SOIL-MOISTURE AND IRRIGATION STUDIES II

PROCEEDINGS OF A PANEL HELD IN VIENNA, ORGANIZED BY THE JOINT FAO/IAEA DIVISION OF ATOMIC ENERGY IN FOOD AND AGRICULTURE

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1973
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PROCEEDINGS OF A PANEL
ON THE USE OF NUCLEAR TECHNIQUES
IN SOIL PHYSICS AND IRRIGATION STUDIES
ORGANIZED BY THE
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IN FOOD AND AGRICULTURE
AND HELD IN VIENNA

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FOREWORD

The International Atomic Energy Agency and the Food and Agriculture Organization of the United Nations support research contracts, symposia, panels and various other activities concerned with a wide range of investigations in agricultural research involving the use of radiation and radioisotopes.

The bulk of the work supported by research contracts in agriculture is devoted to practical problems, the solution of which would be of immediate practical value to the food supply and the economy of the developing countries.

Improving significantly the efficiency of water use could contribute a great deal to the increase of food production for a given amount of water and would have a marked impact upon the water shortage problem. To achieve this, a better insight into soil-water-plant relationships and their vital role in crop production is essential. Nuclear techniques could contribute a great deal to gaining a better understanding of certain important aspects of the soil-water-plant system, and this would in turn lead to the development of more efficient methods of water use.

The Joint FAO/IAEA Division convened a Panel of experts in Vienna from 2 to 6 November 1970, to examine how isotope and radiation techniques could best contribute to increasing crop production through sound research leading to a better understanding of soil-water-plant relationships. The Panel, which was attended by 27 experts from developing and developed countries as well as from FAO and the IAEA, discussed recent progress in the design of the relevant radiation equipment and the advantages and limitations of using such equipment in soil moisture and irrigation studies. The use of tracer techniques in the essential studies of water and solute movement under field conditions was handled by the Panel in detail. In addition, the very important studies of water balance in the field and plant response to irrigation, and the role that nuclear techniques can play in such investigations, received due consideration.

This publication contains the papers presented to the meeting together with edited discussions and the Panel recommendations. The Agency is particularly grateful to Mr. W.H. Gardner for his editorial help, especially in preparing the discussions.

It is hoped that the information will be of use to all those concerned with the urgent problem of ensuring water-use efficiency, and with related subjects of soil moisture, irrigation and drainage.
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INTRODUCTION
Opening address

IMPLICATIONS TO AGRICULTURE IN DEVELOPING COUNTRIES OF USE OF NUCLEAR TECHNIQUES IN SOIL PHYSICS AND IRRIGATION STUDIES

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Abstract

IMPLICATIONS TO AGRICULTURE IN DEVELOPING COUNTRIES OF USE OF NUCLEAR TECHNIQUES IN SOIL PHYSICS AND IRRIGATION STUDIES.

FAO/IAEA projects using radioactive nuclides in water-use efficiency studies have contributed materially to the 'Green Revolution'. Knowledge of water-use efficiency is particularly crucial to planning in working on problems of nuclear powered desalting of sea water for agricultural purposes. Energy is playing an increasingly important role in improving agricultural efficiency, not only in agricultural operations but in producing fertilizer materials crucial to high agricultural production. Nuclear power appears to be the primary future source of energy to supply increasingly important needs of agricultural production and to sustain the 'Green Revolution'.

My informal remarks at the opening of this session will not attempt to offer assessments of economic or quantitative values of the project on nuclear techniques in determining water-use efficiencies by crop plants which are just being completed, nor for the new projects which may materialize from deliberations of this panel during the next two weeks of these sessions. Nevertheless, I do want to emphasize most strongly that these FAO/IAEA projects have made important, favourable contributions at this point in time when many separate skirmishes are combining into successful, major battles in the war against hunger.

It is appropriate and satisfying that these joint FAO/IAEA projects using active nuclides in water-use efficiency studies have provided effective support in the effort to consolidate the 'Green Revolution'.

Indeed, we have gained sufficient experiences during the past five years to assure ourselves that these studies will have far reaching implications for agriculture in developing countries, because each increment of gain in the efficiency of water use for crop production can be considered the equivalent of making new agricultural land available for food production.

There are many circumstances where goals might well be set for doubling water-use efficiency. In some instances, the potential gains to be made are more than double because very little of irrigated agriculture is conducted with full water-use efficiency in mind. As for timeliness, two years ago, here in Vienna, I enjoyed working with the FAO/IAEA contractors on the water-use efficiency study project and because of this, I was able to get significant new technical information to take back to the Oak Ridge National Laboratory (ORNL) where we were working on problems of nuclear powered desalting of sea water for agricultural purposes.
When one like myself becomes associated with a group of engineers making plans for creating new water supplies for agriculture, whether by desalting, building dams, or any other means, it is quite unsettling to one having spent his life in agricultural science to have to admit to the facts of a relatively haphazard state of affairs when it comes to really knowing how much water a given crop might actually require in producing a specified amount of usable agricultural product. The term 'water-use efficiency' had come up many times among people of the engineering group at ORNL and they always meant: what is the cost in water used to produce a specific unit of wheat in a sack, cotton in a bale, etc. Even though agronomists can pretty well respond to those who ask the question: "How much wheat can be expected from an acre or hectare of a given crop variety grown in a given climatic zone?", the uncertainties of climatic, plant pest, and management factors dictate caution in the reply. Therefore, agronomists are rarely willing to be positive about yields-to-be-expected except within broad limits of, say, 20 to 30 per cent. This is in contrast to an engineer's points of view or a banker's point of view because engineers are in a habit of working to a few per cent of uncertainty and bankers want to be assured of exact rates of interest from investments. Obviously, the engineer has the advantages of knowing strengths of materials and costs of construction which can be depended upon more reliably than vagaries of climate, uncertain rainfall, plant diseases, or wind storms which can markedly influence the productivity of agricultural crops within any given growing season. But irrigation water is one of the facets of agricultural input requirements where waste can occur and which can be overcome so that closer planning can be effected through improved knowledge.

Whenever a new irrigation project is being justified, planning depends on matching water to projected cropping patterns for the area to be served. Complications become particularly severe when planning for irrigation of desert lands where there is no previous experience with crops to draw upon. The morals are that those who plan for expansion of food-production are desperately in need of real numbers on water use and water-use efficiency, especially for arid zones, both for the planning of new projects and for establishing new goals for irrigation agricultural efficiency.

For example, in 1968, when this project was in its third year, the new information being developed on water-use efficiencies was of immediate benefit in strengthening the conceptual studies for nuclear desalting of arid coastal regions which were then in progress. Even though the FAO/IAEA data had been obtained from lysimeters and small plots, the increased degree of confidence which resulted from these studies was appreciated. It makes a tremendous difference to be able to state unequivocally, with real data as the base, that for a given climate — say that of Cairo, for example — one can expect a maize crop to exhibit a water-use efficiency of 1.25 g of harvested maize kernels per litre of water expended as against a nebulous opinion that may offer the same figure.

Two points are to be made about the value of firm numbers derived from well planned, properly executed experiments of the type which the FAO/IAEA project has sponsored. First, goals for water-use efficiency can be set. Second, where project planning is involved, specific points of reference take the place of more nebulous subjective planning inputs derived from opinion and judgements. Thus, the real numbers derived from experiment have great value even though they may have to be refined
later. If new experiments demonstrate possibilities for improvement in water-use efficiency numbers at a later date, the change will be received favourably, just as a new alloy of greater strength which permits improved engineering designs is viewed with favour. The point to be made is that the creation of genuine, pertinent numbers associated with water-use efficiency must not be underestimated. Having good water-use efficiency figures available or not having them available may very well make the difference between being able to proceed with a project or not being able to do so. Such are the trends of modern society which demand facts and figures where in former years 'opinions' of experts might have sufficed.

I take this occasion to express both my own appreciation and that of the groups working on plans for nuclear desalting for the timely efforts and the results which were forthcoming as early as 1968 from the IAEA's co-ordinated studies on water-use efficiency. Their data appeared at an opportune time.

Now I want to speak more broadly about the peaceful use of atomic energy with particular emphasis on its potentials for increasing outputs from agriculture in developing countries. To those of us here, atomic energy and agriculture seems a natural combination, but I wish to assure you that recognition of such relationships doesn't go much beyond small groups of scientists because the role of basic non-farm energy in relation to agricultural productivity has not as yet become a part of general thinking in world agriculture. But changes are taking place rapidly. For example, during the past two weeks I've been touring Austria looking at its agriculture and interpreting the activities as I observed the fields being worked by horses, tractors, and oxen. The profound changes which have taken place in the past ten to fifteen year interval can only be described as dramatic. The farm is rapidly converting to an energy consumer. In 2400 kilometres, I saw but one team of oxen and but one team of horses working, but tractors were everywhere. So were distribution outlets for synthetic fertilizers. An increasingly great dependency on tractors and synthetic fertilizers means that non-farm energy inputs have now become an essential component of the agricultural process. What is true for the areas just observed in Austria, Northern Italy, Switzerland, and Bavaria in Southern Germany will also be true of other parts of the world where agriculture has even further to go in making the shift from ox powered indigenous agricultural practices to systems which depend upon non-farm energy for power to cultivate, pump water, and make fertilizers.

On the same subject, while on this trip I got a real thrill from a newspaper announcement that this year's Nobel Peace Prize had been awarded to Norman Borlaug for his role as the 'Father of the Green Revolution'. The Green Revolution is a term now understood the world around, even though it is not quite two years since the Green Revolution came to a point of blossoming forth. I bring this to your attention because it raises the point that atomic energy will be coming into the picture as one of the energy resources for agriculture. While on the subject of non-farm energy resources for agriculture, may I illustrate some direct experiences in early 1967 in India where famine conditions were being faced.

The food shortage outlook was serious and of crisis proportions for some millions of people. Ironically, the alluvial Gangetic Plain was one of the more depressed areas. It was not because of transportation bottle-necks or because of lack of money, or similar explanations frequently
brought forth to explain food-shortage situations. Rather, the crisis was due to a genuine absence of sufficient food to feed all of India's people. At that time I happened to be in the Gangetic Plain, where, to me, the resources appeared so vast as to their potential for agriculture that it was practically impossible for me to imagine that particular site as the centre of a famine situation. I was deeply puzzled and set about to see why that should be.

It is often said that people who cannot read or write and have no education are basically handicapped in their abilities to make the best use of available resources. Another way of stating the same proposition is that they lack 'know-how', meaning that they do not know how to apply labour to resources to best advantage. If this were the case, then I, who am supposed to have 'know-how', should be able to set up a small farm in that part of the Gangetic Plain and use its natural gifts of sunshine, land, and water to grow food in abundance. However, it took me no more than a day or so to fully realize that whether I might possess 'know-how' or not, I would not be able to compete with the cultivators who were farming those lands. Perhaps 20-30 years ago I might have been young enough to do so, but in 1967 I do not believe I would have had the physical strength to work as long and as hard as the farmers who were getting about all that they could from the resources of sunshine, land, and water alone.

So I asked myself a series of questions as to what I would need in order to bring myself into a competitive position with the local cultivators. First, there is fertilizer. Nitrogen would be the first choice. Where would I get it? In my country I would buy it and there would always be someone nearby wanting to sell it to me. But such was not the case for the average cultivator farming on the Gangetic Plain. Thus, it became clear that another step or gap would have to be filled which would provide the fertilizer which I knew I would need to make my own farming activities competitive. The nitrogen fertilizer would have to be manufactured.

The minute one says that fertilizer has to be manufactured, the immediate discovery is made that one first has to get one's hands on an energy resource. The easiest way, perhaps, is to dig a hole in the ground and extract methane and to run the methane through a reforming plant which transfers hydrogen from methane to nitrogen so that ammonia is formed. Petroleum, or hydroelectrical power, or even coal could be substituted. But what if there is no fortuitously located petroleum, or natural gas, or coal nearby and, if in spite of substantial hydroelectrical power development, the area is already plagued with electrical power shortages. What next? How much underlying basic energy has to be provided to accomplish what agricultural objectives? Where does one start with the analysis of the essential role of non-farm energy requirements?

If you turn to a chemical handbook for tables of values of thermodynamic properties of molecules, then make a few slide-rule calculations of the energy required to transform nitrogen gas to ammonia, or to transfer hydrogen from methane, ethane, or paraffins over to nitrogen as ammonia, you promptly arrive at certain conclusions about the basic energy requirements for increasing agricultural productivity.

For example, assume that for an established farming system an objective is to secure additional edible calories in the form of wheat. Nitrogen fertilizer is one of the first of the additional components which will have
to be provided. Wheat is a good example to use because the extra calories being sought automatically bring extra edible protein in the amount of about 12 to 14 per cent of the total wheat kernel. Thus, provision has to be made to manufacture that amount of nitrogen fertilizer which is to appear as protein in the wheat.

There are a number of processes by which nitrogen in the atmosphere can be chemically converted into forms which wheat plants can use. But whatever the route or steps selected for the fertilizer manufacturing process, basic non-farm energy will have to be supplied. We also keep in mind that once the nitrogen fertilizer is manufactured and bagged, there will be some unavoidable nitrogen losses associated with the farming operation — as for example, denitrification in the field, competition from weeds, leaching losses and the nitrogen which goes into non-edible plant parts such as roots, straw, and chaff. While keeping all of these latter to a minimum by assuming good farm management, one comes up with a calculable rule for guidance which says: In order to gain an extra, edible cereal calorie from a farming system which is operating at suboptimal yield levels, it is necessary to provide approximately 0.1 calorie from some non-farm energy source in order to make fertilizer nitrogen.

This figure of 0.1 calorie of non-farm energy applies to a favourable energy source such as methane gas or naphtha. It is a minimal practical figure. It could be doubled or tripled depending on the nature or form of non-farm energy which can be obtained and applied toward fertilizer manufacture and the degree of efficiency of fertilizer recovery by growing plants under practicalities of field operations. But, whatever the chemical route followed, whether the energy comes from hydroelectric generators, coal, natural gas, or petroleum, the inescapable thermodynamical fact remains that the quantity of basic non-farm energy, which must be had to secure a specified increase in agricultural productivity by modern methods of more intensive cultivation, represents a substantial percentage of the edible calorie which is being sought through modern farming methods.

For any farming system which starts using fertilizer nitrogen, it is generally true that productivity increases and that phosphorus is the next thing that has to be supplied as a fertilizer, and the non-farm energy requirements mount. Sticking to the unit of one additional, edible calorie, energy has to be found to make the acid required to convert the insoluble tricalcium of the rock-phosphates into soluble monocalcium phosphate, which is usable by plants. This may require another 0.1 calorie of non-farm energy. With essential transportation and other fertilizer supplements, etc., a third 0.1th calorie has to be added. The point of this exercise is to illustrate the fact that non-farm energy has to be brought into the picture and earmarked for agriculture if the agriculture of countries facing food shortages is to make the shift into what we choose to call 'modern intensive cultivation'. However, the reward for making the shift is fairly large — namely three- to five- and even ten-fold increases in yield from a unit land area where reliable irrigation can be provided.

It was in this light that nuclear power began to appear as perhaps the quickest, cheapest, primary energy source to consider for closing the energy gap between low level and high level outputs of agricultural goods from the farms of developing nations.
We haven't, so far, talked of energy input requirements per calorie of secondary foods such as meat, milk, and eggs. Actually, when one in my country sits down to the dinner table, the energetics of the food chain are such that the food being consumed has been procured at about a 1:1 exchange of calories from petroleum, which has gone into the growing, processing, and distribution of food. Thus, from one point of view, it might be said that we now depend upon the energy stored by prehistoric fossil agriculture as much as we depend upon the energy captured from sun for our daily nourishment. Much of the advancement of modern agriculture can, therefore, be credited to having learned how to incorporate non-farm energy resources into systems which grow the food and bring it to the table to be consumed.

So among the limiting growth factors amenable to description in a Mitscherlich equation (such as N or P), a term $E_N$ or $E_P$, meaning the non-farm energy required to manufacture and apply N or P, may be substituted in the equation for N or P. Having concluded that energy is the basic requirement for improving agriculture in a place like the Gangetic Plain, where is the energy to come from? Here the trees have long since been cut down so wood fuel is gone. Hydroelectric power is available because some of the very large dams of the world, such as the Bhakra, are in India. But even so, there are distinct power shortages all through the country because demands for electric power greatly exceed the supply. Irrigation is practised on an enormous scale and has been for some hundred years. There is coal in the country, but not at the site where the agricultural need for power exists. When costs of transportation are figured for getting coal into the places where the agricultural land and irrigation water is, the coal gets pretty expensive. No natural gas or petroleum has been discovered nearby. After looking at the alternatives for getting the requisite power, it appeared that perhaps the cheapest, quickest way to get non-farm energy input for agriculture would be to turn to nuclear energy. It was for these reasons that a proposal was made for what I, at that time, had begun to call a nuclear powered agro-industrial complex. The whole proposition rested on the absolute necessity of getting non-farm energy inputs injected to the agricultural system of the Indo Gangetic Plain where the new energy source would be used to make fertilizers, to pump water, to move water, to turn ineffective drainage systems into effective drainage systems, and to support an essential ancillary complex of agriculturally related industries. Very often with irrigation systems there are no adequate outfalls where drainage waters can be moved away by gravity. This means that power and power for pumping drainage water has to become a permanent feature of irrigation agriculture in many areas which will otherwise go out of production.

Since almost everyone thinks the Green Revolution is here to stay, it behooves the few who have knowledge of the basic power needs of agricultural systems to emphasize and re-emphasize the fact that the Green Revolution is absolutely dependent upon the non-farm energy inputs that can be obtained and sustained within the agricultural system. Without this, the 'Green Revolution' can offer little more than a temporary gain. In other words, the 'miracle seeds' cannot perform alone nor at any level beyond the point that fertilizers and other energy consuming inputs are put at their disposal.
All of the studies sponsored under this co-ordinated project during the past five years are highly pertinent to irrigation agriculture and, thus, the Green Revolution. They clearly represent one kind of cross-linkage between atomic energy and agriculture. Another aspect will be the gross power output of atomic energy itself. I think that nuclear energy for agriculture is bound to step out far beyond the negligible total energy involved where radioisotopes are used for tracing. We will be confronted with many new problems which are related to nuclear energy because agro-industrial activities will be nuclear powered at least in some very important instances. As a sign of nuclear power moving toward the support of agricultural development in nations faced with food-shortage problems, I report that I have just finished a review of some 650 well-written pages of a comprehensive study by the Indian AEC on what they call Agro-Industrial Complexes. Judging from the coverage, I estimate that something like 300 man years of work during the past two years may have been invested in this planning. They have examined in great detail the possibilities of putting nuclear power into the service of agriculture in India—both from the point of view of desalting sea water and for other purposes of making fertilizers, pumping water, and for activating agriculturally related industries which are essential to the success of modern agricultural systems.

There is another reason for attaching more than usual importance to this FAO/IAEA project. I hope there will be some vestiges of it carried through into designs of the next activity that will come out of the deliberations of this session, because it is going to be most necessary to get the research done that will provide good numbers for water-use efficiency potentials as an aid to the engineers who will be doing the planning for new irrigation and land reclamation projects. We cannot expect the engineers to know more about agricultural requirements for water than we do. Therefore, we must be the ones who provide the numbers which say what the system being planned has to have and what the real needs of the moment are and what the future needs are going to be if the irrigation or land reclamation project is to be a permanent agricultural asset.

As for future roles of nuclear energy in relation to agricultural productivity, the Indian study which I just mentioned shows that nuclear power can compete with other energy sources in making nitrogen fertilizers. The trade-offs in choices of basic energy revolve about transportation costs. For the north-western Gangetic Plain, the result of the Indian study says that they can acidulate rock phosphorus, make the ammonia, urea, and other nitrogenous fertilizers by nuclear power, and that nuclear energy is the most economical source of power needed to step up agricultural production in that specific area.

In summary, there are important new dimensions for agriculture in developing nations that have come forth as realities since this FAO/IAEA project was started five years ago. Foremost, the 'Green Revolution' is here and has caught the popular fancy of the world at large. Secondly, the Green Revolution will not go a step farther than energy inputs allow it to go.

I leave these two thoughts with you because it is in the light of the Green Revolution's stepped-up agricultural outlook that the joint FAO/IAEA projects are operating. The facts which we gain through research must be made readily available for the engineering fraternity, for the planners,
and for those who have to make decisions on the routes to be taken toward
effecting agricultural improvements.

We are entering more deeply into the Era of Energy. Some countries
have entered this era earlier than others and, while basking in the benefits,
are now becoming concerned about the consequences as exhibited by
decreasing per capita land resources and environmental matters such as
pollution. But there remains a large gap between per capita energy
consumption of many of the developing countries and the energy consumption
which will be required to satisfy minimal needs for human comfort and
human dignity. The factor may be 5-, 10-, or as much as 20-fold above
what it is now. My reason for putting the level so high is that I believe
secondary foods are certainly going to assume importance in upgrading
food supplies after minimal requirements for survival have been met.
Meat, milk, and eggs will be in increasing demand because people will
not be satisfied with just getting enough rice, wheat, legumes and vegetables
to stay alive and well.

Now, I conclude by saying that we are in an Energy Era and that the
world is beginning to realize that peaceful uses of nuclear energy can be
highly important in overcoming energy deficiencies which have stalemated
prospects for increasing agricultural production capabilities in food-short
'overpopulated' regions.

We can take encouragement from the 1970 Nobel Peace Prize being
justly bestowed upon N. Borlag for his role in bringing the 'Green
Revolution' into being. It is fitting that the IAEA, which is dedicated
to the peaceful uses of atomic energy, should find itself so intimately
involved in the means through which the beach head of the Green Revolution
can be secured for the betterment of mankind in these troubled, critical
times when ideas of unavoidable, widespread famine were beginning to
take deep root.

I have every confidence that the joint FAO/IAEA efforts of the past
will continue on into the future to the benefit of all of the member nations
concerned.

DISCUSSION

D. KIRKHAM: Professor Stout's paper raises important social
questions. Because of the need for new and sophisticated technology,
farmers, particularly in the developing countries, will need to be trained
and educated in the use of new farm machinery and modern management
techniques. Also, farmers in the past have been relatively independent
of other people, and this is the reason that farmers like to be farmers.
With mechanization they no longer can be independent. If there is a
depression, or if for some reason energy sources are interfered with,
the farmer will be in trouble too; he no longer can survive on his own
food as has been true in great depressions of the past. These important
social problems will need to be solved in connection with the green
revolution.

W. R. GARDNER: Professor Stout, you come from a state where
irrigation has been practised and studied scientifically for many years.
Perhaps you can tell us where have we gone wrong in our past research
investigations that we do not now have, after all these years, information
in a form useful in planning for future irrigation; that we yet need more experiments? An answer to this question could well influence our recommendations on what should be done in our own project next year.

P. R. STOUT: We have much information but many people do not think that it would apply to other places around the world. Even in California we don’t, to my knowledge, have all the kinds of information we need. We have just not tried hard enough to see if we could get by with less water. We know that water costs, say, US $4.00 or US $8.00 an acre-foot and we merely stop pumping when water costs more than the farmer thinks he can get out of it. We can ask Don Nielsen, could we actually get from our literature — I have tried and failed — the information we need to, say for example, show how much wheat we could put into the bag per unit of water used in California, say on our Davis campus? Perhaps we could.

D. R. NIELSEN: Well, I think that the questions raised by Professor Gardner are ones for which we do not have answers. Use of atomic power for desalting water, as is being initiated in the United States of America and elsewhere, raises important questions which we agriculturalists have not normally considered. The leaching requirement with a source of distilled water, or with various kinds of desalted water, has not really been much thought about. Most of our considerations have to do with problems of using our existing waters, and not with problems of desalted water and where it might best be used in agriculture. With the availability of reactor power, desalted water, and heated water associated with reactor cooling, many problems arise. Warm water can be used to warm soil in cool seasons to increase crop production. And with inexpensive soil heating available more and better crops may be produced. Plant geneticists may be able to breed plants differently from before to take advantage of higher temperatures. Using nuclear power and nuclear radiation such things as sterilizing soil on a large scale basis followed by back-inoculation with desirable organisms, and creating entirely new soil profiles may become practical. Completely automated irrigation systems, normally expensive, may become highly practical in systems using desalted water and controlled environment to grow high-value crops. But, many problems arise. For example, what criteria must be used to decide whether or not to use desalted water for development or expansion of cities, for industrial production or for agriculture. Broad issues, such as desalination and use of atomic power; in farm or industrial complexes, are unlimited and, since most of us are agriculturalists or agricultural engineers, we likely have not thought much about them. Many of us think only of using tracers or neutron meters for measurements in the soil, rather than looking at broader problems of energy input and output in our systems.

W. R. GARDNER: Professor Stout, I think that your experience in calculating what is needed in developing agricultural systems could help us to know where we really are weakest in terms of the kind of information that has yet to be generated. What should we be doing?

P. R. STOUT: Time and time again I have personally been up against difficult engineering problems in irrigation project planning. Engineers seek maximum efficiency and want to run their pumps all the time at a constant rate; these power devices run best when they just keep running. But crops don’t operate that way, and because they don’t we need to work with the engineers and get reservoir supplements into the scheme so that
pumps can be run efficiently throughout the year. To convince the engineers we need to prepare handbooks with hard figures showing what is needed by way of design to fit the agricultural scene. Work should be done to get such figures.

M. ABDALLA: I should like to add something to what Professor Stout has said. Soil management is one of the most important factors affecting water movement and retention. Depth of moisture penetration is the most effective factor controlling the efficiency of irrigation and tissue dryness of irrigation. Soil management and the tools used for cultivation must be considered because of their effect upon the moisture regime. Although we have been unable to benefit appreciably in our work from the use of neutron scattering in detecting soil compaction, the moisture traces obtained using neutron scattering techniques have revealed some hidden problems of fertilizer use and efficiency and the development of roots. Changes in soil compaction or changes in layering of the profile brought about by deep ploughing affect the moisture regime and the development of roots in the profile. On the alluvial soils of the UAR we have realized great benefit from using subsoil layers through deep ploughing and have achieved yield increases in rice and sugar cane of as much as 50 per cent.

P. R. STOUT: I have a note here on the use of farm machinery, also involving deep ploughing. Computers are now used in the design of large systems. You put in building blocks so that you can program crops, cropping patterns, water into the system and the like. Then you ask the computer what is the best crop to grow for protein, forage or for cash, and it always comes back for California saying: "grow potatoes." This is true just simply because there are good yield figures on potatoes. The yield is 40,000 lb per acre, which is 20 tonnes, and we have farmers in California who have turned in records for their farms of 100,000 lb, or 50 tonnes, of potatoes per acre. This is a very high yield, but what do they do? They plough 3 ft, almost 1 metre, deep and they plough cross-wise 1/2 metre deep, fixing it up so that potato plant roots can get down, carbon dioxide can get out, and oxygen can get in; and then they irrigate carefully and well. Soil management is extremely important. Farm machinery is an essential part of the whole program and where the green revolution has come in the tractors are rapidly becoming part of the farming business. In Thailand and the Middle East states during the past five years tractors have been coming in in large quantities. An agricultural engineering colleague travelling through these areas reports that 35 hp tractors are being bought and used in slash and burn areas in Thailand on holdings as small as one tenth of a hectare where the shortening of the land preparation and cropping time makes it entirely practical, even on such small holdings. When asked what they need in terms of tractor improvements they say that they want more power and better front wheel bearings. They build racks on the tractors and haul the rice and wheat out using them. I have been in the UAR and I know that one can't dig down much further than 4 inches in these long-farmed areas - it's just a plough pan after two or three hundred years of ploughing. I don't think that you can grow potatoes very well on these soils unless tractors are used to break up the plough pan.

D. HILLEL: Dr. Stout touched on the central problem facing this panel, and that is the problem of determining the efficiency of water use in the field under irrigation and I am sure that we will be spending much
of our time here discussing this very problem of how efficiently water is used in the field, how this efficiency can be determined and why so many experiments done in previous years have failed to give us this information in any clear way. I want to throw out an idea or two which may contribute to focusing this discussion. Dr. Stout pointed out that often the tendency to spend a limited amount of water on an as large as possible a parcel of land can be an error, can be misleading; and in fact, it is better to concentrate available water on a limited tract of land. Of course, this can be carried too far. Experience shows, and theoretical considerations confirm, that there is a maximum efficiency. There is a certain quantity of water in a given region, under given conditions of climate, soil and crop, that produces the maximum efficiency of water use. How can this be determined? I think it can best be determined by the study of the total water balance in the field — how much water is applied by irrigation and rainfall, where it goes, how much is stored in pertinent soil zones at the beginning of the growing season, how much actually is required by the crop, how much is wasted in unnecessary evaporation or by excessive leaching. Also, the degree to which insufficient leaching leads to salt accumulation, penalizing the crop by increasing the water stress, must be measured. The need is for quantitative, exact studies of the sort that the Joint Division has sponsored and has been overseeing in these last four or five years. This is really a pioneering study; there are very few studies as complete as this carried out simultaneously in a number of climatic zones. So, I agree with Dr. Stout that the information that was gathered here under the sponsorship of the Agency is in a sense unique and I hope that the experience and the conclusions which can be drawn from the program so far will be brought before this panel and the principles of water-use efficiency will be elucidated more fully than ever before.

J. DAMAGNEZ: Solar energy is the main source of energy which is used in agriculture, and this source of energy often is ill used. I think that atomic energy can in fact be considered as an additional source of energy, but I feel that this additional energy should be used in ways so as to make better use of available solar energy. I mean that in the dry areas, for example, only 50% of the total energy in the solar spectrum is in a range useful for photosynthesis. The remaining 50% of the energy, in the range 0 to 0.8 μm, is thermal energy which goes to evaporate water. This means that under present conditions we cannot ensure the best possible use of the solar energy. Now, when we have energy available in considerable quantities from nuclear sources, couldn't we envisage use of this energy in a way to limit this constraint at the level of the plant. I am thinking of certain possibilities of growing crops in covered or enclosed areas — it would be sort of a glasshouse where we could use a fraction of the solar energy in order to reduce the evaporation at the level of crops and thus make better use of the total energy which is available in improving agricultural production.
MEASUREMENT OF WATER IN SOIL
USING RADIATION TECHNIQUES
RECENT PROGRESS IN THE DESIGN OF RADIATION EQUIPMENT AND ITS PRACTICAL IMPLICATIONS*

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Abstract

RECENT PROGRESS IN THE DESIGN OF RADIATION EQUIPMENT AND ITS PRACTICAL IMPLICATIONS.

Giant strides have been made in the past decade in the development of radiation equipment for use in agricultural research. Some of these improvements provide the means for measuring phenomena which could not previously be observed. Use of these new techniques has to a large extent been limited to laboratory experiments, but the techniques are also applicable to field measurements with small design changes. Such changes need to be made, and soil moisture studies moved from the laboratory into the field, so that the theory developed during the last several decades can be evaluated under environmental conditions.

The end product of agricultural research should be the optimum production of food. To reach this target, knowledge of the various growth processes is necessary. One facet of this aim is the proper utilization of water and plant nutrients. For growth to continue, nutrients, including water, must reach plant roots in the necessary quantities. Soil physicists have approached this aspect of the plant's need through laboratory and field studies on the movement of water and nutrients through soil and to plant roots. In the past, soil physicists have concentrated primarily on learning about the behavior of water and nutrients by using laboratory methods, to avoid the compounding factors present in the field. In doing so, they have avoided the complexities faced by a growing plant but have enhanced our knowledge of the physics describing the movement of water and solutes in porous media. The recent developments in nuclear methods should reverse this imbalance and permit meaningful interpretations of large-scale experiments designed to overcome the heterogeneities present in field situations. In this paper we shall describe some of the recent developments in radiation equipment for both field and laboratory use and try to estimate their relevance.

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to soil physics and irrigation studies. The list of developments is not complete and, perhaps, these developments are not all relevant; however, we hope that those listed will be thought provoking and will stimulate the imagination of the panel members.

Recent progress in the design of radiation equipment logically falls into four categories: commercially available radiation sources, improved detectors, recent developments in field instrumentation, and recent developments in laboratory instrumentation. Each of these categories will be discussed briefly.

COMMERCIALY AVAILABLE SOURCES

Before 1934, only naturally occurring radioactive substances were available. At that time F. Joliot and I. Curie (daughter of Mme. Curie) announced that boron and aluminium could be made radioactive by bombard-

<table>
<thead>
<tr>
<th>TABLE I. COMPARISON OF $^{32}$P AND $^{33}$P</th>
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<tr>
<td>$^{32}$P</td>
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<tr>
<td>Half-life (days)</td>
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<tr>
<td>Beta-particle maximum energy (MeV)</td>
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<tr>
<td>Percentage of activity remaining after 140 days of decay</td>
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<tr>
<th>TABLE II. CHARACTERISTICS OF ISOTOPIC NEUTRON SOURCES (NORMALIZED TO $5 \times 10^{10}$ neutrons/s)</th>
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<tbody>
<tr>
<td>Source</td>
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<tr>
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<tr>
<td>$^{19}$Kb-Be</td>
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<tr>
<td>$^{21}$Po-Be</td>
</tr>
<tr>
<td>$^{24}$Cm-Be</td>
</tr>
<tr>
<td>$^{25}$Cf</td>
</tr>
<tr>
<td>$^{244}$Cm-Be</td>
</tr>
<tr>
<td>$^{240}$Pu-Be</td>
</tr>
<tr>
<td>$^{241}$Am-Be</td>
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**1 watt = 1 joule/s = 0.2312 g-calories/s.
**Not including void space for helium from alpha decay. $^{252}$Cf sources need less void space for helium than the other sources because there are fewer alpha disintegrations per neutron emitted from $^{252}$Cf sources.
ment with the alpha rays from polonium (Joliot and Curie, 1934). Since that time the number of artificially produced radioactive species has grown rapidly. Although many radioactive species are known, only some are commercially available because of half-life, production, or application difficulties. Two radioactive nuclides that have recently become commercially available should have significant impact on soil physics research in the coming years.

The first of these commercially available sources is $^{32}$P (Robinson, 1969). Inasmuch as water movement and nutrient movement are of immediate concern to soil physicists and phosphorus is an important element in biological systems, the availability of two radioactive isotopes of phosphorus ($^{32}$P and $^{33}$P) should enhance the research possibilities immeasurably; for example, the movement of organic and inorganic phosphorus could be determined. A comparison of some of the properties of the two isotopes is given in Table 1. The longer half-life and lower maximum beta-particle energy (therefore reduced radiation dose) increase $^{33}$P's versatility. Detection of the low-energy beta particles poses no difficulty with modern liquid scintillation spectrometers. In phosphorus diffusion studies and plant uptake studies, the ability to tag one fertilizer with $^{32}$P and another with $^{33}$P and then to apply them simultaneously to the same experimental configuration should be most productive. In addition, the long half-life of $^{33}$P will increase the time available for determining the effect of leaching on phosphorus movement. Pesant, Kirkham, and Piere (1970) found phosphate movement in Hagener sand accelerated after five months of leaching. They also found that an equilibrium or quasi-equilibrium in phosphate leachate concentrations was not reached until four or five months in Edina silt loam and Nicollet clay loam. ($^{33}$P is available from the Isotopes Development Center, Oak Ridge National Laboratory, P.O. Box X, Oak Ridge, Tenn. 37830, USA, in small quantities at US$35/mCi or in batch quantities at US$3300/200 mCi or US$3500/300 mCi).

<table>
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<tr>
<th>TABLE III. NUCLEAR PROPERTIES OF $^{252}$Cf</th>
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<tbody>
<tr>
<td><strong>Effective half-life</strong></td>
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<tr>
<td><strong>Alpha decay half-life</strong></td>
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<tr>
<td><strong>Spontaneous fission half-life</strong></td>
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<tr>
<td><strong>Average neutron energy</strong></td>
</tr>
<tr>
<td><strong>Average alpha particle energy</strong></td>
</tr>
<tr>
<td><strong>Gamma emission rate</strong></td>
</tr>
<tr>
<td><strong>Decay heat (51.3% from fission, 48.7% from alpha decay)</strong></td>
</tr>
<tr>
<td><strong>Neutrons per spontaneous fission</strong></td>
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<tr>
<td><strong>Specific neutron activity</strong></td>
</tr>
<tr>
<td><strong>Neutron emission rate</strong></td>
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FIG. 3. Neutron capture gamma-ray spectrum of granite taken in the field with a mobile $^{252}$Cf neutron source and Ge(Li) spectrometer.

when $^{252}$Cf is used for neutron activation in a borehole (Fig. 5). Because $\text{Al}_2\text{O}_3$ is an abundant oxide in clay minerals, a continuous activation log may be useful in applications where the clay content of soils must be analysed.

**IMPROVED DETECTORS**

NaI crystals (activated with about 1% thallium iodide) are the most widely used detectors for gamma-ray measurements. Recently, lithium-drifted germanium detectors Ge(Li) have come into use. The advantage of the Ge(Li) detector is the high resolution available over that attainable with a NaI(Tl) detector. As shown in Fig. 6, with a 4096-channel pulse-height analyser, the entire $^{137}$Cs peak is less than 80 channels wide with the Ge(Li) detector, but the peak is about 800 channels wide with a NaI(Tl) detector. This improved resolution is very important when gamma rays have similar energies, such as those found during activation analysis studies. Two disadvantages of the Ge(Li) detector are its low efficiency (it has a detection efficiency for $^{137}$Cs of only 0.2% compared with an efficiency of 20% for the NaI(Tl) detector) and the requirement that the detector be cooled to liquid nitrogen temperatures to reduce thermal excitation of
electrons. The Ge(Li) detector is not likely to find much practical use in field studies of soil physics because of its cost (US$4000) compared with a NaI(Tl) detector (US$250), but it is almost a necessity for laboratory studies involving activation analysis (Haller, Rancitelli, and Cooper, 1968).

Another type of detector is the thermoluminescent dosimeter. Thermoluminescent dosimeters work on the principle that in some materials a small fraction of incoming ionizing radiation is stored in metastable energy states. Some of this energy can be recovered later as visible photons if the material is thermally heated. A number of books describing the principles and use of thermoluminescent dosimeters have been written (Cameron, Suntharalingam, and Kenney, 1968; IAEA, 1967). The detectors are used primarily in health physics applications, such as estimating the radiation dose received by an individual exposed to radiation.

New thermoluminescent materials are continually being produced. The two most popular materials are $^6$LiF and $^7$LiF. $^6$LiF is sensitive to both gamma rays and neutrons; $^7$LiF is primarily sensitive to gamma rays alone. The two dosimeters are normally used together: the $^7$LiF is used to determine the gamma-ray dose, and this dose is then subtracted from the dose measured by the $^6$LiF detector to determine the thermal neutron dose.
These dosimeters are extremely small (Fig. 7) and would be useful for measuring the neutron distribution in soil from nuclear probes. They would not require large access holes as for the entrance of a BF$_3$ thermal neutron detector, but could be placed in very small tubes. They have a very small volume so that point readings could be obtained. Thermoluminescent dosimeters are currently used instead of film badges for measuring radiation exposure (Wright, 1968; Cusimano, Clipperley, and Culley, 1967). They have a large number of advantages over film badges: energy independence, wide range of sensitivity, and lack of fading. Recently,
neutron dosimeters using thermoluminescent dosimeters have been developed (Korba and Hoy, 1970; Preston, 1988). These dosimeters are sensitive to the entire neutron spectrum, a major improvement over the nuclear track emulsion film used heretofore. A final use of thermoluminescent dosimeters is for integrating the dose received from low-level environmental exposures where long periods of time are required to obtain a measurable dose (Shambon and Freezwick, 1970).

RECENT DEVELOPMENTS IN FIELD INSTRUMENTATION

Rugged probe for neutron studies

The wide use of the field soil moisture probe based on the thermalization of neutrons has resulted in a wide variety of commercial variations of the
FIG. 7. Some representative thermoluminescent dosimeters. The dosimeter on the left is a polyethylene vial containing LiF powder; the one in the centre, a high sensitivity extruded LiF rod; and the one on the right, a high sensitivity extruded LiF ribbon. The scale is in inches.

FIG. 8. Experimental design for using intermediate neutron transmission for measuring the water content of surface soils (dimensions shown are in cm).

instrument (Troxler, Nuclear Chicago, Berthold, etc.). Recently the Atomic Weapons Research Establishment, Aldermaston, England, produced a prototype neutron probe that is light, sturdy, and thermally and electronically stable. This new probe has several good design features. The probe contains the amplifiers, pulse shaping, high voltage generation and voltage stabilization circuits, eliminating the need for the cable connecting the scaler to the probe to carry high voltage. The circuitry is designed so that the
FIG. 9. Gamma transmission equipment for use in field studies (all dimensions are in inches).
output pulse from the probe can be accepted by a variety of commercial ratemeters and scalers. In addition, the probe is temperature insensitive between -10 and +40°C, and has no warm-up effects after switch-on and no discernible drift throughout the working day. The lack of warm-up difficulties conserves battery life because the instrument can be shut off between measurements. This probe is being produced by D.A. Pitman Limited, Jessamy Road, Weybridge, Surrey, England. Practical use of the probe is reported by Eeles (1969).

Neutron transmission

Wack (1967) has designed and patented (Fig. 8) a device for measuring the water content of surface soils based on the transmission of intermediate energy neutrons. A neutron source of intermediate energy is placed at known depths in a vertical tube in the soil, and the number of neutrons reaching the soil surface is measured using a BF$_3$ counter surrounded by a paraffin cylinder 3 to 5 cm thick. The exterior of the paraffin cylinder is covered by a layer of cadmium to eliminate incident thermal neutrons from reaching the detector. The method is specific for water contents in surface soils and eliminates the uncertainties present in surface or depth moisture probes based on thermalization of neutrons. The technique should have wide application in measuring water content in the soil surface where plant roots are known to be most dense.

Gamma transmission

The gamma-ray transmission techniques that have been widely used in laboratory measurements are applicable to field studies (Fig. 9). Although the potential exists in these techniques for obtaining water contents over narrow ranges by using a two-hole technique, the potential has not been attained because of electronic drift problems (Ligon, 1969). The electronic drift is probably due to either changes in the gain of the photomultiplier tube or preamplifier, with temperature changes. Another likely cause, however, could be a change in scintillation-crystal light output. In any event, the gain shift in the gamma-ray energy spectrum with temperature and the count-rate change are appreciable (Fig. 10) (Reginato and Stout, 1970). Reginato and Stout found that the use of a spectrum stabilizer in conjunction with a secondary $^{60}$Co source taped to the end of the crystal overcame problems inherent in the system when a spectrum stabilizer was used alone. Troxler Electronics Laboratories (P.O. Box 5997, Raleigh, North Carolina, 27607, USA) report a similar method using $^{241}$Am to adjust the location of the single-channel-analysery baseline in their portable two-probe density gauge that has just recently been released. Topp (1970) overcame the difficulty of drift by using an ionization chamber. With the current interest in accurate measurements of water content changes with depth and the electronic design capabilities available, temperature instabilities should not pose problems for long.
FIG. 10. $^{137}$Cs gamma ray energy spectrum shift as a function of temperature.

FIG. 11. Schematic drawing of experimental apparatus used for simultaneous measurement of water content and soil density changes using $^{241}$Am and $^{137}$Cs gamma-ray transmission.

RECENT DEVELOPMENTS IN LABORATORY INSTRUMENTATION

Simultaneous measurement of soil density and water content

With the increased interest in the behaviour of water in swelling soils and the resulting theoretical studies (Smiles and Rosenthal, 1968; Philip, 1969) on the subject, a method is required for measuring changes in both the water content and soil density to experimentally evaluate these theoretical analyses. Soane (1967) illustrated the effectiveness of the dual gamma method for measuring bulk density and water content of three soils. The samples were placed between a caesium source and the detector, and then between
FIG. 12. Water content and soil densities determined by the dual gamma method prior to and 24 hours following the addition of 85 ml of water to a 5.1 x 5.1-cm clear plastic column partially filled with Cecil Soil. The attenuation coefficients used in the calculations were \( \mu_{\text{Am}}^0 = 0.20495 \text{ cm}^2/\text{g} \), \( \mu_{\text{C}}^0 = 0.0865 \text{ cm}^2/\text{g} \), \( \mu_{\text{Am}} = 0.27126 \text{ cm}^2/\text{g} \), and \( \mu_{\text{C}} = 0.17603 \text{ cm}^2/\text{g} \).

FIG. 13. Water content and soil densities determined by the dual gamma method prior to and 24 hours following the addition of 200 ml of water to a 5.1 x 5.1-cm clear plastic column partially filled with Houston Black soil. The attenuation coefficients used in the calculations were \( \mu_{\text{Am}}^0 = 0.20495 \text{ cm}^2/\text{g} \), \( \mu_{\text{C}}^0 = 0.8985 \text{ cm}^2/\text{g} \), \( \mu_{\text{Am}} = 0.33463 \text{ cm}^2/\text{g} \), and \( \mu_{\text{C}} = 0.07197 \text{ cm}^2/\text{g} \). The dashed line indicates the water content that would have been calculated if the measurement had been made by cesium attenuation alone.
an americium source and the detector. Corey, Peterson and Wakat (1971) (Fig.11) combined the low energy $^{241}$Am and higher energy $^{137}$Cs gamma sources and made both gamma transmission measurements for exactly the same geometry. Simultaneous measurement is made possible if a multi-channel analyzer is used to avoid the complications introduced by the Compton scattering from the $^{137}$Cs source in the $^{241}$Am region (59.6 keV). Corey, Peterson and Wakat (1971) obtained by their techniques the variation of water content and soil density with depth before and following the addition of water to both non-swelling (Cecill) and swelling soils (Houston Black) (Figs 12 and 13).

**Gamma-photoneutron method for laboratory studies of soil water**

Gamma transmission, as already stated, is usually used to measure non-destructively the water content changes in laboratory soil columns. The primary limitation of this approach is its sensitivity to soil-density changes that appear as water-content changes. This limitation can be overcome by using combined transmission measurements of gamma beams from $^{137}$Cs and $^{241}$Am. An alternative is the gamma-photoneutron method proposed by Corey, Hawkins, and Overman (1970a). The gamma-photoneutron method is more versatile than the dual gamma method because the interface between displacing and displaced solutions along a soil column can be measured easily and rapidly (Corey, Hawkins, Overman and Green, 1970b).

The gamma-photoneutron method is based on the interaction of gamma rays having an energy greater than 2.23 MeV (Hanson, 1949) with deuterium present as heavy water ($^2$H$_2$O). This interaction produces photoneutrons and protons. The photoneutrons are detected by thermal neutron detectors (Fig.14). The method is independent of high-water ($^2$H$_2$O) content, of soil density, and of soil type (Fig.15). The technique requires a large source of high-energy gamma rays because the cross-section for the reaction with D$_2$O is small. Corey et al. (1970a) used a 1.4 Ci electro-deposited $^{208}$Tl source (4.5 Ci of $^{228}$Th). This large source required extensive shielding (25 cm of lead) because the radiation intensity of the unshielded source exceeded 60 rads/h.

The gamma-photoneutron method can also be used to follow the intrusion of heavy water into a soil column or the displacement of light water by heavy water by using the same experimental design as shown in Fig.14. Two experiments illustrate the utility of the method. These experiments show both the downward displacement of D$_2$O (specific gravity of 1.105 g/cm$^3$) by H$_2$O, and the downward displacement of H$_2$O by D$_2$O + NaNO$_3$ (specific gravity of 1.291 g/cm$^3$) (Figs 16 and 17). This method can be used to measure non-destructively the interface between the displacing and displaced solutions to readily evaluate the effect of such parameters as column length, flow rate, and density on the shape of the transition zone between the fluids. The technique was used successfully in field studies to non-destructively follow the redistribution and flow rate of water (Haskell and Hawkins, 1964; Hawkins and Horton, 1967) the technique at that time, however, had limited value because it required $^{24}$Na as the gamma source. The use of $^{24}$Na with its short half-life requires frequent neutron activation to maintain adequate source strength. $^{208}$Tl, when in equilibrium with $^{228}$Th, eliminates that difficulty.
FIG. 14. Schematic drawing of experimental apparatus used for production of photoneutrons from deuterium by a high energy gamma source.

FIG. 15. Calibration curve relating heavy water content to neutrons detected. The data points represent two soils and a wide range of bulk densities and light water contents.
Fig. 16. Calculated and measured D₂O contents at distances of 5, 20, 35, 50, and 65 cm from the introduction end of a vertical soil column when H₂O displaced D₂O.

Fig. 17. Calculated and measured D₂O contents at distances of 5, 20, 35, 50, and 65 cm from the introduction end of a vertical soil column when D₂O + NaNO₃ displaced H₂O.

Flow-cell detectors

In the foregoing, we have touched on a type of miscible displacement experiment that measures non-destructively the shape of the interface in the column. If one is interested in studying the interaction of certain fertilizers or chemicals with soil, collection and analysis of the effluent is normally practised. The use of a continuous flow cell connected to a graphic recorder obviates the need for sample collection if the solution of interest is tagged with a beta-particle emitter. Yoo and Kirkham (1971) have described such a system. In their experimental configuration (Fig. 18) the pump is placed ahead of the flow cell to prevent air bubbles, that
FIG. 18. Schematic diagram of miscible displacement experiment using flow cell.

eventually accumulate during unsaturated flow experiments, from entering the detection system. In addition, they used a very short length of 1 mm inside diameter tubing between the end of the soil column and the flow cell to reduce mixing effects.

Although the flow-cell technique is well known, the recent commercial production of reliable equipment simplifies its use in soil physics laboratories. A typical commercially available flow cell consists of two shielded photomultiplier tubes that face anthracene crystals packed in the centre of a transparent tube. The fluid of interest flows over the anthracene crystals, and beta particles from tracers in the fluid produce light pulses in the anthracene crystals. A beta-ray analyser discriminates against the low-energy portion of the spectrum to give the most precise counting rate for the radioisotope used. The analyser feeds into a count-rate meter and from there to a chart recorder. The record of the beta activity in the effluent reveals the type of interaction that took place within the soil column. The equipment is commercially available from Nuclear-Chicago Corporation, Des Plaines, Illinois, USA. This technique is readily adapted to gamma-emitting isotopes as well as to other detectors, such as a NaI(Tl) detector, in place of the anthracene crystals; hence, the method has wide applicability in laboratory flow measurements of solute-soil interaction.

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DISCUSSION

J. DAMAGNEZ: I would like to ask a question on the use of the germanium-lithium detector in the field. We use a germanium-lithium detector and the problem is that we have to cool it. Now, I do not know whether there are germanium-lithium detectors at present which one can use in the field without having some sort of cooling system.

My second question concerns the lithium-fluoride detectors. We have also used lithium-fluoride for dosimetry, but the problem we had as far as neutrons went was the sensitivity of these detectors. Could you give us some figures concerning the radiation time for these sources — americium-beryllium — and the rate of emission of neutrons that you would have?

J.C. COREY: The lithium-drifted germanium detector has to be cooled with liquid nitrogen. Hence, use in the field is of limited value. The data that was shown on the bore holes was obtained using sodium-iodide detectors, so that I agree that there is no way you could get the high sensitivity at the present time in the field without cooling, and this is difficult because you have to have a flask of liquid nitrogen with you. At the present time, for activation analysis at the level of that I was showing you on that piece of granite, it has to be confined to laboratory studies. The same thing would be true if you were looking at the various rare earth contents of vegetation. We found the lithium-fluoride dosimeter to be very good. It is far superior to what we call the NTA neutron film; this is an emulsion which is sensitive to neutrons and, actually, what we do then is to develop it and count the holes that go through the emulsion. I have not used the lithium-fluoride detector for the use that I proposed in the paper. I would say it is adequate for the type of information we are after. I have used it to some extent, and I agree that it is not as sensitive as we would like, but it is the best non-electronic detector we have for neutrons. If you want to go around and look at a big tube, you can say, well, your distribution on that tube isn't as good as a single point. I mean if you are going to plot something, you are going to have error bars because of your BF₃ tube being 10 cm or 12 cm long and 1 cm in diameter. How much error does that introduce versus looking at a single point, and getting a number of them around in a sphere. I think it is superior.

W.R. GARDNER: Is the necessary information on the efficiency of these thermal-luminescent materials available so that we can use them? We've never, to my knowledge, used integrated values, we are always using rates. I think there are many applications where we could use integrated values for certain kinds of measurements of water content and I wondered if enough information is available in the references you give?

J.C. COREY: The information, to my knowledge, is not available in printed form. It is available to our laboratory and I will see if I can obtain the data for you.
P.R. STOUT: Question to Dr. Corey. These lithium-fluoride dosimeters are such remarkable things. They have been in general use for about three or four years now in a pretty reliable way. When you said that information was not available — they use them all over — I just wondered, is it the lithium-7 that is the tricky one? There must be information, somewhere.

J.C. COREY: This question is a little more specific. It has to do with its energy dependence across the spectrum. There is one region, at least, where we are still working and that we are not happy with, particularly the thermal region. At least some of the fellows in the laboratory have questions about this.

P.R. STOUT: We should stay on top of it because this is just bound to be of enormous help in these kinds of studies. We want to stick them in hills to find old bones which have been buried and that sort of thing — it could save us an enormous amount of time. We practically had to give up trying to get equipment out in the field, but these work.

J.C. COREY: You can leave them out there for an indefinite period of time and accumulate the dose. This is a very nice thing, as you point out, even though dose rate is extremely low in environmental problems, that you can leave the dosimeter out there for months, and then go out and pick it up and it's the same as if you had never left the laboratory.

P. REININGER: What kind of electronic equipment did you use to keep your americium and caesium constant?

J.C. COREY: Let's look at that spectrum shown in Figure 5. If you look at the bottom graph on the figure, you will see that we don't need to worry about the Compton effect in the caesium. Let's suppose you wanted to put your baseline at channel 3200. In that case from 3200 up we will consider our caesium reading. Now, the americium we run from about channel 400 down to the bottom of the next peak. Then, we would use from 400 up, say a small section 15 channels wide, to determine the base count to subtract from the americium peak, after multiplying by an appropriate factor to get the same number of channels under the americium peak. We know that this was all right, because we took the americium source out of the system to look at the caesium Compton effect in that region and to make sure that it was fairly flat. I mean, this is all right as long as you don’t have an edge or something in that region. You can get the same information using three single-channel analysers, one set on the caesium region, one set on the americium region and one set on the Compton region, or background region, that you need to subtract from the americium. By using a 400-channel analyser you can do it automatically.

P. REININGER: We did it with a single-channel analyser with a crosswise arrangement of americium-caesium sources, and it was quite bothersome. The caesium background increased when we put our soil column in the beam path.

J.C. COREY: I would like to make a comment on this. I think we in soils have worried too much in the past about money. Do you realize that if we can produce an extra ten bushels per acre times a thousand acres for 50 years, or millions of acres times even a dollar, such money is nothing? But, are we getting this through to people? It doesn't take much multiplied by vast areas of acres to return investment very rapidly. I actually have access to all these kinds of equipment, so what I try and do is the things that you can’t do because you don’t have the money. Having done this, I
would say the 400-channel analyser is the way to go because if you have any instability and your peak shifts out of a region, say, because of a temperature instability, this shows up instantaneously from your study. With a single-channel analyser you are never sure whether it is a "true" in what you are measuring or an electronic distortion.

P. REINIGER: I would like to add something about the germanium-lithium detectors. You can also get them without the liquid nitrogen cooling, if the temperature is stabilized, and you measure continuously the temperature. I think they are using the piezoelectric effect and they keep the temperature constant. So this is one method used at our institute to monitor the movement of radioisotopes in plants by putting these detectors on various places on the plant.

J.C. COREY: I think that those may be different detectors. The detectors which I have referred to are solid-state, and you get diffusion of ions if the temperature warms up and we'll lose the detector. You know, if the technician forgets it, this is US$4000 down the drain, and a US$6000 analyser then becomes cheap. So, it may be a different detector because ours have to be cooled. Now, you may have a later model which may have a lot of advantages. You could then go to the field and use it, and look at all spectra much more sensitively.

P. REINIGER: You couldn't go to the field with those because they have quite a voluminous apparatus to keep the temperature constant. Not, with liquid nitrogen, but at a constant temperature, so that you have to keep them in the laboratory.

D. HILLEL: I find this paper extremely interesting and it raises my curiosity about a number of new possibilities. I would like to ask two questions of Dr. Corey and one question of Dr. Kirkham.

The first question to Dr. Corey: In discussing the use of different detectors for gamma rays, you failed to mention the much-touted plastic detectors, and I wonder if this was on purpose or because you don't consider them important, or what? I am not familiar with them, but I am in the position of needing to know what are the relevant advantages of the plastic versus the sodium-iodide detector, or some of the other detectors that you mentioned — particularly in connection with dead-time and what it does to peaks in the energy spectrum. The second question: On the use of single-channel analysers; are you familiar with the technique which locks the single-channel analyser on to the energy peak that is being monitored, so that if there is a shift resulting from some change in temperature, the window of the single-channel analyser shifts along with the shift in the peak.

J.C. COREY: I have the answer to both this time. Detectors, gamma/plastic: We don't use them, except for neutrons when they are zinc-sulphide loaded. Their dead-time is fine, they are fast enough; that's not our problem; the problem is in our analyser. The resolution is less than that of either of the other two detectors — you get much more smearing of the peak. If you only have one energy that may be fine, it depends on what you want to do.

On the second question — use of a single-channel analyser-peak stabilizer to avoid temperature drift: I haven't used it, but I have talked to people who have been unhappy with it. It doesn't work as well as they want. The peak may stay at the same point but what happens if the spectrum shifts? It would be fine if the shape stayed the same, but if the shape, instead of being a normal curve suddenly is skewed, you are in trouble.
This has been their feeling about it. We don't use single-channel analysers in non-temperature control situations, but I have talked to people who have, and they are unhappy. I wouldn't recommend them at this point, but that is a second-hand observation.

D. HILLEG: Now, Dr. Kirkham, you mentioned the new probe for neutron moisture measurements being sold by Pitman in England and I would like to know more about the characteristics of this. I understand that what they use is not a BF₃ detector but a Geiger counter. Is this information correct, or if not, what kind of detector do they use, and what are the advantages and disadvantages? I have heard a few conflicting reports about this.

D. KIRKHAM: I think the best thing for us to do here is to look at the company's brochure, which I have here, and read the exact details.

P. COUCH: I could reply to your question, because we have had this piece of equipment at Cadarache for some time. The principle is the following: you have a beryllium-amerindium radioactive source and a BF₃ detector. The pulses are recorded on an integrator, but it seems that this variant of the equipment is not satisfactory to most users. I think that within a short time there is going to be a numerical integrator instead of the present one.

P. R. STOUT: Dr. Corey, is there any hope in sight for getting solid state devices activated, say, by an alpha emitter that might pick up neutrons? The reason I ask the question is because of the remarkable resolution that we are getting now from solid state detectors in the 5 MeV range where we resolve, easily within one per cent, between energies, and get distinctive curves.

J. C. COREY: Just a point of clarification. Do you want an (n, α) detector?

P. R. STOUT: Yes, if this is on the cards at all, then it would open some real possibilities for small field-type equipment that would be temperature insensitive.

J. C. COREY: The problem that I can see would be that the cross-section for anything other than thermal neutrons is fairly low to begin with, so that the efficiency of detection is low. I don't know of any that we are using. Of course, we have neutron fluxes where we don't really need to be concerned, but it would certainly be worthy of an investigation to see if there is a possibility of a suitable (n, α) reaction. I agree with you that the resolution on alpha rays is remarkable and the backgrounds are negligible.

W. KUHN: I have a question for Dr. Corey. Could you tell me, please, when you use this thermal luminescent detector, what is the accuracy when you record the intensity of radiation? In the determination of water content we want to count thermal neutrons with an accuracy of 1 or 2%. Now, could one get a stable count of this accuracy if we were to use this thermal luminescent detector?

J. C. COREY: I don't believe we have 1% accuracy at the present time with the lithium-fluoride detector. From a dosimetry point of view we don't require that much. We have some studies under way where we do have that sort of information available. Obviously, I don't do all of this work that I am reporting. Jack Hoy is the one who works with this. I would say that 1% is far better than we could do right now, but if you have seven of them and you are plus or minus 2 or 3 and you average over something like a sphere I would say that it is not too bad.
LES RECENTS DEVELOPPEMENTS
DE LA METHODE NEUTRONIQUE
DE MESURE DE L'HUMIDITE DES SOLS
ET SES PERSPECTIVES

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Abstract-Résumé

RECENT IMPROVEMENTS IN DEVELOPMENTS AND FUTURE PROSPECTS OF THE NEUTRON METHOD OF MEASURING SOIL MOISTURE.

Although the principles involved in the neutron method of soil moisture determination are well known and the method is widely used in practice, further improvements have been made recently, including: (a) extension of the method's scope to stony soils; (b) simultaneous counting of thermal and epithermal neutron fluxes, enabling soil moisture to be determined regardless of dry bulk density; (c) development of a system for measuring $E_2$ in a soil sample, this parameter representing the macroscopic cross-section for the absorption of thermal neutrons in cases of average dry bulk density (the system involves observing the perturbation of the thermal neutron spectrum of water or graphite caused by a dry soil sample and relating the perturbation to the measured $E_2$ values). Moreover, preliminary results suggest that it might be possible to build equipment which makes use of the transmission of fast neutrons (about 1 MeV) in determining the moisture content of thin soil layers. Such a method would possess high sensitivity and satisfactory resolution. The field remains wide open for research aimed at developing equipment based on the principles discussed in the paper.

LES RECENTS DEVELOPPEMENTS DE LA METHODE NEUTRONIQUE DE MESURE DE L'HUMIDITE DES SOLS ET SES PERSPECTIVES.

La méthode neutronique de mesure de la teneur en eau des sols, bien connue dans son principe et ses applications, a fait l'objet de perfectionnements récents portant sur: a) l'appliicabilité aux milieux calcaires; b) la mesure simultanée des neutrons thermiques et épithermiques, qui permet la détermination de l'humidité indépendamment de la densité sèche; c) la mise au point d'un empilement qui permettra de mesurer sur un échantillon de sol le paramètre $E_2$ qui représente la section efficace macroscopique d'absorption des neutrons thermiques pour une densité sèche moyenne (son principe repose sur la perturbation du spectre thermique de l'eau ou du graphite par un sol sec, perturbation que l'on relève aux valeurs de $E_2$); d) des résultats préliminaires qui permettent d'envisager la construction d'appareils utilisant le principe de transmission des neutrons rapides (environ 1 MeV) pour déterminer la teneur en eau de faibles couches de sol humide; une telle méthode aurait une bonne sensibilité et une résolution satisfaisante. Le champ reste ouvert aux recherches pour la mise au point d'appareils utilisant les principes signalés dans le mémoire.

Bien connue dans son principe et ses applications, la méthode neutronique de mesure de la teneur en eau des sols a fait l'objet de développements nouveaux concernant en particulier son applicabilité aux milieux calcaires. Au cours de ces recherches on a pu noter l'apport substantiel d'informations fournies par le flux de neutrons épithermiques; cette mesure complémentaire du comptage thermique nous conduit à proposer une méthode de détermination de l'humidité indépendante de la densité sèche. Par ailleurs, la méthode d'oscillations de pile permet une mesure nucléaire de la probabilité de capture des sols vis-à-vis des neutrons thermiques; à l'avenir, nous comptons obtenir par un empilement de graphite une mesure rapide de cette valeur sur échantillon.
Par ailleurs, l'étude expérimentale et théorique de la spectrométrie des neutrons rapides issus d'une source d'américium-fluor (AmF) dans un sol humide ouvre et précise les directions possibles de travail sur la méthode neutronique : l'analyse du spectre montre en effet qu'après avoir exploité le pic thermique éventuellement corrigé de la queue de spectre épithermique, il importe de se tourner vers le pic source. La possibilité de disposer de sources avec un pic peu énergique (AmF ou 252Cf) et bien connu ainsi que de détecteurs permettant une spectrométrie des neutrons de ces sources (³He ou protons de recul) nous autorise à envisager l'application du principe de transmission des neutrons aux mesures de faibles couches de sol humide.

Sols caillouteux

Les résultats obtenus en laboratoire sur des mélanges artificiels d'alumine hydratée et calcinée et de cailloux peuvent être classés en trois catégories :

- Influence du pourcentage volumique. C'est le facteur essentiel d'influence des cailloux sur la réponse de l'humidimètre. L'erreur enregistrée peut atteindre 5 points volumiques pour une humidité de 20 points lorsque le taux de cailloux passe de 0 à 50% si l'on prend une courbe d'étalonnage unique ; les expérimentations ont été menées avec une granulométrie de 4/6, 3 mm (fig.1). La comparaison des résultats aux comptages calculés par un programme à trois groupes de neutrons en géométrie cylindrique (fig.2) montre que l'on peut dans tous les cas remplacer le sol caillouteux (à répartition monotone) par un milieu homogène équivalent à condition de lui affecter une densité équivalente fournie par l'ensemble sol plus cailloux ; l'utilisation de l'humidimètre dans de tels sols requiert en conséquence la même procédure que dans le cas de sols non caillouteux.

![Diagram](image_url)

**FIG.1.** Courbes d'étalonnage $N(\text{imp}A)$ en fonction de l'humidité $H_v$ (a : 9% de cailloux, b : 10%, c : 30%, d : 50%, e : 80%).
— Influence de la granulométrie. Dans une gamme de diamètres allant de 0 à 50 mm, on a montré que l'influence de la granulométrie est nulle sur le comptage; ceci s'entend évidemment à pourcentage volumique constant (fig. 3); ce résultat étaye encore l'applicabilité de l'humidimètre aux sols caillouteux.

— Influence de la distribution. La répartition hétérogène des cailloux nécessitait de mettre en évidence l'effet sur l'humidimètre de leur distribution dans le sol. Bien qu'il soit pratiquement impossible d'obtenir une fonction de distribution représentative des sols caillouteux on a mesuré l'influence d'une répartition non homogène de couches de cailloux; les
résultats montrent à l'évidence que l'humidimètre construit sur le principe de rétrodiffusion des neutrons est inadéquat dans les sols à fort gradient de concentration des cailloux (fig. 4). Dans ce cas une autre méthode devra être mise en œuvre.

Mesure simultanée des neutrons thermiques et épithermiques

Le modèle expérimental des sols caillouteux, qui est représentatif d'une gamme importante de densité sèche, a fourni l'occasion de préciser les informations données par les neutrons épithermiques. On constate que le flux épithermique est beaucoup plus sensible aux gradients de densité sèche que le flux thermique (fig. 5). Ceci exclut l'utilisation des neutrons d'énergie voisine et supérieure à 1 eV comme principe d'humidimètre à neutrons.
Par contre on peut mettre à profit cet effet en utilisant le comptage épithermique comme facteur correctif du comptage thermique en remplacement de la valeur de densité sèche. On passe ainsi de la fonction

\[ N = (a \rho + b) H_v + c N_d + d \]

à la fonction

\[ N = (a N + b) H_v + c N + d \]

où \( a, b, c, d \) ainsi que \( a, b, c, d \) sont des constantes du sol.

On montre par ailleurs que si \( H_v \) représente l'eau totale, c'est-à-dire l'eau liée des argiles plus l'eau libre, les constantes \( a, b, c, d \) ne dépendent que de la probabilité \( \Sigma_a \) d'absorption des neutrons thermiques.

**Probabilité \( \Sigma_a \) d'absorption des neutrons thermiques par les sols**

En plus de l'intérêt qu'il présente pour les mesures à double comptage, le paramètre \( \Sigma_a \) est un facteur important de la courbe d'étalonnage des humidimètres à neutrons thermiques. Sa détermination par le calcul à partir de l'analyse chimique s'est avérée délicate sinon impossible car elle requiert la mesure de traces d'éléments comme le manganèse, le bore, le cadmium, le gadolinium, aussi a-t-on préféré la mesure par oscillations de pile de \( \Sigma_a \). Nous avons rassemblé quelques valeurs:

<table>
<thead>
<tr>
<th>Sol</th>
<th>( \sigma_a (\text{mm}^2/\text{g}) )</th>
<th>( \bar{\Sigma}_a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0,39</td>
<td>0,660</td>
</tr>
<tr>
<td>2</td>
<td>0,65</td>
<td>1,03</td>
</tr>
<tr>
<td>3</td>
<td>0,75</td>
<td>0,97</td>
</tr>
<tr>
<td>4</td>
<td>0,85</td>
<td>1,06</td>
</tr>
<tr>
<td>5</td>
<td>0,92</td>
<td>1,25</td>
</tr>
<tr>
<td>6</td>
<td>1,02</td>
<td>1,20</td>
</tr>
<tr>
<td>7</td>
<td>1,33</td>
<td>1,86</td>
</tr>
</tbody>
</table>

\( \Sigma_a \) représente la section efficace macroscopique suivant la formule \( \Sigma_a = n \rho \) où \( n \) nombre de noyaux par cm\(^3\), pour une densité sèche moyenne.

Ce tableau montre que l'écart de \( \Sigma_a \) entre les sols n'est pas négligeable et qu'il convient de mesurer ce paramètre. Un appareil est en cours d'essai, destiné à fournir des mesures sur échantillons. Son principe repose sur la perturbation du spectre thermique de l'eau ou du graphite par un sol sec, perturbation que l'on relie aux valeurs de \( \Sigma_a \).

**Spectrométrie des neutrons rapides**

La spectrométrie des neutrons rapides, tant expérimentale que calculée, révèle l'existence de trois plages où l'on peut travailler si on veut établir...
FIG. 6. Allure de la répartition du flux aux alentours de la source.

FIG. 7. Répartition spectrale des neutrons issus d'une source d'américium-fluor normalisée au pic source.

a: sol sec, b: sol humide.
une méthode de mesure de l’humidité des sols (fig. 6). Un pic thermique suivi d’une queue de flux épithermique, une zone de ralentissement de neutrons et un pic rapide qui peut être le pic source. L’évolution de la répartition énergétique des neutrons lorsqu’on passe d’un sol sec à un sol humide montre (fig. 7) que l’on ne peut pas attendre beaucoup de cette zone de ralentissement. Les deux zones utilisables restent le pic thermique et le pic source. Nous savons le parti que l’on peut tirer du pic thermique éventuellement corrigé du flux à 0,8 eV, mais il semble possible de mettre à profit la zone rapide pour construire des appareils utilisant le principe de transmission. Les premiers résultats obtenus sont prometteurs et une telle méthode devra aller (si on se place vers 1 MeV) une bonne sensibilité à la teneur en eau à une résolution satisfaisante; il y a là un champ d’investigation intéressant.

**Conclusion.** On peut dire que la méthode neutronique telle qu’elle est appliquée actuellement est au point; son utilisation combinée avec le traitement automatique des données la rend d’ailleurs opérationnelle. Par contre le champ reste ouvert aux recherches technologiques et techniques pour la mise au point d’appareils utilisant les principes signalés dans cet article.

**BIBLIOGRAPHIE**


**DISCUSSION**

A.I. DANILIN: Could you tell us please, considering all the calculations you have made, what error limits you have in percentages when you measure the moisture for different types of gravel? Do you have calculations of this kind? Perhaps your errors are not very great. Depending upon the varying
content of gravels in the soil, this might lead to errors in your calculations. Could you give us a few figures just to give us an idea as to the possible size of the errors?

P. COUCHAT: Yes, I think I mentioned at the beginning that the important criterion is the volume percentage of gravel. When we move from a percentage of zero to 50% then, for the same sort of counting, the difference in moisture content obtained is about 5%.

A.I. DANILIN: Taking into account that there is a change of about 5% in the count of thermal neutrons, if moisture changes by 1% then perhaps we could assess what would be the equivalent in percentage rate in the change of the moisture.

P. COUCHAT: No, this is what I meant. If I obtain the counting rate as a function of the volume moisture content I get the various calibration curves which I have shown. For a given counting rate, which would correspond to an average moisture of 20%, then the error here represents only 5%.

W. KÜHN: What you have in the curves you show is a density effect. If you have different densities then you have different intensities, but only if you measure in weight per cent; but the neutron curves are in volume per cent. The dependency is on the volume per cent of water. I pointed out earlier some years ago that if you have a volume per cent, and a weight per cent the curves are different; for the same water content we have different values for different densities.

P. COUCHAT: Yes, what I meant to stress a little while ago is that you can simulate the heterogeneous soil, which is a soil plus gravel; this can be compared to a homogeneous soil for which the effective density would be equal to the global density of this soil, I mean soil plus gravel. I think this is very important. We must understand that in the case of the moisture meter, and within the context of our experiments, the heterogeneity of the soil does not enter at all. We consider the soil as being homogeneous and, of course, we adjust for dry density, but this is not the case if we work with gamma rays because then the volume of measurement is so different. The curves of absorption cross-sections are also rather different because hydrogen atoms are not the main element. Other elements with important atomic masses are involved. Also, the variations in dry density due to the presence of gravels are more important here than those due to compacting.

M. ABDALLA: Have you found any abrupt change in the curves where the density changes according to the arrangement of coarse and fine particles? Of course, you are not using soil, but I am asking, if you were to use soil, might you get some abrupt change, because the density changes according to the volume of finer fraction and the volume of coarser fraction?

P. COUCHAT: Yes, there are two different factors. First of all, in the distribution of particles, that is, in a soil where we could have both fine and coarse particles: if the distribution is heterogeneous it is almost impossible to obtain good results for the calibration curve. If the distribution is heterogeneous, we have shown that a soil having gravel that is such that the maximum length would be 50 mm and other soils with a grain size between 4 to 6.3 mm would have the same calibration curve. And, if these different types of soils are mixed — the soils having 4 to 6.3 mm size with other soils — I will also get the identical calibration curve.

P.R. STOUT: Do you have any direct comparisons of use of ‘wet’ or real water with that of ‘dry’ water, in the form of aluminium hydroxide? I understand that in this apparatus you used aluminium hydroxide to simulate
water, yet stones might become moist if the water were actually 'wet' water. Along with that, do your stones in themselves — they come in many porosities — contain water that is of use to plants?

P. COUCHAT: Well, this is a problem of an agronomic nature. However, I said that in fact there was no difference between water simulated by aluminium hydroxide and free or real water. We decided to use aluminium hydroxide because the experiments were easier to make in a dry soil than in a moist soil. As regards these stones, we didn't find any water in the stones we used — they were dry stones — but I know that there are soils where stones contain a certain amount of moisture or water. With regard to the neutron moisture meter, the important thing to remember is that the response in a gravel soil is representative of the global moisture which is in the soil. If there is water in the stones, then it will be detected and counted, as if it were outside the stones. It is impossible with this neutron meter to see whether or not the water is in the stones or in the surrounding soil. If the distribution is homogeneous I don't think that it will have really important repercussions on the response of the moisture meter. The problem for us was to see whether or not we could replace the heterogeneous soil by a homogeneous soil. This was the case, otherwise we would not have been able to use the moisture meter in this gravel soil. Your second question is one which agronomists have been asking for the last 20 or 30 years. That is, at the time gravimetric measurements are made is it necessary to sieve the soil before making water content measurements? I think that no satisfaction has been given to this question thus far.

P. REINIGER: This is an answer to Prof. Stout's question. There is actually some work published on the use of water contained in chalk rock by grape vines for which I have references. Neutron meters were used in these studies.

P.R. STOUT: I was thinking of a place called Homestead, in Florida, where they grow all kinds of things on nothing but calcareous rock, and water goes through this rock quite freely.
ОПЫТ И НЕКОТОРЫЕ ОСОБЕННОСТИ ПРИМЕНЕНИЯ ГАММА-ЛУЧЕЙ И НЕЙТРОНОВ В ИССЛЕДОВАНИЯХ ВЛАЖНОСТИ ПОЧВ И ГРУНТОВ

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Abstract—Аннотация

EXPERIENCE WITH AND SOME FEATURES OF THE USE OF GAMMA RAYS AND NEUTRONS IN INVESTIGATING SOIL MOISTURE CONTENT.

Gamma ray and neutron scattering methods of measuring soil moisture are reviewed and their application in the field discussed. The scattering of gamma rays between a detector at the soil surface and a cobalt-60 source located in an access tube at various depths is described, it being regarded as the best method for following changes in the water concentration in surface horizons. For greater depths, down to the groundwater level, neutron moisture meters are recommended; the neutron method has been successfully employed in land improvement and irrigation studies in the USSR and has proved to be more economical than conventional methods.

ОПЫТ И НЕКОТОРЫЕ ОСОБЕННОСТИ ПРИМЕНЕНИЯ ГАММА-ЛУЧЕЙ И НЕЙТРОНОВ В ИССЛЕДОВАНИЯХ ВЛАЖНОСТИ ПОЧВ И ГРУНТОВ.

Рассматриваются методы рассеяния гамма-лучей и нейтронов для измерения влаги в почве и их использование на местах. В качестве наилучшего метода для измерения последующих изменений содержания воды в поверхностных горизонтах описывается рассеяние гамма-лучей между детектором на поверхности почвы и источником гамма-лучей Кобальт-60, помещаемом в трубке на различные глубины в почву. Для измерения на больших глубинах, приближающихся к уровню грунтовых вод, рекомендуется нейтронный влагомер. Методы с использованием нейтронных влагомеров с успехом использовались в исследованиях по улучшению почв и ирригации, проводимых в СССР, и зарекомендовали себя более экономичными по сравнению с обычными методами.

Метод определения влажности почв и грунтов, основанный на отборе проб, их сушике и взвешивании, помимо своей трудоемкости, дает локальную, часто случайную и малопредставительную информацию. Этот метод ограничен, пригоден для изучения динамики влаги, поскольку при систематическом отборе пробм буром участок, выбранный для исследования изменений влаги в почве, становится непригодным.

Почвы и грунты в отношении всех характеристик и показателей обладают пространственной изменчивостью. Поэтому изучение процессов влагопереноса в них наиболее целесообразно осуществлять в стационарных условиях, т.е. в постоянных слоях или скважинах. Исключение составляет лишь методы изучения передвижения влаги в почвах и грунтах с помощью индикаторов (радиоактивных или стабильных изотопов).

Известно, что ядерно-физические методы определения влажности и наблюдения за ее изменением, основанные на использовании гамма-лучей или нейтронов, к настоящему времени уже достаточно разработа-
ны. Эти методы свободны от ряда недостатков, присущих термометрическому и весовому методу. Основное их преимущество состоит в том, что они позволяют:

а) осуществлять наблюдения за влажностью в ненарушенных слоях почв и грунтов;
б) получать более объемную информацию, т. е. более представительные результаты измерений, что принципиально отличает их от других методов;
в) наблюдать за процессом влагопереноса и элементами баланса влаги, такими как испарение, сток, инфильтрация и др.;
г) определять влагозапасы в слоях почвы непосредственно в см водного слоя, что является весьма важным для оценки и прогноза влагообеспеченности сельскохозяйственных растений;
д) определять зоны различной степени увлажнения почв и грунтов у оросительных каналов и водоемов и следить за скоростью перемещения фронта увлажнения;
е) оценивать количество влаги, впитываемой в почву, при таянии снега, при поливах и выпадении дождевых осадков;
ж) получать информацию о влажности почв и грунтов в случае необходимости непрерывно и до больших глубин при меньших затратах труда и времени на производство измерений;
з) поддерживать оптимальные влагозапасы в почве на орошаемых землях, наиболее благоприятные для развития сельскохозяйственных культур, и наиболее рационально расходовать влагу на поля, что дает несомненный экономический эффект. Этими примерами далеко не исчерпывается перечень возможных применений ядерно-физических методов в исследованиях физических свойств почв и грунтов.

Другие методы определения влажности почв и грунтов, такие как, например, контактосмотрические, дилатометрические или гидротермометрические, в сравнении с ядерно-физическими методами менее пригодны для решения перечисленных выше задач. Градиурочные характеристики, полученные ранее для подобных датчиков влажности, не остаются постоянными во времени и испытывают изменения под влиянием минерализации "почвенного раствора", его температуры, плотности почвы и других трудно учитываемых факторов. Поэтому внимание исследователей и практиков за последние годы сосредотачивается на развитии и применении в сельскохозяйственной практике ядерно-физических методов определения влажности почв и грунтов.

В пределах дождевальной и вегетационных периодов важно иметь сведения о влажности верхнего корнеобитаемого слоя почвы. Исходя из этого, для последнего наблюдения за влажностью в этом слое наиболее доступным и простым является гамма-метод, основанный на поглощении гамма-лучей слоем почвы и находящейся в ней водой.

Этот метод является более помехоустойчивым в отношении влияния на результат измерения химического состава почвы.

Принципиальные основы гамма-метода наблюдений за изменениями влаги в постоянных слоях почвы изложены в наших работах [1-6].

Известно, что гамма-лучи, проникая сквозь вещество, испытывают поглощение и рассеяние. Интенсивность проникающих сквозь вещество гамма-лучей зависит от их первичной энергии и от массы вещества, находящегося на их пути. Если известна интенсивность $I_0$ гамма-лучей когда на их пути нет вещества и интенсивность $I_1$ когда на их пути есть
вещество с плотностью \( \rho \) и толщиной \( L \) см, то масса вещества может быть получена из соотношения

\[
\rho L = \frac{\ln I_0 - \ln I_1}{\mu}
\]

(1)

здесь \( \mu \) — массовый коэффициент поглощения гамма-лучей.

Применительно к получению слоя воды в почве \( d \) с известной толщиной слоя почвы \( h_p \) и плотности ее скелета \( \rho_s \) г/см\(^3\), формула (1) принимает вид

\[
d = \frac{\ln I_0 - \ln I_1}{\mu_p \rho_p} - \frac{\mu_s \rho_s h_p}{\mu_p \rho_p}
\]

(2)

где \( \mu_p \) и \( \mu_p \) соответственно массовые коэффициенты поглощения гамма-лучей данной энергии почвой и водой, а \( \rho_p \) — плотность воды в г/см\(^3\).

Плотность воды можно считать равной единице, а отношение коэффициентов поглощения гамма-лучей почвой и водой \( \frac{\mu_p}{\mu_b} \) для гамма-лучей \( ^{60}\text{Co} \) равно 0,9. Подставляя эти величины в формулу (2), получим

\[
d = \frac{\ln I_0 - \ln I_1}{\mu_p} - 0,9 \rho_p h_p
\]

(3)

Произведение \( \rho_p h_p \) есть масса почвы или грунта на пути гамма-лучей, которую для стационарных условий измерений можно принять постоянной. Тогда определение слоя воды (влагозапаса) в почве или грунте производится только на основе известных \( \mu_p \), \( I_0 \), \( I_1 \).

Для получения абсолютных величин влагозапаса достаточно при определении начальной интенсивности гамма-лучей \( I_0 \) измерить одновременно другим независимым способом начальный влагозапас \( d_0 \), тогда в любой другой момент он может быть найден из соотношения

\[
d = d_0 \pm \Delta d = d_0 \pm \left( \frac{\ln I_0 - \ln I_1}{\mu_p} \right)
\]

(4)

Если требуется следить только за изменением влагозапаса, то определение начальной величины влагозапаса отпадает. Для вычисления величин влагозапасов по формулам (3) и (4) заранее составляются готовые таблицы или номограммы.

Приведенные здесь рассуждения относятся к случаю, когда слой почвы "просвечивается" узким монохроматическим пучком лучей. Однако, их можно распространить и на случай использования широкого пучка гамма-лучей, если просвечивать ими слой почвы с массовой толщиной, соответствующей трем и более длинам свободного пробега гамма-квантов данной энергии. В этом случае, массовый коэффициент поглощения гамма-лучей остается практически постоянным, имеет лишь несколько меньшую величину в сравнении с теоретическим (расчетным). Для \(^{60}\text{Co} \) его значение близко к 0,040.
Применение амплитудной дискриминации позволяет получить коэффициенты поглощения гамма-лучей близкие к теоретическим.

Существует несколько вариантов устройств для наблюдений за динамикой влаги в почве при помощи гамма-лучей. Они хорошо известны. Остановимся лишь на одном из вариантов, который, по нашему мнению, наиболее пригоден для наблюдений за изменениями влаги в верхнем, корнеобитаемом слое почвы. Этот вариант позволяет следить за изменениями влаги в слоях почвы толщиной 30, 40, 50 и 60 см. Для осуществления наблюдений в весенний сезон в почву закладывают вертикально трубку небольшого диаметра (12-16 мм) на глубину 70 см так, чтобы ее верхний открытый конец выступал над поверхностью почвы на 3-4 см. В сроки наблюдений за влажностью в эту трубку вводится стальная стрелка (штырь-зонд), диаметр которого от 1-2 мм меньше внутреннего диаметра трубки. В нижнем конце штыря-зонда помещен источник гамма-лучей, а в верхнем, выступающем над поверхностью почвы, в защитных коробках, смонтированных перпендикулярно к оси штыря, находятся детекторы гамма-лучей. Опуская штырь-зонд в указанную выше трубку на глубину 30, 40, 50 и 60 см, определяют по поглощению гамма-лучей изменение влажности от одного срока наблюдений к другому в почве, соответственно в слоях 30, 40, 50, 60 см. На участке для наблюдений за влажностью может быть установлено несколько таких трубок. А для того, чтобы они не повреждались обрабатывающими почву машинами, целесообразно устанавливать их вблизи корней растений. Такой способ наблюдений за влажностью в десятки раз дешевле нейтронного и отличается своей простотой. Результаты наблюдений за изменением влаги в почве получается тут же по готовым таблицам или номограммам. На их обработку требуется несколько минут.

Поскольку при помощи гамма-лучей определяется масса вещества в г/см², заключенная между источником гамма-излучения и детектором, то гамма-метод подобен весовому методу определения влажности, с той лишь разницей, что гамма-лучами как бы вз вещается слой почвы или грунта в их естественном сложении, в то время как весовой метод требует извлечения небольшой пробы из почвы или грунта, что ненабожно связано с нарушением исследуемого на влажность грунта. К этому следует добавить, что гамма-метод позволяет осуществлять наблюдения за влагой в почве при любом ее водонасыщении и при любой концентрации соей.

Если учесть, что в нейтронном методе объемная влажность грунтов определяется в так называемой "сфере влияния", диаметр которой при влажности в 20% составляет 110 см [71], то чувствительность гамма-метода к объемной влажности при использовании гамма-лучей ¹⁰⁹соС (µ₂ = 0,0625) получается сопоставимой с чувствительностью нейтронного метода. Действительно, на 1% объемной влажности при нейтронных измерениях счет тепловых нейронов изменяется на 5%, а при определении влажности гамма-лучами он изменяется на 6,2% (рассуждения относятся к слою почвы толщиной 100 см).

Нижее, в табл.1 приведены данные определений влагозапаса в верхнем слое почвы с помощью штыревого зонда за два очередных срока наблюдений, которые были сопоставлены с одновременными определениями влагозапаса термостатно-весовым методом.

Заметим, что для слоя почвы толщиной 50 см при объемном весе ρₚ скелета 1,6 г/см³ расхождение влагозапаса на 2,4 мм эквивалентно
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0,3% весовой влажности. В этих измерениях источником гамма-лучей служил $^{60}$Co активностью 3 мг.экв.радия, а детектором гамма-лучей являлся блок параллельно включенных 4-х счетчиков типа СИ-22 т. В качестве измерительного пункта использовались пересчетное устройство. Прибор с штыврьевым зондом одновременно является и гамма-плотномером, позволяющим определять плотность почв и грунтов в слоях толщиной 30, 40, 50 и 60 см с точностью $\pm 0,015-0,020$ г/см$^3$.

Производительность определений плотности грунтов этим прибором в 25-30 раз выше в сравнении с методом отбора проб грунта режущими колбами. К этому следует добавить, что определение плотности гамма-плотномером освобождает от затраты труда на отбор проб и их взвешивание.

ТАБЛИЦА 1. ОПРЕДЕЛЕНИЕ ВЛАГОЗАПАСА В ВЕРХНЕМ СЛОЕ ПОЧВЫ С ПОМОЩЬЮ ШТЫРЬЕВОГО ЗОНДА

<table>
<thead>
<tr>
<th>Слой почв, см</th>
<th>Влагозапас в мм водного слоя по измерениям</th>
<th>термостатно-весовым методом</th>
</tr>
</thead>
<tbody>
<tr>
<td>с помощью гамма-лучей</td>
<td>термостатно-весовым методом</td>
<td></td>
</tr>
<tr>
<td>0-30</td>
<td>68,8</td>
<td>69,3</td>
</tr>
<tr>
<td>0-40</td>
<td>93,0</td>
<td>95,0</td>
</tr>
<tr>
<td>0-50</td>
<td>117,6</td>
<td>119,0</td>
</tr>
<tr>
<td>0-60</td>
<td>68,2</td>
<td>63,6</td>
</tr>
<tr>
<td>0-70</td>
<td>95,1</td>
<td>90,0</td>
</tr>
<tr>
<td>0-80</td>
<td>117,8</td>
<td>117,7</td>
</tr>
</tbody>
</table>

Ниже, на рис. 1 представлен ход влагозапаса в верхнем 25 см слое почв, полученный при помощи гамма-лучей и термостатно-весовым способом. Здесь же приведены суммы атмосферных осадков. Из рисунка видно, что в течение сезона наблюдений за влажностью величины влагозапасов, полученные тем и другим способом, между собой хорошо согласуются. Небольшие расхождения могут быть отнесены к пространственной изменчивости влажности почвы, поскольку контрольные пробы на влажность отбирались каждый раз в другом месте около установленной трубы.

Удовлетворительная точность определений влажности методом по- глощения гамма-лучей в слое почвы толщиной 50 см может быть подтверждена и опытами по наблюдению за испарением влаги с поверхности почвы в испарителях. В одном из последних опытов по определению испарения с помощью гамма-лучей был использован испаритель ГГИ-500-50, который имеет высоту 50 см и площадь поверхности испарения 500 см$^2$. Под дно этого испарителя был заложен источник гамма-лучей ($^{60}$Co) в коллиматоре, а сверху над испарителем помещался блок параллельно включенных газоразрядных счетчиков типа СИ-22 г на
строго фиксированной подставке. Каждый раз при определении испарения влаги с поверхности почвы в испарителе при помощи гамма-лучей последние взвешивался на весах. Результаты параллельных определений величин испарения нанесены на график (рис. 2). Из рисунка видно, что за весь сезон наблюдений разница в величинах испарения не превышала 1,7 мм, что эквивалентно 0,2% весовой влажности. Оценку влажности с такой точностью во всем 50 см слое почвы в испарителе вряд ли можно получить другим каким-либо способом, кроме весового. В дополнение к ранее опубликованным данным [5] приведем сравнительные вели-

Рис. 1. Влагозапасы, полученные для 25 см слоя почвы при помощи гамма-лучей и термостатной сушики проб почвы.

Рис. 2. Величины испарения воды с поверхности почвы, полученные для весового испарителя типа ГГП-500-50 при помощи гамма-лучей и весового способа.
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ТАБЛИЦА II. СРАВНИТЕЛЬНЫЕ ВЕЛИЧИНЫ СУММАРНЫХ ВЛАГОЗАПАСОВ

<table>
<thead>
<tr>
<th>Дата измерения</th>
<th>Влагозапасы в мм водного слоя</th>
<th>Разница</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Измеренные гамма-методом</td>
<td>Полученные термостат-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ной сушкой</td>
</tr>
<tr>
<td>20. V.I</td>
<td>304</td>
<td>311</td>
</tr>
<tr>
<td>10. V.II</td>
<td>302</td>
<td>309</td>
</tr>
<tr>
<td>19. V.II</td>
<td>290</td>
<td>313</td>
</tr>
<tr>
<td>30. V.II</td>
<td>292</td>
<td>287</td>
</tr>
<tr>
<td>8. V.III</td>
<td>292</td>
<td>292</td>
</tr>
<tr>
<td>18. V.III</td>
<td>280</td>
<td>282</td>
</tr>
</tbody>
</table>

Чины суммарных влагозапасов в мм водного слоя, полученных по огло- шению гамма-лучей и термостатно-весовым методом для слоя почво- грунта толщиной 100 см (табл. II).

Метод наблюдений за изменениями влаги в верхнем слое почвы с помощью гамма-лучей особенно полезен для орошаемых земель, поскольку в этом случае удаётся следить за накоплением влаги в почве во вре- мя поливов и за её расходом между поливами.

Нейтронная влагометрия в СССР используется в мелиорации, почво- ведении, агрохимии, гидротехники, гидрогеологии, почвенной гео- логии, гидротехническом и дорожном строительстве и в других областях, где возникает необходимость в определении влажности грунтов.

Если гамма-метод наблюдений за влажностью применён для верхне- го слоя почвы, то нейтронные влагомеры используются для исследования влажности во всей зоне аэрации, т. е. до уровня грунтовых вод. Исключением составляет лишь самый верхний слой почвы на полигонах землях, где в силу больших градиентов влажности правильная интерпретация результатов измерений влажности нейтронным влагомером становится затруднительной [8]. Надежность нейтронных определений влажности обеспечивается тогда, когда градиуровка зондов нейтронных влагомеров производится в моделях тех грунтов, в которых в дальнейшем предполагается осуществлять определение влажности. Хотя таким способом градиуровки и удается свести к минимуму влияния на результат измерения влажности аномальных поглотителей тепловых нейтронов, таких как бор, хлор, кадмий, железо, марганец и др., все же полностью избавиться от него не удаётся, особенно при площадной съемке влажности на исследуемой территории. При режимных наблюдениях в постоянных скважинах нейтронная влагометрия обеспечивает высокую воспроизводимость результатов измерений при меньших затратах труда и времени. Как показали выполненные нами полевые измерения влажности при использовании Pu-Be источника быстрых нейтронов, исключающего 4·10^6 м/сек, и щитового детектора типа ЛНДМ [9], на одно измерение требуется всего 20-30 сек. Статистическая погрешность в счете тепловых нейтронов в этом случае была порядка 0,5-0,7%. Детектор ЛНДМ имеет в качестве световода оргстекло цилиндрической формы с радиально
размещеными пазами, которые заполнены светосоставом, изготовленным на основе сернистого цинка, активированного серебром [ZnS(Ag)], и борного ангидрида (B₂O₃). Стабильность работы двух нейтронных влагомеров, использованных в полевых наблюдениях за режимом влаги в постоянных скважинах, характеризуется среднеквадратичным погрешностями. Для первого прибора эта погрешность, вычисленная на основе 44 измерений, оказалась 0,15%, а для второго — 0,41%. Считаясь с возможным влиянием на результат измерения других, трудно учитываемых факторов, можно допустить, что погрешность измерения равна 3 ± (при доверительном интервале — 90%), т. е. 1,23%.

В практике инженерно-геологических исследований под мелоративное строительство успешно применяются пентационно-каротажные самоходные установки [6], в которых каротажные зонды в рыхлый грунт вдавливаются до глубины 15-20 м, нагрузкой до 10 т.

Такой способ погружения зондов обеспечивает их надежный контакт с породой и исключает образование каверн, которые, как известно, могут вносить существенные погрешности в результаты измерений.

Для режимных наблюдений за изменениями физических характеристик почв и грунтов (плотность, влажность, пористость) под влиянием мелоративных мероприятий пентационно-каротажные станции менее пригодны. В этом случае более успешно режим изменения указанных выше характеристик может изучаться путем систематического опускания в постоянно оборудованные скважины каротажных зондов для регистрации плотности и влажности грунтов. В нашей практике скважины для режимных наблюдений обсаживались стальными двухъярусными трубами. Вдавливание их вертикально в грунт осуществлялось статической нагрузкой или забивкой в скважину, предварительно пробитую буровым станком. Для исключения образования каверны и обеспечения плотного контакта трубы с породой проходка скважины выполнялась на 3-5 мм диаметром меньше, чем обсадная труба. Хотя стальные трубы с толщиной стенок 3-4 мм уменьшают счет тепловых нейтронов, использование их, тем не менее, является приемлемым, поскольку трубы из других материалов труднее забивать в грунт или вдавливать под большими нагрузками.

Широкое использование нейтронной влагометрии было осуществлено в районах строительства Каховской оросительной системы для изучения процессов промачивания грунтов около оросительных каналов и степени их увлажнения на разных расстояниях от этих каналов, а также для определения пористости. Нейтронные влагомеры и гамма-гамма-картограф площади были применены и для оценки устойчивости болочных земляных дамб Северо-Крымского канала против размывов. Здесь выявились новая область применения ядерно-физических методов в гидротехническом строительстве.

На Каховском оросительном массиве в летне-осенний сезон 1968 года было произведено двумя приборами нейтрон-нейтронного и гамма-гамма каротажа около 40 тыс. измерений плотности и влажности грунтов в постоянных скважинах до глубины 16-20 м. Стоило большое количество измерений вреда ли возможно было выполнить другими методами.

Экономический эффект от использования только этих двух приборов в течение одного сезона измерений плотности и влажности грунтов составил около 50 тыс. руб. Результаты исследований скорости просачивания воды из оросительного канала и водоема в лесосидных суффозиях
с помощью нейтронов были изложены в нашем кратком докладе, зачитанном на симпозиуме, состоявшемся в марте 1972 года при МАГАТЭ.
Коротко эти результаты сводятся к следующему:
1) скорость движения "фронта промачивания" в лессовидных суглинках вблизи оросительных каналов составляет 0,3-0,5 м/сутки;
2) степень водонасыщения грунтов у оросительного канала достигает величины 0,6-0,86, что по-видимому объясняется наличием воздуха, оставшегося в порах грунта;
Рис. 4. Изменение влажности грунта вдоль обсаженной скважины по измерениям нейтрон-ным влагомером (скачкообразное возрастание влажности на глубине 6 м соответствует уровню грунтовых вод).

3) зона увлажнения грунтов у оросительного канала в лессовидных суглинках не распространяется далее 20 м и лишь на глубине 16 м она достигла расстояния в 37 м;
4) оценка пористости методами гамма-гамма и нейтрон-нейтронного каротажа хорошо подтверждается контрольными определениями плотнос-

тин и влажности грунта методом отбора проб, их сушки и вз вещивания, на основе которых параллельно была вычислена пористость;
5) движение "фрона промачивания" в лессовидных суглинках у кан-

ала хорошо отмечается по скачкообразному возрастанию влажности на
ОПРЕДЕЛЕНИЕ ВЛАЖНОСТИ ПОЧВ И ГРУНТОВ

tой или иной глубине в скважинах, находящихся на известном расстоянии от канала или водосбора после запуска в него воды (рис. 3).

Устойчивость земляных боковых дамб оросительных каналов оценивается по характеру распределения влаги в скважинах, заложенных на этих дамбах. Если от одного срока наблюдений к другому на какой-либо глубине будет отмечено резкое возрастание влажности до состояния полного насыщения грунта и одновременно с этим замечено уменьшение плотности, например, за счет выноса частиц грунта или растворения в нем гипсовых и других включений, то это укажет на неустойчивость дамб и на возможность ее размыв.

Нейтронная влагометрия позволяет определять уровень грунтовых вод непосредственно в породе, т.е. в заскважинном пространстве, когда каротажный зонд нейтронного влагомера спускается в сухую, обсаженную трубой скважину. Последнее важно потому, что фильтры пьезометров могут кольматироваться и уровень воды в пьезометрической скважине может поэтому не соответствовать действительному уровню.

Пример таких замеров уровня в обсаженных скважинах с помощью нейтронного влагомера представлен на рис. 4. На глубине 6 м в песчаной среде влажность возросла до величины, соответствующей водонасыщению песка. Контрольные замеры уровня воды в соседнем пьезомете показали, что уровень воды находится именно на этой глубине.

Следовательно, режимные скважины, обсаженные закрытыми снизу трубами, могут служить не только для наблюдений за влажностью в окружающих их почво-грунтах, но и за колебанием уровня воды в песчаных и супесчаных породах.

Практический опыт использования гамма-лучей и нейтронов для наблюдений за влажностью почв и грунтов показывает, что оба метода могут успешно применяться в сельском хозяйстве.

Для наблюдений за изменениями влаги в верхнем 50-60 см слое почвы целесообразно применение метода, основанного на поглощении гамма-лучей, который позволяет получать информацию о влагозапасе в почве непосредственно в см или мм водного слоя при условии одного (начального) определения влагозапаса другим независимым способом, например, термостатной сушкой проб почвы. Этот метод дешевле и проще нейтронного.

Чувствительность метода не зависит от степени увлажнения почвы и от ее химического состава.

Нейтронная влагометрия позволяет определять влажность почв и грунтов во всей зоне аэрации до уровня грунтовых вод с достаточно высокой воспроизводимостью результатов измерений, при условии градуировки зонда влагомера в тех грунтах, в которых в дальнейшем предполагается осуществлять измерения влажности.

Нейтронные влагомеры были успешно применены для изучения изменений влаги в почво-грунтах в районах гидромелиоративного строительства и у оросительных каналов, а также в земляных боковых дамбах магистральных каналов для оценки их устойчивости.

Экономический эффект от использования только двух нейтронных влагомеров при массовых измерениях в течение сезона составил около 50 тыс. рублей. Определение влагозапаса в верхнем 50 см слое почвы при помощи гамма-лучей освобождает от труда по отбору проб почвы, их сушки и взвешивания и требует на одно измерение небольшой затраты времени (3-4 мин).
ДАНИЛИН

ЛИТЕРАТУРА


DISCUSSION

D.R. NIELSEN: When the cobalt-60 source is placed at 2 m depth what would be the counting time required to measure water with the accuracy and precision that you have indicated?

A.I. ДАНИЛИН: There are two possibilities for determining the water down to a depth of 60 cm, first using the vertical depth probe where you have gamma ray detectors at the surface, and, second, where you scan a layer of soil between two tubes. The vertical method will not be good except to a depth of 60 cm. At greater depths the absorption will be too strong. If you have a depth of 60 cm you have to increase your counting time by a factor of 2 to 4 from what it would be at shallower depths. It depends on what kind of statistics you want to accumulate. If we want to measure the water in deeper layers we scan the soil in horizons between two tubes which are 40 to 50 cm maximum distance apart and we can use a source with an activity of about 2 mCi and in two minutes we have a count which is about 10,000. But this, of course, can be calculated; I do not quite remember exactly the number of counts. So, it doesn't make any difference whether it is 2 or 4 m, because we use a horizontal beam at any depth in the soil.

D.R. NIELSEN: Do the engineers or the fluid mechanics people in your country use the method which you have described using a cone with a source and detector to measure the depths of water flowing through water conveyance or measuring structures? In our country we have many engineers who use little hub-gates to measure the level of water flowing through a channel. Of course, the water fluctuates and, by using gamma attenuation, you can measure very accurately and obtain integrated values of the depths of water much more accurately than by conventional mechanical means. Do your scientists or engineers in Russia use this method for water conveyance structures?
A.I. DANILIN: The method of determining the water level by the absorption of gamma rays is being used in the Soviet Union in engineering techniques, but in order to accurately measure the fluctuating water level it is appropriate to scan a thin layer. As a surface detector they use soft emitters with a small gamma energy. One can make precise measurements, but if we use beta particles near the level of the water we can study the rate of evaporation from the water surface with high sensitivity. The method of determining the water level by means of gamma rays as the basis of absorption is in fact being used in the Soviet Union, and special equipment has been developed for that purpose.

W. KÜHN: If one uses cobalt-60, a high energy, then we can see that the mass absorption coefficients of soil and water are not very different. Therefore we have only the Compton effect and not the photo effect. Did you take this into consideration in these equations?

A.I. DANILIN: In our method of following the dynamics of moisture there is no need to determine separately the mass absorption coefficient for the water or the soil. It is not necessary to separate these coefficients. The effect of mass coefficient for a broad gamma ray would be practically the same for water and for the mass of the soil. The method of measurement makes it possible to determine the intensity of the gamma rays which go through a cylinder if we know the initial water content, thus you are linking the initial intensity to the water which is contained in the soil. Then you just follow the dynamics controlling the water layer which is changing. Thus the soil as such, or the mass, would not be of any interest. Only the variations in the intensity of the gamma rays due to water changes in the soil are of interest. If we measure, for example, at a length of 1 m we must have a reference or zero point. The zero point is the initial water content which we determine by another independent method only once or twice during a season. Then all the calculations are done in the normal way. The mass absorption coefficient for such measurements where we use gas discharge detectors of special construction rather than scintillation detectors is almost 0.0036, that is less than the present theoretical coefficient.

J.C. COREY: I think it might be interesting to the panel if you could go into a little more detail on your neutron detector. I think most of us are familiar with, say, a boron-trifluoride tube, or boron-10 or helium-3 detectors, but not too many are familiar with your zinc-sulphide detector. Could you tell us a little bit about that and its advantages over the other types, please?

A.I. DANILIN: The boron detectors require very high voltage, 1400 volts or more. We use a photomultiplier in connection with the zinc-sulphide detector which I have mentioned, which requires a voltage of about 1000 volts, a bit lower. It is about the same as we need for proportional counters. The efficiency of thermal neutron counting using this detector, which we call LD, is not very high, as it is assessed by comparing it with a scintillation detector for gamma rays of the type using thallium-activated sodium-iodine. The difference in the efficiency is not very great. In our measurements we have used detectors with a diameter of 30 mm and a height of 30 to 40 mm as well as detectors of smaller size. These detectors use a light guide made of organic glass which is less fragile, less brittle or more robust, than the other neutron counters, and we consider that these detectors are
very convenient detectors. The BF-3 detectors, which we call SNM, with different diameters are also being used for the counting of thermal neutrons when there is a change in the water content. We must have a detector very near to the neutron source to have a good set-up for measurement; for example, for Samatky argil clay where we could have present up to 70% moisture on a weight basis we were still able to use this detector to carry out our measurements. We can reproduce measurements easily with our equipment. If the characteristics of the photomultiplier and detectors change, that is a bad thing, but there is a possibility even to get around this if we take it into account by using the proper calibration. Using the type of detector and the probes I have described, we were able during the whole season of May through October to make measurements in deep horizons with a high reproducibility of results. If we carry on our experiments from one period to the other then the final curve can exactly be superimposed on the initial curve.

M. ABDALLA: When considering your Figure 1 I think that you have a soil with a high moisture retention power which is indicative of the type of clay. What is the role of the inter- and intra-micellar expansion which may arise with different cations in the exchange complex on the readings of the apparatus?

A.I. DANILIN: The chemical processes that are going on in the soil layer through which the gamma ray passes do not have any effect on the measurements. I should like to repeat again that we determine the mass which is in the path of the gamma rays between the source and the detector; and, irrespective of the chemical processes that are going on, if they do not change the total content of matter or mass then the intensity of the gamma rays will be the same. It can only change in the case where part of the mass or the matter is removed; for example, for a vertical beam the mass must remain constant and there must be no such processes as erosion of the particles in the upper layer. The cation exchange could not possibly have any effect on the results of the measurements. Perhaps there can be a migration of salts. That is possible, of course, but the quantity would be so small that it would not have any substantial effect on the measurement of the water content.

J. DAMAGNEZ: What is the influence of the ruggedness of the soil? The method of using a vertical gamma ray through a layer of soil does require that after initial calibration nothing should change, that conditions should remain static. If the total content of mass changes between measurements then you will again have to make a kind of re-determination to determine the initial water content and refer your measurements to your point of departure. The coefficient, of course, is known and this coefficient is the effective coefficient for a given set of experimental conditions and it really remains practically constant.

P. COUCHAT: I have read very recently in a bibliography that you have replaced the method of measuring thermal neutron flux on the basis of the neutron reaction with cadmium and an end window gamma ray counter by a similar measurement of the thermal flux using the reaction of neutrons with tungsten. Do you have information on this?

A.I. DANILIN: The use of tungsten shielding does not really have anything to do with the water content measurements using thermal neutrons. This is being used in order to determine the density of rocks in the ground by measuring scattered gamma radiation. If we would bring a gamma
ray source close to the detector, say, at a distance of 4 or 5 cm, then we would get a dependency of the gamma ray count which would be practically linear and would decrease as a function of density, but in normal borehole logging when the density goes up the gamma ray count goes down. Tungsten has a density of about 19 g/cm³ and by its use it is possible to put the gamma source very near to the detector so as to get a linear function, and this is the advantage of the probe. Unfortunately, however, this probe is not yet widely used.
MOISTURE MEASUREMENT IN THIN SOIL LAYERS
BY ABSORPTION OF GAMMA RAYS
IN A CAPILLARY POROUS BODY

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Abstract

MOISTURE MEASUREMENT IN THIN SOIL LAYERS BY ABSORPTION OF GAMMA RAYS IN A
CAPILLARY POROUS BODY.

Water content in thin soil layers is measured indirectly by measuring water content of a capillary
porous body in contact with the soil using gamma-ray attenuation. Water content is inferred by taking
the slope of a curve giving measured pulse rate of gamma rays passing through the porous body as a
function of time. Equipment is described.

1. INTRODUCTION

It has been found repeatedly that there is a need for continuous moni-
toring devices, independent of environmental influences, in investigations
of soil moisture content in connection with agricultural irrigation projects.
Nowadays neutron probes as well as gamma probes, based on the principle
of thermalization and scattering of neutrons and gamma rays, are available.
The mode of working of these probes has often been described. However,
even these modern devices are affected by some environmental conditions,
so they are unusable in some special cases. One of these is the measure-
ment of the water content in thin soil layers not far below the surface in
relatively low concentrations of about 4-8%, as is often the case in arid
climates. For this purpose we have devoted some attention to the question
whether it is possible to measure the moisture content indirectly by means
of a capillary porous body consisting of clay silicates, placed in a gamma-
absorption equipment. If such a porous body is in contact with the soil the
exchange of water between soil and porous body should be measurable by
attenuation of the gamma radiation.

2. THE THEORETICAL FOUNDATIONS

From the physical viewpoint, soil is a structure of solid components
traversed by pores. The volume of all these pores is called the pore
volume, depending on the specific weight and on the grain structure. The
specific weight of a soil is its density with the pores included. Another
characteristic of a soil is its average pore diameter, decreasing with in-
creasing specific weight. When a dry soil is soaked by water, the water
will be first absorbed by the surfaces of the grains until the surface power
is saturated, and more added water is sucked by the pores of the soil until
the whole pore volume is filled. The water in the pores is held by the capillary potential \( \psi_c \) arising from the surface tension of the water.

\[
\psi_c = \frac{2\alpha}{\rho \cdot r_c}
\]

where

\( \alpha \): surface tension of H₂O,
\( \rho \): density of H₂O,
\( r_c \): pore radius.

If the distribution function of the water-filled pores is \( f_w(r_c) \), with the radius \( r_c \) at the moisture content \( w \), then the average capillary potential of the soil is given by

\[
\overline{\psi}_{cw} = \frac{2\alpha}{\rho} \int_{r_{\text{min}}}^{r_{\text{max}}} \frac{f_w(r_c)}{r_c} \, dr_c = \frac{2\alpha}{\rho} \left\langle \frac{1}{r_c} \right\rangle
\]

(1b)

In this equation \( \left\langle 1/r_c \right\rangle \) is the mean value of the reciprocal capillary radius. Its value depends on the specific weight \( \rho \) and on the moisture content of the soil. For this reason \( \overline{\psi}_{cw} \) is a function of \( w \) and \( \rho \). The extraction of water from the soil requires therefore a potential \( \psi_D \) greater than \( \overline{\psi}_{cw} \). As \( \overline{\psi}_{cw} \) increases with lower moisture content, \( \psi_D \) can only remove water from the soil until equilibrium with \( \overline{\psi}_{cw} \) is reached. Otherwise the average velocity of the water movement \( \bar{u} \) follows the Hagen-Poiseuille-Law and the velocity of a fluid through a tube is proportional to the difference \( \psi_D - \overline{\psi}_{cw} \), given by Eq. (2)

\[
\bar{u} = \text{const} \cdot (\psi_D - \overline{\psi}_{cw})
\]

(2)

The Eqs (1b) and (2) connected with the known equation for \( \gamma \)-absorption

\[
I = I_0 \cdot \exp \left\{ -\left( \frac{\mu}{\rho} \right) (\rho \cdot d) \right\}
\]

(3)

where

\( \frac{\mu}{\rho} \): mass absorption coefficient,
\( \rho \cdot d \): weight per unit of area,

are the theoretical suppositions of the principle.

A capillary porous cylinder with a definite pore volume and a given average capillary radius \( r_D \) with definite average capillary potential \( \overline{\psi}_{cw} = 2\alpha/(\rho \cdot r_D) \) is, for example, put in a horizontal position into the soil. At the front of the cylinder a \( \gamma \)-source is attached while at the other side there is a scintillation counter. In the case \( \overline{\psi}_{cw} > \overline{\psi}_{cw} \), the porous body will suck water from the soil and therefore it increases its weight-area causing a reducing pulse rate at the detector in accordance with Eqs (3a, b)
\[ I_1 = I_0 \cdot \exp \left[ -\frac{\mu}{\rho} (\rho \cdot d)_{H_2O} \right] \]  (3a)

\[ I_2 = I_0 \cdot \exp \left[ -\frac{\mu}{\rho} [(\rho \cdot d)_{H_2O} + (\rho \cdot d)_{H_2O}] \right] \]  (3b)

\( I_0 \) \text{: counting rate without the porous body,}
\( I_1 \) \text{: pulse rate with dry cylinder,}
\( I_2 \) \text{: pulse rate with cylinder and \( H_2O \),}
\( \mu \) \text{: mass absorption coefficient of water and cylinder (nearly equal, when \( ^{137}Cs \) is used),}
\( \rho \) \text{: weight per unit area of the dry cylinder and the water.}

As the average penetration velocity \( \bar{u} \) of the water is proportional to the increase of the weight per unit area in the porous body

\[ \bar{u} \sim \frac{d}{dt} (\rho \cdot d)_{H_2O} \sim \frac{d \log I_2}{dt} \]  (4)

the slope of the curve \( I_2 = f(t) \) measured by a recorder will be a measure of the moisture content.

3. EXPERIMENTAL CONTEMPLATIONS

At the beginning of our investigations there was first the question of the reproducibility of the moisture measurement with different porous bodies of the same material; also the sensitivity, i.e. the relative variation of the intensity per relative variation of the weight per unit area, depending on the length of the body. Furthermore there was the particular interest in the volume of sensitivity of this body, i.e. the spatial 'resolving power' which is very important for the measurements in thin soil layers. And finally there arose the question of the spacing of such cylinders in a soil profile.

First of all the need to use thin cylinders for good spatial resolution is obvious. From this view and based on technical reasons we used capillary porous cylinders 14 to 15 mm in diameter.

We examined about 17 bodies having different chemical constitution. The pore diameters of these materials were in the range from 1 to 90 \( \mu_m \). Those bodies showing a pore diameter of more than 40 \( \mu_m \) were unusable, because there could arise an obstruction by the grains of the soil. Otherwise those materials have only a small capillary potential, about \( \sigma < 7.3 \times 10^4 \text{erg/g} \), which is only suitable for large-grained soil.

Finally a test with a given sand shows only three capillary porous bodies to be convenient. But only one kind has a sufficient constancy of the pore diameters showing reproducibility of the measurement. This one consists of a silicate with an average capillary radius of 9 \( \mu_m \) and a pore volume of 50%.

The sensitivity following from Eq. (3b) is

\[ E = \frac{\Delta I_1}{I_2} \frac{\Delta (\rho \cdot d)}{\rho \cdot d} \left( \frac{\mu}{\rho} \right)_{H_2O} = \frac{\mu}{\rho} (\rho \cdot d)_{H_2O} \]  (5)
where $E$ depends on the water content in the body, i.e. on the filled pore volume, on its length $d$, and on the mass-absorption coefficient $(\mu/\rho)$, i.e. on the $\gamma$-energy. For example, $E$ was 40% taking $^{137}\text{Cs}$ ($661$ keV), when the cylinder had a length of 100 mm and a diameter of 14 mm. With the view to increase $E$ we later used an $^{241}\text{Am}$ $\gamma$-source (60 keV), getting a much higher sensitivity. A larger cylinder would be unsuitable, because the volume of the measurement should not be large.

The spatial resolving power, i.e. the volume which contributes to the measurement, is determined as shown in Fig.1. This figure shows that the minimal thickness of the soil layers is less than 40 mm until there is no influence on the slope of the curves, whereas a thickness of only 15 mm gives a very different result.

From a practical viewpoint, the economy of this method is not negligible. Although the porous cylinders are the most stressed parts of the whole equipment, it is possible to clean and to regenerate the porous material and to use the single body very often.

4. MOISTURE MEASUREMENTS ON TWO DIFFERENT KINDS OF SAND

Moist sand is filled into a small container and a capillary porous cylinder in the horizontal or vertical position between the $\gamma$-source and the detector is at its centre. The electrical equipment consists of a single-channel analyser with ratemeter, the scintillation counter, and a recorder. The penetration of the water into the cylinder is continuously recorded by monitoring the intensity of the $\gamma$-rays. Figure 2 shows some of these curves, where the high resolving power for moisture measurement between 1.5 and 10 wt% $H_2O$ can be seen. From this figure the moisture content could be approximately determined. For an exact
FIG. 2. Moisture measurement in sand. Calibration curves $I_t = f(t)$.

FIG. 3. Moisture measurement in sand. Penetration velocity $\Pi = f(\% H_2O)\$

$\times$: large-grained sand

$\Delta$: small-grained sand
determination of the water content the pulse rate $l(t)$ is drawn on the logarithmic scale. After about 1 to 1.5 hours these curves have a straight part (see Eq. (4)); the gradient as a function of wt% $H_2O$ is shown in Fig. 3 for two different kinds of sand. This figure makes already clear the difference between two soils caused by their different grain structure effecting variable capillary potentials. A dependence on the soil’s specific weight could not be noticed in this case. The exact determination requires about 2 to 4 hours utilizing the whole sensitivity of the method of about ± 0.1 wt% $H_2O$. This relatively long time is necessary for scientific soil- and irrigation studies only, whereas for agricultural purposes calibration curves like the ones shown in Fig. 2 should be sufficient.

5. MOISTURE MEASUREMENTS IN LOESS

In the range of from 1-10% $H_2O$ the capillary potential of loess can rise to $10^7$ erg/g and more. Such high values of the potential are not given by capillary porous materials. It is therefore impossible to extract water from loess by such materials, as we have seen. Equation (2), however, can also be interpreted in another manner: a soil having $\psi_{cM}$ extracts water from a capillary porous body with a potential $\psi_D < \psi_{cM}$. The problem of moisture measurement in loess could therefore be solved by a capillary porous hollow cylinder ($15 \times 10 \times 100$ mm), filled with water, inserted in

![Diagram](image-url)

**FIG. 4**. Moisture measurement in loess. Scheme of the whole equipment.
FIG. 5. Moisture measurement in loess. Calibration curves.

Abscissa = pulse rate of the density measurement;

Ordinate = gradient of the function $C_1 = f(t)$.
a vertical position into the soil. The loess sucks the water from the surface of the cylinder while new fluid continually passes through the cylinder wall. Thus the water column inside the body decreases and hence the pulse rate increases. For this case only very fine porous material can be taken into consideration, as the hydrostatic pressure of the water column should not lead to any loss of water during the measuring time. A suitable material was again a ceramic one with a pore diameter of only 0.5 μm and a pore volume of 48%. It should be noted that we could increase the sensitivity, E, with an $^{241}$Am γ-source up to a factor of 2.5. As the given loess is very highly compressible (0.9–1.4 g/cm$^3$) the measurement is influenced by the specific weight of the soil. Therefore we constructed a density measurement based on the principle of γ-ray back-scattering for this purpose too. The whole equipment for the moisture measurement is shown in Fig. 4. The density test probe is at first pushed into the soil. The porous cylinder is inserted into the same bore-hole after the density determination. Thus the density is measured at the same point as the moisture content is determined. Figure 5 shows the calibration curves for the moisture content in loess with the very high sensitivity of the method.

It is planned to use the equipment especially in arid soils to measure the water content in low concentrations and in distinct thin soil layers below the surface.

**DISCUSSION**

D. KIRKHAM: As I understand it your unit is something like a Bouyoucos block, a small plaster-of-paris block with two electrodes in which one measures the resistance change due to the moisture change in the block. Now, here, as I understand it, the plaster-of-paris block is replaced by a clay cylinder and instead of using electrical wires to measure resistance change Dr. Kühn sends gamma rays through which measure the moisture that has been picked up by the porous block. The purpose of this — as I see it — is that you can measure in a thin layer. I would like to know the advantage of this over the simple plaster-of-paris block where you measure resistance change. I can see one advantage here, at least. With the plaster-of-paris blocks, if you had a high salt content there would not be enough buffering action of the calcium in the plaster-of-paris to eliminate the effect of salt on resistance. With Dr. Kühn’s unit you don’t care about any fertilizers or anything else because your gamma rays are calibrated against moisture content. Also, the plaster-of-paris blocks work best when the soil is rather moist. You can work this unit over a whole range, which would be an advantage.

W. KÜHN: I agree that the salt content in the soil is a disadvantage to the electrical conductivity measurement. This nuclear method permits us to measure in thin layers.

J. C. COREY: I have two questions. First, have you used this in the field or is it still in the laboratory? Second, if you were going to use it in the field, in how many locations in a profile could you place it?

W. KÜHN: We have not used it in the field; we have worked out just the method. Now we intend to go into the field and we believe that we can use it in four or five places in a profile, and perhaps more.
D. HILLEL: It is a characteristic of a porous body that there is a certain relationship between the potential or the suction of the water, the number of pores filled, and the degree of saturation. If you use a clay body then in most cases the clay will remain saturated until there is a considerable suction or considerable tension developed in the soil surrounding the clay. This means that throughout the moist range, which may be of greatest interest in irrigation and field studies, the porous clay plug would probably remain saturated. And, any method of measurement designed to determine the water content of the clay would not register any sensitivity in the wet or low-tension range. This was, in fact, the case with the old Bouyoucos blocks. They were not sensitive in the wet range, but were more so in the drier range, which was again of lesser interest in field studies. Have you given any attention to the problem of designing the porous plug so as to have a wide range of pore sizes and to increase the sensitivity to small changes in the water content of the surrounding soil?

W. KUHN: Yes, thank you, I know this problem. We use four types of cylinders differing in porosity, since the water potential depends on the diameter of the pores.

D. HILLEL: As I understand it you want the clay plug to resemble the soil, except that it must have a constant density, that is, it must not swell or shrink, but resemble the soil as much as possible in other characteristics.

H. KEPEL: Why have you used caesium and not a source material of lower energy so that the absorption would be higher and the sensitivity would be much higher?

W. KUHN: This is what we will do now, we intend to use lower energy, and we can use smaller clay volumes.

J. DAMAGNEZ: I would like to ask a question which is related to the time response of the unit and to the variation in the time of response according to the soil characteristics. Since this is a porous cylinder you must have a certain hysteresis. Will the response be the same when you have a humidified soil and a soil under desert humidification? This is what we observe with the Bouyoucos block. The response of a porous system subject to hysteresis will be different according to where the soil is placed.

W. KUHN: Yes, you have a certain hysteresis, but the behaviour of such a cylinder is the same as that of a tensiometer. Concerning the penetration of the water vapour and the loss of water to the clay in the cylinder, it is the same situation that you have with tensiometers. Only here you measure attenuation of gamma rays.

J. DAMAGNEZ: However, with a tensiometer you can measure the pressure and the response as regards the pressure. The tensiometer responds much faster to the variation of humidity or moisture.

P. REINER: Well, in fact this is a tensiometer. At least at equilibrium it corresponds to a certain vapour pressure or to a certain tension. One should, perhaps, if one wants to use it, calibrate it in tension units. If you know the pore size distribution you could devise tensiometers for various ranges. But, of course, the problem of equilibrium remains, you don’t know exactly where you are. One may perhaps try to calibrate it against vapour pressure in the very low range. I would also like to ask how you propose to move this around in the field. It seems quite complicated to me.
W. KÜHN: It may be, but we have had no other method until now with which to measure the water content of thin layers continuously, except for electrical conductivity, but no nuclear techniques which can measure the water content in such layers.

J. C. COREY: Referring to the experiment where you dry the surface of the soil at 35°C, in my experience there is a temperature dependence on the response at the detection end of the apparatus. Was your sodium iodide detector shielded from these temperature effects, or was it exposed as well to a change in temperature? What I mean is, as you heat up your detector the spectrum response changes. The end result is that you can be showing a loss in count rate which is due to nothing except temperature effects. This is one of the real problems of taking a gamma apparatus of any sort to the field or outside of a temperature controlled situation. It is why the dual gamma apparatus which is available for looking at water content changes is not as satisfactory as we might have hoped. However, there is work being done to improve it. Are you aware of these temperature problems?

W. KÜHN: In these experiments we have had no temperature increase near the scintillation counter.

A.I. DANILIN: This is a comment rather than a question. Of all the methods we know about the gammascopic method is the only one which enables us to determine or to assess the mass of non-disturbed substance in soils and sub-soils. Therefore, we are able to evaluate this non-disturbed mass which is on the path of the radiations. We can write the well-known exponential relationship for gamma-ray absorption in any porous substance. If the mineral density remains constant then the thickness of the layer of water may be obtained from a simple calculation from the intensity of the transmitted ray. If the mineral density is not constant then it is not so easy. I think that Dr. Kühn has a very good approach to solving this problem, but the method proposed may be difficult to adapt to field conditions.

J. DAMAGNEZ: In the general field of measurements it is always difficult to adopt as the parameter of measurement a dynamic phenomenon. Dynamic phenomena can be influenced not only by the characteristics of the measuring instrument but also by the environment. For example, the dynamics of water entry into a porous substance like soil will depend upon the dynamics of water already in the soil. Therefore, from a physical point of view it is always better, where possible, to make a measurement in the static state rather than in the dynamic state.
COLLIMATION OF
A 60-keV COLUMN SCANNER*

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Abstract
COLLIMATION OF A 60-keV COLUMN SCANNER.
Collimation of 60 keV americium-241 gamma rays, as used in a soil column scanner for water content,
is described. Lead collimators 2 mm thick, on both source- and detector-side were the final choice deter-
mined from experience.

In 1968 a soil column scanner was built by the Institute for Atomic Sciences in Agriculture in co-operation with the State Agricultural University of Wageningen. This communication represents the experiences with americium as the gamma source and its collimation.

In 1968 the demands for the column scanner were; (a) to permit fast measurements (which means low counting time) with high accuracy, making it possible to measure fast infiltration phenomena; (b) to permit selective measurements of 1 mm disc thickness; (c) to make possible measuring 2 m long columns in a vertical as well as a horizontal position. We chose to use americium-241 which emits mainly 60 keV energetic photons. The optimum column thickness is about 4 to 5 cm. Therefore, long columns are still of light weight and are easily handled. Shielding for the low energetic gamma rays is of light weight, so that the entire column scanner would be of light structure. Our source (231 mCi 241Am in oxide form) was packed in a slit of 1x10 mm size. Due to the self-absorption of the low energetic photons, the resulting intensity is only 2 per cent less than the intensity at infinite source thickness. This source thus provides the highest possible count rate.

Before measuring water content in soil columns one problem must be solved. As is well-known, the water content is calculated from two countings using Beers law, \( I_o = I_0 e^{-\mu t} \). This law, however, is only valid for narrow beam geometry, so that only the decrease in the intensity of mono-
energetic gamma rays had to be counted. Obviously, we must collimate the detector so that almost no scattered photons can reach the detector. The usual alternative method for high energetic \( \gamma \) rays is to discriminate electronically between scattered and unscattered photons, according to their diminished energy. At the time this work was done there was little information in the literature on collimation requirements for americium equipment. As is well known, every increase in collimation thickness results in a lower count rate, which we wanted to avoid. It was in the research program to find out the most probable compromise between a sufficiently large collimation and the highest possible count rate.

* Research work done by Dr. P.H. Groenevelt and J.G. de Swart.
Looking at the collimation problem it is important to know what type of scattering is significant at the energy level of the photons present. As can be seen from Fig. 1 the Compton scattering forms the main part of the total attenuation coefficient [1]. This total attenuation coefficient for water is 0.204 cm and is built up of Compton scattering (0.165), Compton absorption (0.017), photoelectric effect (0.014) and coherent or Rayleigh scattering (0.008). The other effects are negligible. The main characteristics of the important Compton scattering are shown in Figs 2 and 3.

As can be seen from Fig. 2 the energy loss per interaction is less for low energetic photons than for high energetic ones for any angle of photon scattering. This makes it more difficult, if not impossible, with low energetic photons to discriminate electronically the scattered photons from the unscattered ones [2]. Therefore, collimation must prevent most scattered photons from reaching the detector. Figure 3 shows that the
probability for scattering under a certain angle is greater for low than for high energetic photons [1]. This means that for low energetic photons the chance to scatter out of the narrow beam is greater than for high energetic photons, but also that the chance to scatter back into the beam is greatest for low energetic photons. Prevention of these scattered photons from reaching the detector requires good collimation. Thus, the low-energy photons cause the severest problem and this explains why the choice of americium gives rise to a more severe collimation problem than would a choice of, for example, caesium.

In the literature attenuation coefficients of 0.179 and 0.186 for soil water and pure water are found [3]. Insufficient collimation gives a lower attenuation coefficient and it is important to keep the attenuation coefficients as nearly as possible to the theoretical value for at least four reasons: (1) the higher the coefficient, the fewer scattered photons are counted, which results in a vanishing small influence of the region outside the narrow beam on the measurements, (2) the higher the attenuation coefficient, the more sensitive the water content measurement, (3) the higher the attenuation coefficient for americium, the greater will be the difference in attenuation between caesium and americium where the two sources are used together, and (4) the worse the collimation, the more attenuation coefficients are dependent on the location of the absorber between source and detector due to interaction geometry.
In the research program reported here three types of load collimators were used. The effects of these on the practical attenuation coefficients are shown in Fig. 4 for the case where source- and detector-side collimators are 2 mm thick [2], in Fig. 5 where the source-side collimator is 2 mm thick and the detector-side collimator is 9 mm thick [2]; and in Fig. 6 where both source-side and detector-side collimators are 9 mm thick. The sizeable influence of the location of the absorbent on attenuation coefficients, where insufficient collimation is used, may be observed in these figures. The values of the total attenuation coefficients are far too low compared with theoretical values. Collimation with 9 mm on both source- and detector-side was the final choice for the design of our column scanning apparatus. A detailed drawing of the source + detector system is presented in Fig. 7 [4].
FIG. 4. Effect of 2 mm thick source- and detector-side lead collimators on the practical attenuation coefficients.

FIG. 5. Effect of 2 and 9 mm thick source- and detector-side collimators, respectively, on the practical attenuation coefficients.
FIG. 6. Effect of 9 mm thick source- and detector-side collimators on the practical attenuation coefficients.

FIG. 7. Source and detector system.
Practical values of the attenuation coefficient ranged from 0.192 to 0.202, depending upon the soil type; values as follow were obtained.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Coefficient (cm²/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure water</td>
<td>0.196</td>
</tr>
<tr>
<td>Coarse sand (silversand)</td>
<td>0.192</td>
</tr>
<tr>
<td></td>
<td>0.196</td>
</tr>
<tr>
<td>Fine sand (blokzand)</td>
<td>0.194</td>
</tr>
<tr>
<td></td>
<td>0.199</td>
</tr>
<tr>
<td>Loess</td>
<td>0.198</td>
</tr>
<tr>
<td></td>
<td>0.202</td>
</tr>
<tr>
<td></td>
<td>0.200</td>
</tr>
</tbody>
</table>

Preliminary experiments with a double-beam Am-Cs column scanner carried out this year showed a practical attenuation value of over 0.200 cm²/g with even thicker collimation in front of the detector. The increase in collimation thickness in this case is required to reduce the caesium-137 contribution in the Am channel. Therefore if an increased counting time can be used it is advisable to increase the collimation thickness to more than 9 mm in order to decrease the collimation angle. However, since the purpose of our research program was to find the most suitable compromise between sufficient collimation thickness and the highest possible count rate, it is obvious that for this type of slit the optimum collimation thickness is 9 mm.

REFERENCES


DISCUSSION

D.R. NIELSEN: One of the criteria that you proposed was a slit 1 mm wide. May I ask the reason for choosing such narrow collimation? When a soil column is hand-packed, in any manner possible, the limiting factor still is the heterogeneity of the column. Water will not move in such a soil column with sufficient uniformity to permit trying to measure water content distribution with points 1 mm apart.

L. STROOSNIJDER: This soil column scanner was built by Dr. Groenevelt who has thermodynamical interests. He is interested in transport phenomena such as salt sieving effects in soils and swelling of soils. He wanted to measure water conditions at fixed places in a soil column directly behind a small clay plug packed in the soil. This was the reason why he chose such small collimator dimensions — only 1 mm.
D. R. NIELSEN: Well, I believe that whether it be clay or sand, and if columns as long as 1 m are used, or even columns 15 cm long, one can waste a tremendous amount of energy trying to achieve such narrow resolution. I mention this because we have fallen into the same trap and have ourselves stumbled on it a few times. If one has data from real cases and uses such data to predict what happens in other cases, such narrow collimation is not, in fact, needed. We worked with half-millimetre slits because we were going to measure such things as, for example, conditions during infiltration right at the wetting-front, or associated salt movement and water movement during wetting and drying. If one takes a column of soil and measures the oven-dry bulk density at 1 mm intervals the variation is tremendous. So, it is better to take just a little bigger average value, I believe, if you are worried about transport. Other than at a sharp wetting-front, which goes from fully wet to fully dry, I would say you could get by easily in many experiments with 1 cm, where, of course, the length of the column is 1 m or 2 m.

P. REINIGER: I should like to report that, in fact, for the design of a double beam scanner, we have increased the slit width to 4 mm in making about the same kind of observations.

J. C. COREY: I think you will find that americium is coming into a lot of use for gamma work. I know that George Vachaud at Grenoble is using it to scan columns both horizontally and vertically. The real advantage, as was pointed out, is the light weight of shielding required. You don't have to have a large lead shield so that your carriage equipment can be lighter and much more versatile.

L. STROOSNIJDER: I like to answer Dr. Nielsen. Obviously it is only the ratio between the slit width and the collimation thickness, which we call the collimation angle, that is important. In fact it is this collimation angle, combined with the distance between source and detector which detects the region of the soil column in which the measurements take place. In our case this region has the shape of a meniscus. Theoretically the maximum height of the meniscus in the middle of the column will be approximately 7 mm in our case. The observed detectable height of this meniscus was 5 mm.
SOLUTES IN THE SOIL-WATER SYSTEM
SOME FACTORS INFLUENCING THE INTERPRETATION OF SOIL-SOLUTE-WATER INTERACTIONS*

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Abstract

SOME FACTORS INFLUENCING THE INTERPRETATION OF SOIL-SOLUTE-WATER INTERACTIONS.

The effect of tracer, soil, water content and biological population on soil-solute-water interaction studies is reviewed. Radionuclides, particularly tritium, and anions such as chlorides are the tracers discussed. Water content has a drastic effect upon the movement of solutes in soil and upon soil-solute-water interactions. Such studies as are discussed suggest ways to improve leaching efficiency by altering the manner in which water is applied. Methods for studying the interaction of biological populations with biodegradable substances are reviewed.

The soil physicist is one of the many agricultural scientists providing answers to problems faced by the world's ever-increasing human population. The problems under investigation by the soil physicist are not only the classical ones previously studied and of continuing importance, such as the use of irrigation and drainage techniques for increased food production, but also those of recent and future needs such as the behaviour of animal wastes, pesticide-soil interactions, and the migrational behaviour of viruses and bacteria through soils. In pursuit of answers to these problems, the soil physicist is continually determining soil-solute-water interactions.

Many of the soil-solute-water interactions are poorly defined because of the lack of a co-ordinated research effort on a world-wide scale. This situation will be improved as a consequence of this meeting inasmuch as the purpose of this joint FAO/IAEA panel is to prepare a proposal for co-ordinated research programs in which various institutes in different Member States carry out identical experiments. At the conclusion of these co-ordinated research programs, much more should be known about the range and practical importance of soil-solute-water interaction in relation to efficient water use.

* Joint contribution from the Savannah River Laboratory, E.I. du Pont de Nemours and Company, Aiken, South Carolina 29801 and Department of Water Science and Engineering, University of California, Davis, California 95616. Some of the information contained in this article was developed during the course of work under Contract AT(01-2)-1 with the U.S. Atomic Energy Commission.
In this paper we have used selected laboratory and field data from the recent literature to show how the tracer, the soil, the water content, and the biological population affect the results obtained by the soil physicist in his study of soil-solute-water interaction.

THE TRACER

Radionuclides, and in particular tritium, have been used extensively in soil-water movement studies. The suitability of this radionuclide for following water movement has been questioned by Stewart [1] because of possible tritium interaction with clay minerals as water diffuses. Stewart concludes that isotopic exchange and fractionation of hydrogen isotopes in certain clay-water systems may be significant for some age-dating and water tracing investigations where water flow is slow. In general, however, the isotope effect is not important because it is small in relation to the accuracies required of the data. The latter conclusion is corroborated by studies of water movement in the field by Blume, Zimmermann, and Munnich [2] and laboratory studies of water movement through soil columns by Corey and Horton [3]. Blume et al. injected at approximately 15 cm below the surface of a plot of bare ground $^2$H$_2$O and $^3$H$_2$O at 10 to 15-cm intervals along a straight line 2-m long. Ten days later following the infiltration of water from both natural rain and irrigation, the peak concentration was at 41 cm (Fig.1) with no appreciable difference in the distribution of deuterium and tritium. Corey and Horton displaced 170.5 ml of distilled water containing 94.9% of the hydrogen as $^2$H, 1.37% of the oxygen as $^{18}$O, and 150 $\mu$Ci of $^3$H upwards through a 136+ cm long and 7.62 cm in diameter clear plastic cylinder (Fig.2) filled with water-saturated acidic kaolinitic soil. They found no detectable differences in the relative concentration (concentration in the effluent/concentration added to column) of the three water tracers (Fig.3) as they appeared in the effluent. Inasmuch as the breakthrough curve calculated for this system, assuming no interaction, adequately described the shape of the observed breakthrough curve, Corey and Horton concluded that the three tracers, $^2$H, $^3$H, and $^{18}$O, can be used with
FIG. 2. Schematic drawing of experimental design used in miscible displacement experiment of relative movement of H, ^3H, and ^18O tagged water. (From Ref.33)

FIG. 3. Relative deuterium, tritium, and oxygen-18 distributions in the effluent from a 186-cm-long column of water-saturated Vaucluse soil for a displacement velocity of 1.22 cm/h. (From Ref.33)
TABLE 1. THE EFFECT OF CaCl₂ CONCENTRATION ON THE PERCENT H₂O WHICH EXCLUDES CHLORIDE

<table>
<thead>
<tr>
<th>Exchange material</th>
<th>N of CaCl₂</th>
<th>% H₂O with no Cl⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td>Houston Black clay</td>
<td>0.01</td>
<td>26.0</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>6.5</td>
</tr>
<tr>
<td>Llano vermiculite</td>
<td>0.01</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>2.8</td>
</tr>
<tr>
<td>Amarillo</td>
<td>0.01</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>0.05</td>
<td>2.5</td>
</tr>
</tbody>
</table>

FIG. 4. Breakthrough curves of 0.01N chloride and D₂O on a column of Houston Black clay. (From Ref.[4])

assurance that they adequately describe water movement in acidic kaolinitic soils with a maximum retardation of less than 1%.

Following tritium, the next most common type of tracers are anions such as chloride. In a recent paper, Thomas and Swoboda [4] discussed the effects of anion exclusion on chloride movement in soil. They examined the miscible displacement chloride curves obtained following the displacement at 1.0 cm/h or Ca(NO₃)₂ solutions by CaCl₂ solutions through three Texas soils: Houston Black clay, Llano vermiculite, and Amarillo sandy loam. Table I shows the amount of water present in the soil that does not contain chloride. The volume of water not containing chloride decreases as the chloride concentration of the tracer increases as can be readily explained by the Gouy-Chapman double layer theory. These data imply that chloride will move faster than the water through these soils.
Figure 4 confirms this hypothesis and shows the relative breakthrough curves for chloride and deuterated water when displacement occurred through Houston Black clay.

Corey and Fenimore [3] followed tritium and chloride movement through an acidic kaolinitic soil in laboratory and field studies and found just the opposite result to Thomas and Swoboda. Corey and Fenimore displaced 190 ml of a solution containing 0.8 μCi of ^3H/m1 and 0.0073 g of CaCl₂·2H₂O/ml through a water-saturated column of acidic kaolinitic soil using a laboratory set-up similar to that shown in Fig. 2. The column was 186 cm long. Unlike the data in Fig.4, the positions of the breakthrough curves for tritium and chloride using the kaolinitic soil were reversed, and their shapes were radically different (Fig.5). Similar observations have been found in a field study. The site selected had an unconfined water table 8.2 m below the soil surface. Two 10.16-cm-diameter aluminium-cased wells were installed 3 m apart (Fig.6). The bottom 1.5-m depths of the wells were screened with No. 60 gauge sand points. The wells were repeatedly surged and pumped until they produced a flow of 3.78 l/min for a 3.6-m drawdown. The drawdown and pumping rate were maintained throughout the test by using a positive displacement piston pump with a capacity greater than that of the well. After equilibrium had been reached (5 d), the circulation was stopped and 1324 ml of solution containing 454 g of CaCl₂·2H₂O and 3.1 Ci of tritium was added to the return well. The
FIG. 6. Schematic drawing of field study for measuring the relative movement of chloride and HTO. (From Ref. [15])

FIG. 7. Relative tritium and chloride distributions in a pumped well following injection of a mixture of tritiated water and CaCl₂ into a well 3 m away. (From Ref. [15])
solution in the well was thoroughly mixed with a 10-min air sparge, and then circulation was resumed. The breakthrough curve for the field experiment is shown in Fig. 7. Tritium first arrived at the well at 3700 litres and chloride first arrived at 6200 litres. Needless to say, interpretations of the type of flow path and the pore volume of the system would be considerably different depending upon the use of an anionic tracer or tritium.

The difference in movement of chloride and tritium through the acidic kaolinitic soil is due to anion exchange. Thomas [6] evaluated the retention of various anions in columns of montmorillonitic and kaolinitic soils. He found that the distribution coefficients for chloride, nitrate, and sulphate in a montmorillonitic soil were zero (no anions retained by the soil), but those for a kaolinitic soil with abundant iron oxides were 2.5, 2.7, and 4.8, respectively. In acidic kaolinitic soils, such exchange would reduce the mobility not only of the gamma-ray emitting anionic tracers $^{131}$I and $^{85}$Br$^{-}$ [7] but also the chelated cations $^{60}$Co [8] and $^{51}$Cr. As a consequence of this solute-soil interaction, tracers deemed suitable in one region of the world would not necessarily be appropriate in other regions.

THE WATER CONTENT

Water content has been shown to drastically affect the movement of solutes through soil. Tritiated water was used to follow the movement of water from various depths in the soil to the atmosphere above the soil to determine the relationship between initial water content and depth of placement [9]. The time for tritiated water to evaporate from soil with either an initial water content of 0.05 g (moist) or 0.10 g (wet) of water per gram of soil and at three placement depths (0 to 14, 14 to 28, or 28 to 42 cm) were examined using laboratory columns 13 by 13 by 51 cm. The columns were filled to approximately 42 cm with a loamy sand (81.8% sand, 6.7% silt, and 11.5% clay). Prior to adding the soil to the column, the soil was oven-dried at 105°C for 48 hours, and then the appropriate amount of tritiated or non-tritiated water was thoroughly mixed with the soil. Duplicate soil columns were prepared for each treatment. The resulting tritium content in the soil water and the bulk densities are given in Table II. Figure 8 shows the experimental design used to maintain dry air above the soil column and shows the location of the three placement depths. In a given experiment, one location (for example, Location 2) would have the soil wet with tritiated water, and the remaining locations (Locations 1 and 3) would be wet to the same water content with non-tritiated water. The silica

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Bulk density (g/cm$^3$)</th>
<th>Tritium concentration $\gamma$Cl $\times 10^7$/ml of soil water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet</td>
<td>1.883</td>
<td>3900</td>
</tr>
<tr>
<td>Moist</td>
<td>1.758</td>
<td>3900</td>
</tr>
</tbody>
</table>
FIG. 8. Apparatus used to evaporate water from the soil and recover the water that is evaporated. (From Ref. 10)

FIG. 9. Cumulative evaporation as a function of time from initial water contents of 0.10 and 0.05 g of water/g of oven-dry soil and from a free water surface. (From Ref. 10)

gel column was removed at daily intervals to determine the amount of water lost from the column. The water on the silica gel was removed by vacuum distillation, and its tritium content determined with a liquid scintillation spectrometer. The water loss from the two treatments (moist and wet) is given in Fig. 9. Figure 10 illustrates the change in the tritium concentration in the water vapour above the wet soil columns. The deeper the tritiated water was placed, the longer the tritium took to reach the soil surface. Figure 11 illustrates the change in the tritium concentrations in
FIG. 10. Relative tritium concentration in the water vapour above the wet soil column as a function of time.  
○ = data from one column;  
● = data from a duplicate column;  
1, 2, 3 = location in the column of the tritium-tagged water

FIG. 11. Relative tritium concentration in the water vapour above the moist soil column as a function of time. (From Ref. [9])  
○ = data from one column;  
● = data from a duplicate column;  
1, 2, 3 = location in the column of the tritium-tagged water

the water vapour above the moist soil columns. There is a much smaller release of tritiated water from the moist soil than the wet soil. The duplication between columns in both treatments is excellent. Following evaporation, the columns were sectioned to determine the tritium remaining at each depth (Figs 12 and 13). No tritium from Location 1 remained in the wet column while considerable amounts remained in the moist column.

Although no attempt was made to conduct the preceding experiments in the field, Zimmermann et al. [10] watched the redistribution of tritium
in the field where the water content varied widely. They have shown the large effect that soil type and vegetation have on the redistribution of tritiated water in the soil with time (Fig. 14). The primary disadvantage of field studies with tritium is the requirement that soil samples must be removed for analyses. An alternative approach to the use of tritium would be the application of heavy water ($^2$H$_2$O). Its movement (Fig. 15) can be followed non-destructively [11] using the reaction $^2$H + $\gamma$ → $^3$H + $\frac{1}{2}$n. The technique requires gamma energies greater than 2.23 MeV. Suitable gamma sources for such high energies are $^{26}$Na and $^{203}$Tl [12].
Figures 14 and 15 illustrate the wide variety of concentration distributions that exist within soil profiles. These distributions have been described theoretically with solutions of the following differential equation

\[
\frac{\partial C}{\partial t} = \frac{\partial^2 C}{\partial x^2}
\]

(1)

where C is the concentration of the solute, t is the time, x is the distance along the column, and D is the coefficient of dispersion analogous to an
FIG. 15. Initial, maximum, and final tracer peaks of D_2O in three different plots obtained non-destructively by measuring the photon neutrons produced by the γ,n reaction. (From Ref.[1])
apparent molecular diffusion coefficient \([13, 14]\). A particular solution to this differential equation which is applicable to leaching, if we assume a constant average pore-water velocity \(v\) and no solute-soil interaction, is,

\[
\frac{C}{C_0} = N \left\{ \frac{x + x_0 - vt}{\sqrt{2Dt}} \right\} - N \left\{ \frac{x - vt}{\sqrt{2Dt}} \right\}
\]  

(2)

for the conditions

\[
\begin{align*}
C &= 0 & x &= 0 & t &= 0 \\
C &= C_0 & x &= 0 & 0 < t < t_0 \\
C &= 0 & x &= 0 & t > t_0 \\
C &= 0 & x \rightarrow \infty & t > 0
\end{align*}
\]

where \(x_0\) is the length of column that the compound of concentration \(C_0\) will occupy if no mixing occurred, \(t_0\) (not explicit in equation) is the time for the fluid to travel a distance \(x_0\) in the column, and \(N(x)\) is the normal probability integral.

Corey, Kirkham, and Nielsen \([15]\) used values of the coefficient of dispersion obtained from laboratory columns for a number of soils, and Eq. (2) to calculate the curves shown in Fig.16. These curves illustrate the influence of the saturated water content on the leaching of a narrow band of solute initially at concentration \(C_0\) with known quantities of fresh water. Comparing the solute distribution curves for the Idia and Clarion soils (each having approximately equal water-filled porosities), 15.24 cm of fresh water displaces the solute approximately to the same depth (35 cm).
But for the muck soil, having a much greater water-filled porosity, 15.24 cm of water displaces the solute to a shallower depth (22 cm). In all soils, the deeper the solute travels, the greater its spread throughout the profile. The tendency for the solute to spread or be dispersed differs among soils. In the Ida, the solute band, having been displaced to the 70-cm depth, occupies only 10 cm of the profile. For Clarion soil, the solute band at this depth is spread over 30 cm, and for the muck, over 40 cm. At this 70-cm depth, the maximum concentration in the Ida is 0.8 and that in the muck about 0.2. This spreading action, the result of water moving at different rates through soil pores of different sizes, has been discussed by Nielsen and Biggar [18].

Although solute distributions measured in the field may be quantitatively described by Eq. (2), additional data indicate that the manner in which the leaching is accomplished influences greatly the salt distribution. For a Panache soil (Figs 17(a) and 17(b)), the manner in which chloride, applied at the soil surface, is displaced through the profile [17] under continuously ponded conditions is compared with that for repeated irrigations of 2 in. of water where unsaturated flow conditions are allowed to develop between irrigations. For the ponded condition, 6 in. of water reduced the salinity in the top 2 ft of soil little more than did 4 in. of water (Fig. 17(a)). When the soil was leached intermittently (Fig. 17(b)) with the same total amount of water (6 in.), the chloride concentration in the top foot of soil was approximately one-half that measured for continuously ponding and 6 in. of water applied intermittently was much more effective than 4 in. of water applied intermittently.

After continuously leaching with 12 in. of water, some salt moved into all depths of the profile, but a major portion of the applied salt was left in
the top 30 in. with the concentration at 12 in. being nearly 100 milliequi-
valents per litre. The concentration at the 12-in. depth for 12 in. of inter-
mittently ponded water was about 25 milliequivalents per litre, with the re-
mainder of the curve indicating that the centre of the salt distribution had 
moved to 36 in. The concentration of salt at all soil depths down to 54 in. 
was reduced to lower values with 24 in. of intermittently ponded irrigation 
water than with 36 in. of continuously ponded water. Data such as these 
indicate the dynamic nature of the leaching process and show how water 
content directly influences soil-solute-water interactions. In addition, 
these studies suggest ways to improve leaching efficiencies by altering the 
manner in which water is applied.

THE BIOLOGICAL POPULATION

With the current emphasis on research into the movement of bio-
degradable soil additives such as pesticides, the contribution of microbial 
activity to the ultimate fate and location of these soil additives must be 
determined. Because of the heterogeneous and dynamic character of soil 
microbial populations, a critical examination of the degradation of an additive 
moving in soil-water requires that the population be identified and its 
activity known.

Corey et al. [18] presented a method whereby soil can be not only 
sterilized and inoculated but can be used in a procedure to conduct long 
term, controlled flow experiments with soil additives that are decomposed 
or altered by microbial activity. In their method, gamma radiation from a 
$^{60}$Co source was used to sterilize the soil, and the miscible displacement 
methods of Nielsen and Biggar [19] were used to control the flow velocity 
of the solutions. Although nitrate was used as an illustrative ion of a sub-
stance whose movement is influenced by microbial activity, the method is 
applicable to any biodegradable substance that can be prepared in a sterile 
form.

![Graph](image_url)

**FIG. 18.** Breakthrough curves for a 50-ml aqueous solution of chloride and nitrate displaced at 0.055 cm/h through a 12.5-cm long column of Webster soil and silica sand (50/50 by weight). (From Ref. [18])
Corey et al. [18] illustrated the effectiveness of their approach for obtaining and maintaining sterile conditions within the soil column by comparing the breakthrough curves of chloride and nitrate in non-sterilized and sterilized soil columns. In the unsterilized soil experiment, 50 ml of a chloride-nitrate solution was displaced through a column of non-sterile soil with a dilute CaSO₄ solution (0.005M). The area under the breakthrough curves (Fig. 18) from this experiment represents the amounts of chloride and nitrate recovered in the effluent. If no chloride or nitrate was lost while passing through the column, the recovery should represent the original 50-ml volume of chloride or nitrate added to the column. In this experiment, the entire amount of chloride was recovered but only 65% of the nitrate. The symmetrical nature of the nitrate curve implies that the microbial population remained relatively constant throughout the non-sterile experiment. In the sterilized soil experiment, the same experimental method was used as in the unsterilized soil column study except an irradiated soil column was used with aseptic techniques. The purpose of this experiment was to illustrate the effectiveness of the suggested method for maintaining sterile conditions. The breakthrough curve for nitrate (Fig. 19) showed no loss of nitrate during passage of the solution through the soil column. An extension of the sterile soil column technique would be to inoculate the soil with known microbial species and measure their influence on the breakthrough curves of biodegradable compounds.

Mansell, Nielsen, and Kirkham [20] have devised methods to alter the environment of the microbial population within soil columns. They pass or recirculate gas of known composition through unsaturated soil. Water moves through the soil at a constant rate (Fig. 20). The advantage of this technique over previous column methods is in its flexibility to allow a greater number of environmental parameters to be simultaneously controlled and continuously monitored. The rate at which the constituent quantities of soil air change because of microbiological processes may be
ascertained. The fate of chemical materials, dissolved in water, entering the soil may be determined from analyses of the liquid effluent coupled with analyses of the soil air. With the soil water content and tension distribution measured throughout the column, it is possible to calculate changes in hydraulic conductivity owing to physical and biological processes.

This technique is adaptable to many specific experiments dealing with filtration in the production of potable water and with degradation of organic wastes and chemicals added directly to the soil surface. The technique should be applicable to developing methods for increasing or decreasing the rate at which nitrogenous material is decomposed as this contaminant seeps through porous media. Some other possible uses are in studies of the rate viruses or bacteria introduced in water at the soil surface move downward through a soil under different conditions and in studies of the fate of radioactive organic materials introduced in fluids at the soil surface.

CONCLUDING COMMENTS

Soil-solute-water interactions are extremely complex and difficult to evaluate. They depend on a wide variety of variables that are intricately
intertwined with one another. We have listed some of these variables and have mentioned methods to reduce their influence. In addition to the points discussed in this presentation, many unanswered questions remain. The opportunities for meaningful research provided by these unanswered questions will be limited only by the research workers' imagination.

REFERENCES


DISCUSSION

M. ABDALLA: May I ask about the effect of a fluctuating water table and how it is of concern to our work here? A fluctuating water table affects water movement in the profile very much and should affect these studies.
D.R. NIELSEN: I believe the biggest change in leaching probably occurs in the rather wet range where small changes in water content, up or down, fill or empty a few of the larger pore sequences. This, then, is related to the depth of the water table. Certainly salt moving up or salt moving down too would in many cases be affected significantly by the fact that the water table would be fluctuating. However, I have not worked on the fluctuating water-table case and these data that I show are in an area where the depth to the water table is in excess of 10 metres.

W.R. GARDNER: I have a minor question to ask Dr. Corey on his use of tritium. How well can you estimate, from the type of data you are collecting, the evaporation rates from the soil in terms of spatial and time variations?

J.C. COREY: Since we have only done laboratory studies we really don't know. There would be a problem of interaction. The tritium behaves differently from the water. Essentially the tritium concentration above the soil is zero and the relative humidity is some, say, 50%. So the tritium gradient is infinitely greater than the non-tritiated water gradient. This difference would cause tritium to go upwards. Thus, there are fractionation effects—more tritium leaving than ordinary water, if the tritium is free to leave. In the same way if you have tritium in a layer, you have diffusion downwards, because there is no tritium below. So, tritium will be lost both downwards and upwards. We don't find this fractionation in the system that I described because there is no water vapour in the air. But, if water vapour in our experiment had been at 100% so that we would have no net water loss, we would still find tritium. Taken to an extreme, say in a rain forest, tritium data could very well be meaningless.

W.R. GARDNER: Well, I think the extreme is more likely to be in the other direction and very very low.

J.C. COREY: It depends upon where you are interested in working. Most of the people here are from arid countries, but is this where our potential lies, or does it really lie in the tropics where water is not the limiting factor? Maybe it is cheaper to put fertilizers where water is not limiting than it is to put water somewhere else. I think this is something that no one has discussed today, or has been brought out.

W.R. GARDNER: Did you estimate the diffusion rates for this downward movement of tritium? And, is it diffusion, or dispersion? Do you have a number for the rate?

J.C. COREY: I don't have a number. I can't see where it would be dispersion because the mass flow is upwards.

W.R. GARDNER: Well, that can still result in dispersion downwards.

D.R. NIELSEN: I think the question Dr. Gardner asked is a good one. However, he is getting into areas where we don't have answers. Dr. Corey might well have responded by saying that we have used those two equations on the board simultaneously and have found that the 'D' for tritium diffusion through the soil—whether it be upward or downward—is in fact influenced by mass transport. So, the use of a tracer, tritium, deuterium, etc. in predicting evaporation is really tricky and we do not have answers even to a first approximation. I think that the work that Gardner and Hillel and others have done on evaporation, particularly during the initial stages of evaporation, could be tied in with diffusion or dispersion coefficients that we have measured for tritium moving through the soil. This might give us some insight into the problem.
P. REINIGER: As an off-the-cuff comment I would say that you simply would have to superimpose the self-diffusion of tritium and the water movement, and you would take this into account in your theoretical analyses. I would like to ask a question about the gamma-neutron reaction you mentioned where you used a thorium source to activate deuterium. Could you give some information on this? I understand also that you are doing some work on californium.

J.C. COREY: Yes, Dr. Kirkham and I have co-authored a paper in which we discuss the uses of californium and some of our data on both the thorium studies and also some work on americium-caesium combined gamma transmission. This will be covered tomorrow.

P. REINIGER: Also, you have been working a little on combining two equations using a continuous system simulation idea. I think we have succeeded in modifying those two equations so that one can treat, in theory, a system of, say, four cations and transient water flow together.

D. HILDEL: I note that Dr. Corey pointed out that one would expect chloride ions, and anions in general, to precede cations because of the anion exclusion effect. Then he indicated, rather surprisingly, that in fact his experiments showed that chloride ion followed the tritium, that is, followed the main body of water rather than preceding it. I am doubly puzzled now because the data shown by Dr. Nielsen had a curve in which the chloride preceded the tritium. I would like an explanation, if possible.

J.C. COREY: There is one big difference in the two experiments which leads to this. Our soils are capable of anion exchange. There is very little work done on anion exchange, but this soil is in a tropical environment in South Carolina. We have high rainfall rates and our pH values are of the order of 4 to 5. We have kaolinitic soils and our cation exchange capacity is extremely low, 3 to 4 meq./100 g. It is in a non-arid region type of study where you find this. One would expect to find the same kind of studies in Puerto Rico or any of the other high rainfall regions where the soils are kaolinitic. This is interesting, because I went down to South Carolina expecting to find the chloride preceding the tritium in such work and I didn't.

A.I. DANILIN: Could you tell me, please, how you managed to exclude the effect of the frequency of sampling on experimental results, because in order to observe the movement of the front of water with tracers you have to take samples. Thus, you had to destroy the column of soil. How did you exclude this effect, and what kind of errors did you have as a result of this?

J.C. COREY: It would depend upon which slide you were referring to. In the evaporation study with tritium the whole column is destroyed. In other words, we completed the experiment and at the end we sampled. In the data from the field on tritium distribution done by German workers and reported by Zimmermann, they had a 2-m long increment for study, and I surmise from reading reports of their work that they sampled in random locations, and then plugged the holes with soil after sampling, so that they did not get a preferential evaporation. Certainly a destructive system is not as good as a non-destructive system and it will introduce errors. On our column studies, of course, sampling was at the end of a column. I don't know exactly how much error is introduced by destructive sampling. Dr. Nielsen will talk tomorrow about the distribution on a larger scale where he uses destructive testing.
A.I. Danilin: Dr. Nielsen, when the front of water containing salt moved from the surface and you added new portions of fresh water, was there not migration of this salt in the opposite direction to the surface? That is to say would you not have a mixture of higher concentration that met the fresh water that you were putting in?

D. R. Nielsen: I believe that you are referring to the last slide showing results from an infiltration experiment. The soil chloride had a water content of 20% to a depth of 180 cm, and then we added on the soil surface 7½ cm of water containing chloride and nitrate. (I have only shown the chloride in the figure.) As soon as that water was all imbibed by the soil we added a thin layer of water which was free of chloride and then continued to add thin layers until 30 cm of water had been added. Of the 30 cm of water 22½ cm were fresh water and 7½ were salt water. As the salt pulse then moves through the profile, one sees two things happen: the water contents within the profile increase, and diffusion and dispersion occur so that you do have a tendency for salt to go both directions. However, this experiment lasted for only 17 hours and with mass transport going to a depth of 180 cm (80 cm for the salt) molecular diffusion longitudinally would be negligible. On the other hand molecular diffusion from the salt into pore sequences that are nearly stagnant would have some bearing, and these are the interactions that we do not know enough about.

P. R. Stout: I would like to remark that I find Dr. Corey's data on the hold-up of chloride in soils most intriguing. I call attention to his remark that they had no chloride in the waters in the area from which he comes. But, chloride is an essential element so obviously he has chloride in his water, or there would be no plants there. It has been a mystery to me for many, many years as to how tropical rain forests can actually maintain enough chloride in the soil profile to meet the obvious chloride needs of the cover that you see. So, I appreciate very much Dr. Corey's presentation showing that acid soils hold chloride up beyond what you would have guessed if you were looking at one of our arid soil situations. The situation where chloride stays behind is to be fully appreciated out of respect for the vast areas of rain-fed agriculture where we do not get more than two cuttings of clover, and at the end of those two cuttings you are finished. There is no more chloride and no more plant and the whole process stops. This is one fertilizer which is provided around the world with the rains which come each season.

W. Kuhn: I have a remark to Dr. Gardner. We carried out some studies about water vapor in soil using tritium, deuterium and normal water, and we couldn't find any differences among the behaviours of the three molecules in the soil. But, where we used glass spheres of soil dimensions we observed an isotopic effect, but not as high as we expected; but none was observed in the soil.

M. Abdalla: Dr. Nielsen, may I ask what sort of chloride salt you used in this experiment? And, what would be the effect of different cations exchanged—say exchangeable calcium or potassium, including low rates?

D. R. Nielsen: We have used calcium chloride, sodium chloride and potassium chloride, and depending, of course, on the total concentration of the soil solute, and what fraction of the exchange is satisfied by sodium or the monovalent ions. I know the reason why you are asking, but these
experiments would not be significantly changed regardless of the cation. The water used was essentially chloride-free, I did not say that it was salt-free. So, the plain water still had sufficient salts to keep the soil from dispersing. We have performed the experiment on cation exchange in unsaturated soils at different water contents and flow rates, and Dr. Biggar is currently working on the rates of exchange for sodium and calcium, and other ions of agricultural significance. I might also say to Dr. Reiniger that we also have been working on exchange, and more recently have been working on the miscible displacement of gases where one has ammonia and CO$_2$ not only being adsorbed by the surfaces, but also being dissolved in the water. We have treated those cases, not only as equilibrium isotherms, but also where we have first-order rate reactions going on.

P. COUCHAT: I want to ask Dr. Corey a question concerning the combined use in one of their experiments of the three isotopes: tritium, oxygen-18 and deuterium. One of the figures showed that the behaviour of these three isotopes is the same for the case where you have made a column test in a saturated medium. Have you made identical experiments in a non-saturated medium? Would the behaviour of tritium then be the same as for oxygen-18 in the saturated medium? Do you think that there is a future for oxygen-18 as a tracer for water?

J.C. COREY: No, we have not done the same experiments in unsaturated media, but there is no reason why it couldn't be done. I'm hesitant to say exactly what would happen because I could be wrong. However, I believe that oxygen-18 would precede tritium in a long column, but only by a small difference. But, in general, we should look at the big picture — the differences in movement of the deuterium, tritium and oxygen-18 are going to be so small in relation to variations resulting from packing a soil column that it really doesn't matter very much.

The purpose of our study was to answer the question which I've heard posed so many times: what difference is there in the behaviour of the three isotopes. I realize that I only did one small part of it and there are an infinite number of ramifications such as column length, type of soil, water content, etc. So our purpose was to find out whether the three behaved similarly in our system, the type of system on which I do most of my research. The experiment told me that the three could be used interchangeably.

Is there a future for oxygen-18? Well, let's look at the advantages. It is stable and it can be analysed. Since it is a stable isotope, you use a mass spectrometer and mass spectrometers are extremely sensitive so that you can get very good data. The disadvantages are that it is expensive, far more expensive than tritium, and requires an expensive instrument for analyses. So, if I had a choice of tracers in a system I would pick tritium. It is easier to analyse for than oxygen-18, for which a mass spectrometer is required, because you can use liquid scintillation counting. This also is very sensitive and involves a much less expensive instrument to purchase, use and maintain. Lower levels of activity can be used with tritium than with oxygen-18. Of course, there is a health hazard with radioactive tritium that can be eliminated by using oxygen-18. I don't believe that there is a good future for oxygen-18, at least not in my work. I can analyse tritium myself, but I cannot run a mass spectrometer.

P. COUCHAT: In the evaporation study using tritium were you able to make a balance of the tritium concentration?
J.C. COREY: Yes, we made both a balance of the tritium concentration and the water concentration. They weren't 100% but they were very close.

P.R. STOUT: Dr. Corey has just discussed oxygen-18 in relation to tritium. Where does deuterium fit in at the present. It is cheap, you can get lots of it, and let's just conceive use of a density gradient measuring device. Does this fit into the picture now?

J.C. COREY: I like deuterium for the gamma-photoneutron method that Dr. Kirkham will mention tomorrow. The advantage of this method is that it is non-destructive. It is the only way we can measure water, or tag water, non-destructively in the field.

P.R. STOUT: Yes, for samples. Now a lot of good work has been done with density gradient tubes as the measuring instrument. I am wondering for this kind of work whether or not we want to think in terms of the density gradient tubes as the measuring device for the obvious reason that these are things that you can get hold of in many places.

J.C. COREY: But, if you are going to buy heavy water, and a lot of it at US $20.00 to US $30.00 per pound, that's not going to go very far. But, it depends on the experiment. I like tritium because it is easy to analyse. Its measurement can be completely automated: you put it in liquid scintillation equipment one night and the next morning you come in and it is all counted and tabulated for you. With deuterium or oxygen-18 someone must sit and do the experiment for you. However, one can't give a definitive answer because some places may have lots of manpower – manpower may be extremely cheap and then you are not dealing with the same thing. For us manpower is more expensive.

D. KIRKHAM: I think Dr. Corey meant that if he needs just one tracer he would prefer tritium over oxygen-18 or deuterium, because with oxygen-18 or deuterium you have to use an expensive mass spectrometer. But, if he had three things to trace, for example if he wanted to know whether water from below the water table or water from irrigation was supplying water to the roots of the plant, and this was complicated by an interchange of water from the plant itself, he might need all three of the tracers going at once. Then, of course, there would be a use for them all.

D. HILLEL: Just a small question for Dr. Nielsen: How good in your opinion is the method of sampling the soil solution by extraction through a tensiometer cup?

D.R. NIELSEN: You've asked a very good question and I know exactly the kind of answer you want me to give. The extraction of the solution through a tensiometer cup is plagued with exactly the same problems as extraction of the soil solution through a pressure plate or through a Buechner funnel, so that, certainly, one has to regard concentration measurements obtained as giving a first-order approximation. Also, it is not wise to disregard the fact that under wet conditions you are probably sampling predominantly the large pores and if water flow through the profile is sufficient you may not even be sampling what you think you are. I think that if we can use some of the non-destructive techniques that Dr. Kirkham will speak about tomorrow, in particular when we have support from this Agency, that it will give us an opportunity to study this. Perhaps we can find out under what conditions we can use other techniques in place of the more expensive isotope methods.
I'd like to add a general comment. I believe that we don't recognize completely the kinds of experiments that we have seen this morning. These were displacement experiments, in which the water content was constant, and we merely had the fluid flowing through in some average way. Here we can talk about things preceding or following, depending upon their isotopic nature. You will recall that in my last slide the wetting front was way ahead of the chloride so you might say that chloride lags. The grosser aspects of the mixing problem involve both water content and salt concentration change, added to the fact that flux is changing. When you get into a real system with plants growing, which I'm sure one of our panelists will talk about, you will have an additional source or sink to consider. All those things must be put together to say how well an isotope can be used as a tracer. You really must ask yourself the question: "do you want tracers to point out spatial distances over several hundred metres where ground water is flowing, or, do you want to find out the intricacies of molecular behaviour at the root or molecular level, or the mixing associated with the clay?" And, those are two different things. Tracers will give you answers to both, but to think that a tracer is going to give you the rate at which water is moving in a simple way is sort of naive. Having thought about it for a little longer it becomes rather complex - it requires a little more consideration than merely to ask what makes a good tracer.

W.R. GARDNER: I would like just to make an observation with respect to several of these questions and answers. I think Dr. Corey has such fine instrumentation and techniques that he is a little afraid of committing himself to precise answers because he knows that he can detect many, many effects that interfere or are irrelevant with respect to this so-called simple-minded equation that Dr. Nielsen has put down. One of the reasons the equation is simple-minded is that we know that the velocity is not a constant even in a homogeneous soil. There exists a distribution of velocities even through an individual pore and the concentration is not constant. These averages are conveniences and if we are talking about field use then we have to come up with ways of averaging over many many processes. I think one of the significant points to bring out at this stage in our understanding of transport in soils is that the very fact that we can discuss many of these second- and third-order effects means that we understand the first-order effects. We understand them sufficiently well that when we come to a problem like that of management of a large system as introduced by Dr. Stout this morning the study of these minor effects gives us confidence in predicting what is going to happen in a large field on a large scale. The challenge to us now is to come up with rational simple ways of averaging the many effects so that we don't have to calculate the fate of each single molecule one by one. We must average over a large scale.

D. HILLER: I think that the burden of the message that we have been hearing from Dr. Nielsen and Dr. Corey is that solute movement, the movement of soluble substances through the soil, is extremely important; that there are studies in this field which now make it possible to introduce this effect into field measurements with which we are concerned; that this really contributes an essential part to the study of water use efficiency in the field and should become part of any future program sponsored by the Agency on water management. It is impossible to separate water management from the management of the soluble materials in the soil, and I think this is an extremely important message.
ANALYSING SOIL WATER AND SOLUTE MOVEMENT UNDER FIELD CONDITIONS

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Abstract

ANALYSING SOIL WATER AND SOLUTE MOVEMENT UNDER FIELD CONDITIONS.

Methods are reviewed for assessing water content distribution and water flux out of a soil profile using potential or diffusion equations and data obtained by means of a neutron moisture meter or by tensiometers. Applicability of such measurements to field soils with the attendant variability are discussed together with movement of solutes in the profile.

Leaching of soluble salts is both a desirable and an undesirable process. Although leaching is necessary for sustained irrigated agriculture, losses of fertilizer and other soil additives, together with valuable water below the root zone, are costly. Because leaching occurs whenever some surface-applied water passes completely through the crop-root zone, we usually estimate leaching losses from balances between water applied and that evaporated and transpired by the crop. Too often, however, we fail to consider how water and solutes actually move through the profile and do not recognize that the degree of leaching accomplished at various soil depths can be significantly altered through different water management practices. Moreover, the presence of a crop with its extraction of water from the soil profile influences the amount of water and solutes lost to deep percolation and these losses, in turn, depend upon irrigation frequency, even for equal quantities of water applied during the growing season. Because of the complex nature of the soil-water-plant system, radioisotopes are frequently used to ascertain the pathways of fertilizer elements and other materials added to the soil in relation to efficient crop production and water utilization.

Soil-water content plays an unprecedented role in the physical behaviour of soils. The rates of transfer and retention of water, gases, heat, solutes, microbes and particulate matter are all related to the water content of the soil. Even though the soil-water content is probably the most commonly measured physical parameter in field soils, investigators rarely report soil physical properties which would allow its prediction or estimates of soil-water movement. Although analytic expression based upon Darcy's equation for unsaturated soil-water movement have long been available (Richards, 1931), relatively few investigators have described soil-water behaviour using measured values of both hydraulic conductivity and hydraulic gradients of soil depth. Recently, Nielsen et al. (1964), Rose et al. (1965), van Bavel et al. (1968), and La Rue et al. (1968) have reported hydraulic conductivity values for various soil depths for relatively small areas (0.005 hectares). These values point out clearly the heterogeneous nature of field soils in the vertical direction owing to genetic horizons or poorly-defined layers stemming from alluvium.
The equation usually applied to describe vertical water movement through unsaturated soils

\[
\frac{\partial \theta}{\partial t} \equiv \frac{\partial}{\partial z} \left( K \frac{\partial H}{\partial z} \right)
\]

(1)

has often-times been used for layered soils. Here \( \theta \) is the soil-water content \( (cm^3/cm^3) \), \( t \) time, \( z \) the vertical co-ordinate measured in the downward direction, \( H \) the hydraulic head, and \( K \) the hydraulic conductivity taken as a function of \( \theta \) which would differ for each soil layer. Accurate solutions \( \theta (z, t) \) of Eq. (1) for infiltration and redistribution have been sought using both analytical and numerical techniques for several boundary and initial conditions (e.g. Hanks and Bowers, 1962). A major effort during the past decade has been spent in the laboratory and to a lesser extent in the field to measure precisely and with minimal error the soil-water pressure and the soil-water content distributions within profiles. Emphasis has been given to hysteresis, to functional relations between \( K \) and \( \theta \), and to some soils that swell and shrink during wetting and drying. Consequently, the neutron gauge has been, and continues to be, redesigned to measure water content within smaller and better defined geometries. The two-probe density gauge, if not now, should soon yield reliable estimates of water and soil density distributions within vertically heterogeneous, swelling and shrinking soils. With these more sensitive measurements of soil-water content and those of matric potential considered as point values, critical examination and description of soil-water behaviour with analytical or numerical models are feasible.

Although accurate estimates of water movement and retention have been and will continue to be achieved for a limited variety of boundary conditions involving infiltration, redistribution, evaporation and drainage with and without a transpiring crop, it is readily apparent that descriptions and predictions are needed that can be applied to large land areas – areas of sufficient size to be of economic value to agricultural production or

![Diagram showing soil water content profiles](image)

**FIG. 1.** Soil-water profiles for 24, 48 and 96 h during drainage following a 35-5 cm water application (Nielsen et al., 1957). Solid lines calculated from Eq. (2) predict the measured profiles depicted by the right-hand broken line in each graph.
and water resource development and management. The transport of water and solutes through field soils over large land areas has usually been inferred rather than measured directly.

Methods for ascertaining the movement of solutes and water through field soils comprising scores or hundreds of hectares with their attendant natural variability have not yet been devised. We have examined rainfall patterns and predicted runoff from both large and small watersheds. We have examined evapotranspiration from a uniformly cropped area. We have measured the quality and quantity of water drained from farm lands, but we have not utilized measured soil-physical parameters to predict how water infiltrates and percolates through field soils. The same is true for solute behaviour. Inasmuch as the water and solute conducting properties of soils depend so strongly upon soil-water content and textural and structural properties, the spatial variability of a soil may be sufficient within a field or other geographic unit to warrant the use of semi-empirical or approximate solutions of Eq. (1) or others to predict solute and water behaviour. Gardner (1969) recognized such an approach when he suggested that a field soil initially wet, might lose water from all depths at approximately the same rate, and over a limited time interval. Consequently, a constant, average value of the soil-water diffusivity $\bar{D}$ (Kdh/d$\theta$, where $h$ is the matric potential head) could be used to describe the process. Such assumptions lead to the following solution of Eq. (1)

$$W = (W_f - W_i) \exp[-\pi^2 \bar{D}t/4L^2] + W_i$$

where $W$ is the average water content, $W_f$ is the water content of the profile at the initiation of drainage, $W_i$ an approximate final water content at equilibrium, and $L$ the soil depth below which no water content change occurs. Equation (2) has been used to describe the manner in which 15.2 cm of water infiltrated into an already wet soil, redistributes, and drains to greater depths (Fig. 1). The broken line at the left-hand edge of the shaded area is the same for each graph and represents the value of $W_i$ established one week following a previous 15.2 cm irrigation. The broken lines on the right-hand edge represent the soil-water content distributions for the three drainage times of 24, 48 and 96 hours. A value of $\bar{D}$ equal to 20 cm$^2$/h is comparable to independently measured values of $K$ and dh/d$\theta$ averaged over the profile depth $L$ adequately describes the measured soil-water content profiles and the flux of water leaving depth $L$.

A similar analysis, but one which utilizes a functional relation between $K$ and $\bar{\theta}$ averaged over the profile depth $L$ is that suggested by Black et al. (1969). If Eq. (1) is integrated for depths between 0 and $L$ and it is assumed that a unit hydraulic gradient exists at $L$ during this drainage period, we have

$$L \frac{d\bar{\theta}}{dt} = -K \text{ at } z = L$$

where $\bar{\theta}$ is the average soil-water content of the profile. Equation (3) may be integrated to express the average water content as a function of time

$$\bar{\theta} = \theta_0 - \frac{1}{a} \ln (1 + \frac{aKt}{L})$$
Here, the hydraulic conductivity is

\[ K = K_0 \exp\{a(\theta - \theta_0)\} \]  

(5)

where \(a\), \(K_0\) and \(\theta_0\) are constants with the subscript zero referring to a maximum water content. Figure 2 shows values of \(K\) plotted against \(\theta\) for Yolo loam — an unusually uniform soil. The data, stemming from values of \(K\) measured in situ over 30-cm depth intervals to a depth of 180 cm, are adequately described by Eq. (5) (solid line) for values of \(a\), \(K_0\) and \(\theta_0\) equal to 48.2, 50 cm/d, and 0.474 cm³/cm³, respectively. For a 40-day drainage period, without evaporation, the flux at the 180-cm depth calculated from Eq. (4) is shown in Fig. 3. For a more heterogeneous profile, values of hydraulic conductivity for Miller silty clay range over 4 orders of magnitude for a given water content as presented in Fig. 4. Nonetheless, the flux of water at the 152-cm depth (Fig. 5) was adequately described using the solid line given in Fig. 4. These examples illustrate that for relatively simple conditions without transpiring plants or evaporation, analytic expressions of the hydraulic conductivity for each layer or horizon may not be necessary.

For most conditions, water and fertilizer losses take place in the presence of a transpiring crop. The results presented by Corey and Nielsen in the panel suggest that irrigation scheduling should be based not only on the plant available water being temporarily stored in the profile, but on the irrigation frequency and quantity of water applied. This suggestion is supported by the results of La Rue et al. (1968) whereby the net water flux...
FIG. 3. Measured and calculated soil-water flux leaving the 180-cm profile of Yolo loam. (From Davidson et al. (1969).)

FIG. 4. Hydraulic conductivity versus soil-water content for Miller silty clay measured at 15-cm depth intervals to a depth of 152 cm. The solid line stems from Eq. (5). (From Davidson et al. (1969).)
below the root zone of a grass crop was measured in the field for plots receiving equal total quantities of irrigation water, but applied in unequal amounts at different frequencies. At the commencement of the irrigation treatments, all plots, which had previously been treated identically, received two large irrigations of 18 cm of water. Four irrigation treatments were established: (1) a 4-cm irrigation of water once a week; (2) an 8-cm irrigation every two weeks; (3) a 16-cm irrigation every 4 weeks; and (4) no irrigation except the initial irrigation common to all four treatments. The average daily evapotranspiration during the entire experiment was nearly constant at 0.6 cm. The flux of water leaving the root zone was calculated on a daily basis using measured values of the hydraulic conductivity and the hydraulic gradient at the 180-cm depth. Figure 6 shows during the first 50 days of the experiment that more water left the root zone of the more frequently irrigated plots even though all plots received identical total quantities of water. The 4-cm treatment plots lost 3.9 cm of water by deep percolation while that for the 8-cm and 16-cm treatments was 2.5 and 1.5 cm, respectively. Moreover, for the 4- and 8-cm treatments, the direction of water flow was always downward for the 50-day period. For the other two treatments, water started to move upward into the profile after 22 and 27 days.

This example shows not only what is commonly known—that a crop influences the amount of water lost to deep percolation—but that these losses or amounts of water and solutes moving past the root zone are influenced by irrigation frequency. It is also obvious that had the soil-water content distribution within the profile been different initially—that is, essentially dry rather than wet or some other non-uniform distribution—the deep percolation losses would have been different and perhaps opposite those given in Fig. 6. Hence, it is no longer adequate to consider leaching, fertilizer and irrigation requirements solely on the basis of crop yield, treating the soil as a water reservoir and believing that a small leakage
below the root zone is insignificant. Soon after a heavy irrigation or rainfall, water losses below the root zone are substantial as seen in Fig. 6 with plants or in Figs 3 and 5 without plants. For water balance studies, it is essential to estimate accurately the flux during these irrigation periods owing to the relatively large rates of water transfer. It is during these times when water contents are large that the hydraulic conductivity is most sensitive to water content changes and, additionally, to variations of soil-physical properties occurring vertically within the profile. Estimates of the hydraulic conductivity must be accurately known. On the other hand, during a major portion of the interval between irrigations the flux of water from the bottom of the profile is only 0.1 mm per day. Is this significant or not? It may well be insignificant in terms of the amounts of water stored in the soil available to the crop and replenished by irrigation, but if multiplied by 300 days in a year, and again by the concentration of its solutes, we have more than enough water to be significant, particularly if it is laden with solutes. Besides being important to identify a general salt balance for a given area, depending upon the kinds of solutes being leached, it may be used to examine the extent to which our ground waters are being contaminated. We must, therefore, be developing methods for monitoring the amounts of water and solutes added to the surface of soils and leached through soil profiles to not only produce crops efficiently, but to control the quality of our soils and our environment.

To understand and to be able to monitor, predict, and control the movement of water and solutes, an accurate and reliable method for analysing soil-water movement on a field scale is an absolute necessity.
It is not only surprising, but disconcerting that a quantitative effort has never been made to analyse how uniformly water moves through a natural field soil, that is, not one which includes only the vertical variations already discussed, but one that includes the horizontal variations which occur across a field. An experiment now in progress (Biggar and Nielsen, 1970) is designed to examine the spatial variability of the hydraulic conductivity and soil-water characteristics in relation to the reliability of predicting infiltration, redistribution and drainage of water in unsaturated soil on a field basis. Twenty 6.5 metre square plots were randomly established over a 150 hectare site. The soil is a deep alluvial profile classified as Panoche clay loam in the Central Valley of California. Within each plot 2 mercury manometer tensiometers were placed at depths of 30, 60, 90, 120, 150, and 180 cm. Two suction probes for sampling the soil solution were also placed at each of these depths. In five plots, additional tensiometers were installed at 300 cm with suction probes at 300, 450 and 600 cm. Three 7.6 by 7.6 cm soil cores were removed at each 30-cm depth on two opposite sides of each plot. These

![Graph showing hydraulic conductivity vs soil water content](image)

**FIG. 7.** Values of hydraulic conductivity versus soil water content calculated from Eq. (1) from measured values of hydraulic head and water content.
cores are being analysed for soil-water characteristic curves, soil-bulk density values, and concentrations of cations and anions in the soil extract at each applied soil suction head (0, 10, 30, 60, 90, 120, 150, 200 cm with some greater values).

After steady-state flow conditions were established in each plot by continuous ponding, a 7.5-cm application of water containing Ca(NO$_3$)$_2$ and CaCl$_2$ was introduced into the plot, followed by a 60-cm application of chloride- and nitrate-free water. After the last increment of water had infiltrated the soil surface, the plot was covered with plastic and a thin layer of soil to prevent evaporation. Redistribution following infiltration was ascertained by tensiometer readings taken initially at 1-hour intervals and progressively less frequently for approximately 100 days. Values of hydraulic conductivity versus soil-water content for each 30-cm depth interval were calculated. The leaching of the chloride and nitrate during infiltration and redistribution was measured.
It will suffice to report here in a preliminary manner only some of the water-movement data. The soil-bulk density values averaged over the entire field (720 samples – 120 at each 30-cm depth to 180 cm, taken in groups of 3 at 40 locations) was 1.356 g/cm³ with a standard deviation of the mean equal to 0.104 g/cm³. The 30-cm depth manifested the greatest value of 1.468 while the least value of 1.312 g/cm³ was found at the 120-cm depth. The Panoche soil, although not strictly uniform but possessing a certain degree of heterogeneity, judging by these bulk density values, is not unlike many recent alluvial soils used throughout the world for crop production.

Taking similar averages for the soil-water characteristic, at water saturation, the standard deviation of the mean was 0.048 cm²/cm³. At a matric potential head of 200 cm, the mean and standard deviation was 0.324 and 0.077 cm²/cm³, respectively. These values, together with those for intermediate water contents and potential heads not reported here, indicate that for a given soil suction mathematical models such as Eq. (2)
which assume the soil is homogeneous horizontally and vertically, predict values of soil-water content no better than \( \pm 0.05 \text{ cm}^3/\text{cm}^3 \). Improving the model to include the soil-water characteristic values for each 30-cm depth to account for the vertical variation would not be too helpful inasmuch as the standard deviation would be decreased generally to only \( 0.05 \text{ cm}^3/\text{cm}^3 \). In this wet range of soil-water contents, the hydraulic conductivity values change by 1 or 2 orders of magnitude with changes of soil-water contents between \( \pm 0.05 \text{ cm}^3/\text{cm}^3 \). Hence, the horizontal heterogeneity of the soil precludes serious considerations of hysteresis and complex boundary value problems involving vertical heterogeneity of a given location if estimates of water movement over an entire field are sought.

Similarly, only a few examples of the hydraulic conductivity values are given here. Figures 7 and 8 show typical measured values of the hydraulic conductivity and soil-water diffusivity versus soil-water content, respectively, for given depths and plots calculated from Eq. (1) using methods reported by Nielsen et al. (1964).

Upon integrating Eq. (1) for depths between 0 and \( L \) assuming the soil-water characteristic and the hydraulic gradient are known, we obtain

\[
D = -L \frac{\partial \phi}{\partial t} \frac{\partial H}{\partial z} \quad \text{at } z = 1
\]  

(6)

where \( D \) is the soil-water diffusivity and \( \phi \) the matric potential head measured with a tensiometer (Gardner, 1970). If the hydraulic gradient \( \partial H/\partial z \) is assumed to be unity, the diffusivity is merely

\[
D = -L \frac{\partial \phi}{\partial t}
\]  

(7)

Figure 9 shows measured values of the soil-water diffusivity (values like those in Fig. 7 multiplied by \( \partial \phi / \partial \theta \) from the measured soil-water characteristic) and those calculated using Eqs (6) and (7). These data and those from all 20 locations and the various soil depths indicate that within the limitations of the soil variability, such approximate methods for measuring \( K \) or \( D \) are more than adequate for predicting water movement within a field, particularly during initial stages of redistribution following irrigation or rainfall.

CONCLUSION

It is suggested that the neutron gauge be used to assess the hydraulic conductivity versus soil-water content relations of field soils together with the reliability of these measurements taken over land areas of sufficient size to be of use in the management and control of soil-water and solutes for crop production. Equation (3) could be applied directly, monitoring soil-water content changes after an irrigation within a field at several locations. The values of \( K \) from Eq. (3) could also be adjusted if the hydraulic gradient were known from tensiometric data rather than assuming it to be unity. A simple, yet effective method would be the use of Eqs (6) and (7) which necessitate the use of tensiometers. If resources were available, the values of \( K \) could be measured by methods similar to those reported by Nielsen et al. (1964). For this latter case, the two probe density gauge would prove most valuable.
With reliable estimates of the hydraulic conductivity for a field, particularly those below the root zone where water contents do not vary substantially, the flux of water and solutes integrated over a week, a growing season, or a year would yield the water and solute lost by deep percolation. These values, together with measured values of the quantity and quality of water applied, would offer a significant step toward crop and water management even if measurements within the root zone were ignored.

BIBLIOGRAPHY


DISCUSSION

J. DAMAGNEZ: I should like to come back to the situation that you raised in your presentation, in which you observed the flux as a function of time in heterogeneous soil where there was sand and clay. This observation is valid for a certain time, but the dispersal of points showing the measured flux when the soil still is very moist is always on the same side of the curve. I was thinking that if we had a highly heterogeneous soil with alternate permeable and impermeable layers, and if the permeability was rather high, it would be the less permeable layer that would somehow govern infiltration into the soil. You know well that, if we have a discontinuity in the permeability, then we have the formation of suspended water tables.
This would explain why we always have a dispersal of points on the same side of the curve which would result in more points for the most permeable parts of the terrain which you have in your profile.

D. R. NEILSEN: Well, generally you are right, certainly a less permeable layer is a layer that would be the limiting factor. On the other hand, we have examined those profiles under fully wet conditions. They are not, in general, in the state they would be in the field under conditions, perhaps, where moisture is extracted by plants, or after irrigation, and/or rainfall. I would think that under irrigation you could always control the application rate to whatever favourable value is desired. Your observation about why the data are always on the same side of the curve is essentially correct.

W. R. GARDNER: I hope you will permit me a comment rather than a question, because I want to endorse your suggestion that in future programs we consider carefully measurements such as this on soils. I think that Dr. Nielsen and his colleagues have assessed about 99% of the world's supply of this sort of data. Such data are extremely useful in terms of predicting the behaviour of soil water and we have very very little of it in the major soils of the world. If a group such as this recommended nothing more than this sort of experiment, the feasibility of which has been demonstrated, I think they would have accomplished a great deal.

D. KIRKHAM: You emphasized the use of the neutron meter. Have I slipped something here? Are you still going to have to have tensiometers or can we get by completely with the use of a neutron meter?

D. R. NEILSEN: If we return to equation (1),

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left( K \frac{\partial H}{\partial z} \right)
\]

and integrate it from the soil surface \((z = 0)\) to the depth, \(L\), we have

\[
\int_{0}^{L} \frac{\partial \theta}{\partial t} \, dz = \left[ K \frac{\partial H}{\partial z} \right]_{z=L}
\]

This equation holds if we assume that there is no water flux at the soil surface after an initial soaking period to thoroughly wet the profile. The left-hand side of the above equation is merely the time-rate of change of the total amount of water stored in the profile to a depth \(L\) which can be estimated easily with a neutron meter. The right-hand side of the equation is the product of the hydraulic conductivity for the water content manifested at depth \(L\) and the hydraulic gradient. If we measure the hydraulic gradient, or assume it to be unity, then we have an estimate of \(K\). Relying on the data given in the series of slides we have just seen, together with those of Davidson recently published in Water Resources Research, the assumption that the gradient is unity is met reasonably well. Assuming the gradient is unity, the neutron meter alone could be used to estimate the values of the hydraulic conductivity at each depth \(L\). It is our opinion that the spatial variability of many field soils, especially if we consider areas of 100 hectares or greater, is sufficiently large to overshadow any error involved by assuming the hydraulic gradient to be unity.

D. KIRKHAM: Your integration of that integral has to be taken between two limits, now if your other limit is zero is \(dH\) going to be 0, and, if so, why?
D. R. NIELSEN: We assumed that there was no flux of water at the soil surface, i.e., no infiltration and no evaporation. For one experimental condition we covered each plot with a sheet of plastic.

D. KIRKHAM: But true evaporation would again be a correction?

D. R. NIELSEN: For experiments involving evaporation at the soil surface, corrections would have to be made. The time rate of change of water stored in the profile above a depth $L$ should be only that water that moves downward past depth $L$ and not that lost by evaporation. Corrections for evaporation could be made based upon additional measurements, or indeed, for certain circumstances evaporation could be neglected.

D. KIRKHAM: Well then, it is a marvellous circumstance that you can get down at the bottom of the profile where the gradient does seem to be unity because you have the same moisture content along there, and it is just a change with gravity.

D. R. NIELSEN: Another situation could be considered at this point. On a much broader scale, we have generally monitored or have known the amount of water and its quality that enters an irrigated valley or basin. Seldom, however, have we measured or monitored the quantity and quality of the water leaching past the root zone of crops. If we were to estimate the hydraulic conductivity of the soil below the root zone and at the same time install suction probes to sample the unsaturated soil solution, we could estimate the recharge of both water and salts into the groundwater. It would appear to us that this use of the neutron meter is ideally suited to water resource development and management in irrigated agriculture.

W. R. GARDNER: I would like to comment on this question, because it is not just fortuitous that this gradient turns out to be nearly unity. It is a general principle arising from the fact that you have gravity working all the time to have a matric gradient you have to have substantial water content differences. If you are talking about a water table at some depth, that is saturation. And, if you are talking about downward movement it is very difficult, then, to have a matric gradient working downwards over a great distance. It is interesting to note in Dr. Nielsen's data that the point where the term was not unity is exactly where you would expect to get into the most difficulty — at the lower depths in the later stages of the drainage process when you are approaching equilibrium. When you eventually reach an equilibrium it must go to zero, so it has got to lie between 1 and zero. Now, we are not talking about 1 and 1000, we are talking about 1 and 0. Looking at Dr. Nielsen's data it appears that it got as low as maybe 0.5, at the most. We are talking about a 50% difference in the extreme.

D. KIRKHAM: Well, this is truly amazing. There is another amazing thing there in that you take the average integral of the moisture content with time. Now, one of the first things you did when you were a student at Iowa State was to show that there are tremendous differences in the most homogeneous soils we could find in the state. It shocked everybody that on these loess soils you found that the moisture content was, maybe, twice as much at one place as at another place nearby. People couldn't believe it until you showed them the data. Now, you are showing here that it doesn't matter.

D. R. NIELSEN: In those days we were only measuring plots that were spread over a distance no longer than this room, and we were looking for very small differences within the profiles. We were obtaining data to be
used in this equation for a numerical or analytical analysis in which we would account for each and every layer. But, if we consider enough soil to make 100 hectares and then try to use the equation exactly for each soil layer, we would still have to average all the values in some way to yield answers applicable to the entire area. Such computer time to grind out answers even for relatively simple cases for one location. And, as you well know, Dr. Kirkham, if we were to ask the computer for calculations at each and every spot over the whole field the electrons don't move fast enough in the wires of the computer to be practical.

W. CZERATZKI: I would like to ask to what suction do you assumptions apply?

D.R. NIELSEN: The suctions manifested in these data ranged from about zero to 200 cm. For soils containing more clay suctions would extend to larger values. For our experiment suctions greater than 150-200 were not measured even after two or three months drainage.

W. CZERATZKI: I would like to add something about the variations of the soil moisture measurement as covered by the gravimetical method. For four years we have been measuring the water content by weekly borings on a loess soil. One soil is ploughed to 1 m and the other is in its natural state. If we compare, or are looking at the coefficient of variation as a per cent of the mean, we find that at low suctions values, or high water contents, we have values between 5 and 8%. If we go into the dry end we find, I dare not say it, variation coefficients of 35 to 40%.

J. DAMANGE: I have two questions to ask. The first one perhaps is not really a very good one because, maybe, I simply have not had time to assimilate what you have said. What would happen if, when we have absorption of water by plant roots, we extended the method in order to explain the specific role played by the roots, as compared to a situation where there would be absorption without the root system? This might explain how the roots absorb the elements of the soil. Secondly, can we also apply this method if we have an aquifer close to the surface. I am thinking, for example, of a water table one metre under the surface. This is a very frequent situation in a dry zone.

D.R. NIELSEN: The best way to obtain an answer to your first question is to listen to Dr. Gardner speak on that topic later this afternoon or tomorrow. Dr. Gardner has provided leadership in analysing soil water equations that include absorption of water by plants.

The second question relates to a high water table condition. Dr. Gardner pointed out yesterday that tensiometers will not provide values of the hydraulic gradient with sufficient accuracy to calculate the flux of water immediately above a water table. In our large field experiment the water table was several metres below the deepest tensiometers.

D. HILLEL: I think this whole question of whether the assumptions that Dr. Nielsen put on the board are tenable or not is related to the question of the time-scale in which we are interested. I think over a long period of time the anomalies will have ironed out, and these approximations may give a good estimate of the total drainage during a season or during a month or two months. But, if you are interested, as many people in irrigation are, in shorter periods of time then it becomes very dangerous. It can be highly misleading. Then the suction gradients whip up and down at the bottom of the root zone, changing in magnitude, so that it is not good
to assume, that somehow or other, on the average the gradient is unity. This is the same difficulty that micro-meteorologists have. It is relatively easy to estimate total evapotranspiration for a season but it becomes more and more difficult for shorter time periods. When one gets down to the scale of a day, or even a shorter period of time, then it becomes crucial to take exact measurements and to avoid tempting simplifying approximations. In support of this we have data which shows, a good part of the time during the season, that the moisture movement below the root zone is upward; at other times it is downwards. Now, Dr. Nielsen said that there is a zone somewhere below the root zone where the gradient is nearly unity and can be considered unity all the time.

D. R. NIELSEN: It is unfortunate that you arrived a little late today, because we showed the results of several experiments, one of which showed measured daily values of the hydraulic gradient below the root zone with an actively transpiring crop. If the water table is sufficiently deep, then some place below that root zone water will not be moving upward, in fact it is going to be moving downward virtually all the time. It is most difficult to define accurately the depth which delineates the bottom of the root zone. Our philosophy here has been, not to measure water movement within the root zone, but only that occurring below it. Many investigators are attempting to analyse the movement of water, solids, fertilizer and other materials within a root zone at a specific location within a field. We have emphasized the overall water and salt balance in an irrigated area, or natural rainfall area. The use of average values is about the best one can do, particularly if the spatial variability of the field is considered.

D. HILLEL: You really have not fully considered spatial variability because you consider this thing to be one dimensional. Indeed, all of these equations here are based on a one dimensional flow and the movement is up and down, whereas in a spatially heterogeneous field you would have considerable lateral components because of the heterogeneity and the layering not being entirely parallel or horizontal.

D. R. NIELSEN: In a large, nearly flat field, how much water would be expected to flow horizontally?

D. HILLEL: The scale you are assuming is the scale of a measurement with a neutron probe because you have shown equations from which you say that you can extract the conductivity or the diffusivity, as the case may be, based on measurements with a neutron probe. A neutron probe measures something of the order of 30 to 50 cm, which means that within this imaginary column of soil you are considering movement as up and down, and in a heterogeneous field this may not be the case. But, my main point is that it is very well possible that, since, as Dr. Gardner said, gravity works all the time whereas suction gradients change direction during the season as moisture is extracted by the roots, the suction within the root zone tends to be greater than the suction in the moisture layers below. Then, as some of the moisture is replenished by irrigation or rainfall, the suction in that zone tends to be lower so that it charges up and down, but on the average they may pretty much cancel each other out. Since gravity works all the time it is very possible that in the long run deep percolation pretty much obeys the assumption of unity gradient, that is, gravity alone and non-suction gradients operate somewhere below the root zone. This is very possible, and can be very general—I don't know how general it is, but it doesn't offend my experience or logic. The place where I would be very
careful is in trying to establish the short-term rate of deep percolation, that is, over a period of, say, a week or 10 days, or the period between successive irrigations.

D. KIRKHAM: This probably has been covered, but I think, Dr. Hillel, that at the beginning of Dr. Nielsen's paper he was talking about what might happen in twenty years. He was talking of long-term averages, so I wanted to defend him just a little.

W. CZERATZKI: If there is a drainage below the root zone, is that not a sign that too much water is passing through this root zone — that the irrigation has too much water? Of course the question arises, as to what extent the soil should be furnished with available water.

D. R. NIELSEN: There is some minimum value of deep percolation that would be required to maintain a salt balance in the soil. The question we have not looked at though it is related to this requirement, is the quality, and quantity of drainage. For a field in which a tile drainage system is operative, the amount of water and its quality collected by the drains does not necessarily reflect the average condition of the field owing principally to the spatial variability of the field. In the case of unsaturated, vertical flow, this panel serves a valuable function to help provide information in order that we can predict the quantity and quality of water leaving the soil zone of crops.
FIELD WATER BALANCE AND PLANT RESPONSE
FIELD WATER BALANCE AND WATER USE EFFICIENCY

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Abstract

FIELD WATER BALANCE AND WATER USE EFFICIENCY. Concepts of field water balance and water use efficiency are discussed under conditions where both plant use and percolation below the rooting zone are involved. Illustrative drainage rates, profile water storage, evapotranspiration rates and an outline of methods for their estimation are given.

1. INTRODUCTION

This paper summarizes briefly a number of recent studies on the water balance of soils in the field by members of the physics group in the Department of Soil Science at the University of Wisconsin. Since most of the experimental results presented here have been or shortly will be published, few details will be given, attention being focused upon the concepts.

Our concern for the field water balance arises out of an interest in many problems related to the energy budget of the earth's surface and in the transport of water through the soil-plant-atmosphere system. Evaporation of water from the soil or plant surfaces has long been a problem of practical and theoretical interest. Soil water content measurements have often been used to obtain an estimate of evapotranspiration. Such measurements give a reliable estimate of evapotranspiration only to the extent that water flux across the bottom of the root zone can be neglected. One of the objectives of the studies described here has been to develop procedures for measuring and predicting the direction and magnitude of this flow. The soil water content measurements in the field were obtained for the most part by use of the neutron moisture meter. It should be emphasized at this point that several of the field studies would not have been feasible without this instrument, although its use is not free from problems.

2. DRAINAGE

From a study of the water balance of an uncropped profile of a sandy soil, Black et al. (1969) found it possible to determine a unique function between the soil profile drainage rate and the average water content of the profile. From such a relationship they predicted with considerable accuracy the drainage rate for the profile over a two-month period, knowing only the rainfall and the evaporation. Figure 1 shows the predicted and measured
FIG. 1. Calculated (smooth curve) and measured (open circles) rates of drainage from a lysimeter. (From Black et al. (1960)).

FIG. 2. Rate of drainage from a lysimeter and field planned to snap beam (Black et al., 1970). The smooth curve was estimated by eye and used to predict the drainage curve shown in Fig. 3.
drainage rates during the experimental period. Success with the bare soil problem led to a study with a row crop, in this case snap beans (Black et al. 1970). A precision weighing lysimeter provided accurate evapotranspiration drainage data. The lysimeter has a depth of 1.5 metres and contains a suction drainage system such that the lysimeter and the natural soil profile drain in a similar manner. Figure 2 shows the drainage rate from the lysimeter compared with that calculated from the surrounding field, using the measured hydraulic head gradient (tensiometrically) and the capillary conductivity as determined in the field. The cumulative drainage, both calculated and measured, is shown in Fig. 3. The hydrologic balance procedure was the same as that employed for the bare soil. The curve for the hydrologic balance illustrates the value of making a water balance. Even though the drainage rate varies markedly with profile water content (Fig. 2), errors in predicting drainage tend to cancel out as long as one keeps a precise account of the total water in the profile. Although the hydrologic balance calculation underestimated drainage during July, this error was compensated in early August, and the cumulative total in early September is in good agreement. It should be noted further that even during the dry period in mid-August when the soil was very dry and the plants were badly wilted there was drainage from the soil profile. The rooting depth was about 45 cm and from about 50 cm depth on below water movement was downward throughout the entire measurement period. These data are presented in a different form in Fig. 4 in which the drainage rate
and the total water stored in the profile are plotted as a function of time. It is not to be expected that all soil profiles will behave in such a simple manner as this soil, but the experiments of Davidson et al. (1969) lead one to hope that the approach would prove useful on many soils.

3. EVAPOTRANSPERSION

If the drainage rate can be calculated from the soil profile water content as described above, then profile water content changes can be used to estimate evapotranspiration rates. This approach was tried by Lambert et al. (1971) in a young red pine plantation on the same soil type and about 15 miles from the experimental farm where the above experiments were carried out. It had long been known that removing the weeds during the early years of a pine plantation resulted in a marked growth response. However, little change in soil water content had been observed as a result of the cultivation of the weeds. In the present study the water balance in control and weeded plots within the plantation was monitored for two years. Results from the first year's study are shown in Fig. 5. Over the fraction of the season shown in the figure the total water stored in the profile did not change greatly. For the control plot the evapotranspiration exceeded the drainage by about 30 per cent. Removal of the weeds reduced the evapotranspiration by about 49 per cent, but resulted in a comparable increase in drainage. Thus, most of the water saved due to reduced transpiration did
not stay in this highly permeable profile, but drained on downward to the water table. The effect of this treatment upon tree growth will be discussed later. It should be noted that in the weeded plots the water content distribution was not uniform since the trees were sufficiently far apart so that higher water contents were to be found between trees rather than under the trees. Much of the drainage from the profile undoubtedly occurred from the region between the trees. Some of the energy which would have normally been used in transpiration from the grasses was transported through the plantation to the trees and used in transpiration from trees.

The remainder of this energy escaped the canopy in the form of sensible heat, as indicated by the lower evapotranspiration from the weeded plots.

One important, but as yet unresolved, problem in evapotranspiration research is the separation of evaporation from transpiration. In the study of evaporation from bare soil (Black et al. 1969) it was found possible to predict the evaporation from the soil surface from a simple expression relating the evaporation to the square root of the time since the most recent wetting of the soil surface. From this expression Black estimated the maximum rate at which the soil could transport water to the surface for evaporation. He then calculated the energy available for evaporation at the soil surface in the bean canopy. When the evaporation rate corresponding to this energy was greater than that which the soil could maintain he used the soil curve to estimate the evaporation. Otherwise, the evaporation was assumed to be the actual evapotranspiration minus the measured transpiration. Figure 6 shows a comparison of the potential evapotranspiration, $E_T$,
the actual evapotranspiration, $E_{\text{actual}}$ as measured by the lysimeter, the calculated evapotranspiration, $E$, and the calculated transpiration, $E_t$. The transpiration was calculated from the potential transpiration and stomatal resistance and leaf area measurements. It is of considerable interest to note that in the mature bean stand with a leaf area index of about 1.75 the transpiration and the evaporation from the soil surface were approximately equal.

In a later study Goltz et al. (1971) found it possible to estimate the evaporation from the surface of this soil from measurements of the water content in the top ten to twenty centimetres of the profile. Their experience suggests that it might be worthwhile to explore the possibilities of using the two-hole gamma-ray apparatus to measure surface soil moisture in order to estimate surface evaporation. In Goltz's experiments the field was planted to onions and there was little or no interference from plant roots, insofar as the evaporation process was concerned. Whether this would be the case with a much higher plant density is questionable. We are actively seeking better means to measure and to calculate or predict evaporation from the soil surface during active plant transpiration. One serious weakness in present models of transport of water through plant canopies is the uncertainty as to how to deal with the soil surface when it cannot be assumed to behave as though it were completely wet or completely dry.

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A.I. DANILIN: If above the soil there is moist air which has a different (higher) temperature than that of the soil there will be no evaporation. But the opposite result is shown here. How do you explain the diagram which shows evaporation as a linear function of the external conditions, yet in this case you also have moist air which has a rather higher temperature than that of the surface of the soil?

W.R. GARDNER: In general the evaporation from the soil surface can be shown very nearly to be limited by either the atmosphere or the soil. The region where the two interact is small. If the energy available is adequate, whether this is a consequence of sensible heat transfer from the atmosphere or transfer up through the soil, even though you have relatively dry atmosphere you will get evaporation only as fast as the soil can supply water. Now in the case referred to by Dr. Kirkham earlier, where the soil surface was cool, this meant that much of the energy for evaporating the water was coming from the atmosphere so that one has to look at the dynamics of water movement and see how fast this water can move upward to the surface. Then one calculates from the equations which Mr. Damagnez has shown for evaporation, including both sensible heat and net radiation, how much water you can evaporate due to meteorological conditions. Then usually you will know which is the smaller. Now, this doesn't mean that you have described the system completely because there are many complex processes going on at the soil surface, e.g. there is change of phase, which may occur over several centimetres of space so that you don't know exactly where the evaporation is occurring. Thus this sort of a calculation is not valid over very short times, but is only a good average over one or two or three days. But, generally, you can have high or low humidity, high or low wind speed and high or low radiation and they won't influence evaporation very much if the soil is itself limiting. If the soil is not limiting then all these things have influence in accord with the equations for the evaporation processes.

D. HILLEL: What we've just heard is a very elegant and, to my mind, a very beautiful packaging of the application of soil physics and micrometeorology to the complete and continuous description of the direction and quantity of water movement in the field. I have only one reservation. I believe that Black and Gardner and their co-workers are fortunate to be working with a soil which is atypical. It may be typical of large areas of Wisconsin, but not typical in my experience, but then my experience also is limited so I must qualify that. My reservation concerns mainly the kind of soil that permits them to make two very important assumptions. Assumption number one is that the hydraulic gradient at the bottom of the root zone
was nearly unity over much of the season, so that there were no appreciable suction gradients. This meant that the rate of drainage or deep percolation was approximately equal to the hydraulic conductivity. The second assumption is that when flow to the surface of the soil controls evaporation it is possible to calculate the potential rate of water delivery to the surface from a simple measurement of the average water content in the surface zone, 0-5 cm; and that it is possible to measure this in a separate laboratory column (I understand that this is the way the measurement was obtained—yes?—this is the way one would normally do it). These two assumptions are not likely to hold in other soils of different texture. In fact, unfortunately for me, in looking over my own data and being tempted to apply the same approach, I found that tensiometric measurements below the root zone indicated that there were appreciable suction gradients. Part of the time they were downward so that there was deep percolation, and part of the time they were upward so that deeper moist layers were actually contributing water to the root zone. Under the conditions I worked using a medium textured soil, I found that the soil was not evaporating at the rate that a fully charged soil would be in the absence of plants. And, it was not possible from a mere measurement of the surface soil water content to determine, from a soil rather than from a meteorological point of view, what the potential evaporation rate should be. So, whereas this approach is a very good one in principle, I think it will have to be modified for conditions which differ, particularly from the soil physical point of view, from the conditions of the particular study reported by Dr. Gardner.

W.R. GARDNER: Firstly, one should not assume that the hydraulic gradient is unity without measuring it. That was one of the reasons for emphasizing measurement of the average water content. There are many cases in which it may not be so, in which case the hydraulic gradient can be measured with adequate precision and put in. In our experience in California, and in working with the loamy clay soil over in eastern Colorado, the gradients were as low as 0.6 cm/cm and this must be taken into account. Secondly, I didn't mean to imply that our understanding of the evaporation process was nearly so far along as that of drainage. I think it was just good fortune that for this row crop we were able to take the equation for evaporation from a bare soil and get an answer that was of the right order of magnitude. I really wouldn't want to speculate on how many other soils you could do that with; but somehow we have to be able to separate those two things. I don't think this will be that useful. We need to have a way of measuring it.

J. DAMAGNEZ: I am not sure that I really understood the method used to separate evaporation from transpiration. You make separate measurements for evaporation on a bare soil and then you show that there is a relationship between the evaporation from the soil and the square root of the time. How do you apply this calculation to the evaporation from a soil covered with vegetation?

W.R. GARDNER: I can only answer for this particular experiment. A number of different ways were tried and we used the one that worked. It was not the one which was first expected to work. We accounted for all of the available energy, subtracted out that which was used by transpiration by plants as measured independently, and then assumed that the remainder was available for evaporation from the soil, assuming very good air mixing. If the remaining energy was lower in terms of its evaporation equivalent than the rate at which the soil could supply water, this is what
was used. So, the soil was treated as though it were a wet surface whenever energy was limiting. In the other case, if there was energy left over after plant transpiration was deducted then it was assumed that the rate of evaporation was limited by the soil. Now, the only reason one can justify doing this is that it works; and the data from the lysimeters show that it works. The problem is, of course, that in general you don’t have the necessary data and you can’t be sure it would work under different circumstances. It is not a generally valid procedure.

D. KIRKHAM: You said we shouldn’t use lysimeters to predict what will happen in a field, but you had to use a lysimeter here for this delicate research work. I understand then that lysimeters may be used for very careful experiments such as this. Otherwise you should some way find the capillary conductivity, and also the moisture tension curve with depth to provide the hydraulic gradient, for fields representing huge areas, and this way you could characterize and predict what would happen. Now in these experiments I didn’t see any use made of a neutron meter to predict moisture use or storage. Why was no neutron meter used? Do we need neutron meters in this method to assess what is going on? You also mentioned the possible use of sub-irrigation. You were in Turkey a few years ago, in 1967, when we presented evaporation data where we used a tank filled with clay soil, with a layer of sand over the surface and sand slots extending downward to carry water down underneath the surface. We then evaporated water from this surface using tremendous heat lamps. The soils where we had that layer of sand on the top did not lose water by evaporation. They remained soaking wet. The presence of a sand layer made a tremendous difference. This is reported in the proceedings of that Istanbul meeting. Now, if we get to the point where we are going to use these big super irrigation systems, it may pay us to put a layer of sand on the surface to prevent the capillary rise of water as was done in this sub-irrigation experiment. This is a tremendous way to stop evaporation. First, you have got to get the water in the top, and there are some problems involved, but if you once get it in, this really stops evaporation back out.

W. R. GARDNER: The neutron meter was used. We used the water content, as measured with a neutron meter, to get the 89/91 and we used tensiometers to get the hydraulic gradient, which – assuming that everybody knew – I didn’t mention.

The other question involves things that we don’t understand as yet, which may not be important for all crops, but may be for some. We must calculate how much energy we are going to have available for transpiration or evaporation from this sandy surface. If this energy, which is available and is not used for evaporating water because the surface is dry, now goes upward and evaporates water from the plant leaves, we may not have gained anything. We may only have sent all of this water through the plant, and one could argue on theoretical grounds that, perhaps, we should keep the soil surface wet and grow these plants in a humid atmosphere. I don’t think that there is a single right answer to that – I think that some plants may do better if the soil surface is wet and some may do all right under these other conditions. It’s a question of what happens to this heat – does it get out of the canopy and out of the system vertically, or does it go down to the next field and mean that the next farmer has higher transpiration? We don’t know on a large-scale basis what this really means. And this could vary
easily during the growing season; we start out with completely bare soil
and end up with some fraction covered — it depends upon the crop.

W. KÜHN: As I understand you, you want to measure the evaporation,
not only from the surface of the soil, but also from within the soil?

W.R. GARDNER: Well, I would like to know both if I could, but I will
settle for knowing evaporation from the surface if that is all I can get.

W. KÜHN: It is just this kind of experiment that we are doing. We
have a soil column about two metres high and about 80 cm in diameter,
with the water table below labelled with tritium. At different heights in
the column and at the surface we have tubes arranged to collect water
vapour which is forced out by nitrogen into a proportional counter outside
of the column. Also we have such collectors outside of the soil column
in the air.

W.R. GARDNER: Do you have plants growing in these? And, if you
had plants could you tell how much of the water collected was from evapora-
tion and how much was transpiration?

W. KÜHN: We didn't have plants, but it would be easy to grow plants.
And, we could separate evaporation from transpiration.

W.R. GARDNER: Could you do this in the field? If so, I would be
greatly interested.

W. KÜHN: Yes, we intend to do this. We have it now in the labora-
tory but we intend to make experiments in the field.

Y. BARRADA: I wanted only to ask why you didn't put surface run-off
in the water balance equation? It might play a significant role under certain
conditions.

W.R. GARDNER: I guess mentally it is implicit in another term. This
to us would be extremely important, because in Wisconsin surface run-off
results in erosion which is more serious for us than water shortage.

P. REINIGER: On your slide where you show conductivity and drainage
rate as a function of water content, I was quite surprised to see that all you
needed for your calculations was a range of three moisture per cent. Is this
all you need in your calculations?

W.R. GARDNER: Well, in the sand, yes. However, you will note in
Fig. 2 of my paper we do show more points. In a clay you have a larger
range, but this is why the capillary conductivity in coarse soils especially
is assumed either to be all or none, that is, it is such a sharp curve that
above a certain water content you have very high values and below that
they are very low. But, the range of water contents where we are interested,
meaning drainage rates that are large compared to transpiration rates down
to those which are negligible compared to transpiration rates, often is very
narrow. This is why sampling by use of gravimetric methods from one day
to the next usually doesn't detect this kind of a rate. The range of moisture
contents found in field samples due solely to field variability is much greater
than this.

P. REINIGER: Yes, but it starts at about 11% I think, and I don't know
if it was flood irrigation or sprinkler irrigation, but in any case, depending
on the rate, it could have gone up to 30% or even 25% quite easily. Didn't
you have to take this range into account?

W.R. GARDNER: Well, we have these data, it goes up to about 30%
and the calculated conductivity is about 300 cm per day. We just don't get
rainfall rates that high, and so you can't get this soil much wetter than 15%
by volume. However, the range is there and we have data for it, but it's not important in this particular problem.

P. R. STOUT: I don't wish to let you all go without making at least one pertinent remark. If you can really get 'E' separated from 'T' there are some rather vast implications because of the many places where high water tables exist in many millions of hectares of land in developing countries as well as in others. And, if you can genuinely come forth with solid information that will let all of us know how much water is lost that need not be lost, say, if we could get water tables down to about three metres, this may save the need for many, many desalting plants, and that is a very important question that is raised frequently. So this kind of information is very much needed along with studies of the whole water problem.
PLANT RESPONSE TO FIELD WATER BALANCE

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Abstract

PLANT RESPONSE TO FIELD WATER BALANCE.

The effects of soil and leaf water potential and related stomatal conductance and transpiration upon photosynthesis and plant growth are reviewed. Rate of growth of red pine is shown to be reduced as soil water potential is reduced in the wet range well above -0.7 bar. Similar data are available for onions and beans. Such data show the need for frequent measurements of soil water conditions such as may be obtained using a neutron moisture meter.

The plant is neither a completely passive nor completely active element in the water balance. The transpiration flux through the plant is an inexorable consequence of solar radiation, which provides more than enough energy for photosynthesis, and of the plant's need to maintain a pathway for gaseous (CO₂) diffusion into the leaf. The plant does exercise some degree of control over this process through its stomatal apparatus. Our results are consistent with Troughton's (1969) findings that stomatal resistance correlates almost inversely with rate of photosynthesis. Figure 1 shows the relation between stomatal conductance as a function of total leaf water potential and as a function of turgor pressure for seed onions. Details of the experimental procedure are given by Millar, Gardner, and Goltz (1971). The relation between soil water potential and leaf water potential depends upon the transpiration rate. Our results, as well as those of others, indicate that the relation between the water flux through the plant and the potential difference between soil and plant leaf is not linear. Therefore, the simple resistance models which are rather widely used now do not correctly predict the leaf water potential. When the transpiration rate is sufficiently high the leaf water potential tends to be less dependent upon transpiration and the daytime value of the leaf water potential tends to remain below the soil water potential by a constant amount until the soil is extremely dry.

The dramatic decrease in stomatal conductance with decreasing leaf water potential (Kanemasu and Tanner, 1969) has important consequences with respect to the so-called availability of water. It implies that even at the very wet end of the available range any lowering of the soil water potential should result in a reduction in photosynthesis rate. Figure 2 shows that this does, in fact, happen. These data are for red pine (Lambert et al. 1971), but we have similar data for onions and beans (Millar and Gardner, 1971). In Fig.2 the rate of diameter growth in both
FIG. 1. Stomatal conductance as a function of leaf water potential and leaf turgor pressure for onions in a growth chamber.

FIG. 2. Diameter growth rate for red pine as a function of soil water potential at 30 cm depth below the tree. Open circles indicate data from the weeded plots and closed circles are for the control.
FIG. 3. Measured stomatal conductance for seed onions plotted as a function of soil water content. These data were obtained in the growth chamber and the measured growth rates were in good agreement with the stomatal conductances.

FIG. 4. Dry matter production rate and transpiration rate for field grown snap beans plotted as a function of water content and soil suction.
the weeded and the control plot are shown as a function of soil water potential. It should be noted that the range of water potential values was above -0.7 bar and that both sets of data fall on the same curve. The main reasons that such a marked reduction in growth with decreasing water potential is not normally observed in the field are probably the imprecise measurements of instantaneous growth rates and the fluctuations in light and other environmental factors.

Figure 3 shows the stomatal conductance for onions as a function of soil water content under growth chamber conditions (Millar, Gardner, and Goltz, 1971). For the Plainfield sand the curve is so steep that it comes very close to the concept of equal availability as propounded by Vehmeyer. For the finer textured soils any decrease in water content causes a reduced rate of growth below about -0.3 bar water potential, which is roughly the potential value at the upper end of the curve in Fig. 3 for the loamy sand and clay loam.

The closure of the stomates also causes a reduction in transpiration rate. Figure 4 shows the dry matter production rate and the transpiration rate for snap beans in the field plotted as a function of both soil water suction and soil water content. The curves are similar and a cursory inspection might lead one to conclude that they are identical in form. However, in Fig. 5 the dry matter production rate is plotted as a function of the transpiration rate. These data represent a single drying cycle during which it is assumed the potential evapotranspiration was relatively constant. One would expect a different curve for a different potential rate. It is highly significant that as the soil dries out the partial closure of the stomates results first in a reduction in growth rate and then later in a reduction in transpiration rate. The relatively small initial decrease in transpiration is due, of course, to the compensating effect of an increase in leaf temperature which serves to increase the water vapour pressure
in the substomatal cavities and hence the driving force for water vapour diffusion. No similar effect is operative in the CO₂ diffusion process.

It has proven possible in the very special case of a sandy soil to obtain a useful quantitative picture of the field water balance from relatively simple field measurements. In these studies the neutron moisture meter has proved to be an invaluable tool. These studies, coupled with appropriate plant measurements and micrometeorological measurements, illustrate very clearly the central problem with respect to efficient water use. The farmer must keep the water content of the soil sufficiently high so that he does not risk serious water stress. This means supplying water at very near the potential evaporation rate. On the other hand, the curve relating to water content is so steep that excessive losses due to steep percolation are a constant risk. In a soil such as the Plainfield sand the farmers elect to risk the percolation losses rather than the growth reduction. Where water is extremely expensive, as would be the case with desalted water, percolation losses which are acceptable in central Wisconsin would be totally unacceptable, since they may easily exceed the evapotranspiration. Thus, more careful control is necessary. This will almost certainly require some system of continuous monitoring of the soil water. The difference between the potential and the actual evaporation is too great to permit the use of computed water balances alone without frequent verification. On the other hand, for hydrological purposes where water budgeting rather than plant growth is of major importance, it appears quite feasible to develop very simple predictive equations requiring only a modest input of field data.

BIBLIOGRAPHY


DISCUSSION

A.I. DANILIN: Dr. Gardner, can you please tell me how you propose to study the following phenomena which are related to the application of tensiometers, for example, during the day when you have sun-light. Now, if there is above the surface of the soil a part of the tensiometer which is warmed up, and if in the volume there is a void then the volume of the water corresponds to a given temperature. When the whole system is warmed up by the sun, the pressure increases and the additional quantity
of water is ejected from the system. This is done through the porous cup which you have. Since this process cannot be reversed because of the hysteresis, how do you take this phenomenon into account? Can we still rely on the tensiometer? Well, personally, we doubt that the tensiometer can be of any use in this case when there is this phenomenon of thermal expansion.

My second question is as follows: What is the discreteness of these detectors as far as the depth goes? In order to get really good information on moisture content how many detectors would you have to use on a plot in order to get correct results for the determination? What is your opinion?

W.R. GARDNER: The effect of temperature on tensiometer behaviour is, of course, a disturbance which is known to be one of the things that one has to avoid. In good tensiometer practice you don't put any of the tensiometer parts out in the direct sunlight. We have been using both mercury manometers and pressure transducers. The pressure transducers can be buried below the soil surface where temperature gradients are not very large, and you have fairly constant temperature. With mercury manometers or other liquid manometers we shield them from the sun, if possible. We generally use a material with a low thermal conductivity to connect our manometer with the cup so that we do not transmit heat down to the cup itself. The magnitude of the effect of temperature, of course, depends on the relative temperature coefficients to the expansion of the material containing it. These problems, I think, can be resolved. It is not too difficult to insulate the tensiometers so that you don't have large temperature effects on the manometer itself. There are temperature effects in the soil, and one will see diurnal temperature waves reflected in tensiometer readings, and these are serious near the soil surface. Generally, these do not confuse the interpretation of the data, particularly if one is careful to read the tensiometer at the same time every day, or makes a continuous record. The tensiometer is an extremely precise instrument and so one sees small variations that generally you don't see by any other method. And, you become aware of phenomena that are going on and are influencing the potential. We have not found that this temperature effect is a serious problem if you take reasonable precautions. With respect to the second question, the number of tensiometers that you would install depends on the detail of information that you want, and the nature of the soil, whether it is homogeneous or whether it has several layers, so that you need a tensiometer to explore what is happening in each. Without any specific information, I would say that about 5 tensiometers give you considerable detail. These I would place closer together near the surface, perhaps every 30 to 50 cm, and then further apart as you go down. About 2 m is the reasonable limit for a tensiometer with a manometer on it. Below that it is very difficult to install and you don't have much suction range left, and so we have not used them below 2 m. This generally takes us far enough down into most root systems so that this is not a problem.

J. DAMAGNEZ: I would like to come back to the figures which you have shown concerning the behaviour of onions in the field and also in the climatized chambers. I don't know the exact nature of your experiments. I do know that it is difficult to achieve conditions of evaporation which are similar to those in the field. Very often there is a relation-
ship of 1:5 or even 1:10 between the potential evaporation values outside in the field and in the room. So, I believe that the figures or the diagrams which we have largely used of potential resistance in order to explain the circulation of water from the soil to the plant, are perhaps not quite correct. It might be a little over-simplified, in fact I feel that what happens might be slightly different. In an air-conditioned room, of course, it is possible to have values which are similar to those observed in the field, but the difference is in the energy which is brought to the system at the level of the exchange surface and at the level of the leaves, and I was surprised to see that it doesn't result in differences as regards values of the potential of water in the plant, or the stomatal resistance, etc.

I also wanted to come back to a remark you made. You said that the water and light are completely independent. I think these factors are not really completely independent because of the potential evapotranspiration; the energy which reaches the evapotranspiration surface is of radiative nature and it is also this sort of energy which brings the light. If in a control room we have the same conditions, or the same situation as in the field, this would be a means to evaluate the effect of the energy part of the solar spectrum which produces the evapotranspiration, since in the air-conditioned room we bring light only and much less energy than in the normal outside conditions. Thus, we want to go on with work we are doing using a method to modify the energy spectrum due to the sun and trying to create different conditions as regards the relationship of light-energy and therefore water-light and then photosynthesis.

W.R. GARDNER: It is difficult in a few sentences to put all the qualifications and ifs and ands and reservations. So I agree, in principle, with what you say, because, of course, chambers and the out-doors are usually quite different. In the particular experiment with the onions, pains were taken to make sure the evaporation rates were comparable. The rate of water loss from an onion plant of the same size was about the same inside the growth chamber as in the field. Now, the radiation and the wind velocities were not identical inside and outside and this is very difficult to achieve as you know. But the fluxes were of the same order of magnitude. They were not different by a ratio of 1 to 5, they were within 20%, at least, if not closer, so that if we do have a difference in the type of energy, whether it is radiant energy or sensible heat causing the evaporation, we may have temperature effects on stomatal behaviour. This is particularly true with onions, and I mentioned it. As far as the light and water being independent, this was meant as a first approximation in terms of how to look at the effects of water in influencing growth. They certainly are not independent in the overall scheme of stomatal behaviour, because stomates are very sensitive to light. They are only independent in the sense that, if we have two different light levels resulting in two different growth rates in, say, maize, and if we have a reduction in the water potential, I would expect both systems to show a reduction in growth as we decrease the water potential, rather than one of them being different from the other. This is a case of over-simplifying the picture. Something that we need much more information about is the interaction of light, temperature, CO₂, and water, etc.

L. STROOSNIJDER: I want to ask you two questions. First, when one measures water potential using a vapour pressure method why is it so difficult to measure below one bar? Is it a question of accuracy?
Second, I didn’t really understand how you measured the potential of the water in the leaf. Will you explain that again, or enlarge on your explanation?

W.R. GARDNER: I think the principal reason that it is difficult to measure water potential near one bar or between one bar and zero is, of course, that you are measuring a relative humidity that is very nearly 100% and it is easy to get dew formation somewhere in the system. It is difficult to get a completely clean system, or a completely non-absorbing system, except for the thermocouple junction you are working with. For example, it has been found in making measurements on leaves that if they are very dusty and dirty because you take them out of the field under dry conditions, the dust on the leaves will absorb enough water to give you erroneous results. In cotton plants the salt that is exuded on the leaves is sufficiently hygroscopic to give you errors. With the psychrometer one can only measure using plant materials with our present techniques probably to within 0.3 bar anyway, and as you approach zero potential you are getting closer and closer to having condensation in some part of your system, and as soon as you get that your measurement becomes questionable.

Our measurements on the plants were made, almost without exception, by cutting the leaves off, putting them in a small chamber and measuring the vapour pressure using a constant temperature bath. We do have some measurements which were made in situ in the onion leaves with a little psychrometer. The top of the leaf was cut off and the psychrometer inserted. These measurements agree quite well with the measurements made on detached leaves. I might say, in this regard, that Dr. George Thurtell at the University of Guelph in Canada has modified the procedure for making measurements with a thermocouple psychrometer and I think may have made it quite feasible to make measurements in situ under a wide variety of conditions. He does not have any reports as yet available, but the preliminary indications are extremely encouraging. He has devised a scheme to eliminate many of the temperature errors, and make in situ measurements on plant leaves. This is something which I said years ago, that no one would ever do, but I think it may now have been done.

P. REINIGER: You quite firmly believe in tensiometers. But, there are some problems. Quite often you notice there are pronounced root concentrations around tensiometer cups if you dig them up. This might give a quite erroneous result sometimes. What is your experience with this? Have you also encountered it?

W.R. GARDNER: Well, my belief is that a tensiometer measures the water potential in the soil in contact with the tensiometer. I don’t understand root distributions — they grow around stones, and they grow where they will grow — but I do believe that tensiometers will measure the water potential, if they are operated properly, with the roots right around them, and I don’t think that this is greatly different from the water potential some distance away. If in the process of operating the tensiometer you have been filling it every day and introducing a lot of water into the system which doesn’t belong there, you may be altering the normal regime. Tensiometers should not perturb the system that much. I don’t think that this is a serious problem in general.

P. REINIGER: You were looking for a flux meter. In fact there is one for measuring the water flux above a plant or the water flux out of
plant leaves by infra-red absorption, and there are apparatuses which you can use in the field that were mostly developed by, I think, the Forstbotanisches Institut in Munich. They are also commercially available and there are quite a lot of these around in Germany and Holland, and there is one in Israel. Both in the laboratory and also when working outside in the field they can be used to measure both photosynthesis and transpiration.

W.R. GARDNER: I am aware of these methods as well as others for use in the atmosphere. It is down in the soil that the problems are more difficult. Unfortunately, you can't use this infra-red analyser for measuring soil moisture flux.

A.I. DANILIN: I should like to make an additional comment to what Dr. Gardner has said concerning the measurement of the moisture using a tensiometer, and quite apart from the radiative methods that can be used, such as gamma and neutron rays. There are also other methods that look quite promising and I would like to mention one of them. This is the photoelectric method. Depending upon the water content in the soil sample there is a strong variation of its absorption and scattering properties with regard to light. We have a piece of equipment which is very simple — its description is given in the Journal of Soil Sciences in 1969, Volume 11. This instrument contains a photoelectric counter and a small lighting device, a lamp about the size of a pocket battery. We have a tube into which a ceramic unit has been put. It is the same type that is used in the tensiometer with the same kind of porosity. Now, we put into this tube a device containing the light and the photoelectrical resistance and you get a reflection of the scattered light from this ceramic block. You can use them to very great depths. If you have several such devices you can monitor the moisture content of such blocks and the measurements can be done promptly, within seconds, because the scattered light will be recorded immediately. Of course, there are some drawbacks. For example, inside the tube there may be water vapour and if the tube is covered with such a film of water, then for each measurement you must clean it up again. But, in any event, I think that this sort of method is a very simple one and there is no irradiation risk. It makes it possible to get very quickly the data on moisture content. We have carried out some experiments concerning the infiltration of water through a sandy soil where the measurements are made directly in the soil column which we had behind a glass shield. This counter or detector was simply moved from place to place and we got excellent results that made it possible to monitor the rate of movement of the wet-front in a sandy soil.

I would say, also, that we should pay more attention to the development of methods that are based on gamma radiation. I am convinced that it is a very good method, because it is based on the possibility of determining the mass or quantity of the water. It is based on the use of gamma rays and it is a highly promising method for the future. Of course, the neutron method is also very promising, but there are still lots of problems, and they always come up at all of our regular sessions. Nevertheless, these methods will make it possible for us to directly determine the quantity of water.

In agriculture, we need to know the amount of water per day, necessary for plant growth which can be measured by this method. Now, any failures we had were because in the past we simply had bad measuring
equipment. But now a great deal of progress has been made and we can use small equipment with transistors and can very successfully determine the water content directly in centimetres of the water column. Of course, the mechanisms of water movement in the soil are a very complex thing, but I would like to draw your attention to the fact that we sometimes observe evaporation in rather deeper layers with a water content less than that of the top layer where we have more water. We usually have a relative humidity which is about 90% and very slight changes in the temperature would already cause a transfer from one particle to the next if they are of a different radius, for example, because the film of water surrounding the particles is different. Therefore, it is very difficult to solve the problem of water or moisture transfer in soil; this process is an extremely complicated one, and it also depends on external factors, meteorological factors — and I am thinking here of the temperature of the air, the moisture in the air, solar radiation, whether there is wind or not. All of this, of course, affects the exchange of moisture. Another factor is atmospheric pressure — which can, within a very short time, change by 100 mm and this change in the pressure could be a kind of a piston that pushes down or sucks up the moisture together with the air. Well, we do not attach too much importance to this process, but this is one of the factors which plays a role in the transfer of water and I am thinking here of the upper part of the soil.

W.R. GARDNER: I won't attempt to comment on each of these points. I am interested in and intrigued by this optical method, and would like to learn more about it. I would like to agree strongly with the final comment about air pressure fluctuations. I think that our equations for water movement near the soil surface, which take into account only temperature and moisture gradients and ignore the pressure fluctuations, are ignoring what may be one of the most important terms.

D.R. NIELSEN: Yesterday I mentioned that we have been measuring soil water content in the field probably more than any other physical parameter. To that end, I do not believe that I would throw out any meter, because in various soils and for what purpose it is being sought, each meter has its own relevance and importance. I agree with you also that we would like to know what the water content is today. I believe, though, that we also want to predict what it will be tomorrow or the following week; and, therefore, we have to be more analytic mathematically and must use every means possible to predict and measure the fluxes of water. This cannot be done only by examining water content, and classifying water within soil around particles in terms of different film thicknesses and how they change. At field capacity, which we have already recognized as a rather loose, poorly defined term, there are somewhere in the order of two dozen molecules of water on the average surface and there are many, many kinds of surfaces in the soil. At the permanent wilting percentage there is a layer somewhere in the order of two or three molecules, perhaps five molecules, thick. If you then couple those dimensions with what solutes are in the water, and considering the fact that their rates of transfer are also having an influence on the water movement, we must really concentrate on both the transfer of water and the transfer of solutes and heat; and, we have to do it with a predictive concept. We have to look at fluxes, and how to predict fluxes, and not
merely contents. So we need both water contents and fluxes, and this is why it takes all the instruments we have at our power and why we need to develop as many more, to be able to take those measurements.

P.R. STOUT: I would like to point out that it has just occurred to me with your last remark, that this is very good radiological evidence that atmospheric fluctuations are indeed important and it comes from the observation of lead-212 in the atmosphere. The precursor for lead-212 has to be thoron which has a half-life of some 59 seconds, and the diffusion distance for one half-life is about 1 mm, yet if you measure the amount of thoron in the air, which you can do simply with a suction cup and catching the lead-210 and counting it you will find that it cannot possibly account for this coming from thoron and it was a great puzzle to me at one time as to what was happening. However, I came across an article which dates back to about April 1954 by a Japanese investigator looking at microbarometric pressure changes and he was worried about why soils dried out too fast. You get a flushing of the top centimetre of the air depending upon the pressure changes which go with wind gustiness and this is enough to just account for the amount of thoron you find. I have been very happy about that. But I would guess that if you did measure lead-212 over any given soil at any time that you could get a good measure of it. I have done that by putting a guinea pig cage down on the ground, letting air in for only 2 minutes and then catching air as it comes through and you can get some remarkably high counts.

A.I. DANILIN: I did not want to make a further comment, but do want to say that Dr. Nielsen has apparently not understood me quite correctly. I am sure you got the drift of what I said. I said that, depending on the radius of curvature of particles, there is a different elasticity of the vapour and this has an effect on transfer. For example, in the atmosphere you have completely identical particles in a cloud and they are stable and no rain is falling. If in this cloud a few large particles come in then upset the equilibrium of the pressure, then big drops of rain will come down as the stability is upset. I should like to draw your attention to the fact that in the soil, since we have some air in it, it is possible, as a result of different radii of curvature of particles and different thicknesses of the films surrounding them, that the radii would be increased, and that this might upset or disturb the equilibrium. This then would cause a flux or flow of moisture to rather dry parts, and this has already been observed. Abramov, a scientist who has observed this, found that there was movement not only on the top surface of the soil but even inside. There was evaporation going on, in fact, this has also been observed by others. There is evaporation, not only from the top surface of the soil but lower down, and that from the rather drier part there is evaporation going on even though the higher parts of the soil are wetter. I just want to say that these processes that are going on are so complicated that we cannot have a completely clear idea of what is going on and which method would be the best one.

D.R. NIELSEN: Thank you very much. I agree that it is complicated and also recognize that we have both liquid and vapour transport within the profile.
LES BILANS HYDRIQUES ET ENERGETIQUES ET L'ETUDE DES FACTEURS DU MILIEU

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Abstract—Résumé

WATER AND ENERGY BALANCES AND THE STUDY OF ENVIRONMENTAL FACTORS.

Water and energy balance concepts have made it possible to derive analytical relationships in studies of the climatic factors affecting crop production. The water balance concept involves determining the contributions of rainfall and irrigation, and the losses by deep percolation, surface run-off, evapotranspiration and storage within the profile. The energy balance concept reflects the necessary balance between net radiative energy and the energy used in evaporation, heat convection, heat conduction in the soil and photosynthesis. Aerodynamic and wind profile techniques can also be used to evaluate evapotranspiration. The relationships thus established reflect the nature and intensity of exchanges between vegetation and its physical environment – the soil and atmosphere.

LES BILANS HYDRIQUES ET ENERGETIQUES ET L'ETUDE DES FACTEURS DU MILIEU.

Les notions de bilan hydrique et de bilan énergétique ont introduit des solutions analytiques à l'étude des facteurs climatiques de la production agricole. Le bilan hydrique repose sur la détermination des apports par les précipitations et l'irrigation et des pertes par percolation profonde, par raisonnement superficiel, par évapotranspiration et par stockage, dans le bassin versant. Le bilan énergétique traduit l'équilibre nécessaire entre l'énergie radiative nette et le flux d'évaporation, le flux de chaleur par convection, le flux de chaleur par conduction dans le sol et la photosynthèse. Pour évaluer l'évapotranspiration, on peut aussi utiliser les méthodes aérodynamiques et du profil de vent. Les relations établies traduisent la nature et l'intensité des échanges entre la végétation et son milieu physique, le sol ou l'atmosphère.

1. INTRODUCTION

Le climat au voisinage de la surface du sol est la conséquence de l'équilibre entre l'énergie reçue, exprimée essentiellement par le bilan radiatif, et l'énergie cédée à l'atmosphère sous forme d'échanges turbulents de chaleur et de masse: convection, évaporation, photosynthèse. La nature et l'intensité de ces échanges témoignent également d'une certaine réaction du milieu biologique aux conditions macroscopiques d'environnement; en particulier la température du couvert végétal est la résultante de l'équilibre nécessaire entre les différents termes de ce bilan des échanges d'énergie.

L'analyse des échanges au niveau de l'interface végétation-atmosphère et au sein même de la végétation est nécessaire à la compréhension du mode d'action du climat, du niveau le plus élémentaire, la cellule, jusqu'aux relations «sociales» entre les différentes espèces qui traduisent les biotopes. Toute modification de l'un des termes de ces échanges – facteurs externes du microclimat: rayonnement solaire, vent, sécheresse – ou même
TABLEAU 1. TABLEAU RECAPITULATIF DES DIFFERENTES METHODES UTILISEES POUR L'ETUDE DES ECHANGES ENTRE LA VEGETATION ET L'ATMOSPHERE

<table>
<thead>
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<th>Bilan d'énergie</th>
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<td>Evaporation-transpiration ET</td>
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<td>Evaporation-transpiration ET</td>
<td>- mesure directe au lysimètre ou bac d'évaporation</td>
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<td>Drainage</td>
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<tr>
<th>Signification (échelles d'espace et de temps)</th>
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<th>Quelques heures à 1 jour ou plus</th>
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<td>A la limite et dans certains cas particuliers 24 heures</td>
<td>Pas de relation entre échelles d'espace et de temps</td>
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<td>Méthode mixte (bilan d'énergie × méthode aérodynamique)</td>
<td>Méthodes aérodynamiques</td>
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<td>Bilan radiatif</td>
<td>Profils ou fluctuations</td>
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<td>- CO₂</td>
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<td>- chaleur sensible</td>
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<td>Relation entre ET et</td>
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<td>- bilan radiatif</td>
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<td>- rapport de Bowen</td>
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<td>Etude des échanges entre la végétation et l'atmosphère</td>
<td>Étude des échanges entre la végétation et l'atmosphère</td>
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<td>- permet cependant d'étudier le poids relatif des échanges radiatifs et convectifs sur ET</td>
<td>- flux élémentaire à l'intérieur du couvert végétal</td>
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<tr>
<td>10 minutes à 1 heure</td>
<td>Étude de la couche limite turbulent</td>
<td></td>
</tr>
<tr>
<td>Pas de relation entre échelles d'espace et de temps</td>
<td>Étude de l'influence des caractéristiques de la turbulence sur le microclimat et la végétation (rugosité, brise-vent, ...)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>≈ 20 minutes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Relation entre échelles d'espace et de temps</td>
<td></td>
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</tbody>
</table>
indirectement par une modification de la structure de la végétation: techniques cultures, aménagement du territoire — se traduit par un déplacement de l'équilibre qui entraîne des modifications de tous les autres paramètres. La climatologie, discipline jusqu'alors essentiellement descriptive, fait appel dès lors à des considérations dynamiques qui permettent de mieux comprendre les mécanismes d'action du climat.

Le bilan hydrique, le bilan d'énergie et, plus récemment, les méthodes dites «aérodynamiques» sont des méthodes analytiques souvent utilisées pour étudier les principaux termes d'échange entre un couvert végétal et son milieu physique environnant — le sol ou l'atmosphère:
- échanges radiatifs
- flux de chaleur par conduction dans le sol et par convection dans l'atmosphère
- circulation de l'eau dans le sol, dans la plante et évaporation dans l'atmosphère
- flux de CO₂ correspondant à la photosynthèse.

Chacune de ces méthodes ne peut cependant être utilisée indifféremment: elles ont les unes et les autres leurs exigences particulières, une signification correspondant à des échelles de temps et d'espace souvent différentes; elles ne conduisent pas toutes, suivant les objectifs de l'expérience, à la mesure des mêmes paramètres, et il sera nécessaire dans le cadre d'une recherche particulière de définir la méthode la mieux adaptée au domaine étudié, en relation avec les échelles de temps et d'espace correspondantes (tableau I). Dans la mesure où les échelles le permettent, leur emploi complémentaire ne peut qu'être recommandé.

2. LE BILAN HYDRIQUE

L'analyse du bilan hydrique (figure 1 et tableau I) repose sur la détermination de l'ensemble des apports et des pertes d'eau dans la tranche de sol exploité par les racines:

\[
P + I - D + R + ET = \pm \Delta W
\]

\(\text{I})\) Apports: \(P = \text{Pluie}\)
\(I = \text{Irrigation éventuellement}\)

\(\text{II})\) Pertes: \(D = \text{Drainage: percolation profonde au-delà de la profondeur } Z_h\) fixée par la limite au-delà de laquelle l'humidité du sol n'accuse que des variations négligeables; elle correspond le plus souvent à une profondeur légèrement supérieure à l'enracinement final de la culture ou à une discontinuité importante dans le profil pédologique (encroûtement, nappe phréatique)

\(R = \text{Ruisseau superficiel, qui peut être positif ou négatif}\)
\(ET = \text{Evapotranspiration}\)
III) Variation totale de la réserve en eau de la tranche de sol exploitée $\Delta W$

$$\Delta W_{\text{nn}} \# \sum_0^{Z_h} \frac{\sigma}{10} \cdot \Delta H \cdot \Delta Z_{\text{cm}}$$

$s = $ Densité apparente du sol
$\Delta H = $ Variation d'humidité pondérale dans la tranche de sol élémentaire $\Delta Z_{\text{cm}}$ explorée (fonction de la technique de mesure, de l'hétérogénéité du sol et de la précision exigée).

La méthode du bilan hydrique a été et reste encore la méthode la plus couramment utilisée en hydrologie pour les études de bilan d'eau de bassins versants. En agronomie, elle conserve encore, malgré les développements récents de la méthode du bilan d'énergie et des méthodes aérodynamiques, un rôle essentiel dans les recherches sur la dynamique de l'eau du sol et dans certaines études appliquées à l'irrigation.

2.1. Applications hydrologiques

À l'échelle d'un bassin versant l'écoulement représente sensiblement les quantités d'eau mesurées à l'exutoire, c'est-à-dire sensiblement la somme $(D + R)$ ; le déficit d'écoulement $[P - (D + R)]$ est égal à la somme $ET \pm \Delta W$. Si l'on désire déterminer l'évapotranspiration réelle $ET$ d'un bassin versant, pour étudier par exemple l'influence d'un type
de couvert forestier sur le bilan d'eau, il faut chercher à éliminer le
terme $\Delta W$ en choisissant le découpage de l'année hydrologique:
- en zone sèche, le bilan annuel est généralement fermé en été car le
déficit d'eau $W$ dans le sol est alors toujours maximal.
- en zone humide le bilan annuel est fermé quand les réserves d'eau
du sol sont reconstituées; ces réserves sont pratiquement toujours
reconstituées en hiver et le déficit du sol est alors pratiquement nul.
Sauf cas exceptionnel, il est souvent illusoire, à l'échelle d'un bassin
versant, d'espérer recueillir des informations sur des bilans partiels
portant sur des périodes réduites. Toutefois l'étude de la cinétique de
l'écoulement—hydrogramme de crue—fournit alors des indications
intéressantes sur la rétention superficielle et sur la dynamique de
l'infiltration.

2.2. Applications agronomiques

Si l'hydrologue s'attache surtout à l'étude des termes d'écoulement,
lagronome s'intéresse plus particulièrement aux deux termes suivants:
$\pm \Delta W$, variations des réserves en eau du sol
$\text{ET}$, évapotranspiration.

Variations de la réserve en eau du sol ($\pm \Delta W$)

Ce terme peut être considéré à l'échelle du volume de sol exploité
par les racines; dans ce cas, il donne une information sur la contribution
globale du sol à l'alimentation en eau de la culture en économie d'eau réduite.
La sonde à neutrons répond de manière très satisfaisante à ce type de
problème.
Il peut aussi être décomposé en tranches de sol élémentaires, d'épaisseur
variable en fonction de la résolution de la technique de mesure de l'humidité
du sol (sonde à neutrons ou gamamétrie); il fournit alors des informations
sur la dynamique de l'exploitation de l'eau du sol par la plante. Les varia-
tions d'humidité observées sont la conséquence de deux phénomènes distincts
que l'on s'efforce de dissocier:
- mouvements de l'eau dans le sol, que l'on peut relier au potentiel
  hydrique de l'eau du sol
- absorption d'eau par les racines, fonction de la densité du système
  racinaire, des gradients de potentiel de l'eau entre le sol et la plante
  et de la «résistance» au passage de l'eau du sol dans la racine.

Evapotranspiration (ET)

L'évapotranspiration représente la somme de deux termes qu'il est
souvent difficile de dissocier: évaporation au niveau du sol et transpiration
du couvert végétal.
Ce terme d'évapotranspiration est généralement l'inconnue du bilan;
elle est dite potentielle si les disponibilités en eau au niveau du couvert
végétal ne sont pas réduites. La détermination, in situ ou en cas lysimé-
trique, reste délicate car les sources d'erreurs sont multiples; on peut
en particulier citer:
— les difficultés d’apprécier le terme de drainage difficilement mesurable dans les études in situ et souvent perturbé dans les déterminations sur lysimètres
— les difficultés de s’assurer une zone homogène suffisamment vaste pour éviter tout effet de bordure.

Excepté les mesures faites à partir de lysimètres pesables, la méthode du bilan hydrique ne permet pas d’accéder à des études portant sur de courtes périodes; les échelles de temps adoptées ne sont généralement pas inférieures à la décennie ou au mois et, contrairement aux méthodes aérodynamiques par exemple, qui se prêtent mal à l’intégration dans le temps des flux mesurés, les études de bilan hydrique seront d’autant plus précises qu’elles portent sur des périodes plus longues. C’est aussi la seule des méthodes envisagées ici qui fournit des informations sur la manière dont le sol cède son eau à la plante.

3. LE BILAN D’ÉNERGIE ET LES METHODES AERODYNAMIQUES

3.1. Bilan d’énergie

La quantité d’énergie disponible au sol et qui résulte essentiellement du bilan radiatif se répartit entre les différents flux de chaleur et de masse qui prennent naissance au niveau de la surface d’échange, le sol ou la végétation: la photosynthèse $Q_p$ qui résulte d’un flux de CO$_2$ et de réactions photosynthétiques, le flux d’évaporation $Q_e$ qui correspond à une conversion de l’énergie en chaleur latente au niveau de la surface évaporante, le flux de chaleur par convection dans l’atmosphère $Q_H$ et par conduction dans le sol $Q_s$.

L’équation du bilan d’énergie traduit l’équilibre nécessaire entre ces différents termes$^1$:

$$R_N + Q_E + Q_H + Q_s + Q_F = 0$$

L’utilisation d’énergie pour la photosynthèse ne représente qu’une fraction infime, 4 à 5% au maximum, des apports nets d’énergie solaire. Ce terme est bien souvent négligé dans l’expression du bilan d’énergie et son estimation relève d’autres méthodes soit biologiques, soit physiques – méthodes aérodynamiques.

En effet, la quantité d’énergie utilisée pour la photosynthèse et qui se traduit dans les basses couches de l’atmosphère par un flux de CO$_2$, obéit aux mêmes lois d’échanges turbulents que le flux d’évaporation $Q_e$ ou que le flux de chaleur $Q_H$.

La répartition qui s’établit entre les divers flux détermine la température d’équilibre de la surface d’échange, et l’importance relative des différents termes $Q_E$, $Q_H$, $Q_s$ dépend:

$^1$ Sont compris comme positifs les flux dirigés vers la surface du sol.
- de la vitesse de transport de l'eau dans le sol jusqu'au niveau de la surface évaporante
- de l'état de turbulence de l'atmosphère
- de la rugosité de la surface d'échange
- des propriétés thermiques du sol.

Autant d'informations que la seule considération du bilan des échanges d'énergie est incapable de donner.

L'intérêt de cette méthode en tant que telle est donc essentiellement théorique. Puisqu'elle nécessite la mesure directe du flux d'évaporation — mesure qui reste soumise aux aléas de la mesure lysimétrique —, elle n'est pas, à proprement parler, une méthode de détermination, mais plutôt de contrôle.

3.2. Méthodes aérodynamiques

L'étude directe des flux de chaleur et de masse nécessite des informations complémentaires généralement liées à l'étude aérodynamique de l'écoulement de l'air au voisinage de la surface du sol. Par suite des propriétés de rugosité de la surface constituée par un sol nu, une végétation, une forêt, une étendue d'eau, le relief, etc., cet écoulement est turbulent et l'intensité des transferts verticaux de chaleur et de masse est d'un ordre de grandeur bien supérieur à celui qui résulterait d'une diffusion moléculaire sans turbulence.

Les diverses quantités qui caractérisent la masse d'air (vitesse, température, concentration en vapeur d'eau et en gaz carbonique) varient alors aléatoirement dans le temps et dans l'espace. L'étude statistique directe de ces fluctuations ou de relations semi-empiriques qui en découlent (méthodes du profil de vent) (tableau II) permet de relier le flux de quantité de mouvement, ainsi que les flux de chaleur et de masse qui lui sont associés, soit directement aux fluctuations des grandeurs dont on désire mesurer les flux (méthode des fluctuations), soit indirectement par l'étude du profil vertical des vitesses et du gradient moyen de température et de masse (méthode du profil de vent).

**TABLEAU II. EXPRESSION ANALYTIQUE DES FLUX TURBULENTS AU VOISINAGE DU SOL**

<table>
<thead>
<tr>
<th></th>
<th>Méthodes des fluctuations</th>
<th>Méthodes aérodynamiques</th>
</tr>
</thead>
<tbody>
<tr>
<td>Densité de flux de quantité de mouvement $\varphi_D$</td>
<td>$\rho \overline{w'\varphi'}$</td>
<td>$\rho \overline{U} \overline{\varphi}$</td>
</tr>
<tr>
<td>Densité de flux de chaleur sensible $\varphi_T$</td>
<td>$C_p \rho \overline{w'T'}$</td>
<td>$C_p \rho \overline{K} \overline{\varphi}$</td>
</tr>
<tr>
<td>Densité de flux de masse $\varphi_M$</td>
<td>$\rho \overline{w'\varphi}$</td>
<td>$\rho \overline{K} \overline{\varphi}$</td>
</tr>
</tbody>
</table>
La méthode des fluctuations ne nécessite aucune hypothèse, elle est théoriquement la plus rigoureuse, l'obstacle majeur à sa mise en œuvre est d'ordre technique car la mesure et le traitement de grandeurs fluctuantes nécessitent des capteurs de très faible inertie ainsi qu'un appareillage d'enregistrement et de traitement important.

La méthode du profil de vent est relativement plus aisée à mettre en œuvre; les hypothèses de travail qu'elle suppose sont cependant très contraignantes et limitent considérablement son domaine d'application. Elle ne peut plus en particulier être appliquée sans restrictions au voisinage d'hétérogénéités ou de discontinuités importantes: zones cloisonnées par des brise-vent, limites entre un espace irrigué et une zone sèche adjacentes par exemple.

Appliquées au même phénomène étudié sous des aspects différents, l'étude énergétique et l'étude aérodynamique sont par nature complémentaires.

Le groupement des informations qu'elles apportent est d'une très grande importance à deux niveaux:
- détermination des échanges entre végétation et atmosphère, généralement appelée méthode du bilan d'énergie, qui combine l'équation du bilan d'énergie et les relations aérodynamiques
- sur un plan plus général, étude théorique des échanges énergétiques entre le sol et l'atmosphère, qui est à la base d'une étude «analytique» et non plus descriptive des micro et même des mésoclimats.

Le bilan d'énergie est un des éléments de l'aspect global des phénomènes et il est indispensable de le considérer. Les informations d'ordre aérodynamique sont directement liées à des éléments de structure plus fine, dans le temps et l'espace. Elles conduisent à l'étude du fonctionnement instantané du couvert végétal, et permettent l'examen analytique de l'influence de facteurs précis tels que la structure de l'écoulement turbulent, la rugosité de la surface considérée, etc.

C'est le rapprochement de ces deux points de vue qui a conduit aux formules fondamentales de calcul de l'évapotranspiration potentielle telles que celle de Penman, ou à l'élaboration de considérations théoriques sur la signification de l'ETP.

C'est aussi le rapprochement de considérations énergétiques et aérodynamiques qui a permis d'établir les lois générales de refroidissement du sol, d'expliquer le mécanisme de formation des gelées prin- tanières et de proposer des méthodes de lutte passives (considérations topographiques, techniques culturales, etc.) ou actives (chauffage, brouillards, irrigation par aspersion, etc.).

4. CONCLUSION

Les notions de bilan hydrique et de bilan énergétique ont introduit des solutions analytiques à l'étude des facteurs climatiques de la production. Les relations établies traduisent la nature et l'intensité des échanges entre la végétation et son milieu physique, le sol ou l'atmosphère. Chacune des méthodes exposées, bilan hydrique ou bilan énergétique, a ses caractéristiques et ses objectifs propres. L'étude d'un problème particulier nécessitera souvent un rapprochement des différentes méthodes. Cette
confrontation permet d'établir des relations quantitatives entre plusieurs termes de ces bilans:

- relation entre les facteurs climatiques de l'évaporation et les lois de la circulation de l'eau dans le sol
- relation entre l'évaporation et la photosynthèse par exemple.

D. KIRKHAM: I didn't understand, Dr. Damagnez, what you meant by the porosity of the wind break. What do you mean by this?

J. DAMAGNEZ: It is the relationship between the voids. For example, if you take a grid the porosity is given by the relationship between the void areas and the total grid area. This is very simple to do when we are using plastic grids. But, for natural wind breaks it is preferable to use a coefficient of the pressure drop which can be measured. Obviously, to try to indicate the characteristic of a natural system, or the coefficient of pressure drop of a natural system, is much more difficult. But we can do it whilst working on a very well known geometrical system such as plastic wind breaks. We can give a figure for the efficiency of this plastic wind break and then on the natural wind breaks we can try to find out what is the corresponding porosity. It is quite obvious, for example, that a wind break made of cypress is much more dense and therefore impermeable than a poplar wind break, and therefore we try to find a way to characterize the differences in porosity or in pressure drops between these two types of systems. But I know that it is not easy at all to indicate this characteristic in natural environments.

P.R. STOUT: I remember two years ago we discussed similar problems. I was very interested in what kinds of wind breaks could be used out in desert areas where nothing grew before. I was trying to promote cactus as a wind break, and they almost convinced me that the olive tree would be more appropriate as a means of getting both a crop and a wind break than using these 'vegetable camels' of the desert.

M. ABDALLA: May I ask whether the wind breaks did cause a change in moisture content distribution and how they affected erosion?

J. DAMAGNEZ: Yes, there is an effect of the wind break on the distribution of rainfall, particularly in windy areas there results a heterogeneous distribution of rainfall when this zone has been equipped with wind breaks. There is also another effect of wind breaks on wind erosion. Naturally, when the velocity of the wind at ground level is reduced it is much more difficult to have particles of sand suspended in the air. Of course the installation of wind breaks must be on a very large scale, otherwise, if you set up only two or three series of wind breaks they will only trap, so to speak, the particles which have been put in suspension all around. With regard to the effect of wind breaks on the climate we have a particularly acute problem in the western part of France, in Brittany. This area had been provided with different bushes in lines, but recently all these lines of bushes separating the various fields have been destroyed. The engineers working on this problem were not well aware of the effect of the roughness of the environment on the weather conditions and on the agricultural crops. Consequently we have bare areas now. Agriculturalists in the region, or the farmers, later have felt that there was a decrease in yields
in this area, whereas in other areas where these natural hedges have been maintained yields are better. We have been asked to see what would be the optimum way to lay out wind breaks in this region, keeping a certain roughness of the environment in order to favour the microclimate of field plots. There are two separate problems but I will deal only with the temperature problem here. Let us suppose that there is a certain heat flux. Taking into account other parameters, such as the quantity of water available for evaporation, you can see that the exchange of heat is in proportion to the coefficient of turbulent transfer, and to the temperature gradient — that is to say the temperature profile at the ground surface. Now, if the transfer coefficient increases, then for the same quantity of energy released the temperature profile will be less marked and the weather conditions will be completely different.

D. HILLEL: Dr. Damagnez touched on one of the most moot and lively questions in micrometeorology and that is, as far as I can understand, the effect of wind breaks on the evaporation or evaportranspiration. There is a great deal of confusion on this in the literature. Some of the more recent studies that I have come across have indicated that wind breaks, while reducing the velocity of the wind and thereby, initially at least, reducing the transfer of latent heat, actually serve as heat traps because more of the radiation of the sun is converted into sensible heat. This results in a rise in temperature and subsequently in an increase in the evaporative demand so that there is a vicious circle here wherein the wind breaks do not conserve water, and actually do not, in the net, result in a reduction of the evaporation rate in many cases. In other cases the empirical results show that there is, or does seem to be, a significant conservation of water; and those of us who are very concerned with water conservation would like to understand, in simple terms if possible, the principle whereby wind breaks can in some cases conserve water and in other cases fail to do so.

J. DAMAGNEZ: To try to explain all the various principles in detail would be very difficult for me to do. I think it is rather premature to try to give, now, the results of the theoretical study which has been under way, but which has yet to be tested. But, roughly speaking, the results I gave a little while ago with regard to this theoretical study show that, in fact, there are two different effects: the effect of roughness which increases the coefficient of turbulent transfer and therefore increases evaporation, and another effect which is connected with the heterogeneity. For example, certain investigators have studied the effect of different buildings on wind. Now, if we had very sharp shapes there would be a certain type of effect. But, on the other hand, shapes which are not quite so sharp will have a different type of effect. This means that, depending upon the roughness, we can have a decrease in the turbulent transfer because of what happens at the surface of the soil. We can, therefore, show that there is a sort of optimum roughness which will lead to a maximum decrease in evaporation.

D. KIRKHAM: I have two points to make. I was interested in the point made by Dr. Hillel. We did some wind tunnel experiments at Ames, Iowa, where we had the wind blowing over a tank of soil and measured the temperature in the soil and the amount of water lost from the soil. Then we measured the water loss when we had radiation light falling on it, like a bright sun coming down. With the wind coming over it the soil was cool. In Iowa we know that when it gets too hot corn growth is reduced. It occurred to us that if corn was planted in the direction of the prevailing
wind there might be a cooling effect and we would get a higher growth. So, in keeping with this effect you are talking about, proper orientation of corn rows so as to get a cooling effect may be actually beneficial in some cases.

Another case I have seen — I don’t know if you have seen this — is just on the border as you go into Denmark from Northern Germany, right next to the west coast there. We ran into a whole series of farms up there where there were earth fences around the farms about four feet high, and these were wind breaks. I think that these are there to protect against physical damage. I would like to ask Dr. Damagnez if the wind breaks he talked about were there partly to protect against the physical damage of the crop? Do your winds get that violent, as they do up on the west coast of Germany next to Denmark?

J. DAMAGNEZ: It is true that one of the main purposes of the wind breaks that you see in the valley of the Rhône and Durance is to forestall physical and mechanical damage to the crops. The mechanical effects of the wind could spoil by about 50% the surface and therefore reduce by about one half the surface of exchange of assimilation of the crop with its environment. But, the effect of wind breaks on air pollution and the exchange between the vegetation cover and the soil also are important. We have good reason to believe that not only the net quantity of energy and exchange with the atmosphere have to be considered but, also, the way in which this energy is exchanged. It is quite clear that if we have a very marked temperature gradient we are going to have important constraints at the level of the plant. Perhaps not the larger quantity of water vapour that is lost, but the surface temperature will be the important factor. Depending upon the layout that we adopt, we will have a resulting surface temperature which will be different according to whether it is under the effect of the wind or not. Now if, for example, we take Penman’s formula, the term for radiation, which by far is the most weighty one, enters practically into all the areas and is responsible for more than 80% of the evaporation. The variations in evaporation from one point to another for the same value of radiation are not greater by more than 15 to 20% under extreme conditions. But, the same is perhaps not true for carbon dioxide and photosynthesis, and it is perhaps possible that the variations of the turbulent transfer coefficient are important for photosynthesis in order to make it possible to feed the crop because the source of carbon dioxide is the atmosphere. The flow of carbon dioxide would be more or less important depending on the value of the turbulent transfer coefficient. There is also the effect of the mechanical force on the vertical fluctuation of wind speed. I believe that, in any case, if we examine the agronomic results of the various experiments over the whole world with wind breaks we would find as many positive results as we find negative results. In the face of such a situation we are trying to analyse all this to determine why some researchers find negative and others find positive results.

A. L. DANILIN: Could you tell me if you have any experimental verification for your theoretical conclusions? Did you get some results concerning the choice of these wind breaks or, as we call them, wind shields?

J. DAMAGNEZ: No, certainly not. That is what I am saying, that our approach was rather philosophical.

A. L. DANILIN: Your work now is directed towards developing criteria that would make it possible to assess mass transfer, moisture transfer
and so on. I would be interested in the following: your scheme which will make it possible to solve problems of evaporation from the soil surface, taking into account that in 24 hours the gradient of temperature, moisture and the vertical wind are changed. One would have to record all these parameters for 24 hours in order to get good data for computing evaporation. I should like to say that in our country we have tried to use a mathematical approach in order to make an assessment of evaporation, but it turns out that within 24 hours the moisture gradient changes, the temperature gradient changes and we do not have confidence in the results. Errors are up to 50-60% as a result of evaporation. Would it not be simpler, then, to change back to measuring with the usual nuclear methods?

J. DAMAGNEZ: The difficulty of the problem is that one has got to work on a rather short time-scale. This is the reason why we are trying to evolve now towards the method of fluctuations that will make it possible for us to measure these variations at a time-scale of 5 to 10 minutes. The conventional methods or classical methods make it possible for us to measure fluctuations at a time-scale of 20 minutes and we need a means to integrate the whole phenomenon over 20 minutes, and, at the time, to provide details during periods when the flows are most important.

W. CZERATZKI: No question, but some remarks relating to the comment of Dr. Kirkham. In Germany 15 years ago a lot of work was done on wind breaks by the weather bureau to give an order of importance to factors influencing the microclimate. It turned out that the most important effect of wind breaks was in the control of wind erosion. Then there was a big gap and the usual found on evapotranspiration, but on the physical damage to plants, especially vegetables. In the western part of Schleswig Holstein there was a feeling that the recreation value of the landscape is much enlarged by wind breaks. The landscape looks lovely and people feel much better when there is no wind. That would be the order of the factors which were found.

P. R. STOUT: Insurance may be a large part of such programs too, because I get the general impression that people are more afraid of the occasional wind storm which tears the banana leaves to shreds — that's what they are really concerned about first. This would go along with your remarks that mostly there is real physical damage, then there is a big gap and the rest may be chalked up to more desirable landscape and scenery. So, maybe we are a long way from knowing how much water is actually going to be saved.

D. HILLEL: I just wanted to remark that where the effect of wind breaks on evapotranspiration is evaluated, there are two basically different types of situations, one in which the areas surrounding the field in question is pretty much uniform with the field, and the other in which the field is practically an oasis surrounded by generally a much drier environment. Wind breaks seem to have the greatest effect where the advective load is appreciable. I had hoped that Dr. Damagnez would point this out, and I think that he may agree with this. I would like his indication that he does agree, that where a small irrigated field is surrounded by an expanse of dry land, the wind break would have its maximum effect in reducing evaporation.

J. DAMAGNEZ: Yes, I agree.

W. KÜHN: Do you know if there exists a relation between the efficiency of wind breaks against wind velocity and temperature on the soil?
QUESTIONNAIRE ON THE APPLICATION OF RADIATION EQUIPMENT IN AGRICULTURE

JOINT FAO/IAEA DIVISION OF ATOMIC ENERGY
IN FOOD AND AGRICULTURE,
Vienna

Abstract

QUESTIONNAIRE ON THE APPLICATION OF RADIATION EQUIPMENT IN AGRICULTURE,

Completed questionnaires relative to the use and effectiveness of a neutron moisture meter in various situations were received from 24 respondents in various parts of the world. These replies are summarized in this report. Although certain specific limitations were recognized the neutron moisture meter appears to be used extensively and successfully for a wide variety of measurements under different agricultural conditions.

INTRODUCTION

The questionnaire which follows was sent out by the Joint FAO/IAEA Division. Twenty-four replies were received. Two of these, since they dealt only with very specific points, are not included in this survey of the answers. Of the remaining 22 replies, 12 were rather short (mainly yes or no) answers and ten were detailed.

These 22 answers were summarized for each question in an attempt to facilitate the discussions of the Panel.

They are also printed here.

THE QUESTIONNAIRE

The use of radiation equipment is being recommended as a very helpful tool in solving certain agricultural problems, though in specific cases other approaches might be better. Specific recommendations indicating the conditions under which the performance of radiation equipment is very satisfactory and the problems, the solution of which would become much easier with the aid of the equipment, would provide a sound basis for the Joint Division's future advice on its use especially in developing countries.

To facilitate the task of making specific recommendations, answering the following questions is suggested:

(1) Could the neutron gauges be used with satisfactory accuracy for determining the soil moisture content in soil profiles having the following characteristics:

(a) stratified profile with distinct rather thin horizons
(b) rich in montmorillonite (swelling and shrinkage problems)
(c) a high percentage of stone
(d) a poor water holding capacity (sandy soils)
(2) How best could the soil moisture content of the top soil layer be measured? (Special calibration curve, reflector, placing a tray filled with the same soil around the access tube, or other methods)

(3) How useful is the neutron moisture meter in investigating the effect of moisture content on the uptake of nutrients, or the effect of applying fertilizers on the efficiency of water use?

(4) Is the neutron moisture meter an essential tool in consumptive use or evapotranspiration studies?
   (a) under dry farming conditions?
   (b) under irrigation?

(5) Could the neutron moisture meter be used to advantage in determining the adequate irrigation intervals as well as the amount of irrigation water that should be applied?
   (a) in arid regions where irrigation is the main source of water?
   (b) in humid regions where supplementary irrigation is occasionally used?

(6) Could we rely on evaporation estimates based on meteorological data instead of measurements with a neutron moisture meter in the investigations indicated under 4 and 5?

(7) Is the use of the neutron moisture meter advisable in investigating the effect of certain cultural practices, such as the following, on either water conservation or consumptive use?
   (a) including a period of fallow in crop rotation
   (b) choice of a crop rotation that would make the most efficient use of available water
   (c) preparing or making use of a certain slope to benefit of run-off in providing more water to a smaller area
   (d) soil cultivation (compared to weed control using herbicides)
   (e) natural or artificial wind breaks

(8) Could the neutron moisture meter be effectively used in studies of irrigation efficiency?

(9) "Under dry farming conditions the use of the neutron moisture meter to follow the changes of moisture content in soil profiles around the seasons of the year for a number of years would provide data essential for planning development programs, for example:
   (a) choice of tree varieties (forestry or even certain fruit trees) and determining the adequate population density in relation to rainfall and evaporative demand
   (b) choice of grass combination that could be sustained by the water available in the soil profile
   (c) assessing the need for eventual supplementary irrigation ".
   Is this statement valid? or partially valid?

(10) To what extent can a neutron moisture meter provide information on water movement?

(11) Could the neutron moisture meter be helpful in estimating the loss of water through deep percolation?

(12) Could the neutron gauge be used to advantage to follow the water table level fluctuation and assess the need for establishing a drainage system or improving an existing one?
**REPLIES TO THE FIRST QUESTION**

<table>
<thead>
<tr>
<th>Positive</th>
<th>Negative</th>
<th>No experience</th>
<th>Depending on measuring conditions</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>4</td>
<td>4</td>
<td>7&lt;sup&gt;6&lt;/sup&gt; special field calibration curve</td>
<td>&lt;sup&gt;6&lt;/sup&gt; if moisture differences only are required and gradients of calibration curves are similar for different horizons&lt;sup&gt;4&lt;/sup&gt; if reliable field calibration curves are established</td>
</tr>
<tr>
<td>b</td>
<td>3</td>
<td>4</td>
<td>7&lt;sup&gt;6&lt;/sup&gt; calibration at swelling and shrinkage in the field&lt;sup&gt;6&lt;/sup&gt; if not extreme through difference in density</td>
<td>&lt;sup&gt;6&lt;/sup&gt; if the effect is not extreme and the access tube does not become isolated. Vertical movement of the soil surface could be compensated for if a fixed datum is taken as reference, and not soil surface. Plastic access tubes avoid excessive drying</td>
</tr>
<tr>
<td>c</td>
<td>5</td>
<td>6</td>
<td>9&lt;sup&gt;6&lt;/sup&gt; for differences&lt;sup&gt;6&lt;/sup&gt; special field calibration</td>
<td>&lt;sup&gt;6&lt;/sup&gt; percentage and variability of stone content must be known&lt;sup&gt;4&lt;/sup&gt; if access tube can be inserted without undue disturbance&lt;sup&gt;4&lt;/sup&gt; if differences in moisture content are required</td>
</tr>
<tr>
<td>d</td>
<td>14</td>
<td>-</td>
<td>8&lt;sup&gt;4&lt;/sup&gt; for differences&lt;sup&gt;4&lt;/sup&gt; careful calibration in situ</td>
<td></td>
</tr>
</tbody>
</table>

<sup>6</sup> Answers are positive under the indicated conditions.

In conclusion, serious problems will always exist in the use of the neutron moisture meter in inhomogeneous soil (a, c) and where dry bulk density changes with the change of moisture content (b). More studies of the loss of precision are in order.

However, with proper calibration in the field, and especially where differences are considered, one can still obtain results that are as reliable as any other procedure, since inhomogeneities present problems for any water content measuring method.

The two wells gamma attenuation method or the new developments for improving the resolution may bring a solution for (a).

For stony soils, more tubes may be necessary to obtain a required precision, etc.

For sandy soils, generally no problem.
REPLIES TO THE SECOND QUESTION

<table>
<thead>
<tr>
<th>Special calibration curve</th>
<th>Reflector</th>
<th>Extension of soil surface</th>
<th>Gravimetrically</th>
<th>Gamma ray</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1</td>
<td>1</td>
<td>11</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Electrical conductivity failed under low irrigation levels. Tensiometers can be used satisfactorily within their range. Surface probes not recommended. Reflector could cause large systematic error.

The use of the gamma transmission method is the solution indicated by a number of researchers; however, most of them are now using the gravimetric method, while an appreciable number of users recommend the use of special calibration curves as the best possible method, though a certain loss in precision is involved.

REPLIES TO THE THIRD QUESTION

The following answers were given by the indicated number of users:
(a) No experience ........................................... 7
(b) The neutron moisture meter is very useful in investigating the effect of moisture content on the uptake of nutrients, or the effect of applying fertilizers on the efficiency of water use ........................................ 12
(c) As useful as gravimetric sampling .................... 1
(d) The interaction between nutrient and water uptake by plant roots has far-reaching implications both with respect to plant water relations and ion uptake. Could be a major objective of the next study, as the answer to the question is not known ........................................ 1
(e) The neutron moisture meter enables us to study the change of soil moisture content, of soil layers, with time. It does not, however, indicate whether this change in moisture content represents water uptake by roots. Other measurements have to be associated .......... 1

It is obvious that the answers indicated under (d) and (e) are exact, while the positive answers (b) deal with the interaction between nutrient and water uptake, in general terms, mainly in connection with yield response to both fertilizer application and moisture content of soil profiles, as indicated by evapotranspiration measurements.
REPLIES TO THE FOURTH QUESTION

In general all answers were positive. Three users indicated no experience under dry farming conditions. Some research workers suggested the use of weighable lysimeters under irrigation, others indicated that acquiring the necessary know-how and the high purchase cost of the equipment are the main difficulties.

It should be recalled that changes in moisture may not represent total losses or additions to the profile (near the water table).

It is important to point out the greatly enhanced value of the neutron measurements when certain other soil and plant water measurements are made concurrently.

REPLIES TO THE FIFTH QUESTION

Almost all replies were positive in both cases. Two research workers believed that the use of other methods of soil moisture measurement may be preferable.

It is believed that the neutron moisture meter should be used in field experiments aiming at obtaining the necessary information that would serve later as a basis for determining for a given region the adequate irrigation intervals as well as the amount of irrigation water that should be applied, taking the following important factors also into consideration:

(a) meteorological data
(b) properties of soil profiles
(c) crops

REPLIES TO THE SIXTH QUESTION

Distribution of the 22 received answers:

<table>
<thead>
<tr>
<th>Positive</th>
<th>Conditioned 'positive, provided that'</th>
<th>Negative</th>
<th>No experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>8</td>
<td>11</td>
<td>1</td>
</tr>
</tbody>
</table>

The answers in general indicate that evaporation estimates based on meteorological data which can only give an areal mean estimate, neither take into consideration the soil-water characteristics nor rooting pattern of crops and are therefore (alone) not sufficiently precise. This becomes obvious if, for example, the need for an estimate of drainage becomes essential in irrigated soils, especially where salinity is a hazard.

However, evaporation estimates based on meteorological data are better than nothing, could be very helpful in planning experiments, and would be very useful if several years' data are correlated with soil moisture measurements so that estimates then based only on meteorological data would be valid. Even in such a case occasional soil moisture measurements should be made to check the meteorological estimates.
REPLIES TO THE SEVENTH QUESTION

Five users gave no answers, as they had no experience in such studies, while 17 answers indicated that the use of the neutron moisture meter in investigations of the type listed under question 7 is very advantageous, as this tool is very useful in providing reliable quantitative data on changes of moisture content in soil profiles. However, for consumptive use measurements, deep drainage losses must be recognized and accounted for.

As indicated before, moisture measurements in soil profiles with the aid of the neutron moisture meter would gain much more importance if other measurements of plant and soil water status (such as stomatal resistance, plant leaf water status in the field, etc.) are carried out concurrently. This would apply also in connection with questions 8 and 9.

REPLIES TO THE EIGHTH QUESTION

All answers to this question were positive, however, the following important remarks were made by various users:

(a) Confusion between a tool (neutron moisture meter) to measure a parameter and the use of this parameter for subjective analysis should be avoided. This would apply to other questions such as 7 and 9.

(b) A large number of access tubes would be required for such studies.

(c) The inaccuracy of the neutron moisture meter near the surface should be borne in mind.

(d) Additional measurements such as the amount of water applied, surface drainage and an estimate of water losses by deep percolation are essential.

REPLIES TO THE NINTH QUESTION

The majority of the answers (12) fully support the validity of the statement, while 5 users indicated that the statement is partially valid and the remaining 5 gave no answers owing to lack of practical experience.

It was remarked that knowledge of the full circumstances would facilitate answering this question, as under certain conditions other less costly techniques might be just as good.

Under certain conditions, developing a method of monitoring unsaturated vertical flow to or from ground water would be very important.

When dealing with trees, supplementary measurements of stem flow and interception may be needed to correctly interpret results.
REPLIES TO THE TENTH QUESTION

The low resolution of the neutron moisture meter makes it inadequate for this type of study. By itself the neutron moisture meter can only give information on water movement where it is possible to cover the soil surface and observe soil water content changes in the absence of plant uptake. There are many instances where there is significant water movement with little change in the soil water content. Here water content measurements are of only minor value and must be supplemented by other procedures. Water movement studies could be carried out with the aid of tensiometers, gamma transmission equipment and tracer techniques which are by far much more adequate for such studies. It is understandable that the answers to this question mainly gave the above indicated remarks.

REMARKS TO THE ELEVENTH QUESTION

13 answers indicated that the neutron moisture meter could be helpful in estimating the loss of water through deep percolation, especially in deep, light textured, relatively homogeneous soil profiles, and where the water table is sufficiently deep.

5 negative answers were received, very likely, because no generalization can be made. The remaining 4 users gave no answer to this question as they had no experience.

The general opinion appears to be that, in many soils, a relation between the soil water content and the percolation rate could be derived. In this sense the neutron moisture meter, once the procedure is calibrated properly, will give percolation losses.

REPLIES TO THE TWELFTH QUESTION

The answers received indicate that the majority of the users are convinced that for measuring water table fluctuations, piezometer tubes are better, cheaper, and more rapid. The neutron moisture meter can be used to detect phreatic surfaces in sandy soils and loams but not in heavy clays. In the latter, water content in the extensive capillary fringe can hardly be distinguished from that below the phreatic surface. This explains the reasons for the seven negative answers received. Movement of the top of the capillary fringe (associated with water table fluctuations), would be shown by neutron probe measurements and not by piezometers. Also the water table position is not the best criterion for drainage. Water content measurements are essential in drainage studies and the neutron moisture meter shows promise here. Based on this way of thinking 12 positive answers were received, while three users gave no answers.
RECOMMENDATIONS OF THE PANEL
FOR FUTURE RESEARCH PROGRAMS
RECOMMENDATIONS OF THE PANEL
FOR FUTURE RESEARCH PROGRAMS

The Panel takes note of the advances of knowledge in soil plant atmospheric water relationship and in the use of nuclear techniques particularly in soil water studies as exemplified by the papers presented before it, by the results of the co-operative water use studies sponsored by the IAEA during the past five years, as well as other information reported. As a result of their deliberation the Panel recommended that the Joint FAO/IAEA Division of Atomic Energy in Food and Agriculture initiates a co-ordinated research program on "The Use of Isotope and Radiation Techniques in Studies of Soil Water Regimes", and encourages research on closely related problems mainly through research agreements with institutes in developed countries. A more detailed indication of these two major recommendations follows.

1. CO-ORDINATED RESEARCH PROGRAM

The neutron moisture meter has proven its suitability for the measurement of changes in water content in the field more expeditiously than any other procedure in a great many situations. It now appears feasible to make use of such measurement to obtain a better estimate of the drainage of a soil profile and so contribute to a major advance in the quantitative understanding of water movement in unsaturated soils. The first of the Panel's recommendations is that the Joint FAO/IAEA Division of Atomic Energy in Food and Agriculture initiates a co-ordinated research program on the use of isotopes and radiation techniques in studies of soil water regimes. During the first year of this program the implementation of a basic experiment, in order to develop procedures for the characterization and the study of soil hydraulic properties, is suggested. In addition to the basic experiment the contractors and other interested groups are invited and urged to carry out studies of the water balance in the field under a wide variety of soils, climates and crop and soil management systems. Such a concerted effort will provide in five years a wealth of available information which lies well beyond the resources of any individual research group.

1.1. Experiments

(1) Basic experiment
(2) Auxiliary experiments (optional)

The basic data could be useful in one or more of the following studies:

(a) Measurements and control of deep percolation
(b) Salt balance and leaching efficiency as affected by water quality
(c) Dryland farming and water conservation in fallowed soils
(d) Irrigation and water use efficiency studies
(e) Drainage under high water table conditions
(f) Soil and crop management under periodic flooding
(g) Effect of water management on the disposal of waste products.
Details of the basic experiment entitled "The use of radiation techniques in the in-situ characterization of the physical and hydraulic properties of soil profiles", are given in Appendix I.

2. PROBLEMS SUGGESTED FOR RESEARCH

The Panel recognizes that the movement of water in the soil is intimately coupled with the movement of dissolved substances. In some cases these are used as tracers of water movement per se, in others it is the movement of the dissolved substance that is of interest. Isotopic techniques offer many possibilities in soil studies but many unresolved questions remain, before their application can be fully achieved. Therefore it is proposed that studies on a number of problems be encouraged, with particular emphasis upon application to problems of salt balance in irrigated agriculture.

Research agreements, mainly with institutes in developed countries, would be very beneficial in co-ordinating research work and establishing fruitful co-operation not only among these institutes but also between them and co-operators in the above-mentioned co-ordinated research program.

The Panel recommends, encouraging and promoting research on the following important problems, which are closely related to the proposed co-ordinated research program:

2.1. Tracer behaviour

The progress made in the theoretical description of transport phenomena in swelling soil, and of salt transport in soils in general, necessitates an experimental verification of these theories. In view of this aim investigations should be pursued on "The relative migration rates of both gamma and beta emitting isotopes through different types of soil". Some suggested radioactive isotopes for this comparison study are $^{60}$Co, $^{131}$I, $^3$H, $^{36}$Cl, and $^{82}$Br. These tracers are suggested for the study but not intended as a complete listing. The advantage of gamma emitting isotopes such as $^{131}$I is their ease of measurement in situ, i.e. they do not necessitate sampling the soil solution.

Another aspect of the soil environment where isotopes may play an important part in future studies is in the mixing of atmospheric air with the soil atmosphere. The three tracers suggested for this use were $^{18}$O for $O_2$, $^{14}$C for $CO_2$, and $^{15}$N for $N_2$ and $NH_3$.

In many irrigated areas both salinity and high boron concentration cause appreciable reductions in plant growth. Development of the best mode of reclamation and measurements of the different leaching efficiencies obtainable are necessary. A novel way for following boron leaching efficiencies was suggested. The neutron meter response is a function of the boron concentration in the soil. Measurements made at the same location in the soil profile and at the same water content may be related to the change in boron concentration of the soil, and therefore to the leaching efficiency.

2.2. Water content measurements

Although the neutron moisture meter has been found satisfactory for determining the water content in the soil a fixed distance below the
surface, a remaining area, where the water content measurement is needed in the 20 cm surface layer. A number of techniques were suggested for this measurement. These can be broken down into gamma transmission techniques and neutron moderation. Gamma transmission methods suggested by the committee involved the use of various detection methods. Two of these were the use of Geiger-Müller tubes and sodium iodide (thallium activated) crystals. This technique gives specific water content changes in narrow segments of the soil. A suggested neutron moderation technique involved the use of a subsoil tube running parallel to the soil surface. This technique would allow comparison of water content changes over larger volumes and permit rapid comparisons to be made of the depletion rate of water from a large number of locations within a field. Co-ordinated laboratory investigations were proposed in order to evaluate these techniques for their usefulness prior to the implementation in the field. A proposed title for this study might be: "Evaluation of methods for determining water content changes in the top 20 cm of soil". The study would evaluate various methods in the laboratory initially to determine a method that is suitable for measuring moisture distribution in this 20 cm region where plant roots are concentrated and from which evaporation is rapid.

Various research workers would be encouraged to utilize the technique they consider the most satisfactory for these measurements. Their investigations should consider the following problems:

(a) The effect of temperature changes from 0–50°C on the operating characteristics of the instrument. Will the instrument give a correct moisture measurement over the range of temperatures of interest?
(b) The effect of water content changes above and below the layer of interest. Moisture conditions above and below the layer of interest should not influence the reading.
(c) The cost and reliability of the instrument should be known. The instrument should be rugged and resistant to break down. It should be easily repaired. The accuracy of the equipment should be determined. Reliability and ruggedness are more important than high accuracy.

The relative merits of the various instruments available for this study will be known as a consequence of the study and new equipment may be developed. Some available equipment causes a certain amount of soil disturbance. Ideally the equipment needed should either cause no disturbance at all or only very slight disturbance to the soil during installation.

The information obtained in this study will be useful for field research workers who want to study the extraction of water by plants and the loss of water from the soil surface by evaporation.

The problem of water content and soil density changes in swelling soils has received little attention experimentally because of the difficulty of simultaneously monitoring water content and soil density changes. It was suggested that development of double-beam γ-ray attenuation equipment for laboratory investigations be pursued.

2.3. Flux measurements

The importance of the use of tracers to measure various fluxes (mass of substance passing through unit cross-sectional area per unit time) through
the soil and through plants cannot be overemphasized. These fluxes are water and water vapour; gases important in aeration such as O₂, CO₂, or N₂; nutrients such as nitrate and phosphorus; and salts that influence the salinity condition of the soil. Tracers can be used following known methods; however, the recent production of 252Cf permits neutron activation of the ionic components of the soil solution in situ. Studies utilizing this technique might permit one to follow the solute dynamics in a system containing plants. The uptake by the plants of the activated compounds would allow qualitative studies on nutrient movement to be made. It was suggested that an evaluation of this technique be made.

A non-destructive method for following salt fluxes through the soil was suggested. This technique involves the use of X-ray fluorescence analysis to measure quantities as they change during leaching.

Two problems of practical value were suggested. The first is the measurement of the flux of CO₂ from the soil into the plant canopy; such information is vital to photosynthetic studies. A second important flux measurement is the flux of water vapour through the soil, through the canopy and through the first ten metres of atmosphere by turbulent motion. A systematic search for isotope techniques for the solution of these problems should be encouraged.

APPENDIX I

THE USE OF RADIATION AND ISOTOPE TECHNIQUES IN STUDIES OF SOIL WATER REGIMES

OBJECTIVES

To develop improved means for controlling the dynamics of soil water in the field as a basis for the better use of soil and water resources in agriculture. The following specific objectives will be achieved:

(a) To find better methods for characterizing pertinent soil physical and hydrologic properties and to provide basic data for improvement of management methods,

(b) To develop and test radiation techniques applicable to water balance studies with special reference to the determination of the drainage component,

(c) To initiate auxiliary studies in the field and the laboratory to further clarify aspects of water management.

BASIC EXPERIMENT

"The use of radiation techniques in the in situ-characterization of the physical and hydraulic properties of soil profiles".
1. Field site characterization by conventional observations and measurements:

<table>
<thead>
<tr>
<th>(a) Climate</th>
<th>(b) Soil</th>
<th>(c) Crops</th>
<th>(d) Water quality and quantity and other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classical mesoclimate measurements and data necessary for calculation of ETS* by Penman equat. and soil temperature profile</td>
<td></td>
<td></td>
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</table>

* ETS = Evapotranspiration from a bare soil surface.

2. Size, large — up to 100 ha. This field shall serve as a resource for future characterization by standard methods or for future experiments. At 10 locations in the field site the following shall be performed:

A. Determine texture at 30 cm intervals or by horizons, soluble salts, exchangeable salts, mineralogical analysis, other.

B. Obtain 6 soil cores (75 mm diameter by 75 mm height) together with disturbed soil samples near the cores at each depth h interval. Determine, on each core, soil water characteristic curve θ (h), using Buchner funnels or similar other techniques in the laboratory.

C. Neutron access tubes shall be installed before taking the cores for calibration of the neutron gauges to be used in 3. below.

D. Assess water table location.

3. Characterize soil water properties in situ at 5 locations

A. Delineate 5 plots with earthen or man-made dikes. Size ~5 × 5 ~ 10 × 10 m.

B. Install within this plot as a minimum 2 neutron access tubes and tensiometers at vertical intervals of 30 cm to a depth as deep as possible.

The soil water content and matric potential in relation to depth and time shall be recorded as required in C. below.
C. Pond water on the surface so that essentially static conditions prevail as judged by tensiometer readings — record steady state values. Cover the plot (no flux across surface) and read neutron moisture meter and tensiometers periodically as profile drains, for a period of time as long as feasible. It may be desirable to repeat experiment one or more times if water table or season of year are of influence.

4. Analyse the physical data, analyse the variability of the data and relate to other chemical and physical properties. Predict drainage component.
# LIST OF PARTICIPANTS

<table>
<thead>
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<tr>
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<th>Affiliation</th>
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