring snowmelt, and on occasion heavy summer rains, were effective. A large percentage of the snowmelt, however, was made available at the surface prior to the thawing of the frost wedge and therefore, did not infiltrate. Effective infiltration was depression focused, and certain portions of ground water recharge areas might never receive direct infiltration to the water table. Observation well hydrographs of water table fluctuations alone were not sufficient to monitor recharge phenomena; measurements of the hydraulic gradient above and below the water table were necessary. The model was applied to a field case and distribution of pressure head over depth was presented during heavy summer rainfall, summer recession, and spring melt period.

Gardner (69) in 1919 dealt with the movement of moisture in soil by capillarity. The equation of moisture flow was derived, using the continuity equation, Stokes' law and pressure gradient. The equation was solved for a steady-state case. A number of experiments were considered and analyzed from theory. The data was plotted on percent moisture versus distance from source curve and compared satisfactorily with the theoretical equation.

Gardner and Kirkham (70) in 1952 reported on the determination of soil moisture by neutron scattering. It was shown theoretically, and experimentally for five soils, that a method involving the scattering and slowing of fast neutrons by hydrogen may be used for measuring soil moisture. The method rests primarily on two considerations; first, hydrogen is, practically, the only material that will slow fast neutrons; second, hydrogen in soils is present almost entirely in the form of water. In applying this concept, a fast-neutron source and a slow-neutron counter, source and counter combined into a single unit, are lowered into a small auger hole in the soil. The counting rate of neutrons which have been slowed by soil hydrogen is a measure of the moisture content. The method is particularly useful in measuring soil moisture in the field *in situ*.

Gardner and Gardner (71) in 1950 studied the horizontal flow of water through soil contained in a semi-cylindrical lamina 1.0 cm from a source where water could be furnished under any desired pressure. From a practical point of view, this would compare to a vertical section through an irrigation furrow except that as a simplification to the problem it was rotated through an angle of 90° to eliminate the effect of the gravitational fields, the vertical component of the velocity being then disregarded. The experimental data indicated that the permeability decreased rapidly with the moisture content, and this was in agreement with the observed phenomena that irrigation water moved rapidly when first applied but slowed down very appreciably as it moved out from the source.

Gardner and Hsieh (72) in 1956 conducted experiments on velocity of flow in unsaturated porous materials. Rate of flow of moisture in unsaturated porous media at constant temperature depended upon the gradient of the moisture potential, the size of the flow channel, and other factors relating to the fluid and porous medium but which might be held constant. Size of the flow channel likewise was continually changing. An experimental technique had been devised for direct measurement of the velocity of water movement in materials simulating soils. From these data, with the aid of moisture density measurements, rate of flow was computed. Velocity data obtained by this technique were being used to study the mechanics of flow under unsaturated conditions. Further information has been obtained on the nature of the f-function in the Darcy equation, $v = kf \text{ grad } \phi$; where v is velocity of flow, k is saturated permeability, and ϕ is moisture potential.

Gardner (73) in 1959 obtained numerical solutions of the flow equation for the drying of porous media assuming an exponential relationship between diffusivity and water content. Solutions were presented for both semi-infinite and finite porous media for isothermal conditions, when gravity was absent or negligible. The rate of drying of laboratory soil columns was in good agreement with the numerical solutions. The rate of drying was controlled largely by the boundary conditions and physical characteristics of the soil that determined the rate of movement of water in the soil in the liquid phase.

Gardner (74) in 1958 discussed mathematics of isothermal water conduction in unsaturated soil. The equation for one-dimensional vertical flow was derived. The measurement of conductivity and diffusivity was described. For the Pachappa, Indio and Chino soils, the conductivity was related to the suction head by an expression of the form

$$k = \frac{a}{S^n + b} \qquad (1)$$

where S in the suction head and a, b, and n are constants. The diffusivities were plotted for the same soils as a function of water content on a weight basis. The diffusivity varied over a wide range of values but not quite to the extent that the conductivity did. The diffusivities could be related to the moisture content by an exponential function

$$D = D_o \exp \beta(\theta - \theta_o) \qquad (2)$$

in which D_o is the diffusivity when $\theta = \theta_o$ and β is a constant. Some solutions to the flow equation were presented for special cases, such as the steady state, unsteady state, entry of water into soil, steady-state evaporation and drying of soils.

Gardner (75) in 1958 discussed some steady-state solutions of the flow equation in unsaturated porous media. A transformation was given which made possible the exact solution of steady-state unsaturated flow problems and approximate solution for some transient problems. Solutions of the steady-state problem in one dimension were given for several different relations between capillary conductivity and soil suction. Steady-state evaporation from a soil in which there was water table was examined. The maximum evaporation rate was shown to be related to the capillary conductivity and depth to water table in a simple manner. The influence of surface mulch was also considered.

Gardner and Mayhugh (76) in 1958 proposed a diffusion equation with concentration-dependent diffusivity to describe the movement of water in unsaturated soils. For certain initial and boundary conditions the Boltzmann transformation converted the flow equation into an ordinary differential equation. The time dependence of the infiltration rate and distance to the wetting front for flow into a semi-infinite sample could be inferred from this equation. Numerical solutions of the equation were presented for one-dimensional flow, assuming the diffusivity to be an exponential function of the moisture content. Water-entry rates and moisture content distributions measured experimentally were in good agreement with those predicted by the solutions of the equation.

Gardner and Milkich (77) in 1962 developed a method for the measurement of soil-water diffusivity and conductivity from the solution of the flow equation for constant flux of water at one boundary of a soil sample. Experiments were conducted on five different soil samples - The Pachappa sandy loam, Indio sandy loam, Fort Collins loam, Aiken clay loam, and Chino clay. Relationship between suction head and water content was shown for these different soils. The capillary conductivity and diffusivity for different soils were measured by the gamma ray absorption method.

Gardner, Hillel, and Benjamini (78) in 1970 made water content measurements by gamma ray attenuation in soil columns during redistribution following irrigation. Approximate solutions of the vertical unsaturated flow equation were derived that described the water content above the initial wetting front as a function of time. Three cases discussed included the matric and gravitational gradients, gravity negligible, and gravity predominant.

Gardner, Hillel, and Benjamini (79) in 1970 conducted water content measurements by gamma ray attenuation on soil columns during simultaneous redistribution and evaporation following irrigation. Redistribution was shown to reduce evaporation, in some case appreciably. For a deep irrigation the redistribution proceeded at a rate that was relatively independent of the evaporation processes, as predicted from numerical solutions of the flow equation. Expressions were derived for obtaining an estimate of amount of reduction in evaporation due to redistribution when the redistribution rate was known.

Green, Hanks, and Larson (80) in 1964 used the numerical procedure of Hanks and Bowers (88) to solve the moisture flow equation for boundary conditions corresponding approximately to those existing for infiltration into a field soil. Water diffusivity and retention data were measured on field cones by the outflow method. Infiltration estimates were obtained for a simulated two-horizon soil with three non-uniform antecedent moisture profiles. Calculated infiltration rates were in good agreement with field rates measured with a sprinkler infiltrometer.

Green et al.(81) in 1970 developed a mathematical model describing isothermal, two-phase flow in porous media. The model, which consisted of describing differential equations and algorithms for the numerical solution, was applied to the problem of vertical ground water movement in unsaturated soils in the absence of evaporation and transpiration. An iterative implicit scheme was utilized to solve one-dimensional flow equation. A comparison was made between computed results and experimental field data on moisture movement beneath a shallow surface pond. Water was added to the pond at controlled rates to maintain an approximately constant head for a set time period. Following this wetting period, the pond was kept dry but covered to reduce evaporation. At different times during the wetting and drying periods, neutron logs were run to measure water saturation versus depth at depths of upto 22 feet. The experiment was simulated with the computer model and satisfactory agreement between calculated results and the data was obtained.

Guitjens and Luthin (82) in 1971 considered the gravity wells, pumped intermittently, that could have different degrees of drainage in the unsaturated zone at the onset of water table recovery. Each part of the aquifer profile followed a specific scanning curve of rewetting. The measured hysteresis phenomenon of Oso Flaco fine sand and the hydraulic conductivity as a function of moisture content were incorporated in the finite difference form of the partial differential equation for steady and unsteady radial flow to solve for the moisture pressure distribution of one water table drawdown and three different kinds of recovery.

Haines (83) in 1923 conducted experimental study on the volume changes associated with variations of water content in soils. A new and simple method of measuring the shrinkage of moist soil in drying was described, which at the same time gave values for the pore space and and specific gravity of the soil. Diagrams for a number of soils were presented, illustrating the character of soil shrinkage. The shrinkage was shown to take place in two stages in both of which there was a linear relationship to the moisture content. By means of this method the effect of alternate wetting and drying of soil in producing a good tilth was illustrated.

Haines (84) in 1927 studied the theory of capillary phenomena in soils. The theory of the capillary behavior of moist soil was considered for the ideal case and its relationship to various soil properties. It was shown that the moisture distribution attained by capillary rise could be inferred from simple direct measurement of the suction pressure. Various other experimental illustrations of the theoretical conclusions were introduced. The results of a number of suction measurements on materials of a granular nature were given.

Haines (85) in 1930 considered the hysteresis effect in capillary phenomena and the associated modes of moisture distribution. A recapitulation of the main features of the moisture distribution in ideal soil was given. Cases of falling moisture and rising moisture were treated. Experimental data verified the theoretical values of suction head.

Halevy (86) in 1969 indicated the nuclear and isotropic techniques which might aid in investigations of the unsaturated zone. The discussion included methods for the determination of soil water content and methods for investigation for the movement of soil moisture.

Hammad (87) in 1966 investigated several points involved in the design of tile drainage systems for irrigated areas in arid zones. The distribution of moisture in the capillary zone, the drainage and irrigation requirements, the water table fluctuation, and the depth and spacing of tiles were studied. The solution gave a set of equations for determination of the different parameters necessary for the design of tile drainage. The treatment was based on the soil properties, the quality of irrigation water, and the salt tolerance of plants.

Hanks and Bowers (88) in 1962 devised a numerical solution of the moisture flow equation. Solutions obtained for infiltration into a loam over a silt loam and vice versa showed that infiltration was governed by flow through the less permeable soil, provided the wetting front had extended well into the second layer. Solutions were employed for vertical infiltration and for horizontal infiltration into two soils. The numerical solution was found to give excellent results when compared with the methods of Scott (194) and Phillip (165) for horizontal infiltration into homogeneous soils at a uniform initial water content.

Hanks and Gardner (89) in 1965 investigated the influence of variations in the diffusivity-water content relation on evaporation of water from soils. It was shown that where the diffusivity was changed at high water content, evaporation was changed accordingly. However, variations in the diffusivity-water content relation at lower water contents indicated little influence on cumulative evaporation. All the estimates assumed that a diffusion type equation was valid for evaporation.

Hanks, Klute, and Bresler (90) in 1969 described a one-dimensional numeric method for estimating infiltration, redistribution, evaporation, and drainage of water from soil. The type of flow was determined by the water flux at the surface of soil or the bottom boundary. The method provided for hysteresis in the water content-pressure head relation. Comparisons with measurement made on soil columns for infiltration, redistribution, and drainage were presented. Good agreement was obtained between measured and computed values.

Hayday (91) in 1966 discussed the balance equations for heterogeneous continua. The paper presented from the viewpoint of classical continuum physics, a rigorous derivation of the general balance equations for heterogeneous continua-substances consisting of many distinct, possibly interacting, constituents. The treatment was a direct generalization of the well known theory for a simple (one substance) continuum and covered multicomponent media in liquid form. The work was based on axioms in integral form stated for the constituents of the heterogeneous continuum, using well defined material volumes for the whole medium. An explicit hypothesis was introduced asserting how a constituent of a heterogeneous medium was influenced by the totality of the others. This hypothesis allowed for general interactions among the constituents and covered the special results for liquid helium mixtures. The overall integral balance equations were derived by summing over all components of the corresponding balance equations for the constituents. The differential equations for the heterogeneous continuum were consequences of the mathematical form of the resultant equations.

Hill (92) in 1961 defined leaching in irrigation practice and stated three principal purposes: (a) removal of accumulated salts, (b) maintaining a salt balance, and (c) providing equivalent service with changes in salinity of water used for irrigation. Formulas were developed for leaching requirements related to the functions to be performed and to the salinity of applied waters.

Hornberger (93) in 1969 described a model of transient moisture movement in a composite soil moisture ground water system. The model was used to study two-dimensional flow in response to a falling water table. The numeric solutions were checked with the experiments of Todd (220), and good comparisons were obtained.

Hornberger and Remson (94) in 1970 proposed a moving boundary model for one-dimensional transient flow of water through a porous medium of which part is saturated and part is unsaturated. The model was used to study a gravity drainage problem. Two numerical procedures were developed to solve the problem, an approximate Taylor series method and a finite difference method. The validity of the two methods were appraised by comparing the results with experimental data given by Watson (240). The Taylor series method was limited in applicability because of a need for accurate determination of derivatives of hydraulic conductivity and of moisture content with respect to pressure head. The finite different solution was efficient.

Horton (95) in 1939 presented an analysis of runoff plot experiments with varying infiltration capacity. Discussed were the experimental data, determination of varying infiltration capacities from runoff graphs, relation of infiltration capacity to rainfall duration, time required to attain constant infiltration capacity, relation of infiltration capacity of soil moisture, and minimum infiltration capacity.

Ibrahim and Brutsaert (96) in 1968 presented a general solution for vertical flow in unsaturated soils with hysteresis in the absence of evaporation. The results obtained from the digital program were used to analyze the effects of different initial and boundary conditions on the moisture distribution in the soil and on the rate of infiltration.

Irmay (97) in 1954 studied the variation of hydraulic conductivity in unsaturated soils. Unsaturated steady flow of mixtures of a liquid and a gas through sands and similar porous media at low Reynolds numbers followed

Darcy's law. The intrinsic permeability was not constant, except a universal function of degree of liquid saturation. An approximate theory gave its form as a cubic parabola. Numerous experiments from other investigators confirmed the theory.

Isherwood (98) in 1959 presented a digital program to obtain water table recession in homogeneous tile drained soil. Parameters considered were tile depth, spacing, barrier depth, hydraulic conductivity, and drainable pore space. Drain diameter was six inches. The midpoint water table height was found to fall exponentially with time after a slower initial rate. Results presented graphically can be used for the rapid evaluation of the effectiveness of two drains. Tile spacing for any given surface drawdown rate can then be determined.

Jackson, Reginato, and Van Bavel (99) in 1965 tested three methods to calculate the unsaturated conductivity of soil from its moisture characteristic. Calculated values were compared with direct measurements of conductivity for both sorption and desorption for a sand. Also, comparisons were made for three soil materials.

Jackson and Klute (100) in 1967 presented a method of estimating dead-end pore volume in porous materials using transient- and steady-state diffusion coefficients. Available data indicated that dead-end pore volume in soils was a small percentage of the total pore volume.

Jeppson (101) in 1968 obtained solutions to steady-state free surface seepage from axisymmetric ponds through homogeneous and nonhomogeneous porous media to a drained layer at a finite depth by finite difference method. In the formulation of the boundary value problem, the magnitudes of the radial and axial coordinates were considered dependent variables in the plane defined by the potential function and Stoke's stream function. Example solutions were given for seepage through: (1) a homogeneous porous medium, (2) a nonhomogeneous porous medium in which permeability decreased with depth, and (3) a nonhomogeneous porous medium in which permeability increased with depth.

Kemper (102) in 1961 extrapolated the microscopically observed laws of viscous and diffusive flows to flow of water in thin films in porous media. Correction factors were developed to account for the effects of the diffuse layer of adsorbed cations and greater viscosity of water near particle surfaces. Equations for the two types of flow were combined to give a relationship from which molar free energy gradients could be evaluated in comparison with pressure gradients, as to their abilities to move water.

Kemper (103) in 1961 measured osmotic pressures across compacted clays, which were compared with pressures calculated from theory developed by Kemper (102). Tortuosities and effective thicknesses of films in which water flows were calculated from hydraulic conductivity and salt diffusion data. The measured and calculated values of osmotic pressure were in fair agreement and probable reasons were given for the descrepencies observed.

Kemper and Maasland (104) in 1964 derived an equation to measure the effect of salt and water diffusion on salt reduction of solutions forced through thin films of water by pressure differentials. Salt concentrations of solutions which had passed through thin films adjacent to charged particles were calculated from the equation and plotted as a function of pressure differential, ionic mobility, film thickness, and cation balances. Experimental evidence showed that salt sieving increased as the pressure forcing solution through the days increased.

Kemper and Van Schaik (105) in 1966 determined the rates of salt diffusion through homoionic clay plugs after the plugs had been brought to steady state between solutions of the chloride of the cation with which the clay was saturated. Salt and water contents were measured across the clay plugs and were used with the diffusion rates to calculate porous system diffusion coefficients. Diffusion coefficients increased as an exponential function of water content, but for practical purposes, were independent of the salt concentration. Diffusion potentials indicated that the adsorbed cations contributed slightly to the movement of the salt cations.

Kennedy and Edgerton (106) in 1968 determined the response of microwave radiometers to moisture content in soils. Materials investigated included beach sand, unconsolidated tideland mud, playa sediments, and loam. Dual polarization measurements were made at frequencies of 13·5 G Hz and 37 G Hz (1 G Hz = 10^9 cps) with aspect angles from nadir to the local horizon.

King (107) in 1965 presented empirical equations for describing relative permeability as a function of capillary pressure. Of the two, Gardner's equation appeared to fit the experimental data better. An equation was also presented for representing saturation as a function of capillary pressure. The equations were used to calculate relative permeability and diffusivity as functions of saturation.

Kirkham and Feng (108) in 1949 attempted to test the diffusion theory when water moved horizontally under capillary action into uniform air-dry soil from a source of free water. Experiments were conducted to define laws of capillary movement. Two formulas for the quantity of water and the distance of advance of the wetted front were presented.

Klock, Boersma, and DeBocker (109) in 1969 proposed equations to predict the permeability of a porous medium from its pore size distribution. Pore size distributions were obtained by the mercury intrusion method and used in the calculation of intrinsic permeability. The calculated permeability values were compared with measured values for a range of pore size distributions.

Permeabilities and pore size distributions of 54 systematically selected particle size classes of glass beads and sand were measured. Limits of the particle size classes ranged from 44-53 and 208-246 microns for the particle diameters. The equation of Millington and Quirk (152) was used to calculate the permeabilities. The calculated permeabilities agreed with measured values only when a correction factor was used. Some limitations of the mercury intrusion technique used to obtain pore size distributions were discussed.

Klute (110) in 1952 discussed the validity of Darcy's law in unsaturated porous media and the assumptions in its use. The relationship of the permeability coefficient in Darcy's law to various soil parameters was briefly considered. Using the equation of continuity and Darcy's law, an equation of flow was derived, and the general problem of obtaining solutions of this equation was outlined. A numerical solution of the flow equation for a semi-infinite system was given, using a functional relationship between the permeability and the moisture content, and the phenomenon of a wetting front was presented.

Klute (111) in 1952 derived an equation describing the flow of water in unsaturated porous materials from Darcy's law and the equation of continuity. A numerical method employing Boltzmann transformation to this equation for semi-infinite horizontal systems of flow was described and applied to several examples. The phenomenon of wetting front was discussed be indicated when the variation of the diffusivity with moisture content was considered.

Klute and Letey (112) in 1958 investigated the dependence of ionic diffusion on the moisture content of nonadsorbing porous media. The dependence of the self-diffusion coefficient of $Rb^{86}cl$ on the moisture content of packings of 75 and 200 μ glass beads was measured. The ordinary diffusion equation was assumed to apply. Diffusion coefficient measurements were made by a transient method. The results indicated a very rapid decrease of diffusivity as the moisture content was decreased. The results were discussed in relation to the path length and moisture content of the medium. An electrical method was used to evaluate the effective path length.

Klute, Scott, and Whisler (113) in 1965 calculated equipotential and streamline patterns for the case of flow in a saturated inclined soil slab resting on an impermeable base. Two cases were analyzed, one with both upper and lower ends of the slab closed to flow and another with only the upper end closed. Most of the water flowing through the slab entered and left in a surface region near the ends of the slab. For slopes length-to-depth ratios greater than about 10, the total flow could be estimated quite closely by treating the slab as an inclined one-dimensional flow system.

Klute, Whisler, and Scott (114) in 1965 solved the nonlinear diffusivity form of the flow equation numerically for one-dimensional horizontal soil columns of finite length. Both inflow and outflow cases were considered. Dimensional graphs were presented, showing the relationships of the moisture content versus distance and the flux versus time.

Klute and Peters (115) in 1969 discussed the application of the strain gauge pressure transducers in measuring hydraulic and pressure head in unsaturated soils. Strain gauge pressure transducers of the diaphragm type were incorporated into a tensiometer system that had a short response time, was capable of detecting tension changes as small as few millimeters of water and has the advantage of an electrical output that could be recorded. Construction details and precautions to be observed in use and operational procedures were given for direct reading and null modes of measurement. A manifold for the use of a single transducer with a number of tensiometer cups and the possible use of the tensiometer in field measurements were described.

Kobayashi (116) in 1969 investigated on the vertical flow in unsaturated soils. In the case where the fundamental equation could be transformed to an ordinary differential equation, the author showed the necessary conditions that the auxiliary function had to satisfy and indicated that there are two kinds of auxiliary functions, that is, the product form and the linear form. Using the Boltzmann transformation, the problem for one-dimensional horizontal flow by the interactive method was solved and compared with the solution of the fundamental solution by the finite difference method of Hanks and Bower (88). Also, the forward difference scheme for vertical flow was derived and compared with the solution by the iterative method.

Koitzsch (117) in 1969 reported on determination of hydraulic conductivity and diffusivity of soil *in situ*. The theory of an instrument consisting of a tensionmeter with a cylindrical cup to measure the two soil parameters was presented. The theory started from a problem of heat conduction, in which a perfect conductor and the surrounding material were initially at different temperatures. It considered the influence of the finite hydraulic conductivity of the cup wall and the influence of an additional contact resistance which might sometimes exist. Suggestions were made for the design of the instrument and for reducing the number of observations. The results of the experiment yielded the hydraulic conductivity as well as diffusivity, the latter with a smaller accuracy.

Kraijenhoff van de Leur (118) in 1962 discussed some effects of the unsaturated zone on nonsteady free surface groundwater flow studied in a scaled granular model. Symmetrical free surface flow of groundwater to outflow channels was investigated in a sand box model employing screened sand and a spirit-water mixture. Differences between observed and computed hydrographs were analyzed in a combined study of unsaturated and saturated flow.

Krupp and Elrick (119) in 1968 conducted a series of miscible displacement experiments in an unsaturated glass bead medium maintained at a constant average water content during each displacement. The variation in the form of the breakthrough curve with decreasing water content was not large; however, there was a consistent shift of the breakthrough curve to the left of the relative concentration value of 0.5 and 1.0 pore volume and a long tail or slow approach to the final relative concentration of 1.0.

Kunze and Peters (120) in 1966 matched experimental outflow curves with theoretical curves by assuming a change in diffusivity proportional to a ratio of theoretical and experimental time values.

Lagerwerff, Nakayama, and Frere (121) in 1969 analyzed the hydraulic conductivity factor in Darcy's equation for viscos flow in terms of a modified Kozeny equation. The modifications included a correction for swelling and the replacement of the cubic exponent of the porosity term by an exponent varying between 0 and 3. The choice depended on the interplay between surface and volume of soil pores as determined by flocculation-disperson conditions. Swelling was calculated from the theory of the diffuse double layer. A theoretical analysis of experimental results on the hydraulic conductivity of two soils for percolants of variable concentration and composition showed that a single value for the electrical potential parameter sufficed to match theoretical with experimental data when the concentration of the percolant ranged from 10 to 100 meq/liter. Taking into account the effects of pore size, pore density, effective porosity, and flow matrix on the hydraulic conductivity, the above had been explained in terms of expansive swelling of smaller pores at the expense of larger ones. The relevance of the theory with regard to the alleged contrast between grain and pore models of soil was considered.

Laliberte, Brooks, and Corey (122) in 1968 derived an expression for saturated permeability that could be evaluated from capillary pressure-desaturation data. This was a desirable feature since the expression made available the final parameter in predicting the permeability of partially saturated media.

Lehane and Staple (123) in 1953 presented an experimental study concerned with water retention and availability in soils related to drought resistance. Observed differences in the available water-holding capacity of different textural classes of soil were not sufficient to account for the relative droughtness of these soils. Laboratory analyses were made on surface soil samples, representing a wide range in texture, collected at Experimental Substations in Saskatchewan, Canada. Moisture release curves for different textural classes of soils were presented. It was suggested that the greater drought resistance of crops on the five textured clays might be related to the fact that the available moisture in these soils was held under greater stress than was the moisture in lighter soils. Other factors, such as soil temperature and aeration, should be considered in such work.

Letey, Kemper, and Noonan (124) in 1969 measured water movement, in response to osmotic pressure gradients, in clay loam and sandy loam soils at soil water suctions from 0.08 to 15.00 bars. Movement in response to osmotic pressure gradients was compared to movement in response to hydraulic pressure gradients in the soil-water suction range from 0.08 to 0.65 bars. At suction less than 0.50 bars the amount of water moved by osmotic pressure gradients was generally less than 4.0% of the water moved by hydraulic gradients of equal magnitude.

Letey and Kemper (125) in 1964 presented equations that described the movement of solution and salt through a soil system in which there were both hydrostatic and osmotic pressure gradients. The Onsager reciprocal relation was found to be valid for a clay-water-salt system.

Lewis (126) in 1937 presented experimental data on the rate at which capillary water would move through various soil types under the influence of gradients. The experiments consisted of setting up series of soil columns exposed to the evaporating influence of an air current at one end and adding water at predetermined rates at the other end. When a state of steady flow was secured, the soil columns were broken down and moisture content of each short transverse section was determined. Relation between the moisture content of the soil and the capillary potential was obtained.

Liakopoulos (127) in 1966 derived Darcy's law from the Navier-Stokes equation and also presented the equations in cartesien and cylindrical coordinates for unsaturated flow in anisotropic soils. Possible use of a relaxation or an iterative procedure was indicated.

Liakopoulos (128) in 1965 derived the generalized equations for distribution of moisture content and pressure head in time and space in unsaturated porous media. These equations were represented for one-dimensional case and were solved for two conditions, with a column of infinite length and that of finite length. Domain conditions for the capillary rise, infiltration case, and the evaporation case were applied to get solutions for infinite length column. For finite length column, the domain conditions included for the gravity drainage case and evaporation case. The implicit difference scheme was used to solve the one-dimensional partial differential equation. The transient values of pressure head, water content and rate of flow during drainage, evaporation, infiltration, and capillary rise could be predicted.

Liakopoulos (129) in 1965 discussed equations governing the unsteady flow of water through a homogeneous, unsaturated soil system. The mathematical model for one-dimensional infiltration problem of water in unsaturated zone was presented. The appropriate functions were described as the permeability versus pressure relation and the water content versus pressure relation. These functions were obtained experimentally. From a theoretical standpoint the moisture profile during infiltration period could be obtained by solving the one-dimensional differential equation with the initial and boundary conditions together with the two functional relationships between pressure and moisture content and between pressure and permeability. Moisture profile during redistribution of moisture content was predicted by experimental results.

In 1966, Liakopoulos (130) investigated the one-dimensional transient vertical movement of water in unsaturated soils. The mathematical equation describing the infiltration process was derived by combining Darcy's law with continuity equation of mass flux in unsaturated flow conditions. The resulting equation together with the corresponding initial and boundary conditions constituted a initial boundary value problem. Implicit difference scheme was employed to solve the equation. Experiments conducted on a vertical column packed uniformly with very fine sand showed satisfactory agreement between the theoretical and experimental results.

Liakopoulos (131) in 1966 presented theoretical prediction of evaporation losses from ground water. The transient values of water pressure, water content, and rate of water evaporation from soils were predicted from the one-dimensional mathematical model, representing the physical problem of the evaporation phenomenon from soils. The mathematical model consisted of a nonlinear parabolic partial differential equation in which the time and the position in the vertical direction were taken as the independent variables and the volumetric water content as the dependent variable. A finite difference scheme was utilized and a Fortran program was devised.

Lindenbergh (132) in 1957 described a test to determine the quantity of rain and irrigation water which can be stored in a body of dune with a known porosity. The experimental value for the coefficient of permeability of the Leyden dune sand was given. It was concluded that in the dune sand of the catchment area of the Leyden Water Works, the vertical movement above the phreatic level of the ground water originating from precipitation occurred with a rate of infiltration of 16 cm per day. The average degree of soil moisture of the sand above the capillary zone varied from 7.00% to 11.30% of the volume of sand.

Lindstrom, Boersma, and Stockard (133) in 1971 described the theory on the mass transport of chemicals in saturated sorbing porous medium. Three models with different boundary conditions were considered, although the partial differential equations were essentially the same. In the first model the free and sorbed phases moved together. The second model involved a time dependent sorbtion phenomenon, rather than an instantaneous one as was assumed for model one. The rate of sorbtion was characterized by the first order kinetic rate constant. In the third model the change in speed of sorbtion and strength of sorbtion was related to the change in site coverage. This model was considered to be the most realistic.

Low (134) in 1958 summarized the results and conclusions on the study of movement and equilibrium of water in soil systems as affected by soil-water forces. Equations for water movement and water equilibrium were derived. Experimental data were collected and analyzed.

Luthin and Day (135) in 1955 studied the lateral movement of water above a water table under steady-state conditions. The dependence of the capillary conductivity on soil moisture tension was considered in making a theoretical analysis of the problem. Lateral flow was induced in a sand-filled tank by maintaining a small difference in head between constant reservoirs located on either side of the sand-filled tank. The experimentally determined values of hydraulic head and quantity of flow were then compared with the theory which considered the variations of capillary conductivity with soil moisture tension. The hydraulic head determined at various points of the flow section in the steady-state experiment agreed approximately with values calculated from theory. The flow calculated from knowledge of the capillary and hydraulic conductivities agreed with the measured flow. The methods of numerical analysis which were used to develop the theory could be applied to other steady-state flow problems involving variable conductivities.

Lutz and Kemper (136) in 1959 conducted experiments on intrinsic permeability of clay as affected by clay-water interaction. Data concerning the thickness of the water films on several types of clay, the force with which the water was held under several conditions, and the effects of the films on intrinsic permeability were presented. Increasing the pressure gradient increased the intrinsic permeability of the system completely out of accord with Darcy's law. This was particularly true for Na clays, in which the diffuse layer of cations and the water structure extended to distances greater than the radius of the pores between particles; this was attributed to a breakdown of the water structure. In Ca clays, with a restricted diffuse layer and water structure, increasing the pressure had practically no effect on permeability.

Maasland (137) in 1959 considered the problem of water table fluctuations in response to repeated recharges. The effect on the water table of intermittent constant recharge and of intermittent instantaneous recharge was analyzed in detail. The final results were shown to consist of a combination of periodic and transient components; the transients were monotonic decreasing functions. The theory could be applied to problems of ground water flow through aquifers and to land drainage problems.

Macdonald and Waite (138) in 1971 reported on soil moisture detection with imaging radars. The data presented in this study suggested that presently available dual polarized, K-band, side looking imaging radars provided a capability for revealing a qualitative estimate of soil moisture content. When used as a supplement to aerial photography in temperate climates, radar imagery analysis will decrease the ambiguity of soil type reconnaissance. The use of multifrequency multipolarization imaging radars and the relative foliage penetration of each should be investigated as a possible means of gathering quantitative soil moisture information.

Mason, Lutz, and Petersen (139) in 1957 conducted a study on hydraulic conductivity, percent large pores, and bulk density, their interrelationships, and the magnitude of the sampling error components involved over a wide range of soil conditions. Data from approximately 10,000 individual core samples from about 900 sites in 7 states were analyzed. Mean values for hydraulic conductivity, percent large pores, and bulk density, when classified by textural groups, showed a consistent decrease in magnitude with increases in salt and clay content. Mean values for the three properties, when classified by great soil groups, showed consistent differences between groups. Correlations between hydraulic conductivity and percent large pores was positive and comparatively consistent; correlations between hydraulic conductivity and bulk density were negative and generally of a low absolute value. The indicated conclusion was that bulk density, in itself, is a poor indicator of soil permeability.

Variance components for among cores within sites and horizons, and between sites, after removal of all other classifiable variation, indicated that the between site component of the sampling error was 2 to 3 times larger than the one within site c omponent. These compone nts were used to estimate distinguishable permeability classes for various sampling schemes, and by assuming various cost ratios, optimum sampling rates were estimated.

McNeal and Coleman (140) in 1966 investigated the effect of solution composition on hydraulic conductivity. Decreases in hydraulic conductivity with decreasing electrolyte concentration and increasing sodium adsorption ration (SAR) of the percolating solution were assessed for seven soils of varying clay mineralogy. The soils commonly demonstrated rather pronounced hydraulic conductivity decreases in the exchangeable-sodium-percentage (ESP) range of 20 to 35 at salt concentrations of 3 to 50 meq/liter.

McNeal (141) in 1968 described a procedure for predicting the hydraulic conductivity of soils in the presence of mixed salt solutions, after first measuring the absolute hydraulic conductivity of the soil with a single high salt, high sodium solution, and then measuring the relative hydraulic conductivity of the same sample with a low salt solution. Calculated interlayer swelling values for soil montmorillonite served as a frame of reference for the predictions. Swelling values were obtained using a simplified domain model for characterizing the exchangeable cation distribution on Na-Ca montmorillonites. The effect of soil texture on relative hydraulic conductivity to mixed salt solutions appeared to be adequately accounted for through the interlayer swelling values used for the predictions.

McNeal et al. (142) in 1968 investigated into factors affecting hydraulic conductivity of soils in the presence of mixed salt solutions. In a group of soils having variable clay content but nearly uniform clay fraction mineralogy, relative hydraulic conductivity in the presence of mixed salt solutions decreased markedly with increasing clay content, particularly at the lowest salt concentrations employed. The stability of a group of soils under high sodium, low salt conditions was partly reduced by partial removal of the free iron-oxides.

McWhorter and Corey (143) in 1967 derived criteria of similitude for systems in which two immiscible fluids moved simultaneously through a porous medium. The similitude requirements were established by writing the combined equation of flow and scaling this with system parameters. The system parameters were selected so that the equation of flow in terms of scaled variables provided a maximum generality and indicated criteria which were the least restrictive and which could be satisfied with laboratory models. The unique feature of this statement of criteria of similitude was that similitude of the media was determined by the equivalence of a single dimensionless parameter associated with pore size distribution. The validity of the theory was demonstrated by experiments in which the behavior of similar models were compared.

Milanov (144) in 1969 described the neutron method for studying the soil moisture by means of a Danish apparatus. The report dealt with the measuring equipment, calibration technique, and sources of errors. The moisture probe was equipped with a 5 mC AC-Be neutron source, combined with a scintillation crystal of Lithium Iodide as detector. The maximum error for 160 measurements made by the moisture probe was found to be about 1%. The calibration was made in moisture model, consisting of fine sand mixed with a substance containing crystal water. Some soil moisture measurements in the field were presented.

Miller and Richard (145) in 1952 applied a technique for direct measurement of hydraulic head in rapidly changing systems to the infiltration of water into artificially packed columns of dry soil, including three California soils and a sample of silica flour. Results indicated that the transmitting zone in each soil was a region of relatively uniform hydraulic gradient which was greater than unity but decreased with time and might approach unity as a limit. At corresponding stages of infiltration, the magnitudes of the gradients in the transmitting zone differed for the various materials.

Miller and McMurdie (146) in 1953 studied field capacity in laboratory columns. It was shown that the material decrease in downward movement observed as soils approached field capacity could not be explained in terms of capillary conductivity alone. Instead, the combined effects of decreasing capillary conductivity in the drying zone, hysteresis and reduced hydraulic gradients at all levels were involved. The capillary conductivity of the drying zone was always greater than that of the wetting zone. Hysteresis effects, if present, ought to result in larger reductions in hydraulic gradient for an increment of water transfer than would occur without hysteresis. The hydraulic gradients at all levels ought to decline during drainage. Experimental evidence was presented which was in general agreement with expectations. Hysteresis effects were large, and the hydraulic gradients greatly diminished after 48 hours of drainage.

Miller and Miller (147) in 1955 described certain consequences of assuming that the classical differential equations of surface tension and viscous flow governed the behavior of liquids within the microscopic pores and channels of an unsaturated porous medium. These consequences appeared as macroscopic differential equations expressed in reduced variables and containing two time independent functions of pressure which exhibited hysteresis and were characteristic of the medium. This paper interpreted these equations in practical terms. Because of time independence, the term ∇k appearing in Richard's equation becomes $\frac{dk}{dp} \cdot \nabla p$, where k is the hydraulic conductivity and p is the pressure head. Accordingly, it was possible to solve for the conductivity and capacity functionals from experimental flow system data, provided the accuracy was sufficient for evaluation of required derivatives of pressure. The combination of reduced variables and time independence permitted scale modeling of flow systems. In a small scale model the time scale was shortened, while gravity must be increased by means of a centrifuge. One possible application was to laboratory measurement of field capacity.

Miller and Miller (148) in 1955 compared experimental results of other investigators on the theory of capillary flow. Kirkham and Feng (108) assembled data showing that linear diffusion theory predicted the time dependence but not the space dependence of water intake by horizontal columns of dry soil. Nonlinear diffusion theory as used by Klute covered both dependences. For this special case of horizontal wetting, the present theory, after change of variables, reduced to Klute's form. Description curves of Nelson and Baver for a series of sieved sand separated coalesce into a single reduced curve when reduced by the particle size factor. Time invariant hysteresis effects were characteristic of the present theory; other theories did not exhibit hysteresis properties. Published data showed that hysteresis was severe. Time invariance had been assumed by those reporting such measurements.

Miller and Gardner (149) in 1962 conducted a laboratory investigation of the effects of textural and structural stratification within the profile on rate of water infiltration into soil. A recording infiltrometer was devised and a method developed for obtaining uniformly packed tubes of soils. Infiltration data were used to test several infiltration equations. None of the solutions of equations seemed to fit the experimental data.

Miller, Biggar, and Nielsen (150) in 1965 investigated on how chloride, applied to the soil surface as KCl, moved through Panoche clay loam under field conditions. Three soil treatments were established: (a) continuous ponding, (b) intermittent ponding with 6 inches of water, and (c) intermittent ponding with 2 inches of water. Measurements of the chloride concentration in the soil solution at 1-foot depth intervals to a depth of 5 feet were used to ascertain the redistribution of the surface-applied chloride relative to the movement of soil water. The experiments revealed that chloride movement resulted from a dynamic process that might be altered or controlled with the method of water application.

Miller, Overman, and Peverly (151) in 1969 used the transient pressure transducer technique to test for threshold gradients in 9, 30, 40, and 50 weight percent montmorillonite and $< 2\mu$ and $2\text{-}20\mu$ size fraction kaolinite. Threshold gradients were not found in any of the samples tested.

Millington and Quirk (152) in 1959 studied the relation between water content and intrinsic permeability in porous media. An equation for intrinsic permeability was given which agreed closely with the data of Childs and Collis-George (35).

Mobasheri, Shahbazi, and Todd (153) in 1965 studied the lateral movement of water through the unsaturated zone of an unconfined aquifer. The investigation experimentally showed how the lateral flow through negative pressure region changed as the depth of this region increased. The results from the column tests indicated that the hydraulic conductivity decreased as the negative pressure of the porous media increased. The flow rate through unsaturated zone increased with a decreasing rate as the unsaturated zone depth increased while the hydraulic conductivity was kept constant. The rate of lateral flow movement could also be calculated to a reasonable accuracy from flow net diagrams or the graphical integration of the area under a characteristic curve.

Moore (154) in 1939 reported data on pressure potential and saturated and unsaturated permeability using six California soils. The rate of water flow required to maintain shallow water tables in cylindrical columns 8 inches in diameter, was measured in graduated supply buretts. Unsaturated flow was induced naturally; the water rose from the water table to the surface of the soil columns by capillarity, and was evaporated from the surface. Tensiometers were spaced at regular intervals on the vertical axis of the soil columns, and the pressure potential values were read directly on these instruments. When the rate of water uptake and the pressure potentials throughout a soil column became steady, that column was said to be at a steady state. Its moisture distribution was then determined by sampling, and its saturated and unsaturated permeability at various pressure potentials were determined from the velocity of flow and the total potential gradient.

Nelson (155) in 1966 presented a mathematical treatment of various flow equations in heterogeneous porous media. These equations included the relationship of flow velocity and equation of continuity.

Nielsen, Kirkham, and Van Wijk (156) calculated the theoretical moisture profiles from a numerical analysis and compared with experimental profiles for two field soils. After previously being wet to their field capacities, the soil surfaces were kept at saturation for a definite time interval. The distribution of soil water throughout the profiles immediately following this time interval was measured by neutron scattering. The numerical solution using series expansion was developed for a homogeneous porous medium.

Nielsen, Biggar, and Davidson (157) in 1962 reported an experimental investigation of the applicability of the diffusion equation to soil-water movement, using soils and sandstone with water and oil. The fluids were allowed to enter at different negative pressures into air-dry horizontal columns. Using Boltzmann transformation, solution to the equation was obtained and verified with the experimental data.

Nordum and Luthin (158) in 1968 developed a theory for transient drainage of porous media taking into consideration the air that was entrapped within the flow region. The theory was based on the soil moisture diffusion equation with modification made to include the effect of the entrapped air and the effect of changes in pressure due to barometric fluctuations. The model was tested for one-dimensional flow, and the results obtained from numeric solution compared well with the experimental data.

Ohmstede (159) in 1964 presented results of a program of numerical analysis of nonlinear partial differential equations which described unsteady soil moisture transfer. The results, when combined with experimental data, were intended for use in determining the soil moisture transfer characteristics of various types of soil. The results of this study indicated that linear theory was significantly inaccurate in representing unsaturated transient flow of water in soils of finite perturbations. On the other hand, the step-function transient outflow experiments performed for determination of the soil moisture transfer characteristics. The numerical solutions presented allowed all data obtained from the experiments to be used in characterizing the soil-water diffusivity over the full range of the step. If there is a significant membrane impendence, the determination of the soil-water diffusivity becomes more complex. Because of the limited number of solutions presented, practical determinations of the diffusivity require that the membrane impendence effects be minimized. This can be done by increasing the soil slab thickness, by decreasing the pressure step size, and by working at high matric suctions. It was concluded that the effects of gravity on laboratory transient outlfow experiments were negligible.

Overman (160) in 1968 applied the theory of convective diffusion to transport of salt through clay columns. An expression was derived for salt distribution within the column for steady-state conditions. Data from the literature were used to test the applicability of the distribution function to clay systems. The observed nonlinearity was described to high precision by the equation.

Peck and Rabbridge (161) in 1969 described an osmotic tensiometer which used a confined aqueous solution, instead of pure free water, as the reference state in measuring soil-water potentials. The membrane separating the confined solution from soil-water was highly impermeable to the confined solution (polyethylene glycol having molecular weight 20,000), but exchange of much smaller molecules and ions occurred. Thus, the capillary potential of soil-water was measured unless soil solutes were excluded from the instrument by a vapor gap. The advantage of this instrument over conventional tensiometers was that measurements of capillary potential could be made throughout the range 0-15.0 bar. Tests and observations showed that osmotic tensiometers could be used for measurements of capillary potential at depths greater than about 10.0 cm during the redistribution of soil-water, and its uptake by plants. For accurate data, zero checks should be made when possible, and instrument temperature should be recorded to enable correction for its effect on each reading.

Peck and Rabbidge (162) in 1969 developed a new technique for direct measurement of moisture potential over a wide range. The basis of the technique was that an osmotic solution was used to depress the zero of moisture potential in the measuring instrument by a known amount. Water was exchanged between the soil and the instrument through a semi-permeable membrane until an equilibrium of free energy of water was reached. The change of free energy within the instrument could be designed to be almost entirely a result of a change of pressure which actuated a pressure transducer. The instrument can be adapted to measure matric or total potential.

Peck (163) in 1969 described a method of deducing soil moisture diffusivities from laboratory outflow data. This method involved the matching of outflow data to a single theoretical curve regardless of the membrane conductance which need not be known *a priori*. The calculation of a diffusivity value from curve matching factors was an elementary process. As in other outflow analyses, this method involved an assumption of constant diffusivity over the range of moisture contents involved in a step. In order that the experiments should approximately satisfy this assumption, it is usual to use only small steps. Data obtained from some of the outflow experiments reported, wherein the diffusivity varied by up to an order of magnitude, matched the theoretical curve as well as small step data. Diffusivity deduced from these large step experiments agreed well with the integrated means of small step diffusivities. It appears that with the new analysis the use of large steps was reasonable provided that the membrane conductance was greater than the hydraulic conductivity of the test piece.

Philip (164) in 1955 presented a new iterative procedure for the numerical solution of the vertical flow equation in unsaturated porous media which was considered as a semi-infinite solid with simple conditions. Unlike the methods previously available, this procedure converges rapidly and each iterative step is simple. Essentially, the Boltzmann transformation was employed to reduce the one-dimensional partial differential equation into an ordinary differetnial equation. The errors of the method due to incomplete convergence and truncation were studied empirically.

Philip (165) in 1957 studied the theory of infiltration. One-dimensional equations for horizontal flow and for vertical flow were derived, numerical methods for their solution were provided, and an illustrative solution was given.

Philip and de Vries (166) in 1957 developed a theory of moisture movement in porous media under temperature gradients which explained apparently discordant experimental information, including (a) the large value of the apparent vapor transfer, (b) effect of moisture content on net moisture transfer, and (c) the transfer of latent heat by distillation. The theory predicted orders of magnitude and general behavior in satisfactory agreement with experimental facts. Equations describing moisture and heat transfer in porous media under combined moisture and temperature gradients were developed. Four moisture dependent diffusivities arising in this connection were briefly discussed.

Philip (167) in 1957 presented the movement of soil-moisture profile at infinity. The solution of the infiltration equation was approached from the entirely different angle of considering the character of the solution in the limit. Three statements of the infiltration equation were made as the diffusion equations in the moisture gradient, the flux, and the flux gradient. These statements enabled certain theorems about the moisture profile to be established. With the aid of these theorems, it was shown that as time increases without limit, the moisture profile during infiltration into a semi-infinite homogeneous column approaches a constant shape advancing down the column at a constant velocity. A numerical method for computing the profile at infinity and a numerical example were given.

Philip (168) in 1968 dealt with the unsaturated flow in porous media set up by prolonged infiltration into regions with no shallow ambient water table. With hydraulic conductivity represented by an exponential function of moisture potential, the nonlinear equation for steady flow was transformed into a linear equation which was equivalent to that of diffusion of a moving boundary. The point source solution was explored and used as the basis of an analysis of steady infiltration from spherical cavities. For cavities of small radius, the infiltration rate was determined by capillary, while gravity distorted the moisture distribution.

Philip (169) in 1969 introduced a linearization technique for the solution of nonlinear problems in infiltration and other problems of water movement in unsaturated soils. The method consisted, essentially, in matching exactly linear and nonlinear solutions at small times, and in matching the solutions in some integral sense at large times. The method was worked out for one-dimensional infiltration. It was shown to yield results agreeing closely with the exact nonlinear solution and to provide algebraic infiltration equations equally valid for small and large times. The parallel use of similarity solutions provided a good method of approximate analysis. For one-dimensional infiltration, the similarity solution agreed well with the linear solution.

Philip (170) in 1969 described the problems of two-dimensional infiltration from a semi-circular furrow and three-dimensional infiltration from a semi-spherical cavity. The latter problem conserves the principal elements of the problem of infiltration from a shallow ring infiltrometer. The paper began by examining the problems of absorption in two-and three-dimensional radial systems from furrows or cavities of finite radius. Exact series solutions of these nonlinear problems were found which were appropriate for small times. For the three-dimensional case a steady large time solution was evaluated. The corresponding linear and delta function solutions were found; they agreed well with the exact solutions. These various results supported the author's argument that previous attempts to apply the Boltzmann transformation to this group of problems were erroneous.

The corresponding infiltration problems were formulated and the linear solution developed. It was shown that the wetting region for both two and three dimensions was finite no matter how great the time and the final steady-state infiltration rates depended not only on the hydraulic conductivity, but also on the capillary properties of the soil. The influence of gravity in distorting the pattern of wetting decreased as the radius of the cavity or furrow decreased, and it was very much less in three dimensions than in two.

Polubarinova-Kochina, Penkovsky, and Rybakova (171) in 1969 considered problems of ground water filtration. Mathematical treatment of some cases of filtration, such as the effluent to drains in the presence of initial gradients, vertical filtration, and lateral washing problem, was presented. Also, equations for movement of salt in saturated soils, that is, for salt accumulation in soils caused by ground water evaporation and for salt dissolving and salinized soil washing at large values of the Pecks's criterion, were discussed.

Parlange (172) in 1971 developed an approximate expression for the solution of the equation for horizontal absorption of water in one dimension. Numerical comparisons showed that the solution was simple to apply and accurate for actual soils.

Parlange (173) in 1971 investigated on the theory of water movement in soils for one-dimensional infiltration. An analytic representation was derived for the solution of the infiltration equation, valid for all times. For short times, the solution reduced to that of the absorption equation. For very long times, it was shown rigorously that an asymptotic form of the solution existed and agreed with the "profile at infinity" of Philip (167), except in the high water content region. The difficulties encountered with the "profile at infinity" near the surface of the soil did not appear in the present asymptotic solution. Finally, the analytic solution and Philip's numerical solution were in complete numerical agreement for finite times.

Parlange (174) in 1971 presented analytic expressions, which were valid for all times, for the movement of water without gravity in two and three dimensions. For very short times, the expressions reduced to the solution of the absorption equation in one dimension. For moderate times, they were numerically equivalent to the series solution of Philip (170). For very long times, the asymptotic form of the solution depended strongly on the dimensionality of the problem. In three dimensions, the exact steady-state solution was approached as time increased. In two dimensions and for arbitrary diffusivity the solution approached an exact asymptotic limit, which had not been derived previously.

Raats and Klute (175) in 1968 discussed the mechanics of the fluid phase of a soil on the basis of a balance of momentum of each phase. Saturated as well as unsaturated soils were considered. It was shown that with certain assumptions the balance of momentum for a fluid phase reduced to Darcy's law. The meaning and some possible generalizations of the various assumptions were considered. The form of Darcy's law appropriate to soils whose solid phase undergoes a deformation was deduced.

Raats (176) in 1969 presented a theoretical analysis of steady gravitational convection from a line source of salt in a saturated or in a partially saturated soil. The flow pattern of the water-solute mixture and the distribution of the salt were shown to depend upon the source strength of the line source, the effective mass diffusion coefficient of the salt in the soil, the hydraulic conductivity of the soil, and a parameter describing the increase in density due to the added solute. Qualitatively, the analysis agreed well with experimental observations. Theory and experiment both indicated that gravitational convection can be significant only if the hydraulic conductivity is large, which may be the case if the soil is coarse textured and the water content is not too small.

Rawlins and Gardner (177) tested the validity of the diffusion equation for unsaturated flow of soil water. The derivation of the diffusion equation from the potential equation for unsaturated flow of liquids in porous materials revealed that the only additional assumption required was that diffusivity was a unique function of water content. The validity of this assumption was tested by following absorption of water into a horizontal column of soil by a gamma ray densitometer. Diffusivity versus water content curves from experimental data indicated that diffusivity is not a function of water content alone.

Reisenauer (178) in 1963 described a computer program for solving steady-state Darcian transport of fluid in heterogeneous, partially saturated, porous media. The program was capable of handling one, two and three dimensional axisymmetrical problems with up to 8000 grid points. Instability of the equations and its control were discussed.

Remson et al.(179) in 1965 described the nonlinear equation for vertical flow in unsaturated soil. Numerical approximations were developed for the case in which moisture contents were specified at the top and bottom of the soil and for the case of zero moisture flux across the soil surface. The computer programs were presented.

The equation was solved for a 400 cm thick well-drained unsaturated zone draining to the water table from an initial condition of saturation and evaporating from an unvegetated surface. The drainage rates decreased rapidly with moisture content, and the effects of evaporation decreased rapidly with depth. As a consequence, the intermediate zone might be taken at field capacity for purposes of approximation during times of small evapotranspiration and intermittent penetrating rainfall. The equation was applied to the movement of infiltrated rainfall. The solution verified the field data, showing that percolating rainfall moved as a pulse with a steep wetting front.

The unsaturated flow equation was solved for a 23 cm thick belt of soil water draining from an initial condition of saturation, without evapotranspiration, to an intermediate belt as field capacity. The belt of soil water drained approximately to field capacity within 2 days. It was assumed that drainage from the belt of soil water proceeds until this relatively stable state is achieved if no transfer of moisture occurs across the surface. Soil moisture losses in excess of those caused by this relatively rapid drainage occurred mainly by evapotranspiration.

Richards (180) in 1931 derived the equation for the capillary conduction of liquids in porous media. Data were presented and application of the equation was made to study the movement of water through unsaturated soil and clay. The possible existence of a hysteresis effect between the capillary potential and moisture content of a porous medium was considered.

Richards (181) in 1954 described an instrument for measuring the hydraulic head and hydraulic gradient of water in unsaturated field soil. Porous ceramic sections were mounted between plastic spacers to make a rod-shaped instrument for insertion in a hole made by the Standard Veihmeyer soil sampling tube. Five porous sections with a vertical spacing of 10 cm were thus arranged with individual connections to mercury manometers mounted at the top of the assembly.

During infiltration, after 44 cm of water had entered a deep, uniform, fine sandy loam, the downward hydraulic gradient averaged 1.3 in the 10-30 cm depth interval. This would correspond to a downward water-moving force of 1.3 g. Six days later, a few hours after a 1 cm rain, the average downward water-moving force in the same depth interval was 5 g. Four days after the rain, there was a net upward water-moving force of 36 g in the 10-20 cm depth interval, due to the influence of surface evaporation. A much higher value existed in the 0-10 cm layer because of the greater moisture gradient near the soil surface.

The term static zone was used in connection with the soil-water system to designate the locus of points above which water movement was upward, and below which water movement was downward. A static zone passed through fallow soil following wetting. Over a four-day period of warm, dry weather following a heavy irrigation, the static zone passed downward at an average rate of 6 cm per day in a fallow fine sandy loam.

Richards and Moore (182) in 1952 discussed the storage of moisture in soil in the field and explained in terms of the dynamic moisture-transmitting properties of the soil. Published data on capillary conductivity were summarized and additional new data for six soils were presented, along with a new pressure type apparatus for measuring capillary conductivity. A laboratory procedure was used for estimating field capacity that consisted in measuring the moisture content of a mass of soil which had been wetted and allowed to stand a specified time in contact with dry soil. The dependence of this method on the depth of wetting was illustrated by laboratory tests on three soils and the explanation for this dependence appeared to lie in the fact that the capillary conductivity of soils remained appreciable over a considerable range of moisture content below field capacity.

Richards and Richards (183) in 1962 presented the solution of the radial-flow equation for the appropriate boundary conditions. The radial-flow cell was developed and shown to be useful for measuring retentivity, specific capacity, diffusivity, and conductivity of soils.

Rogowski (184) in 1971 proposed a procedure by which reasonable estimates of the soil moisture characteristic can be obtained when a reliable curve is not available. Moisture content and pressure at air entry and at 15 bars constituted the required input parameters. The parameters were easily determined and at times could be readily abstracted from literature or estimated from published data. Applicability of the model was tested on graded sand and eight soils.

Rose (185) in 1969 investigated on water transport in soils by evaporation and infiltration. The equation of vertical flow was adapted to describe the evaporation of water from, and the uptake of water by, a deep uniform soil free from vegetation. The theory was examined by laboratory measurements in long columns having 0.5-1.0 mm size of three soils from Rothamsted and Woburn, England. Evaporation from soil initially at a uniform moisture content decreased as the square root of time and caused moisture profiles invariant with $zt^{-1/2}$ (where z = depth below soil surface and t = time), which differed for each soil. Drying diffusivities calculated from these profiles had an unusual shape, decreasing to a minimum and then increasing as the moisture content fall from field capacity to air-dryness. The uptake of water treated in the same way yielded wetting diffusivities which also displayed a prominent minimum as moisture content increased from air-dryness to field capacity. The shape of these diffusivity-moisture content relations was discussed, and the concept of sorptivity adapted to yield a parameter specifying the water supplying power of a soil when evaporation was limited by soil moisture.

Rubin and Steinhardt (186) in 1963 analyzed soil moisture content changes and rates of water entry during rain infiltration into a semi-infinite soil column. The model considered involved the following assumptions: Darcy's and continuity equations are applicable; the hydraulic conductivity and diffusivity of soils are unique, positive and monotonically increasing functions of soil moisture content; and rainfall entering the soil can be considered as a continuous body of water.

It was shown analytically that an incessant rain eventually resulted in ponding if and only if rain intensity R exceeded the saturated hydraulic conductivity of a soil, K_w. For $R \leq K_w$ it was proved that as infiltration proceeded, soil moisture contents at increasing depths tended to approach a constant level. At this level the hydraulic conductivity of soil equaled the rainfall intensity. For $R > K_w$ it was indicated how to estimate the water uptake at incipient ponding. A different scheme for one-dimensional diffusion equation was described. A numerical example was also presented.

Rubin (187) in 1967 presented the vertical flow equation in unsaturated soils and devised a numerical procedure to analyze the post-infiltration redistribution of water in semi-infinite, vertical soil columns. The method considered the effects of hysteresis by making it possible to find, within the hysteretic system of curves, the unique curve which characterized moisture transformations at each soil depth. The results obtained by applying the method to data on moisture retention and conductivity of a sandy soil demonstrated the importance of hysteresis in the redistribution processes.

Rubin (188) in 1968 solved the Darcian flow equation for two-dimensional, transient transfer of water in rectangular, unsaturated and partly unsaturated soil slabs numerically with the aid of alternating-direction implicit difference scheme. Two alternative processes were considered predominantly horizontal infiltration and ditch drainage. The results obtained for the horizontal infiltration process indicated that it involved upward flow-components which are primarily due to a gravity-induced variation in hydraulic conductivity along the inflow face. The drainage case results demonstrated that transient water flow within the unsaturated zone and the outflow from the seepage zone may significantly affect the water table descent and the total outflow rates.

Rubin (189) in 1969 studied the preponding and ponded stages of rainfall infiltration by solving numerically the partial differential equation of downward moisture flow in unsaturated soils. The method was used for computing moisture content and pressure head profiles during preponding and ponded rainfall infiltration as well as the theoretically expected rainfall infiltration rates. The dependence of the profiles and rates upon rain intensity was studied.

Russel (190) in 1946 presented the results of an experiment on the movement of water downward in confined 6-foot soil columns of undisturbed structure. The infiltration curves from the beginning of application of water until percolation began at the bottom and the percolation curves for an extended period thereafter were shown. Data on the degree to which the columns had become saturated at the end of the period of wetting were presented. A formula was developed for the percolation of a heterogeneous column which involved the percolation coefficients of all the layers that comprised it; data was given to illustrate the validity of this formula. The application to problems of impervious layers within the profile or at the surface were discussed.

Sabey (191) in 1969 studied the influence of soil moisture tension on nitrate accumulation in limed, silt loam, and loessial derived soils to which a non-limiting source of NH_4^+ -N was added. This was done by saturating the soils in an NH_4^+ solution, then subjecting the samples to 0.0, 0.1, 0.33, 1.0, 5.0, and 15.0 bars of soil moisture tension in conventional positive pressure equipment, and incubating the samples in a saturated atmosphere for varying intervals, to characterize the NO_3^- -N accumulation curve with time. The maximum slope of the line gave an estimate of the value of K_m, i.e., maximum rate of NO_3^- -N accumulation in ppm/day. The K_m values in all soils were greatest at 0.1 bar tension, with K_m values decreasing as soil moisture tension increased or decreased. The relative rates of NO_3^- -N accumulation, R_m values, i.e., moisture rate indexes, varied much less than K_m values among soils. An empirical equation was proposed to estimate NO_3^- -N accumulation in soils under varying conditions of temperature and soil moisture tension.

Sagi (192) in 1969 conducted experiments on infiltration. Infiltration into the soil from summer rains was determined on levelled plots of meadow clay soil, 154.0 m by 21.5 m in area, under agricultural cultivation. A close relationship was demonstrated between infiltration and rainfall intensity, amount of rainfall, and initial soil moisture.

Scott and Corey (193) in 1961 derived a differential equation which described the pressure distribution during steady flow in a porous medium occupied by two immiscible fluids such as air and water. It was assumed that Darcy's equation was valid simultaneously to the wetting and nonwetting phases. Each phase was assumed to be continuous. In order to solve the equation, it was necessary to know the relationship between the pressure discontinuity across interfaces between the phases and the conductivity of the flowing phase. Experiments were conducted using a hydrocarbon liquid as the wetting fluid, air as the nonwetting fluid, and long columns of sand as porous media. Several cases were considered, and results of two cases were presented: (a) downward flow through a uniform sand, and (b) downward flow through a sand into another sand of finer texture. Good agreement between experimental data and theory was obtained for all cases.

Scott and Hanks (194) in 1962 used the diffusion equation to describe the flow of water in unsaturated soils for horizontal, one-dimensional case flow. A method for solving the equation for exponential and linear diffusivity functions by power series was devised. Results were shown for horizontal infiltration and outflow in semi-infinite systems for both functions. Equations for computing flux and cumulative water flow were given. Comparisons of the two diffusivity functions, for similar water contents at the boundaries, revealed greater flux for the linear diffusivity functions for infiltration and outflow. The difference was greatest for outflow.

Sine and Bentz (195) in 1969 studied the systematic measurement of diffusivity at low tensions and discussed differences between the theory and experiments. It was reported that the flow through the porous plate might be higher than the value calculated from theory, that the obtained value of the diffusivity was a function of the height of the sample, and that the discharge at the lower boundary of the sample did not at all correspond with the moisture profile predicted by theory. Using gamma-ray equipment for the measurement of the moisture content, the development of the moisture profile in samples of 15 cm height was observed. The deviation between theory and experiments also appeared to exist during a study of moisture profile above a water table.

Singh and Franzini (196) in 1967 obtained a solution to the two-dimensional diffusion equation for unsteady and unsaturated flow in soils. The physical problem was that of flow from a cylindrical source of finite radius and infinite length. Neglecting gravity, the diffusion equation was reduced to a simple form which could be transformed to a nonlinear ordinary differential equation. This transformation was achieved after substituting an empirical relation for the diffusivity of the soil. The ordinary differential equation was then solved by numerical techniques. Two soils, Yolo light clay and Pachappa loam, had been used for examples. Infiltration rates were computed in each case; these were found to be almost constant for this problem. A computer model was presented.

Singh (197) in 1970 presented an approximate solution for one-dimensional equation for flow in unsaturated porous media by the method of weighted residuals. The solution consisted of a polynomial variable in space that had its coefficients as unknown function of time, to be determined from the conditions and by satisfying the equation over the range of space variable. This procedure accepted any kind of diffusivity function including numerical values obtained from experiments.

Smerdon (198) in 1963 presented experimental data on subsurface water distribution from both level and graded irrigation furrows. The data were reduced to dimensionless form for analysis, and empirical equations were presented describing the subsurface wetting patterns. The uniformity of application along an irrigation run was shown to be dependent on both the infiltration equation of the soil and the speed at which the wetting front transversed the irrigation run. A chart was included, relating the uniformity of water application to the infiltration characteristics and the ratio of the time needed for the water to transverse the run to the time needed for the average water application to infiltration.

Srinilta, Nielsen, and Kirkham (199) in 1969 analyzed a laboratory study of water moving steadily through an isothermal two-layer soil by using Darcy's law for unsaturated flow. Factors considered were thickness and kinds of top soil and subsoil, depth of surface water ponding, magnitude of outflow water pressure, and soil-water history of the profile. Soil-water pressure distributions were measured at 5 cm depth intervals along the vertical columns. The unsaturated hydraulic conductivity was measured for sorption and desorption for each of four soils. Values of hydraulic conductivity as a function of soil-water pressure were used to predict the measured soil-water pressure distributions and steady-state fluxes.

Staple (200) in 1966 used a numerical method to compute infiltration and redistribution of water in vertical columns of air-dray Grenville silt loam. Hysteresis was taken into account in that drying tensions and hydraulic conductivities were interpolated from the appropriate scanning curves at each depth in the upper profile as redistribution continued into the dry soil below. Although the computations were not confirmed by independent experiments, results from related measurements showed that the distribution curves were of right magnitude. The moisture contents reached redistribution in the drying zone after 24 to 72 hours, were in agreement with field capacity data. The explicit finite difference scheme for vertical flow was utilized to solve one-dimensional partial differential equation. Computed moisture contents following redistribution in which hysteresis in both tension and conductivity were neglected differed considerably from the accepted hysteresis-dependent values. Computed moisture contents in which hysteresis in conductivities only were neglected were closer to the accepted values when conductivities for wetting were used.

Staple (201) in 1969 measured redistribution of water in three soils following two different initial amounts of infiltration. The measured redistribution profiles were compared with those computed from the flow equation taking into account hysteresis in the drying tension versus water content relationship. Agreement between measured and computed moisture profiles was considered satisfactory. A procedure was outlined for determining wetting diffusivities and conductivities in the wetting front on the basis of soil moisture profiles obtained during redistribution. The different shapes of the drying scanning tension curves provided some insight into the differences in particle size distribution that influenced the water-holding capacity of soils.

Staples and Lehane (202) in 1954 studied movement of moisture in unsaturated soils. Samples taken at different time intervals during the redistribution of moisture in cylinders of soil were used to determine liquid and vapor movement. Mean values of capillary conductivity were presented for Wool Mountain clay loam with apparent specific gravities 1.21, 1.28 and 1.33 and moisture contents 12 to 27 percent. By converting conductivity to diffusivity, that is, to percent moisture conducted into a 1-inch section of soil per day under a gradient of 1 percent moisture per section, coefficients for liquid and vapor movement were plotted as a continuous function of moisture content. Movement in the vapor phase was a little lower than that calculated from vapor pressure data. The results were used to illustrate a numerical method for calculating soil moisture movement.

Stone, Kirkham, and Read (203) constructed and used a portable, battery-powered device for measurement of soil-moisture by neutron scattering. The equipment, aside from being portable, differed from previously reported devices of this type as follows: (a) A fast neutron source in the form of an annulus was placed about the center of a slow neutron detecting tube; (b) Recently developed glow transfer tubes were used for absolute neutron count determinations; (c) A calibrating volume of paraffin, which was also used as a neutron shield, was incorporated as a part of the source-detector carrying case, to permit simple field checking and standardization of the device. The detector tube was partially shielded with cadmium to reduce the vertical extent of the soil sample contributing to the neutron count. Field data were presented. It was found, by locating the source-dectector at various depths in pipes sunk vertically into the soil, that except for the surface 6.0 to 9.0 inches the equipment generally gave the soil moisture per unit soil bulk volume, within the range of the standard deviation of gravimetric determinations. A single calibration curve served for all soil tested (sand, silt loam, and silty clay loam). The equipment, complete with batteries, lead and paraffin shielding, weighed 45 pounds. The shielding protected the operator against radiation hazard and was sufficient for at least 8 hours per day use, 6 days a week.

Stone, Shaw, and Kirkham (204) in 1960 used the neutron device to study the movement of water in unsaturated materials. The performance of neutron device at a location was evaluated in the laboratory and in the field. Observed coefficients of variation for laboratory and field were about 1.5% to 2.5%. Random counting error component accounted for most of this percentage. In comparing gravimetric sampling with neutron measurements at the same locations, a rather poor agreement was observed within locations, but overall average difference in moisture was less than 0.1 inch of water per 6 inch soil depth. Poor individual agreement was believed to be due to limitations of bulk density determination and not to the neutron device. A comparison of the relative ability of the gravimetric and neutron methods to evaluate moisture in a set of plots where sampling locations were randomized indicated that use of seven gravimetric sites for each neutron site gave a comparable standard error of the mean.

Swartzendruber and Huberty (205) in 1958 compared the use of infiltration equations parameters to evaluate infiltration differences in the field. The infiltration equations $y = A\,t^B$ and $\frac{dy}{dt} = a + \frac{b}{y}$ were discussed, in which y is the quantity of water that will enter a soil when water is applied to the surface, and t is the time. In this investigation, the constants A, B, a, and b were considered for their usefulness in characterizing infiltration in field basins on Green field loamy sand, a deep soil without profile development. The product parameter AB was compared with a parameter R_t which was simply the average rate over the first two hours of infiltration. The results showed AB to be 40% better statistically than R_t.

Swartzendruber (206) in 1960 analyzed water movement through a water-saturated soil profile on the basis of Darcy's law for a sectionally continuous hydraulic conductivity along a one-dimensional, downward flow path. The resulting relationships were used to assess the effect of the least permeable layer on the flow through the profile. It was shown that the hydraulic conductivity of the least permeable layer did not of itself control the flow. A second analysis, based on the hydraulic resistance which may be defined as the ratio of the thickness of porous column to the area of cross section and hydraulic conductivity, showed that the hydraulic resistance of the least permeable layer controlled the flow through the profile with much less error than did the hydraulic conductivity. Furthermore, the error became negligible as the hydraulic resistance of the least permeable layer increased.

Swartzendruber and Olson (207) in 1961 studied infiltration of water for a wedge-shaped sand model built as a sectorial portion of the double-ring infiltrometer flow system. Determinations of infiltration velocity for localized portions of the flooded sand surface permitted the assessment of buffer effects. At a given time after infiltration has commenced, the velocity was essentially constant over a rather large central portion of the flooded area, but increased sharply as the outer ring radius, r_n, was closely approached. However, the essentially invariant central velocity could not be taken as the one-dimensional velocity, or infiltration rate, unless r_n was sufficiently large; in this study, the smallest permissible value for r_n was 12 inches. For $r_n=8.0$ inches, which corresponds approximately to many of the ring systems used heretofore, the essentially invariant central velocity was as much as double the infiltration rate.

Swartzendruber and Olson (208) in 1961 extended model studies of the double-ring infiltrometer to include the effects of finer texture and the depth of the wet front. Both factors had a tendency to cause the infiltration velocity measured by the inner ring to overestimate the one-dimensional velocity, or infiltration rate. An exception was noted for small outer-ring radii, but in this case there was other evidence to indicate that the central portion of the double-ring flow system was quite different from a one-dimensional system. The present study showed that large ring systems were desirable. Specifically, an inner ring of 40 inch diameter within an outer ring of 48 inch diameter was found adequate for all conditions considered.

Swartzendruber (209) calculated corresponding values of flow velocity and moisture gradient for water flow in unsaturated soil, using a graphical analysis of moisture profiles obtained during horizontal absorption of water into air-dry Salkum silty clay loam. Plots of flow velocity versus moisture gradient were straight lines through the origin at the higher moisture contents, but Darcy proportionality did not hold at the lower moisture contents. Physically, the non-Darcy behavior was tentatively attributed to non-Newtonian liquid effects caused by clay-water interaction. Consideration of diffusion-type analysis from the standpoint of non-Darcy behavior showed that the diffusivity, D, became a function of moisture gradient, W, as well as moisture content, θ. This accounted for the non-uniqueness of $D(\theta)$.

Swartzendruber (210) in 1966 derived solution of the nonlinear diffusion-type equation, using both an additive form and a product form of separation of variables. The problem considered was a one-dimensional, horizontal, and semi-infinite. The curves of water content ratio θ/θ_n versus $\frac{x}{\sqrt{D_o t}}$ for two values of D_o/D_n, computed from Philip's solution and Kobayashi's equation; in which θ is moisture content, θ_n is moisture content at t=o and x >o, D_o is diffusuvity at t > o and x=o, and D_n is diffusivity at t=o and x >o.

Sylvester and Seabloom (211) in 1963 discussed the water quality changes in irrigation return flow. Marked changes occurred between the quality of irrigation water applied to the land and the residual water draining from the land as return flow to the parent stream. These water quality changes were attributed to evapotranspiration, leaching, ion exchange, filtration, erosion, biochemical action, heat transfer, and possible precipitation of salts. To illustrate field techniques and data obtained, a study on irrigation return flow quality in the Yakima River Valley of Washington was presented together with a comparison of the impact on Yakima River water quality by irrigation return flows and municipal and industrial water waste discharges. In the lower Yakima River, approximately 56% of the river salt content was contributed by irrigation return flows primarily from the process of leaching.

Takagi (212) in 1959 analyzed the vertical downward flow of water through a two-layered soil on the basis of the general theory of unsaturated flow. The purpose of this paper was to present the essential features of the phenomenon that must be tested later from experiments based on some appropriate assumptions; the assumptions were reviewed but not examined.

Task Force on Use of Neutron Meters (213) in 1964 presented the results of a survey on the use of neutron scatter devices in soil moisture measurement. Information on applications of the radioactive method and equipment, its effectiveness, and the gamma-ray scattering devices used for determination of soil density and soil moisture were obtained. The portable nuclear equipment was reported to provide a simple, rapid and effective means of measuring soil moisture and density at depth and at the surface. Equipment malfunction problems were overcome to the point that reliable operation could be expected. The general principles, equipment available, and the variety of applications in hydrologic studies, construction, and agriculture, were reviewed together with a summary of advantages, disadvantages and problems.

Taylor and Cary (214) in 1964 considered theory for setting up interrelated equations describing the transport of one or more components through soil. Darcy's law and the diffusion equation were shown to be components of this general development. Particular attention was given to the non-isothermal flow of moisture and energy through soil. A general relation between the fluxes induced by the combined gradients of moisture content, temperature, and solutes was also suggested.

Taylor and Cavazza (215) in 1956 used an air gap technique to evaluate the movement of soil moisture in response to temperature gradient, and showed that the flow of moisture in the soil from warm to cool regions might largely be in the vapor phase. This was accompanied by a return flow of liquid water due to an induced flow potential gradient. The measured diffusion coefficient for vapor flow was higher than had been expected from diffusion data, but was substantially in agreement with that of other investigators. The reasons for high diffusion coefficient might be that the diffusion of moisture and heat was coupled in soils; the phenomena of surface migration and molecular hopping of adsorbed water might also cause this increase. The factors having greatest effect on the moisture distribution in continuous soil columns in a closed system are: (1) the diffusion and the convection of vapor or some related processes; (2) the evaporation and condensation occurring in the two end regions of the cylinders; and (3) the hydraulic conductivity of the soil. The existence of two distinct drying and wetting moisture characteristic curves were verified, and they played an important part in determining the liquid flow of moisture in the soil.

Taylor and Heuser (216) in 1953 reported progress made in measuring and evaluating the components of the equation of vertical flows in unsaturated porous media for undisturbed soil cores. Six undisturbed cores 10 cm in diameter and 120 cm long and containing different amounts of water were used. Water was allowed to enter the core under a constant head of 1.2 cm. The quantity of water that accumulated in the soil and the depth to the wetting front were measured as function of time. The soil moisture potential was measured at 5 cm intervals of depth and at various time intervals. From these measurements infiltration rates, moisture potential gradients, and apparent moisture conductivities were calculated. Moisture conductivity was calculated from the moisture retention curve. The results indicated that the infiltration rate depended primarily on the gradient of the moisture potential and had secondary dependence on the capillary conductivity. Potential gradients in the wetting zone and across the wetting front might be much greater than in the transmission zone and they appeared to be a principal factor in determining infiltration rates. Potential gradients were measured and used to calculate apparent capillary conductivity values which were always smaller than infiltration rates. As a result of large potential gradients, the infiltration rates exceeded the saturated permeability in five of the six cores studies.

Taylor and Luthin (217) in 1969 analyzed the drawdown in a pumped unconfined aquifer by computer methods. A finite difference scheme was developed for transient flow in a two-dimensional aquifer. The simulation model could predict the flow in saturated and unsaturated zones.

Terkeltoub and Babcock (218) in 1971 devised a simple model of salt movement through a soil profile with uniform initial salinity and moisture content. The parameters required were the initial soil salinity, the initial and one-third atmosphere soil moisture contents, and the salinity of the irrigation water. The model provided satisfactory approximations of the salt distributions resulting from the irrigation of both fine- and coarse-textured soil columns, regardless of the initial soil moisture content, initial soil salinity, and the salinity of the irrigation water.

Thames and Evans (219) in 1968 reported an experimental investigation for vertical infiltration of water into a sandy loam and silt loam soil. Water was allowed to enter air-dry columns of soil at a small constant suction head, and its subsequent distribution was followed with gamma radiation attenuation device. An empirical equation based on experimental data was developed from regression analysis by modifying the diffusivity equation for unsaturated flow.

Todd (220) in 1959 described the physics of ground water movement in saturated and unsaturated porous media. The discusssion on flow across a water table, flow across a boundary of permeability, flow across layers of coarse and fine sand, and formulas for hydraulic conductivity was presented.

Toksoz, Kirkham, and Baumann (221) studied two-dimensional infiltration under field conditions by simulating, in the field, a part of a waste recharge absorption trench by a simple 30 cm wide, open trench, the bottom of which was maintained ponded with a thin layer of water applied at the rate needed. It was observed that the curves produced by the advancing front were smooth and rather regular. An empirical relation from regression analysis for one-dimensional infiltration was presented to predict the vertical distance of wetting front in time.

Topp (222) in 1969 measured soil-water hysteresis in a sandy loam and compared it with the hysteretic domain model. A uniformly packed column of sandy loam soil was subjected to a controlled series of wetting and drying changes. Soil water contents were obtained from gamma-ray attenuation information while simultaneous tensiometer pressures at five locations along the column were measured by a pressure transducer. In addition, the flows of the water solution to and from the column were read in burettes. The data from the tensiometers demonstrated a high degree of uniformity throughout the soil. Analysis of the primary scanning curves of the water content versus pressure head showed that the independent domain theory of hysteresis was an adequate model for both wetting and drying curves. A refinement to the theory could not be tested with these data. Following consolidation during the initial drying phase, there was no measureable hysteresis in the water content-hydraulic conductivity relationship.

Tyagi (223) in 1971 investigated on the dynamics of the transition zone between fresh and salt waters in coastal aquifers. The subject was treated both as a hydrologic phenomenon and as a dispersion phenomenon by seasonal variation in flow in the aquifer and by tidal fluctuation near the coast line. Mathematical models for different interfacial regimes, including the effects of density and viscosity of the sea water and fresh water, were developed and graphically represented. An analysis for the longitudinal and lateral dispersion in saturated aquifers was presented considering various parameters that govern the dispersion phenomena. Using the longitudinal and lateral dispersion coefficients as well as the velocity field in the aquifer, the finite element method was utilized to solve the dispersion equation. The water quality on space and time basis was predicted, superposing the effect of dispersion on various interfacial regimes in coastal aquifers under varying hydrologic condition and tidal oscillations.

Tyagi and Todd (224) in 1971 investigated on dispersion of pollutants in saturated porous media. In order to define the dispersion phenomena, the coefficients of longitudinal and transverse dispersion must be evaluated. Relationships for the two coefficients under specific boundary conditions were presented. Since the variables characterizing the properties of fluid, porous medium, and tracer influence the dispersion of a pollutant, two dimensionless parameters - the inverse Schmidt number and the molecular Peclet number - were obtained. Using these parameters, the experimental data on longitudinal and transverse dispersion were analyzed over a wide range of the flow velocity, grain size, and molecular diffusion of tracer; good comparisons were obtained between observed and predicted coefficients of dispersion.

Tyagi (225) in 1971 discussed the problem of water quality in a coastal aquifer and some aspects of ground water basin development. The importance and occurrence of intrusion of salt water were described in a specific region of northwestern Mexico. Various components, such as the equation of hydrologic equilibrium, data collection for basin investigation, methods of computing safe yield, and conjunctive use of surface and ground water, were presented. Such factors must be considered while evaluating the quality and the amount of water supply available for domestic, industrial, and irrigation uses.

Tyagi (226) in 1971 made several recommendations with regard to the modeling of sea water intrusion in Hermosillo coastal aquifer in northwestern Mexico. A procedure was described through which the water quality could be predicted in the aquifer on a space and time basis. The data required for this analysis were also given.

Vachaud (227) in 1967 suggested a method for checking the validity of the generalized Darcy's law and for computing the values of the hydraulic conductivity at various water contents, from analysis of the water profiles obtained by gamma-ray absorption during infiltration into soil columns. Tests were made for horizontal infiltration and for capillary rise. In both tests, for a given water content, the capillary conductivity was constant, and the generalized Darcy's law was valid and used to describe a transient flow in unsaturated soils.

By analysis of both the moisture profiles, obtained by gamma-ray absorption during an infiltration in a soil column, and the wetting branch of the hydraulic pressure curve, Vachaud (228) in 1969 suggested a method of checking the validity of generalized Darcy's law and obtaining capillary conductivity. At any time t, for each value of the moisture content, θ, the flow velocity q was computed from the moisture profiles by integration of the continuity equation. The capillary gradients $\frac{\partial \Psi}{\partial x}$ were obtained by substituting capillary profiles to moisture profiles. Plotting for a given θ, the corresponding values of q versus $\frac{\partial \Psi}{\partial x}$, and establishing that a linear relationship existed, satisfying Darcy's law; $q = -k(\theta)$. The slope was the value of the capillary conductivity $k(\theta)$.

Vachaud (229) in 1969 conducted experiments on horizontal infiltration. The moisture profiles at the end of an infiltration in a horizontal soil column were measured by gamma-ray absorption. During the redistribution, three different zones in the columns were observed. In the first zone, near the surface the flow was uniform drainage; in the second zone, a wetting process followed by drainage; and in the third one, the flow was a uniform wetting, in the experimental column. Using both drainage and wetting branches of the capillary pressure curves, and analyzing the limit between the wetting and drainage flows in the column, a method of computing the capillary pressure, inside the hysteresis loop, for each point of the column and at any time during the redistribution was suggested.

Vachaud and Thony (230) in 1971 obtained experimental results dealing with flow processes involving hysteresis effects in the water content-pressure relationship. In a vertical column of soil, the following conditions were considered: (a) redistribution of water following a constant head infiltration in an initially air-dried column, and (b) constant head infiltration followed by controlled evaporation and redistribution. Water contents were measured by using gamma-ray attenuation. Examination of the changes of water content and pressure at a given depth permitted to obtain precise information on the hysteresis behavior of the moisture content-pressure relationship.

Van Bavel (231) in 1956 discussed the application of radiation methods to the measurement of moisture content and density of soil. To measure the soil moisture and soil density, the slow neutron method, fast neutron method and gamma radiation method were discussed.

Van Bavel, Stirk, and Brust (232) in 1968 studied the distribution of irrigation water in an Adelanto clay loam profile in a field plot by simultaneous, periodic observations of the water content and hydraulic head profiles. Successive measurement series were made with the plot bare and covered, bare and planted to a sorghum crop. From the first two, the *in situ* and dynamic relations of water content to water pressure and to hydraulic conductivity were obtained. From the cropped field data, the root-extraction pattern was derived, using the established hydraulic properties of the profile. The data demonstrated the variability within depths and locations of water retention and conduction properties and the consequent problem of calculating fluxes. Calculated extraction rates agreed reasonably with independent lysimetric measurements of the water loss from the surface to the atmosphere.

Van Bavel, Underwood and Swanson (233) in 1956 reported the application of neutron method in soil moisture measurement by counting slow neutron density in soils. The instrument consists of a detector and a battery-operated rate meter. The detector can be lowered in a test hole 5 cm in diameter and the moisture content of a layer of soil about 60 cm thick can be determined with standard error of 0.6% by volume below 30% moisture content. The detector may also be laid on the surface of the soil. Thus, the top layer of soil to a depth of about 15 cm is measured with a standard error of 1.0% by volume. The rate meter is capable of precision equivalent to a standard error of about 0.1% of moisture. With special precaution in calibration procedures this accuracy can be approached.

From a practical point of view, the instrumentation as available seems to be satisfactory in regard to portability, cost, and precision. The method is sufficiently accurate and the time per measurement, which is about 3 minutes, is not unreasonably long. The data, given here and those of others, show that one calibration curve probably suffices for all soils. The resolution of the method is not sufficient and it is necessary to report a loss of sensitivity at high moisture contents. These shortcomings are analyzed and the following improvements suggested. For linear response, the counter should not extend beyond 17 cm from the source. The present slow neutron method will probably not be capable of resolution better than about 25 cm. Where greater resolution is required, measurement of fast neutron flux may offer possibilities.

Virta (234) in 1969 used the neutron method for the measurement of soil moisture in Finland. The measurements were taken at two sites in forest with six measuring tubes. In each tube the moisture was determined at different depths. The measurements were carried out once a month during the winter and twice monthly during the summer. The fluctuations of soil moisture were determined, and possibility of computing the evapotranspiration from these measurements was examined. The results of the measurements were presented and the effects of the instability of the measuring system and the irregular areal distribution of the change of moisture content were discussed.

Waldron and Constantin (235) in 1968 conducted studies on bulk volume and hydraulic conductivity changes during sodium saturation tests. Fragmented samples of one organic and five mineral California soils were permeated with salt solutions while confined in cylinders under a constant axial stress of 0.05 bar. Continuous and precise measurement of bulk volume changes during sodium saturation with 1 M NaCl followed by 0.25 M NaCl showed that while hydraulic conductivity always decreased with more dilution, the bulk volume increased in some soils and decreased with others. Such bulk increases occurred only in the first passage of 0.25 M NaCl following sodium saturation and were attributed to aggregate. If 1 M NaCl were reintroduced, hydraulic conductivity increased with all soils so tested and bulk volume decreased. Successive permeations with 1 M and 0.25 M solutions produced hydraulic conductivity increases with bulk volume increases on changing from 0.25 M to 1 M, and hydraulic conductivity decreases with bulk volume increases on changing from 1 M to 0.25 M NaCl. A mechanical explanation was given which was based on a bimodal pore model of the soil and on the way in which variation of stress from point to point within the soil affected volume changes of the swelling materials and the pore size distribution.

Wang, Hassan, and Franzini (236) in 1964 presented a numerical method of analyzing unsteady, unsaturated flow in soils. If the hydraulic and capillary characteristics of the soil and the initial moisture are known the method permits prediction of the future deposition of soil moisture as a function of time and vertical location. The technique is particularly adaptable to problems of infiltration, drainage, and upward flow induced by evaporation. Effects of hysteresis and vapor movement were neglected. Darcy's law was combined with the continuity equation, and a solution was achieved through a step-by-step numerical procedure. Soil moisture profiles were obtained from a digital model.

Wang and Lakshminarayana (237) in 1968 simulated flow of water through unsaturated non-homogeneous soils using the nonlinear diffusion equation for vertical drainage and infiltration. An explicit-implicit finite difference scheme was developed to solve the flow equation. The data utilized in this study for the simulated soil profile were obtained from the experimental work of Nielsen et al. (157) for infiltration and drainage conditions. Computed cumulative infiltration loss and average rate were in reasonable agreement with the field measurements.

Warrick, Biggar, and Nielsen (238) in 1971 studied the simultaneous transfer of water and solutes for an unsaturated soil. Two approximate solutions were derived for vertical distribution of moisture and solutes. In the first solution, the infiltration rate into a homogeneous soil was assumed to approach a constant value independent of the initial condition. For a large water application the time required to establish such a constant rate might be small compared with the overall infiltration time. Also, the values of flow velocity, dispersion coefficient, and moisture content were assumed to be constant in space and time. The second solution ignored the effect of convection term in the differential equation. A field experiment was conducted at the University of California West Side Field Station near Fresno. The soil was classified as

Panoche clay loam. The experimental distributions of soil moisture and chloride concentration for an infiltration time of 17 hours at 0, 2, 9, and 17 hours were presented. Using the two solutions, a range of dispersion coefficient from 0.05 to 0.1 cm^2/min was given that fitted the field data. Measured and calculated distributions of chloride concentration with depth in the field experiment for an infiltration time of 11 hours showed a lag between them, indicating that measured values were underestimated, which resulted from erroneous assumptions involved in the analysis.

Watson in 1967 (239) presented a steady-state method for determining the hydraulic conductivity-water content relationship of unsaturated porous medium. The relationship was obtained from a set of experiments conducted in laboratory.

Watson (240) in 1967 investigated on experimental and numerical study of column drainage. A finite difference scheme of one-dimensional equation of flow in unsaturated porous media was derived to obtain the distribution of moisture. Theoretical and experimental values of moisture content were found very close in time domain.

Watson and Whisler (241) in 1968 found a relationship between water content and pressure head for the coarse sand, during drainage to a water table of a saturated, stratified sand column, which was characteristically different from that obtained during the drainage of a uniform column of the coarse sand. The water content-pressure head relationship for each system was presented and the system dependence of the relationship was discussed. Also, considered were the effect of this system dependence and its limitation on the use of current analytic approaches in predicting pressure head and water content profiles during the drainage of layered soils.

Weeks and Richards (242) in 1967 presented a method for calculating water conductivity of unsaturated soil by the use of data obtained during transient changes in moisture content and suction head along a horizontal soil column. A soil moisture characteristic curve was obtained from the data. An empirical relationship was proposed to calculate the hydraulic conductivity of an unsaturated soil.

Weeks, Richards, and Letey (243) in 1968 used the rate equations developed from the theory of thermodynamics of irreversible processes to analyze water transfer induced by thermal gradients along a sealed cylindrical horizontal column of Pachappa soil. Functional relations to calculate values of coefficients in the flow equations were determined from experimental data which were obtained during steady-state flow conditions. The relations were used to compute the values of coefficients in order to calculate flow rates past selected positions along the column at various times during transient flow periods. Suction head values were maintained in a range that could be measured with tensiometers which were located at three positions along the column. Liquid water transfer toward the warm end was assumed to be due to an induced suction head gradient. This transfer was confirmed by suctioning the column at the end of the experiment and measuring the concentrations of Na^+ and Cl^- and the EC of saturation extracts prepared from the suctions.

Wessling and Wit (244) in 1969 developed a method for the determination of the capillary conductivity based on the infiltration of water into vertical columns. By using accurate drip feeding system and small tensiometers with a soil filling, instead of a porous cup, it was possible to measure suction gradients and to compute the values of hydraulic conductivity. This method was applied to both disturbed soil samples and undisturbed cores. For the sandy material a relatively wide range of suctions was found in which the capillary conductivity remained equal to the value at saturation. A good agreement was found between the point where the moisture content dropped rapidly in the pF-curve with increasing suction and the point where the capillary conductivity dropped with increasing suctions. For the finer textured soils the range of constant values of hydraulic conductivity was practically absent.

Whisler (245) in 1969 used an electrical resistance network analog to analyze the steady-state flow in sloping land modeled as an inclined soil slab for both saturated and unsaturated conditions. At saturation the equipotentials and surface fluxes were symmetrical about the vertical midplane of the slab and agreed with an analytic solution. For rainfall rates lower than that necessary to saturate the slab, this symmetry was lost. For unsaturated flow a step function representation of the pressure head-conductivity relationship gave comparable results to a more complicated function. As the angle of slope was increased, even though part of the slab might be unsaturated, the internal flow rate increased, especially at the lower outflow end of the slab.

Whisler and Klute (246) in 1965 obtained a numerical solution of the flow equation for water in soil for a flow system consisting of a vertical column of soil which had been drained from saturation to equilibrium with a water table. A thin layer of ponded water was assumed to be applied to the top end of the column. The solution of the equation presented the time and depth distribution of water content and pressure head during the resulting infiltration. The effect hysteresis was also evaluated and it was concluded that the position of the front at any one time was overestimated or underestimated, depending upon whether the drainage or wetting curve was used.

Whisler and Klute (247) in 1969 obtained a numerical solution of the flow equation of water in soil for flow systems consisting of a vertical column of stratified soil materials which had been drained from saturation to equilibrium with a water table. Water was assumed to be applied at the top of the column as either rainfall or ponded water. Infiltration into such a system involved hysteresis. The hysteresis phenomena was considered in the solution of the problem. The solution of the equation depicted the time and space distributions of water content and pressure head during the resulting infiltration as well as infiltration rate and accumulated water content. Tables of dimensionless conductivity and water capacity were calculated from tables of dimensionless water content and pressure head, for a set of moisture characteristic curves. Several hypothetical cases were examined. These were coarse textured soils overlaying fine textured soils, fine textured lenses in coarse textured soils, and coarse textured lenses in fine textured soils. Comparisons were made between these cases and also nonstratified cases on the basis of pressure head versus time profiles, moisture content versus time profiles, infiltration rate changes, and accumulated water content changes. The numerical solution predicted a hold up effect on the wetting front as it went from a fine textured layer into a coarse textured one. The rate of advance of the fronts was faster for ponded infiltration than for rainfall infiltration.

Whisler, Klute, and Peters (248) in 1968 developed a method for the measurement of soil-water diffusivity. The method was based on gamma-ray absorption measurements of the water content as a function of time at a fixed position in a horizontal infiltration system. The calculation of diffusivity was based on the assumption that the water content is a function of position divided by the square root of time. The variability of the data led to scatter in the diffusivity function, especially at high water contents. This variability in the data can be traced mainly to the inability to obtain sufficiently accurate data from the recordings of the gamma-ray counting system. When the diffusivity function was used to predict the water content-time relationship in the column, even though the function had been fit statistically, the results were largely dependent upon the wet end of the relationship.

Whisler, Klute, and Millington (249) in 1968 applied numerical analysis to the steady-state flow equation for evapotranspiration from a vertical soil column. The water uptake by the plant roots was incorporated into the flow equation as a negative source term. The evapotranspiration rate and its partitioning between plant transpiration and soil evaporation were specified at the top boundary condition. The lower boundary condition was a water table. The results of the analysis of a Pachappa sandy loam gave pressure head, water content, source strength, and soil-water flux profiles. This study has (i) demonstrated that solutions to the flow equation with a source term can be obtained by numeric means, (ii) shown the theoretical influence of the parameters in the source term model on the flow in the soil, (iii) quantitatively indicated a transfer of water from wet soil through the root system, and (iv) indicated that the source term has little effect on the pressure head profile unless the evapotranspiration rate is about the same order of magnitude as the theoretical limiting value.

Wilson (250) in 1971 investigated on the subsurface disposal of waste effluents in aquifers. The objectives of the study were (a) to obtain mixing data from single- and two-well system and pit recharge experiments in inland alluvium for comparison with field and analytic studies reported by other investigators and (b) to arrive at rational guidelines for the selection, design and management of mixing facilities at potential, inland desalting plants. The two-well method appeared to be the most favorable well technique for *in situ* mixing: after 14 days of recharging effluent at 200 gpm through a 20 inch, 150 feet well with simultaneously pumping at 200 gpm from a downstream 16 inch, 150 feet well, the relative concentration of effluent in pumped water was 26 percent.

Wind (251) in 1969 discussed a realtively simple technique to estimate hydraulic conductivity from the data. A vertical column of soil was allowed to evaporate at the top; all other sides were completely closed. Every day the total weight of the column was read and determinations were made of the moisture content and moisture tension at different depths. The velocity of flow for different depths was calculated from the changes in moisture content and wight. The potential gradient was read from the moisture tension readings, making it possible to calculate the hydraulic conductivity. A difficulty was that a pF-curve was needed when moisture content or moisture tension was determined. In the latter case, used in this paper, the total amount of moisture in the column determined from tension data and the pF-curve did not agree with the amount determined from the total weight. This meant the flow velocity could not be calculated exactly. The reason was that the pF-curves used lacked sufficient reproducibility. They could be fitted to the soil column used by the iteration technique described. The capillary conductivity values, determined with the aid of Bouyoucos' electrical nylon units, were fairly accurate at moisture between 0.1 and 20.0 atmosphere. Below 0.1 atmoshphere they lacked accuracy.

Wooding (252) in 1968 treated steady infiltration from a shallow, circular, and inundated area on the horizontal surface of a semi-infinite porous medium by a method of linearization proposed by Philip (164). Using this method, Philip retained most of the properties of the nonlinear system but reduced the differential equation to a linear type governing steady diffusion in a steady uniform flow. On the surface of the medium, the boundary conditions were of mixed type, although linear. These conditions were reduced to a system of dual integral equations solved by a modification of Tranter's method. Expressions for the distribution of vertical flux, density, moisture content, and Stokes stream function were derived, and numerical values of the last two quantities were illustrated graphically. It was found that the total flux depended almost linearly upon a parameter α, defined as the logarithmic derivative of the hydraulic conductivity with respect to capillary potential. Curves of mean flux over various radii for various values of α indicated the importance of the guard ring in infiltrometer design.

Yaron and Thomas (253) in 1968 determined the hydraulic conductivity of soil-glass bead mixture in columns during the flow of dilute sodium-calcium solutions through the mixture. A decrease in hydraulic conductivity was found as the exchangeable sodium approached equilibrium. The shape of the curve depended on the nature of the soil, the cationic composition, and total salt content of the solution. A semi-empirical method of predicting the hydraulic conductivity was developed.

Yeh and Franzini (254) in 1968 obtained a theoretical solution of moving water in saturated and unsaturated system of soil by combining Darcy's equation with a modified diffusion equation. The nonlinear partial differential equation of diffusion was transformed to a nonlinear ordinary differential equation, and a numerical procedure for its solution was presented. Experiments were conducted at various applied pressures using silica flour as the soil sample. Moisture content as a function of time and position was determined by use of gamma-ray attenuation equipment. The experimental results compared favorably with the results given by numerical procedures based on theory.

Youngs (255) in 1957 investigated on the moisture profiles during vertical infiltration. The theoretical moisture profiles predicted by the equation of vertical flow in unsaturated porous media were compared with those obtained by experiments. Two cases were considered: (a) vertical infiltration into initially dry columns of porous materials with the surfaces maintained at saturation; and (b) the equilibrium condition of vertical infiltration at a constant rate into columns which drain to a water table. Good agreement was found between theory and experiments in both cases.

Youngs (256) in 1958 presented a theoretical and experimental study on redistribution of moisture in porous materials after infiltration. The limitations of the diffusion concept of moisture flow in porous media were discussed, and it was argued that further advances in moisture flow problems involving both wetting and draining, of which the redistribution of infiltration water is an example, must be made by considering the changing potential distribution in the porous media. It was shown experimentally that the potential distribution abruptly changes at the cessation of infiltration and the beginning of redistribution. Mositure profiles were obtained during experiments on the redistribution of moisture after infiltration in the horizontal case and were presented in a dimensionless form. From a knowledge of the hydrologic properties of the porous meterials used, utilizing a special method for obtaining the wetted moisture characteristic so as to produce the relevant experimental conditions, and by making certain assumptions, an estimate was made of the initial transition moisture content from the draining to the wetting zone. This agreed with experiment and explained why redistribution readily occurred in one material and not in another. The moisture profiles obtained were explained qualitatively by considering the potential distribution in the porous materials.

Youngs (257) in 1958 studied the redistribution of moisture in porous media after infiltration. Moisture profiles during the redistribution after vertical infiltration to various depths into two inert porous materials were obtained, using an apparatus employing thermoelectric elements to estimate moisture content. By an extension of the analysis used by Young (256) in an earlier paper for horizontal distribution, the initial transition moisture content from the draining to the wetting zone was calculated from the hydrologic properties of the porous media for various infiltration depths and compared with experimental values. This indicated that the redistribution of moisture would depend more critically on infiltration depth for porous materials with steep wetting moisture characteristics; that is, for materials with limited pore-size distribution. The experimental moisture profiles were discussed.

Youngs (258) in 1960 reported on the hysteresis effect in soil moisture studies. It was concluded that the hysteresis in the relationship between the suction and the moisture content of a porous medium complicated the computation of moisture profiles when both wetting and draining occurred simultaneously. Two examples of such profiles were discussed: first, the profiles obtained during the redistribution of moisture after the cessation of infiltration with the surface maintained at saturation; and secondly, the profiles obtained during the infiltration at a constant rate which was less than the required to maintain the surface saturated. In the latter experiments, after an initial period of time, a constant moisture content region was formed behind a moisture front moving downward with a constant velocity, making possible a measurement of the unsaturated hydraulic conductivity with an easy means of determining the moisture content.

Young (259) in 1964 described an infiltration method of measuring the hydraulic conductivity of unsaturated porous materials. In the experiments,two methods -the suction method and the pressure method - were utilized to obtain the distribution of moisture content with depth in a column filled with porous material. The variation of hydraulic conductivity with moisture content was also presented.

Zaslavsky (260) in 1964 presented the Darcy's formula based on experiments by measuring the discharge through a soil sample under a given head difference. It was found to apply for a linear uniform flow in a chemically and physically unstable porous medium. Later it was extended to three-dimensional flow.

Zaslavsky (261) in 1964 described, qualitatively and analytically, the flow of water through a layered soil. Two types of soil profiles considered were a profile of distinct layer, each of which had uniform conductivity and a gradually varying profile. Each profile was assumed to have a well-defined phreatic surface somewhere below. Both a downward vertical flow and a horizontal flow were considered. The conditions that would cause a transition from a saturated to an unsaturated flow, and those that would cause a transition from an unsaturated to a saturated flow were investigated.

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APPENDIX

Categories of References

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