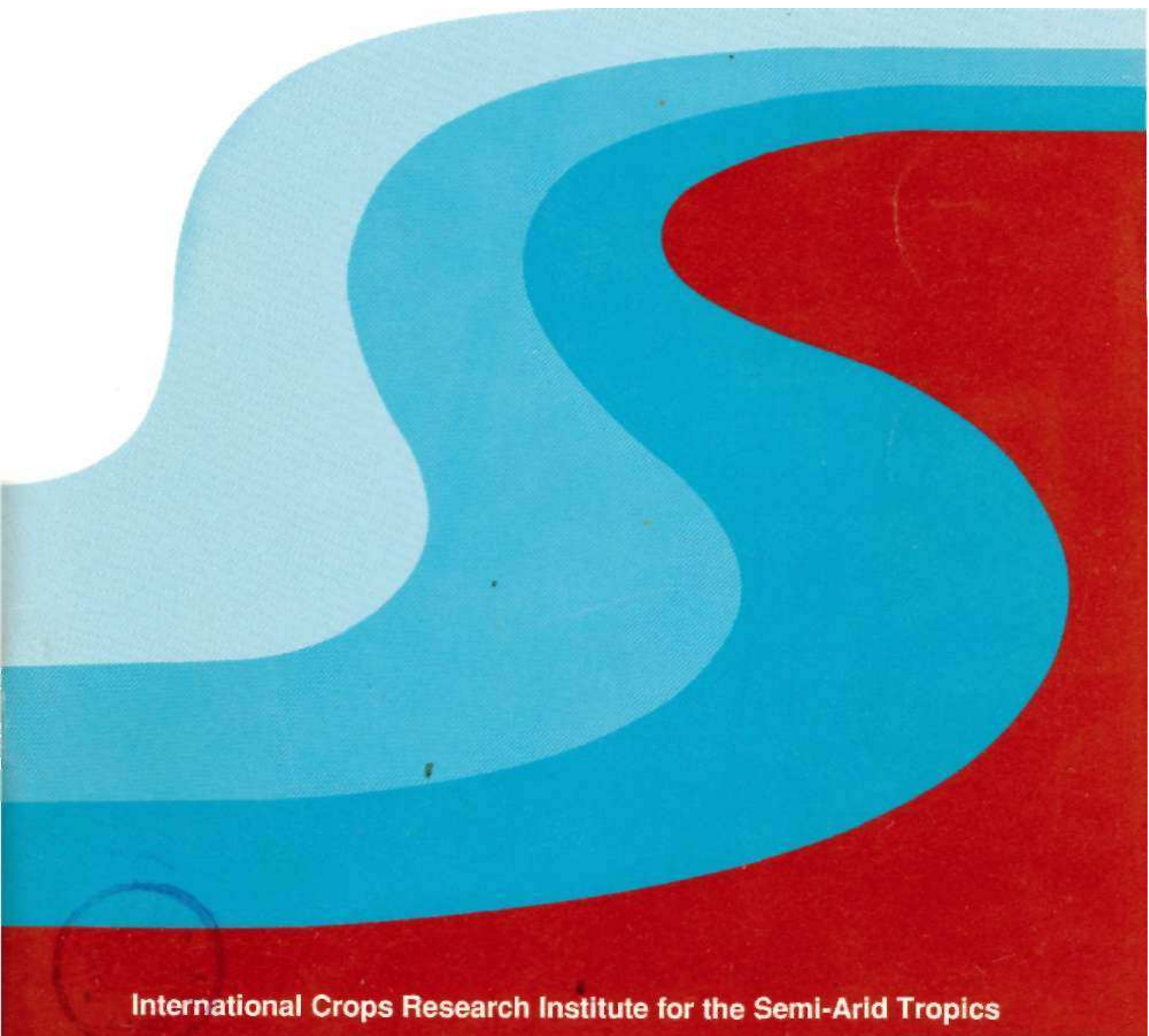




Soil Water Balance in the Sudano-Sahelian Zone



Abstract

Citation: ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1992. Soil water balance in the Sudano-Sahelian Zone: summary proceedings of an International Workshop, 18-23 Feb 1991, Niamey, Niger. (In En, Fr. Summary in Es.) Patancheru, A.P. 502 324, India: ICRISAT. En: 39 pp.; Fr: 40 pp. ISBN 92-9066-210-7. Order code: CPE 072.

Soil water balance is of interest to many disciplines, e.g., soil science, agrometeorology, agronomy, agroforestry, hydrology, and plant physiology. The workshop brought together scientists from different disciplines to share their experience and to contribute to discussions towards evolving an effective synthesis of the state of water balance research in the Sudano-Sahelian Zone.

Participants at the workshop discussed the issues concerning soil water balance in five technical sessions: Current Research and Future Implications; State of the Art of Soil Water Balance Research; Soils of the Sudano-Sahelian Zone; Soil Water Balance Studies in the Sudano-Sahelian Zone; and Operational Applications of Soil Water Balance Monitoring and Prediction.

This volume presents summaries of the five sessions, reports of the planning groups that dealt with the main issues for future research and collaboration—new systems and sites, measurement and analysis of weather, crop, and soil data, modeling, technology transfer, and management—and 21 recommendations for action covering future studies on water balance, definition of minimum data sets, collection and dissemination of information, modeling, and training.

Resumen

Balance hídrico del suelo en la Zona Sudano-Saheliana: resumen de memorias de un taller internacional. Hay muchas disciplinas interesadas en el balance hídrico del suelo, como la ciencia del suelo, la agrometeorología, la agronomía, la agrosilvicultura, la hidrología y la fisiología vegetal. El seminario reunió a científicos de distintas disciplinas para compartir su experiencia y contribuir en las discusiones a desarrollar una síntesis eficaz del estado de la investigación del balance hídrico en la Zona Sudano-Saheliana.

Los participantes en el seminario discutieron acerca de los aspectos concernientes al balance hídrico del suelo en cinco sesiones técnicas: Investigación actual y futuras implicaciones; Investigación de punta del balance hídrico del suelo; Suelos de la Zona Sudano-Saheliana; Estudios de balance hídrico del suelo en la Zona Sudano-Saheliana; y Aplicaciones funcionales del control y pronóstico del balance hídrico del suelo.

Este volumen presenta resúmenes de las cinco sesiones, informes de los grupos de planificación que trataron los principales aspectos de una futura investigación y colaboración—nuevos sistemas y lugares, medición y análisis de datos climatológicos, de cultivos y de suelo, establecimiento de modelos, transmisión de tecnología y dirección—y 21 recomendaciones de actuación sobre futuros estudios de balance hídrico, definición de conjuntos de datos mínimos, recogida y difusión de información, establecimiento de modelos y formación.

The papers presented at this workshop were republished by the International Association of Hydrological Sciences (IAHS), UK, in the following volume:

Sivakumar, M.V.K., Wallace, J.S., Renard, C. & Giroux, C. (eds.), 1991. Soil Water Balance in the Sudano-Sahelian Zone. Proc. Int. Workshop, Niamey, Niger. February 1991. IAHS Publ. no. 199. IAHS Press, Institute of Hydrology, Wallingford, UK.

Soil Water Balance in the Sudano-Sahelian Zone

Summary Proceedings of an International Workshop on Soil Water Balance in the Sudano-Sahelian Zone

18-23 Feb 1991
Niamey, Niger

Sponsored by

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)

Institute of Hydrology (IH)

British Overseas Development Administration (ODA)

World Meteorological Organization (WMO)

International Association of Hydrological Sciences (IAHS)



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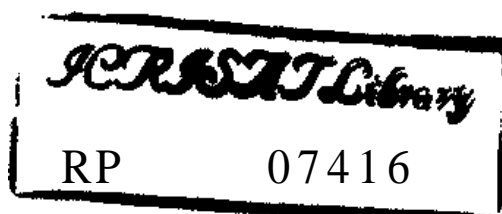
1992

Workshop Organizers

M.V.K. Sivakumar
J.S. Wallace

Scientific Editors

M.V.K. Sivakumar
J.S. Wallace
C. Renard



The International Crops Research Institute for the Semi-Arid Tropics is a nonprofit, scientific, research and training institute receiving support from donors through the Consultative Group on International Agricultural Research. Donors to ICRISAT include governments and agencies of Australia, Belgium, Canada, China, Finland, France, Germany, India, Italy, Japan, Korea, Mexico, Netherlands, Nigeria, Norway, Sweden, Switzerland, United Kingdom, United States of America, and the following international and private organizations: African Development Bank, Agricultural University of Wageningen, Asian Development Bank, Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), International Board for Plant Genetic Resources, International Development Research Centre, International Fertilizer Development Center, International Fund for Agricultural Development, International Fund for Agricultural Research, The European Economic Community, The Opec Fund for International Development, The Rockefeller Foundation, The World Bank, United Nations Development Programme, University of Arkansas, University of Georgia, University of Hamburg, and University of Hohenheim. Information and conclusions in this publication do not necessarily reflect the position of the aforementioned governments, agencies, and international and private organizations.

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ISBN 92-9066-210-7

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Opening Ceremony

Welcome Address

L.D. Swindale

**Director General, International Crops Research Institute for the Semi-Arid Tropics,
Patancheru, Andhra Pradesh 502 324, India**

The Honorable Secretary of State for Higher Education, Research, Technology and National Education, Madame Mailed; Representative of the Institute of Hydrology, Dr Wallace; Representative of the World Meteorological Organization, Mr Krishnamurthy; Secretary General of the International Association of Hydrological Sciences, Dr Colenbrander; Representative of the British Overseas Development Administration, Dr Harvey; Executive Director of the ICRISAT Sahelian Center, Mr Gibbons; Ladies and Gentlemen:

I am pleased and honored to extend to you on behalf of ICRISAT my welcome to this International Workshop on Soil Water Balance in the Sudano-Sahelian Zone. We are grateful to the Government of Niger for giving us permission to host this workshop in Niger. A couple of years ago, when my colleagues at ICRISAT started planning for this workshop we were certainly aware of the importance of water balance, but we did not anticipate such an overwhelming and enthusiastic response to our proposal. The fact that this workshop is cosponsored and supported by organizations situated in five different countries, and that over 100 abstracts were received for our first call for papers presents ample evidence of the tremendous interest. I am told that over 126 participants from 29 countries will attend this workshop. IAHS has done a superb job in bringing out the Volume of papers in time for this workshop and I would like to express my appreciation to the International Association of Hydrological Sciences (IAHS) and the Institute of Hydrology for their hard work and cooperation. I am also pleased to congratulate the authors for writing such interesting papers and submitting them on time to be included in the Volume. The organizers have done a good job in arranging the papers under five headings that progress, approximately, from basic studies to strategic and then to applied, that is from upstream to downstream.

A knowledge of soil water balance is important for efficient land and water management strategies. The very quality of life of over 600 million people who live in the semi-arid regions is affected year after year by seasonal rainfall because it determines ultimately the productivity of their cropping systems, particularly in the Sudano-Sahelian region where the needs are the greatest. In the past, farmers in semi-arid West Africa have managed their cropping systems by fallowing and shifting cultivation on a long enough cycle to ensure that soil fertility was restored and a reasonable level of water-use efficiency was maintained. However, with increasing population pressures and growing number of permanent settlements, fallowing has come to be replaced by continuous cultivation and use of more marginal lands and insufficient attention to the inputs needed and improved management required. Land degradation has followed.

Faced with the problems of rapidly increasing populations and greater food needs, policymakers in recent years have placed more emphasis on irrigation. I am told that irrigated cereal production in the Sahel has received three times more donor assistance than rainfed cereal production even though 95% of cereal production comes from dryland farming or through traditional irrigation systems. In

some cases, the cost of bringing new land under irrigation has exceeded U.S.\$10 000 per hectare. The options for extension of irrigated land in the Sahel are limited and we must explore how we can make the rainfed lands more productive. It is here that a more complete understanding of soil water balance and its application becomes crucial and important. And there is also a need to include supplementary or limited irrigation in the studies.

To help the farmers of the Sahel there needs to be a greater attempt to translate the understanding of soil water balance that is demonstrated in the published Volume into practical production systems. The section in the Volume on Applications seems to deal mostly with the development of models. Several papers in the earlier sections inform us that water is being lost by evaporation from bare soil between the plants, others that there is water left at depth in the soil at harvest which is not there at sowing time the next year. It would be of considerable interest to those who support our efforts to find in this workshop research efforts on the modifications of cropping systems to utilize these findings. I think there has been some research along these lines at the ICRISAT Sahelian Center, in Centre de cooperation internationale en recherche agronomique pour le developpement, (CIRAD)/Institut de recherches agronomiques tropicales et des cultures vivrieres (IRAT) programs and from national programs such as the Institut National de Recherches Agronomiques du Niger (INRAN) in Niger, the Institut d'Economie Rurale (IER) in Mali, but it is not reported here. I am sure all of you are aware of the recent global concern with environment and sustainability. If we can understand and apply the concepts of soil water balance to improve productivity while conserving the soils, we are at the same time also contributing to the overall goal of protecting the resource base. Decreasing sustainability in the Sahel, besides its political and socioeconomic dimensions, has to do with increased cropping intensities using traditional, low-input technologies, declining rainfall, declining fertility, and deteriorating soil structure. There are papers in the Volume that address the first three of these but none that deals with soil structure except indirectly through measurements of runoff—which is more than one would intuitively expect. To relate better to sustainability concerns, soil water balance research probably needs to be more secular, not merely seasonal, in time.

Problems of the Sudano-Sahelian region are far too large to be solved by the efforts of a few organizations. They require concerted action and collaboration between the national, regional and international programs. I am sure that this workshop will improve communications between scientists working on the water balance studies—both those who are present here and those who will read the workshop papers. It is instructive to glance through the reference lists associated with the papers in the Volume. Besides the expected incompatibility between languages, there are obvious incompatibilities between the different schools of thought. You will learn more about each other's work and each other's authorities during this week. The Volume should also prove of great value to scientists in the Sudano-Sahelian countries where scientific documentation is scarce and hard to come by.

The planning meeting on Friday should provide you an excellent opportunity to contribute your ideas towards evolving a set of recommendations from this workshop that could help the research programs in this region reorientate themselves or evolve new programs to better serve the farmers of this region. Somewhere in the Volume I read the remark that we need lots and lots more data before soil water balance studies can be put to use. That is simply not an acceptable statement in today's world where more and more scientists are required to raise their own funds through practical application of their results.

Professor Vauclin and two distinguished colleagues ask in one paper whether water balance studies are scientific dilettantism. They answered the question negatively as we would expect them to do, but I am sure they had good reasons for raising the question. It is not wise to be too far upstream these days. Sources run dry and resources decline. The river Niger has got so low in the dry seasons in recent years that this city has feared for its water supplies.

Many of you have traveled far to bring to this forum your wisdom and ideas and I appreciate your willingness to participate. I hope you will find some time to visit the city of Niamey and appreciate the hospitality of its people. Take time to observe the river as it passes. Let your thoughts mingle with its waters. Perhaps a farmer, down the stream, will apply them with some water to his fields. I wish you all success in your deliberations over the next few days and a safe journey home.

Thank you very much.

Address

J.S. Wallace

**Head, Vegetation and Water-Use Section,
Institute of Hydrology, Wallingford, Oxfordshire OX10 8BB, UK**

Honorable Secretary of State, Directors General, Distinguished Colleagues:

On behalf of the Director of the United Kingdom Institute of Hydrology I extend to you a sincere welcome to this Workshop on the Water Balance of the Sudano-Sahelian Zone. Firstly, let me apologize for the absence of my Director. I know that he was greatly looking forward to visiting Niger and attending this meeting. Unfortunately the vagaries of air travel in Europe at present have left him stranded, but I hope he will be able to join us shortly.

The Institute of Hydrology has a long record of hydrological work in Africa. The earliest studies began over 20 years ago in East Africa and collaboration has continued and expanded ever since. Currently, one of the largest overseas hydrological programs of our Institute is based here in Niger. This work has received the help and cooperation of several Nigerien ministries, and it is a pleasure to have the opportunity to be able to formally thank the Nigerien government for its cooperation.

We would especially like to extend our thanks to Dr Boulama of the Niger Meteorological Service for his advice and permission to make radio soundings during our experimental work. The Institute would also like to take this opportunity to thank ICRISAT, both for its unfailing support throughout our experimental program in Niger and also for its professional and efficient co-organization of this workshop. It has been, and still is, a great pleasure to work with the ICRISAT Sahelian Center.

All our efforts as scientists in the field of water balance research depend on the generous support of our funding agencies. I am therefore happy to have the opportunity to be able to thank one of our principal sponsors, the British Overseas Development Administration, for their financial support of both the Institute of Hydrology overseas research program and this workshop.

Many of you will have already seen the excellent publication of our workshop proceedings by the International Association of Hydrological Sciences (IAHS). I believe this document constitutes one of the most valuable and up-to-date reviews of soil water balance research in the Sudano-Sahelian Zone. The staff of IAHS are to be congratulated for producing such an excellent document especially under the constraints and pressures imposed by the workshop organizers. I would also like to express our thanks to the World Meteorological Organization for their assistance and financial support of delegates attending the workshop.

Finally, I am sure my Director would have wanted to wish all the participants in this workshop a stimulating and fruitful meeting and to express his hope that the results of this workshop should contribute to that pool of knowledge which will benefit all of the countries of the Sudano-Sahelian region.

Thank you.

Address

V. Krishnamurthy

**Scientific Officer, World Meteorological Organization, Agricultural Meteorology Division,
41, Giuseppe-Motta, Case Postale 2300 CH-1211, Geneva 2, Switzerland**

On behalf of the Secretary General of the World Meteorological Organization (WMO), Professor G.O.P. Obasi, I am pleased to extend a warm welcome to you all to attend the International Workshop on Soil Water Balance in the Sudano-Sahelian Zone.

At the very outset, I wish to thank the Government of Niger for its kind invitation to hold this workshop in Niamey. I also thank ICRISAT and other cosponsoring organizations, for their excellent cooperation in the organization of this workshop.

One of the principle objectives of the World Meteorological Organization (WMO) is to assist National Meteorological Services of member countries, in the organization, collection, analysis, exploitation, and application of meteorological, hydrological, and climatological data and information. The Applications of Meteorology Program is one of the major programs of WMO established by the 10th WMO Congress towards meeting this objective. The areas of applications include aviation, marine services, agriculture, energy, and water resources management.

The main purpose of the Agricultural Meteorology Program is to assist members to provide meteorological and related services to the agricultural community to help develop sustainable agricultural systems, increase production, reduce losses and risks, decrease costs, increase efficiency in the use of water, labor, and energy, conserve natural resources, and decrease pollution by agricultural chemicals. Training, education, transfer of knowledge and techniques are the main components of this program.

WMO was therefore pleased to associate itself in the organization of this workshop, whose main purpose is to review, evaluate, and disseminate techniques and methods to integrate soil water balance and plant growth and development and to develop operational applications of soil water balance monitoring and prediction in real time.

I am convinced that this workshop will assist greatly in the understanding of the magnitude of different components of soil water balance and their influence on crop growth and development, as well as to achieve higher water-use efficiency in crop production. It is the wish of WMO that the outcome of this workshop will help National Meteorological Services to make their contribution to increase agricultural production and to use available water resources efficiently.

I wish you all a happy stay in Niamey and a fruitful workshop.

Address

J.A. Harvey

**Natural Resources Adviser, British Overseas Development Administration
Eland House, Stag Place, London SW1CE 9DH, UK**

Honorable Secretary of State for Higher Education, Research, Technology, and National Education; Dr Swindale; Dr Wallace; Dr Krishnamurthy; Dr Colenbrander, Mr Gibbons; Ladies and Gentlemen:

I would like to say on behalf of the British Overseas Development Administration (ODA) how pleased we are to be involved in, and for me personally to attend, this international workshop. The Administration is grateful to its cosponsors ICRISAT, the Institute of Hydrology, the World Meteorological Organization, and the International Association of Hydrological Sciences for their efforts in organizing the workshop—and in spite of some unpredictable last minute problems. I would particularly like to thank the Government of Niger for offering to host this important event.

If I can add a word on ODA's perspective on the workshop, the workshop comes at a particularly appropriate time in terms of developments in the Sahel. Nineteen-ninety was another poor year for the farmers and agropastoralists of the region. Grain harvests throughout much of the Sahel, from Mali and Burkina Faso in the west to Sudan and Ethiopia in the east, were once again very meager. There are many complicating factors, which vary from country to country, but underlying this lies a shortage of rainfall, drought. In particular the droughts of the 1970s and the 1980s have shown just how fragile is the Sahel environment, under the twin pressures of population increase and climate change.

ODA's aid program priorities, in a few words, center on poverty alleviation and environmental and institutional sustainability. Our program covers a wide range of activities; part of the budget goes to support what might be termed frontline projects, often through nongovernmental organizations (NGOs), who work directly with rural communities. Part is given in support of the international agricultural research effort undertaken by the Consultative Group on International Agricultural Research (CGIAR) centers, including ICRISAT. And another part goes in support of commissioned research and development, such as that undertaken by the Institute of Hydrology.

The wider objectives for all these activities are, however, the same. I therefore hope that in our discussions and deliberations, we can keep in mind the man pictured on the front cover of the workshop proceedings, one of millions of Sahelian farmers and agropastoralists, for whom improved soil and water management has become an absolute necessity.

On behalf of the Administration I would like to welcome all the participants to Niamey. I look forward to participating in what I think will be a stimulating and productive workshop.

Opening Speech

H.J. Colenbrander

**Secretary General, International Association of Hydrological Sciences,
P.O. Box 6067, 2600JA Delft, Netherlands**

Excellency, Honored Guests, Ladies and Gentlemen:

It is my great pleasure to address you during this opening ceremony on behalf of the International Association of Hydrological Sciences (IAHS). This international association is one of the oldest learned societies in the field of hydrology and it has a worldwide membership. The association adheres to the International Union of Geodesy and Geophysics. It deals, through its commissions and committees, with all aspects of the hydrological cycle, e.g., surface water, snow and ice, water quality, continental erosion, and subsurface waters, among which is soil water. This explains our interest in the topic of the current workshop, but this meeting is also of particular interest to IAHS since it takes place in a developing country where the availability of water in the soil is of crucial importance.

The IAHS has been active for many years in supporting hydrologists of developing countries in their work. So far this has been mainly done by making funds available to support colleagues of these countries in their participation in symposia and workshops all over the world. Due to the limited funds available, only a small number of colleagues can be supported in this way. By supporting a meeting in a developing country properly, it is hoped that more people of the developing world can benefit and consequently there is a greater spinoff of the money spent. It is therefore with great pleasure and expectation that IAHS is supporting this meeting by contributing to the editing and printing of the proceedings of this workshop and to publish these as no. 199 in the IAHS Red Book series. It is expected that in particular the discussions during the workshop will benefit from the fact that the proceedings are prepublished.

In general, if the signs do not deceive us, we will have an interesting and very well organized meeting. I know that the organizers, Dr M.V.K. Sivakumar and Dr J.S. Wallace and colleagues, have worked very hard to make this event a success. Hopefully for the rest of the week the organization is not further hampered by heavy snowfall(!) in Europe. I have to resist the temptation to tell you more about the activities of IAHS and its publications such as the Hydrological Science Journal and the Newsletter. Information on the Association however, is available in the poster room. Finally I wish you a fruitful meeting and a pleasant stay in Niamey and I am looking forward to meeting many of you in the coming days. Thank you for your attention.

Official Opening

Her Excellency Madame Mailele Mariama

**Secretary of State for Higher Education, Research, Technology,
and National Education, Government of Niger**

Excellencies, Ministers, Director General of ICRISAT, Executive Director of ICRISAT Sahelian Center, Representative of the Institute of Hydrology, Representatives of the World Meteorological Organization and the International Association of Hydrological Sciences, Scientists, Ladies and Gentlemen:

It is for me a great honor and pleasure to welcome you all into our country to participate in the International Workshop on Soil Water Balance in the Sudano-Sahelian Zone. We are honoured by the choice of Niamey as the venue for this workshop. The subject of water balance being of vital interest to us, we will pay full attention to your discussions and recommendations.

Distinguished delegates, Ladies and Gentlemen, as you know the 1990 cropping season has left food deficits in most of the member countries of the Permanent Interstate Committee for Drought Control in the Sahel (CILSS). Food needs in the Sahel already amount to about 500 000 tonnes this year. This figure will probably be much higher by the end of the evaluation which is being carried out currently. Delay in the onset of rainfall in some countries, their poor distribution in others and the early cessation of rains this year may be the reasons for such large deficits. The economic crisis persists, arable land area is decreasing, cereal production is declining and the environmental degradation is continuing.

This situation prompts us to examine carefully the different factors affecting cereal production in the Sudano-Sahelian countries and to develop strategies that should help us stabilize food production in the future. We must first insist on improved utilization of local water resources. The development of sustainable farming systems in the Sudano-Sahelian Zone requires a systematic study of water balance. An understanding of different components of water balance, and the manner in which they affect crop growth, is essential for improved use of water resources to achieve maximum yields. Information on the water balance of crops, of natural vegetation and of soils is also equally important for hydrological studies of the Sahelian region. Furthermore, studies are being conducted to determine if the surface water balance on a regional scale can influence the climate.

To understand different aspects of water balance, the contribution of scientists working in different disciplines is essential: agrometeorology, agronomy, soil science, hydrology, agroforestry, etc. Scientific research today requires a holistic approach to problems in order to find realistic and long-standing solutions.

Going through the program for this workshop, I was happy to notice that many important subjects will be discussed over the next 5 days. I know that your discussions will be free, frank, and fruitful. I am also convinced that the recommendations emerging from your discussions will eventually help to reorientate research programs on water balance in West Africa and elsewhere.

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), the main organizer of this workshop, has an important research program here in Niger. The close collaboration between scientists in ICRISAT and in the national institutes in Niger such as the Institut National de Recherches Agronomiques du Niger (INRAN) and the University of Niamey is becoming increasingly important and the results of this collaborative research will be very useful to the farmers of this country. We attach a great deal of importance to the research activities conducted by INRAN and ICRISAT for increasing the agricultural productivity in our country.

I understand that Dr Swindale, the Director General of ICRISAT, will be retiring this year and that ICRISAT will have a new Director General from September this year. Under Dr Swindale's leadership and vision, ICRISAT in West Africa has grown from a small program of 11 scientists in 1977 to 35 scientists working at the ICRISAT Sahelian Center in Niger and two other major programs in Nigeria and Mali. On behalf of the Government of Niger, I wish to thank Dr Swindale for all his help and wish him a very pleasant retired life. We will of course be pleased to welcome him in Niger at any time in the future.

Distinguished delegates, Ladies and Gentlemen, I am pleased once more to welcome all of you to our country and wish you a pleasant stay. I am sure that your deliberations at this workshop will result in very positive and useful recommendations. I declare this International Workshop on Soil Water Balance in the Sudano-Sahelian Zone open. Thank you.

Recommendations

Future Studies on Water Balance

1. In the future, there is an urgent need to incorporate water-use and water balance studies in the development of new agricultural technologies for the Sahel, and to more rigorously examine the components of the water balance of proposed agricultural production technologies.
2. Several advances have been made in the past decade in the discipline of soil water balance with development of better methodology and instrumentation. The neutron probe was cited as a key factor in this process, but time domain reflectometry (TDR), stem flow instrumentation and geostatistical methodologies should be incorporated.
3. Attempts should be made to separate evapotranspiration into its components: transpiration from plants and evaporation from the soil. The extra information would improve understanding of variations in water-use efficiency and effectiveness of crop management techniques designed to reduce evaporation from the soil surface.
4. More attention should be paid to measurement of the 'difficult' components of the water balance, such as drainage and runoff.
5. Spatial distribution of rainfall is important in the understanding of the soil water balance of the Sudano-Sahelian Zone. Satellite remote sensing techniques offer some possibilities in this area and are therefore strongly recommended for use. National and international organizations (e.g. WMO, FAO) are urged to encourage support and cooperation in this important venture.
6. New strategies, including the Geographic Information System (GIS), stochastic methods and remote sensing techniques [e.g., the EPSAT (Estimation des precipitations par satellite) experiment for rainfall estimation by satellite] should be developed for coping with the high spatial variability of soil water balance components, both at the field and catchment scale.
7. Methods for measurement and/or estimation of infiltration, evaporation and transpiration, runoff, and drainage should be standardized where appropriate so that results from different regions and institutions can be compared. Simple, low-cost techniques should be encouraged.
8. Better characterization of root distributions and their function is needed to determine the true quantity of water used by plants. Greater knowledge of the response of roots to the various attributes of the soil environment is required. This is necessary to improve understanding of the development of root systems.
9. Water balance in the Sudano-Sahelian Zone should be looked at not only in relation to how it affects water supply to the plant, but also in relation to how it affects nutrient availability to the plant through runoff, waterlogging, and leaching.

Definition of Minimum Data Sets

10. Bearing in mind the limited resources of manpower and equipment available to most research teams, and the circumstances under which they are collected, a minimum set of measurements (including soil physical data) needed to adequately quantify the soil water balance for the interpretation of agronomic trials should be identified.
11. Methods to obtain these minimum data sets should be evaluated, in order to come to a selection of recommended techniques for the various water balance components and soil types, which provide an acceptable balance of accuracy, simplicity, speed, and cost. These methods could be de-

scribed, in both French and English, in a publication like the one put out by the Commonwealth Agricultural Bureaux International on preferred soil chemical and soil biological methods in tropical areas.

Collection and Dissemination of Information

12. It is recommended that a commission or a scientific panel be set up to coordinate the various activities covering water balance research in the Sudano-Sahelian Zone and to recommend methods and practices which could be adopted by the countries concerned. Such recommendations should include methodologies, collection, treatment, and interpretation of data.
13. A bilingual glossary of terms compiled from existing glossaries used in soil water balance studies should be available. The cosponsors of the workshop should review the existing glossaries and ascertain whether a new publication is required.
14. A databank should be created containing all available soil physical data from the region, including data from unconventional literature (unpublished reports, etc.). Perhaps funding could be obtained from, for instance, the European Economic Community (EEC), to finance a position dedicated to doing this for 6 or 12 months. The databank should take account of the way data are being collected for the West African Soil and Terrain Digital Database (WASOTER) project, coordinated by the International Soil Reference and Information Centre of the International Society for Soil Science, located in the Netherlands. A similar databank has been published for the Netherlands as the Staring Series. An enormous amount of relevant information is presumably available through various overseas institutions such as the Institut Francais de Recherche Scientifique pour le Developpement en Cooperation (ORSTOM).
15. Availability and communication of basic meteorological and agrometeorological data should be improved.

Modeling

16. Modelers should take into account the complex nature of the semi-arid biological conditions, the variability of soil characteristics and soil management practices. Stochastic models could be used to characterize large-scale spatial variability.
17. Rainfall probability analyses should be included in operational models. The use of remotely sensed data should be increased but it should be used with care and checked against ground-based data where possible.
18. Factors other than the soil water balance should be borne in mind when forecasting, yield, for example: plant water status, root systems, soil biology, farming methods, pest, diseases, and socioeconomics.

Training

19. There should be a greater effort for the use of different improved techniques by national programs. However, it was recognized that there are problems (lack of technical expertise and no repair facilities) associated with this.
22. Training and education are therefore important factors and should be imparted at various levels (from the scientific/technical level to farmer and extension workers level). Making policymakers

more aware should also receive high priority consideration to ensure support of the governments involved. WMO and ICRISAT should take up a lead in this regard with other organizations.

21. Workshops should be organized in interested countries to promulgate these recommended soil physical and water balance methods.

Session Summaries

Opening Session

Current Research and Future Implications

- Chairman:** H. Soares, Centre Regional de Formation et d'Application en Agrometeorologie et Hydrologie Operationnelle (AGRHYMET), Niger.
- Cochairman:** H.J. Colenbrander, International Association of Hydrological Sciences (IAHS), Netherlands.
- Rapporteur:** R.J. Van Den Beldt, ICRISAT Sahelian Center, Niger.

The first paper in the opening session gave an overview of the workshop and was followed by three keynote papers reviewing the current research on soil water balance in the Sudano-Sahelian Zone and the future implications. In the overview of the workshop, it was emphasized that the well-known agroclimatic constraints and the limitations of the traditional agricultural systems both contribute to the declining per capita crop yields in the region. Research and development are hampered because of the large variability in soil types on scales ranging from individual fields to the regional level. Recent research in the Sudano-Sahelian Zone showed that it is possible to achieve more efficient use of soil water by using new cropping strategies (e.g., relay cropping and intercropping), mulches, new crop varieties, and fertilizer.

The three keynote papers elaborated the major constraints to improved soil water-use and brought out several important issues. In separating evaporation (E) and transpiration (T) in the mass balance equation, one must consider the various factors affecting transpiration, since this is closely linked with crop yield. Use of powerful new methods such as time domain reflectometry (TDR), stem flow measurement devices, and geostatistics should be encouraged. Soil heterogeneity is a major problem in many areas including the Sudano-Sahelian Zone and there is a need to draw on the experiences of others. In crops the downward movement of roots stops at anthesis, which effectively limits the soil moisture available for grain filling. Overall, it was concluded that research information on climatic data, water balance, and soil hydrological characteristics for the region was currently highly inadequate.

In a critical review of water balance research in the Sudano-Sahelian Zone from 1960 onwards, three phases in its development were highlighted. A number of lacunae were also pointed out and questions were raised at different levels, for example, databases and their use in calculating potential evapotranspiration, better understanding of crop physiology and the influence of cropping conditions at the farm level.

It was concluded that the present concern was to identify the important weaknesses in current methods and to rectify them in accordance with common priorities.

Technical Session 1

State of the Art of Soil Water Balance Research

- Chairman:** M. Boulama, National Meteorological Services, Niger.
Cochairman: V. Krishnamurthy, World Meteorological Organization (WMO), Switzerland.
Rapporteur: A. Manu, Institut National de Recherches Agronomiques du Niger (INRAN)/Soil Management Collaborative Research Support Program (TROPSOEILS), Niger.

The nine papers scheduled in this session reviewed some of the recent advances in soil water balance research and their application to the problems of water management in the Sudano-Sahelian Zone. The papers could be divided into three groups. The first dealt with rainfall estimation and spatial variability of rainfall. The second group of papers were concerned with infiltration, runoff, and drainage. The third group of papers elaborated the measurement, evaluation, and modeling of evaporation.

Four new methods described in this session are of particular interest: use of cold cloud statistics for estimation of rainfall, measurement of evaporation using eddy correlation devices, estimation of evaporation using microwave remote sensing, and evaluation of evaporation by simulation of isotopic profiles. These methods need to be further studied and exploited in the Sudano-Sahelian Zone. Other salient features of this session were:

- An understanding of the magnitude and dynamics of the soil water balance is important for any sustainable development in the Sudano-Sahelian Zone.
- Remote sensing is an important tool for assessing the spatial distribution of rainfall.
- Measurements of evaporation (including transpiration), infiltration, runoff, and drainage and/or estimation of these parameters should be encouraged, improved and, where possible, standardized.
- Soil characteristics and soil management practices should be given due consideration in modeling the parameters mentioned above.
- Standardization of terminologies used requires urgent consideration.

Technical Session 2

Soils of the Sudano-Sahelian Zone

- Chairman:** P.J. Gregory, Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia.
- Cochairman:** M. Gandah, Institut National de Recherches Agronomiques du Niger (INRAN), Niger.
- Rapporteur:** J. Brouwer, ICRISAT Sahelian Center, Niger.

The 11 papers in this session can be divided into three groups. Firstly there were papers which described the soils and their physical characteristics in various parts of the Sudano-Sahelian Zone. Secondly, there were papers which described methods that might be used to determine soil physical characteristics more readily. Thirdly, there were those describing how such methods are beginning to be used in several countries.

The descriptive papers, from Niger, Mali, Burkina Faso, Nigeria, Benin, and Ghana, all indicated that the soils of the Sudano-Sahelian Zone are generally poor chemically, have a poor available water-holding capacity, and often have poor structural and infiltration characteristics. Only very limited data are available on their soil physical characteristics, and the data cannot always be compared, because of differences in, for example, definition of field capacity. Adequate soil physical data are essential for developing improved agricultural production systems. It is encouraging that such data are now beginning to be collected with new techniques, e.g., in Ghana.

Given the general lack of such soil physical data, however, and the vast size of the region, one would want to use as simple methods as possible to collect them. This issue was addressed in two of the papers, which described simplified methods to determine conductivity-potential and water content-potential relationships, using neutron probe and internal drainage data and various computational methods.

As resulted from the discussion, it would be extremely useful if all soil physical data available for the Sudano-Sahelian Zone were assembled in one database. This database should include those data mentioned in the grey literature (unpublished reports, etc.) Such a database could for instance be used in interpreting existing soil maps for planning purposes involving soil physical aspects.

Four other points emerged as well:

- The data available and methods described often relate only to sandy soils, and not, for instance, to more clayey, more structured soils, with larger numbers of macropores.
- The problem of short-range soil variability, over 10-20 m or even less, is a complicating factor which is generally glossed over.
- The soil water balance depends not only on the capacity of soil to accept and hold water, but also on the ability of the roots to get to that water: root penetration, too, is dependent on soil property.
- Soil physical data are required at various scales for different purposes, from field scale up to regional scale.

Technical Session 3

Soil Water Balance Studies in the Sudano-Sahelian Zone

Chairman: C. Renard, ICRISAT Sahelian Center, Niger.

Cochairman: G. Faustin, Centre Regional de Formation et d'Application en Agrometeorologie et Hydrologie Operationnelle (AGRHYMET), Niger.

Rapporteur: S J. Allen, Institute of Hydrology, UK.

This session contained 18 papers describing studies of the soil water balance in the Sudano-Sahelian Zone. The diversity shown by the contributions was remarkable. The majority were soil water balance studies of the agricultural systems of the area, although measurements from seminatural vegetation were also presented.

The papers broadly fell into two categories on the basis of their objectives: in the larger group the soil water balance was studied to improve understanding of yield variations observed in response to different agronomic practices; the second group presented new methods for measuring or estimating individual components of the water balance.

The key quantity of interest in the agronomic studies was the rate of evapotranspiration (total evaporation) or water-use by the crop system under study. Generally, profile moisture contents were determined by neutron probe and the total evaporation as a residual in the soil water balance. This required assumptions about, or measurements of, the other water balance components: drainage, runoff, and rainfall.

In many cases the difficulty in quantifying these components introduced uncertainties into the calculations of water-use that limited the interpretations of the plant growth variations observed. The difficulty in measuring the various components was often related to high spatial variability, particularly in the case of runoff and drainage.

The problem of quantifying the amount of water actually used by the plants was generally compounded by a lack of knowledge of the root distribution. This is because when calculating plant water-use from the soil water balance, drainage below the root zone is required, rather than drainage below an arbitrary depth.

The main innovations in determining particular components were in the area of evaporation and transpiration. A new method for directly calculating the actual total evaporation from a region of the land surface was presented. The application of two new thermal techniques for measuring transpiration produced promising data for trees, but their suitability for measurements of transpiration in the important cereal crops of the region has yet to be demonstrated.

Technical Session 4

Operational Applications of Soil Water Balance Monitoring and Prediction

Chairman: W.B. Wilkinson, Institute of Hydrology, UK.

Cochairman: M. Ouattara, Institut National de Recherches Agronomiques du Niger (INRAN), Niger.

Rapporteur: J.S. Wallace, Institute of Hydrology, UK.

The 17 papers in this session dealt with water balance models and in particular their application to operational systems. Four papers described water balance simulation models and the way in which the various subcomponents of the models were calibrated. It was stated and generally agreed in discussion that this type of model must be completely calibrated and validated using data obtained in the region where the model is to be applied. The test data should be independent from the information used in the calibration procedure. Even after this, these models should be used with caution and their assumptions and limitations recognized.

Most of the session papers concentrated on operational applications. This included the extension of the above simulation models to, for example, the production of a risk-probability map for millet production. Also presented were the more longer established models, for example, as used by the Centre Regional de Formation et d'Application en Agrometeorologie et Hydrologie Operationnelle (AGRHYMET) and the Food and Agriculture Organization of the United Nations (FAO), and their operational use was demonstrated by both the experts who develop and refine them and by the users of the systems in the national programs. A number of papers also dealt directly with cropping 'risk' assessment, using rainfall analyses.

The relative merits of different types of models were discussed in some papers, e.g., stochastic versus deterministic approaches. Some recommendations were made for the development of operational applications which included the analysis and incorporation of rainfall statistics for the prediction of the onset of rains and growing season length. It was suggested that this would allow a form of 'response farming', where real-time management decisions could be made each season according to the particular rainfall pattern received. Some general issues which came up in the papers and in discussions were:

Modeling

- Are these already complex enough for operational purposes and do we need to include other factors, for example, the separation of total evaporation into transpiration and soil evaporation?
- Better description and account of runoff?
- Should we do more intercomparison of the models that currently exist?
- Are the validations and calibrations adequate?
- Are the ranges of applications of the different models defined clearly enough?
- What criteria can we use for choosing a model for a given purpose?
- What are the minimum data requirements of the various models?
- Should we include interactive growth models?

Data/information

- How can we improve the links and exchange of information and data between research organizations and national and regional centers?

Multidisciplinary Approach

- Do we need to and how can we improve the links and exchange of ideas between the different disciplines which are involved, e.g., hydrogeologists, hydrologists, agronomists, and meteorologists?

Yield forecasting

- The soil water balance is only one aspect. How do we take into account other factors (including farming methods, pest, diseases, socioeconomics)?

No extended discussion or solutions to any of these problems took place, and hence no consensus was reached on priorities or recommendations.

It was pertinently pointed out that throughout these discussions the constraints facing the national programs in obtaining data and their ability to respond to recommendations should be clearly borne in mind.

Planning Meeting Summary

The planning meeting was held on Friday, 22 Feb 1991 under the chairmanship and cochairmanship of J. L. Monteith and G. Girard. The meeting was organized into three discussion groups as follows:

Group 1: Soil characterization and databases for water balance studies

Leader: M. Vauclin, Institut de Micanique de Grenoble (IMG), France.

Group 2: Water balance studies

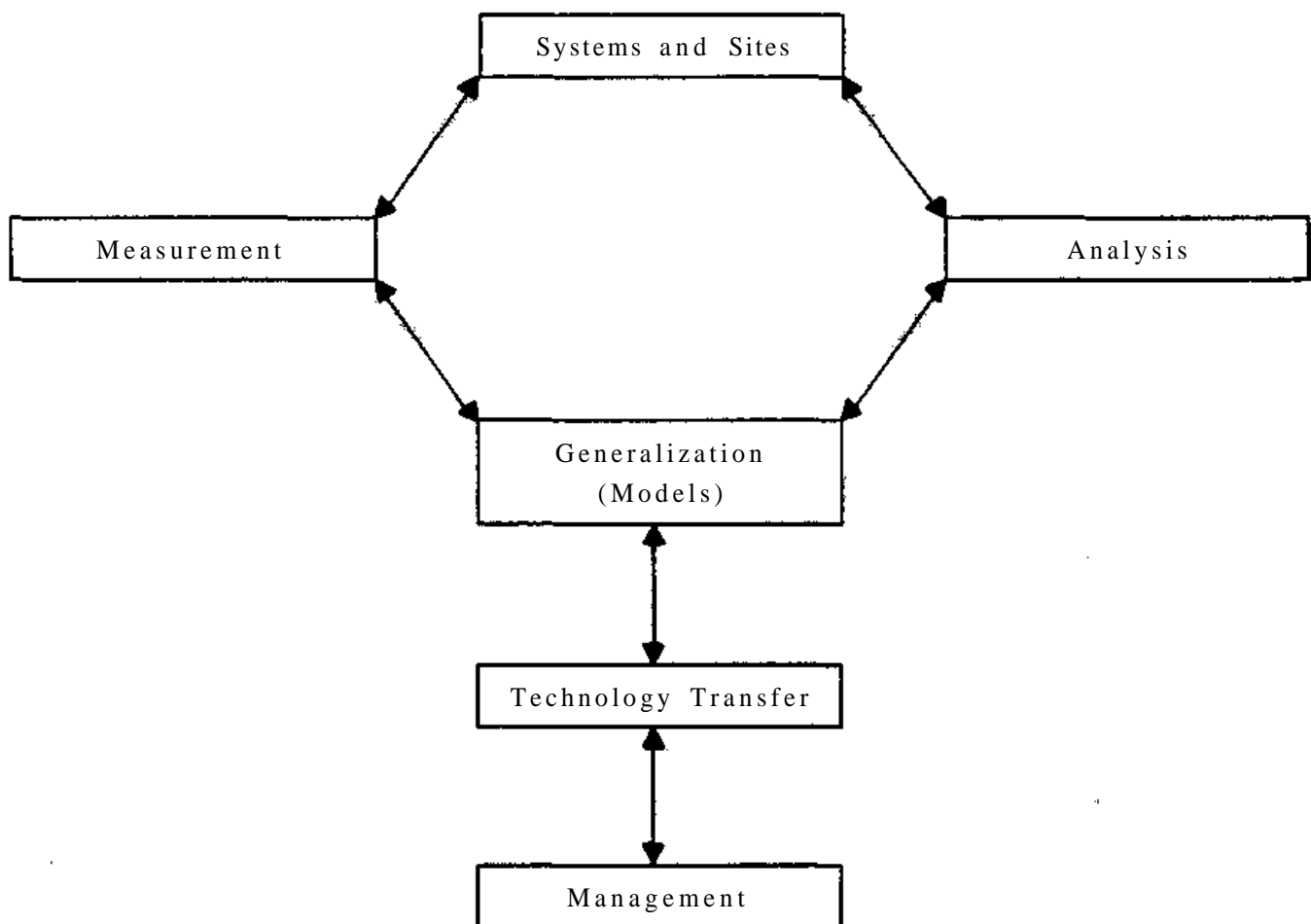
Leader: C. Dancette, Centre Regional de Formation et d'Application en Agrometeorologie et Hydrologie Operationnelle (AGRHYMET), Niger.

Group 3: Operational applications and modeling

Leader: S. M. Virmani, ICRISAT, India.

The summary of the group leaders' reports following these discussions was compiled by J. L. Monteith and G. Girard and is presented below.

Discussion took place about a range of topics which can be arranged in the following way:



Systems and Sites

It was recommended that water balance studies should be extended to include other land uses including agroforestry, forestry, and rangelands. It was also suggested that the potential of low-lying sites be further explored.

Measurements

Weather. It was proposed that there was a need to improve meteorological networks for the collection of basic parameters such as rainfall and global radiation. Given the large degree of spatial variability of these characteristics in the Sudano-Sahelian Zone, it was also recommended that remote sensing be fully exploited in order to obtain the area average water balance data required for crop yield forecasting, water resource assessment, and climate change prediction.

Crop. It was felt necessary to establish firmer relationships between actual and potential evaporation. The need to separate and obtain more information about the soil and plant components of evaporation was also highlighted. This was also necessary for improving the understanding of the relationship between actual evaporation and crop yield.

Too little information is currently available on root systems and it was recommended that the size and functioning of the root systems be much more clearly defined. This was particularly important in those arid zones where actual evaporation and crop yield are more closely related to the ability of the plant root systems to supply water rather than the atmospheric demand.

Other parts of the Sudano-Sahelian Zone have excess water at certain times of the season and it was noted that the response of the crop to this excess water could also be important in some areas.

Soil. The amount of information on soil physical and hydraulic parameters needs to be improved. As these data are gathered they should also be coordinated within some form of database. This would also allow the complete information to be related to large-scale surveys. The formation and function of soil surface crusts should be further examined. This should be done in order to provide a better understanding of the lateral movement of water on soils and the role of faunal activity.

Again in the area of dealing with spatial variability of soil surface properties, remote sensing techniques should be vigorously pursued.

Analysis

Weather. The interactions of the land surface and the planetary boundary layer should be explored. One known attempt at this will be the HAPEX-Sahel project, planned to take place in Niger in 1992.

Crop. There is a need to determine average/bulk surface resistance parameters for the principal crop types in the Sudano-Sahelian Zone, so that crop water balance models can be improved. It was mentioned that the FAO crop water requirements calculation system was undergoing review and that in a few years time crop coefficients would be phased out and replaced with crop canopy or surface resistance parameters.

Since most vegetation systems are supply-limited, there is also a need to develop better root and root water extraction submodels,

Theoretical methods need to be applied to the problem of soil heterogeneity in relation to soil water.

Modeling

Models were thought to be useful tools for assembling the understanding of different parts of the soil-plant-atmosphere system. However, it was felt that there was a need to standardize some models and simplify others. Stochastic models showed some promise for dealing with spatial variability. It was also recommended that models should be used to generalize conclusions from specific studies and it was essential to compare the performance of different models. The need to develop stronger model relations between water-use and yield was also identified.

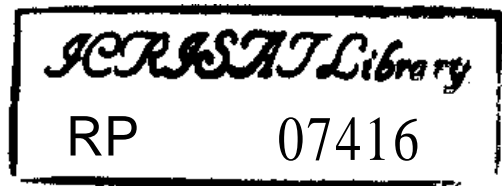
Technology Transfer

There is a need to improve the transmission of data between the point of collection and the place where it can be quality controlled and analyzed. Training and better instruction manuals are required for modeling. Links need to be strengthened between agrometeorological groups and the national agricultural services. National advisory committees for agrometeorology need to be established. The national early warning systems need to be strengthened.

Management

Ultimately this process of site studies, measurement, analyses, modeling, and technology transfer needs must produce an input to the management practices for agricultural, forest and range lands. J.L. Monteith ends his summary with the questions:

- How many of the recommendations will ultimately benefit farmers and their families who live in the Sudano-Sahelian Zone?
- How long will this process take?





Vote of Thanks

M.V.K. Sivakumar

Principal Agroclimatologist, ICRISAT Sahelian Center BP. 12404, Niamey, Niger

It is both a singular honor and rare privilege for me to present the vote of thanks on behalf of all the cosponsors of this workshop and in particular from ICRISAT. The fact that the commencement of this workshop was witnessed by the Secretary of State for Higher Education, Research, Technology, and National Education of the Government of Niger as well as representatives of major agricultural research organizations, and the fact that over 126 scientists from 29 countries in Africa, Asia, Australia, Europe, and North America participated in the 6-day meeting have made this workshop a memorable event. We at ICRISAT take enormous encouragement from the knowledge that the endeavors and achievements of the young Sahelian Center have not gone unnoticed.

I now have a very pleasant task to perform. Firstly, on behalf of ICRISAT, I wish to extend our sincere thanks to the Government of Niger, particularly the Secretary of State for Higher Education, Research, Technology, and National Education and the Institut National de Recherches Agronomiques du Niger (INRAN) for their support in organizing this workshop.

We are most grateful to the Institute of Hydrology and the British Overseas Development Administration for having readily agreed to cosponsor this workshop and for providing significant financial help. Dr Wilkinson, the Director of the Institute of Hydrology and several of their scientists have participated very actively in this workshop and I am grateful to all of them for their help. The assistance and active cooperation of the World Meteorological Organization (WMO) at all stages contributed significantly to the success of this workshop. Through Mr Krishnamurthy, the representative of WMO, I would like to convey our sincere thanks to Mr Derk Rijks, the Chief of the Agrometeorology division at WMO who participated along with Dr Jim Wallace and myself in developing the program for this workshop and in identifying key speakers.

I have received several words of appreciation about the quality of the proceedings of this workshop, and the fact that they were made available before the workshop made it easy for everyone to assimilate the material and participate productively in the discussions during the workshop. The editors of the proceedings, Jim Wallace, Charles Renard, Charles Giroux, and myself are grateful for all the kind words. But much credit should also go to Mrs Penny Kisby of the International Association of Hydrological Sciences (IAHS) and to Mrs Hornsby and Mrs Smith of the Institute of Hydrology who worked untiringly under tremendous time constraints to ensure that the Volume was produced on time. We extend our appreciation to Dr Henny Colenbrander, Secretary General of IAHS for his kind support and encouragement in making all this possible.

I am also grateful to the French Ministry of Cooperation and Development and the Technical Center for Agriculture and Rural Cooperation (CTA) for very generous financial help.

In the planning and organization of this workshop, I have received excellent support and cooperation from Mr Ron Gibbons, the Executive Director of ICRISAT Sahelian Center (ISC) and from Dr Charles Renard, Team Leader of the Resource Management Program at ISC. I am grateful to Dr Swindale, our Director General for his patronage and active participation in this workshop despite his

busy schedule. As members of the local organizing committee, Dr Charles Renard, Mr John Thirsby, Mr Dasgupta, Mr Kumar Ghosh, Mr Kallam Moussa and Madame Solange provided me with significant assistance and I thank all of them.

We want to thank Dr Soares, Director General of the Centre Regional de Formation et d'Application en Agrometeorologie et Hydrologie Operationnelle (AGRHYMET) and all his staff for their cooperation. We are also grateful to Mr Mohammed Boulama, Director of Meteorological Services and his staff for their cooperation and assistance.

To all the session chairmen, cochairmen, and rapporteurs, and to the discussion leaders, Jim Wallace and I would like to convey our very sincere thanks for their tremendous help in ensuring that all the sessions are finished on time and for their kind cooperation in meeting the deadline for preparing the reports for the plenary session.

We owe you, the distinguished participants and speakers at this workshop, our very grateful thanks. You have shown commitment, met the deadlines in submitting papers and have traveled long distances to participate in this meeting.

Many ISC staff worked very hard over long hours on many days before and during this workshop. They are Mr Dossou Galbert Magloir, Mr Seydou Abdousalaam, Mr Adamou Janjouna, Mr Issaka Yougbare", Mr Pierre Sossou, Mr Aliou Dodo, Mr M. Ressay, Mr Yacouba Haldi, Mr Djobo Ouro Sama, Mr Djibril Yaro, Mr El Mahadi, Mr Lansina Diakite, Mr Adamou Souno, Mr Issa Sai'dou, and Mr Amadou Mouroundou. Let us give them a big hand.

The two young ladies in the booths behind you, Madame Tilly Gaillard and Madame Elisabeth Benamar have very patiently and diligently helped us understand each other and to communicate better. Let us give them both a big hand of appreciation.

And finally, it is my privilege to specially recognize the help and support of my good friend and co-organizer of this workshop, Dr Jim Wallace. When I first broached the idea for this workshop to Jim on one rainy evening in June 1989, when we were both waiting for the flash floods to recede on our way home to Niamey, Jim immediately thought it was a good idea. Since then he has been of tremendous support and help. In his good-natured Irish accent he would always say, "OK Shiv, is there anything else that I can do?" I thank Jim for all his help.

I wish you all a very pleasant and safe journey back home. Thank you.

Closing Speech

H.J. Colenbrander

**Secretary General, International Association of Hydrological Sciences
P.O. Box 6067, 2600 JA Delft, Netherlands**

Excellency, Ladies and Gentlemen:

At the end of the workshop I am pleased to express my great appreciation for the way this very successful meeting has been organized. I would like to classify the meeting as top quality or, with other words, a class A* ranking. The star (*) is an extra award since it is far more difficult to organize an international meeting in a developing country in the heart of Africa than in the 'high tech' part of the world.

I think the organizers under the 'command' of Dr M.V.K. Sivakumar and Dr J.S. Wallace have done a magnificent job. They took care of everything: an excellent briefing of chairmen and rapporteurs, a good planning of the lectures (hardly any gaps) and discussion sessions; keeping the speakers on time; good audiovisual presentations and excellent simultaneous translation from English into French and vice versa.

However, an excellent organization and good facilities are useless without interesting and high-quality lectures. I am pleased to report that the lectures were of good quality and mostly followed by stimulating discussions, demonstrating in particular the great interest of the participants from African countries in the current topic. I assume that the prepublished proceedings have greatly stimulated the lively discussion. I am grateful for the expressions of appreciation for the proceedings and I will transfer the words of thanks to the staff of the IAHS Press office in Wallingford. It must be stated however, that the proceedings could not have been produced on time and of such good quality, without the great help of the four editors. In this respect I may mention in particular Dr J.S. Wallace and Dr M.V.K. Sivakumar. For their cooperation and for all other things they did to make the workshop a success, I would like to offer them a small symbolic present, an IAHS tie.

The main findings and conclusions of the workshop were thoroughly discussed and clearly presented during the final discussion session. The conclusions and recommendations must be brought to the attention of the national and international governmental and nongovernmental institutions in the water field. They are very valuable for the planning of future research, but also for decision makers. In this respect it is of crucial importance that the conclusions and recommendations are printed and distributed at short notice. It was suggested by my colleague Dr J. Brouwer to set up a small ad-hoc panel to check, from time to time, whether the workshop findings are implemented adequately. I would like to support this idea.

Finally IAHS is looking forward to a further cooperation with ICRISAT and AGRHYMET and it will strive for closer contacts with our colleagues in Africa.

Thank you for your attention.

Final Communiqué

J.S. Wallace

**Head, Vegetation and Water-Use Section,
Institute of Hydrology Wallingford, Oxfordshire OX 10 8BB, UK**

Honorable Secretary of State, Directors General, Distinguished Colleagues:

At the kind invitation of the Government of the Republic of Niger the International Workshop on Soil Water Balance in the Sudano-Sahelian Zone was held at the Palais des Congres at Niamey in the Republic of Niger from 18-23 Feb 1991. One-hundred-and-twenty-six participants from 29 different countries, including most of the Western African countries, participated in this workshop. The papers and discussions were primarily based on the following subjects:

1. Current Research and Future Implications
2. State of the Art of Soil Water Balance Research
3. Soils of the Sudano-Sahelian Zone
4. Soil Water Balance Studies in the Sudano-Sahelian Zone
5. Operational Applications of Soil Water Balance Monitoring and Prediction

The meeting brought together research and applied scientists of many different disciplines, including the fields of soil science, meteorology, agrometeorology, agronomy, agroforestry, hydrology, and plant physiology. Much useful discussion took place between the scientists from these diverse disciplines and focused on the problems of making soil water balance measurements and predictions and the closely associated variations in crop yield and water resources in the Sudano-Sahelian Zone. Many new links have been made between people from different countries and with different languages. Friendships have been made and as people return home with their record of the meeting in the IAHS proceedings, we hope they will also maintain and cultivate the links and friendships they have begun here at this meeting.

On the penultimate day a planning meeting was held to discuss the main issues for future research and collaboration. Many useful summaries and recommendations were made and these will be published by ICRISAT and made available to the participants, the national, regional and international research centers, and the major funding agencies. It is the sincere hope of this meeting that this document will constitute an important and useful guide to all the above for the direction and planning of their future work and that this work will collectively contribute towards the evolution of sustainable agriculture and water resources in the Sudano-Sahelian Zone.

This workshop greatly appreciated all the facilities kept at its disposal by the authorities in Niger for receiving the participants and for the conduct of the workshop. I am sure we would all wish to express our sincere thanks to the Government of Niger.

Official Closing

Her Excellency Madame Maïlele Mariama
Secretary of State for Higher Education, Research, Technology,
and National Education, Government of Niger

Mr Gibbons, Executive Director of the ICRISAT Sahelian Center; Dr Sivakumar and Dr Wallace, organizers of this International Workshop on Soil Water Balance; Ladies and Gentlemen:

I am very pleased to receive a report from the organizers of this International Workshop on Soil Water Balance that during the last 5 days and today, you have all discussed various issues concerning water balance and the manner in which current knowledge on water balance could be applied to improve crop production in the Sudano-Sahelian Zone.

From the list of participants at your workshop, I have learnt that about 126 participants from several countries have contributed to your discussions. It is gratifying to see the extent to which the representatives of the institutions located in the Sudano-Sahelian region are willing to cooperate and share research experiences. The leadership shown by scientists of the Sudano-Sahelian region in many areas of the discussions during this meeting has amply demonstrated that their institutions are now beginning to realize the need to assign top priority to agricultural research.

Discussions in the different sessions of this workshop have clearly shown that all the institutions involved with agricultural research in the Sudano-Sahelian Zone, be they national or international, recognize the urgent need to improve food production as well as the need to work towards avoiding the potential catastrophic consequences of the degradation of the resource base. In addition, we have seen a remarkable measure of agreement on the need to involve improved farming systems that could significantly improve water-use efficiency and conserve water.

The Government of Niger places great emphasis on improving our understanding of the climatic resources, especially rainfall, in this region and the ways in which we can make a more efficient use of this most important resource. This explains the reason why we are hosting regional institutes such as the Centre Regional de Formation et d'Application en Agrometeorologie et Hydrologie Operationnelle (AGRHYMET) and the African Centre of Meteorological Applications for Development (AC-MAD), and international institutes such as ICRISAT. We should find out the means by which we can establish an effective link between research results on experimental stations and their actual application by farmers on the field.

Needless to say, the farmers in the Sudano-Sahelian Zone have to be informed and better trained in making more efficient utilization of the limited rainfall that is received. I have gathered from the volume of proceedings published for this workshop that recent research in the Sudano-Sahelian Zone has shown that rainfall per se is perhaps not the most limiting factor for crop production; rather it is the proportion of rainfall entering the soil and utilized by the crop that is more important. It is here, in my opinion, that the collective wisdom of this learned gathering can be most useful to our farmers. You have, in your discussions and in the reports presented during the plenary session this morning, drawn some important conclusions and useful recommendations. But I believe the most important work lies ahead. How can we translate your recommendations into real projects so that all this important work which you have carried out bears fruit?

Among the participants here there are several representatives from donor countries of development projects in the Sudano-Sahelian Zone. I hope you will help us translate the recommendations of this workshop into concrete projects by conveying to the donor agencies the fruit of our discussions and help improve the status of resource-use in the Sudano-Sahelian Zone. It is now the collective duty

of all the international, regional, and national research organizations in this region to carry forward the recommendations from this workshop to the benefit of all the farmers in this region.

Despite the problems encountered due to the Gulf crisis in arranging your travel schedules, I am very pleased to see that many of you have managed to visit our country this week and participate in this workshop. I hope you have all had a good stay in Niger and that you will carry back with you the goodwill of the people of Niger. We welcome you back to Niger if you have an opportunity to do so. I wish you all a safe journey home. I declare this International Workshop on Soil Water Balance closed.

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