FAO IRRIGATION AND DRAINAGE PAPER

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Crop yield response to water

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by

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Foreword

Sustainable management and utilization of natural resources is part of the *Global Goals* of FAO Member Countries and essential to the mandate of FAO.

The latest FAO assessment of the state of the world's land and water resources clearly indicated that these resources, already scarce today, will be increasingly scarce as we move into the future, threatening food security. In fact, the outstanding food demand projected for the next decades, due to the world population growth and to the anticipated shift in consumption patterns, will face very limited opportunities for further land expansion and the finite availability of fresh water resources. Such a food demand may be satisfied only if we are able to act effectively and sustainably on both sides of the *food* equation, i.e., *production* and *consumption*, and on the inter-linkages between these two variables, including trade, distribution and access.

Efforts are being made by FAO to address major issues on the *production* side, on the fairness of trade, on the *consumption* side (reduction of post-harvest losses and food waste; promoting nutritious and healthy diets) and other emerging challenges. Among these emerging challenges are: *food price volatility*, revealing the vulnerability of some countries in their dependency on imports, leading to increase production inside their national boundaries; *climate change*, causing greater uncertainties on rainfall patterns, thus requiring higher levels of adaptation and increased resilience of the local production systems; *transboundary* rivers and *competing demands* for land and water resources by other sectors of society and by ecosystems.

Under such circumstances, and looking into the future food demand, it is imperative that agriculture improve the efficiencies of use of the limited resources and ensure substantial *productivity* gains. In the case of water, scarcity is a major threat to the sustainability of food production in many areas of the world. The effective management of water in rainfed and irrigated agriculture is thus a major knowledge-based pathway to increase *productivity* and farmers' income. To combine increased productivity with sustainable management of natural resources, without repeating the mistakes made in the past, will be a challenge.

With the contribution of numerous experts, professionals and scientific institutions around the world, including a few *Institutes* of the *Consultative Group on International Agricultural Research* (CGIAR), *"Crop yield response to water"* is published at a time of high demand for assistance by member countries in order to implement effective water management strategies and practices that are environmentally safe and climate-resilient, and enhance sustainable water productivity and yield of their farming systems, therefore alleviating the risks of food insecurity.

José Graziano da Silva
Director-General
Food and Agriculture Organization
of the United Nations

Preface

The FAO *Land and Water Division* is engaged extensively in the enhancement of global agricultural performance. A part of this effort is the production of landmark publications and guidelines that address food production and water use problems using analytical methods that often serve as standards worldwide.

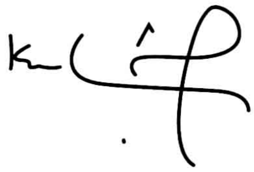
In the face of growing water scarcity, declining water quality, and the uncertainties of climate change, improving the efficiency and productivity of crop water use, while simultaneously reducing negative environmental impact, is of the utmost importance in responding to the increasing food demand of the growing world population. To this end, irrigated and rainfed agriculture must adopt more knowledge-intensive management solutions.

Moreover, competing demands for water from other economic sectors and for ecosystem services will continue to grow. As agriculture is by far the largest consumer of water, efficiency and productivity gains in this sector would free significant amounts of water for other uses.

Abstracting from the scientific understanding and technological advances achieved over the last few decades, and relying on a network of several scientific institutions, FAO has packaged a set of tools in this *Irrigation and Drainage Paper* to better assess and enhance crop yield response to water. These tools provide the means to sharpen assessment and management capacities required to: sustainably intensify crop production; close the yield-gap in many regions of the world; quantify the impact of climate variability and change on cropping systems; more efficiently use natural resources; and minimize the negative impact on the environment caused by agriculture. These tools are invaluable to various agricultural practitioners including, but not limited to: water managers and planners; extension services; consulting engineers; governmental agencies; non-governmental organizations and farmers' associations; agricultural economists and research scientists.

Representing FAO's state-of-the-art work in water and crop productivity, it is our hope that this publication provides easy access to, and better understanding of, the complex relationships between water and food production and, in this way, helps to improve the management of our precious water resources.

Alexander Müller
Assistant Director-General
Natural Resources and Environment



Parviz Koohafkan
Director
Land and Water Division

Acknowledgments

This publication has relied on inputs from a large number of people and institutions in various forms, including expert consultations, contributions at project workshops, experimental data and authorship.

Universities and national and international research institutions from many regions of the world have provided data and insights, which forms part of the vast amount of information and knowledge condensed in this state-of-the-art publication *Crop yield response to water*.

Particularly significant has been the involvement of key CGIAR Centres, specifically IRRI, ICARDA, ICRISAT, CIMMYT and CIP, and the FAO/IAEA Joint Division. Working together with the colleagues from these Centres has strengthened the institutional partnership and enhanced the synergy towards filling the gaps between scientific research and field implementation, theoretical knowledge and field practice, investigation and actual operation.

Most of these scientists, experts and colleagues are listed in this publication either as editors, authors or as scientists who have contributed with data and tests for the model *Aquacrop*. We are grateful to all of them for their highly valuable inputs.

We would like to thank the following experts who were involved in the initial stage of this endeavour: John Passioura (CSIRO, Canberra, Australia), Luigi Cavazza (University of Bologna, Italy), Hugh Turral (formerly IWMI, Colombo, Sri Lanka), John Annandale (University of Pretoria, South Africa), Dogo Seck (CERAAS, Dakar, Senegal), Lamourdia Thiombiano (FAO, Sub-Regional Office for Central Africa, Libreville, Gabon), Netij Ben-Mechlia (INAT, Tunis, Tunisia), Claudio Stockle (Washington State University, Pullman, United States), Florent Maraux (CIRAD, Montpellier, France), François Tardieu (INRA, Montpellier, France), Tsugihiro Watanabe (RIHN, Tokyo, Japan), Hiroshi Nakagawa (Ishikawa Prefectural University, Ishikawa, Japan), Long Nguyen (Joint FAO/IAEA Division, Vienna, Austria), Tim Wheeler (University of Reading, Reading, United Kingdom), Jan Doorenbos and Amir Kassam (formerly FAO, Land and Water Division, Rome, Italy) and Gerardo van Halsema (Wageningen University and Research Centre, Wageningen, The Netherlands). Their inputs have been determinant in correctly setting the initial condition of this work.

The support of colleagues at FAO at different stages has been indispensable for this publication. Special thanks go to Martin Smith, who started the process and later overviewed the various chapters, providing inputs and feedback to the editors to improve harmonization among the chapters and between the present and past FAO publications. Martin was ably assisted by Giovanni Munoz and Robina Wahaj. Shortly after the initial phase, an intense period of work started and we are particularly grateful to Gabriella Izzi and Lee K. Heng who managed the extensive experimental data set collected for calibration, maintained the liaison between all the collaborators, and contributed considerably to the various calibration and tests of *Aquacrop*. After one year of diligent effort at FAO, Lee moved to the FAO/IAEA Joint Division in Vienna, but continued to cooperate enthusiastically on model calibration and testing. Gabriella moved to the World Bank after two years of intense work on the model at FAO. More recently, support has been provided by Michela Marinelli, Patricia Mejías Moreno and Jippe Hoogeveen. We thank them for their continuous help and critical exchange in the completion of this product.

The design and accurate execution of the layout and editing of the manuscript are critical for this publication, requiring meticulous attention to the numerous details in the text, graphs, pictures, drawings, equations, symbols and citations. For their professional and immensely patient devotion to these tasks, we would like to thank the FAO collaborators Gabriele Zanolli, Paolo Mander, Rosemary Allison and Jim Morgan. A very special recognition goes to Margherita Bongiovanni for providing artistic, beautiful and accurate botanical illustrations of the crops.

Finally, we thank the former Assistant Director-General of Agriculture and Consumer Protection Department, Ms Louise Fresco, for her early endorsment and support of the iniciative, and both the Land and Water Division, Mr Parviz Koohafkan, and the Assistant Director-General of Natural Resources Management and Environment Department, Mr Alexander Müller, for their strong and continuous support of the 'Water' programme making possible this publication and the development of the model *Aquacrop*.

Without this collective and interdisciplinary effort, this outcome could not have been achieved.

Acronyms of institutions

CER:	Canale Emiliano Romagnolo, Italy
CNR:	Consiglio Nazionale delle Ricerche, Italy
CMMYT:	Centro Internacional de Mejoramiento de Maíz y Trigo, Mexico
CIP:	Centro Internacional de la Papa, Peru
CONICET:	Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina
CRA:	Consiglio per la Ricerca e la Sperimentazione in Agricoltura, Italy
CRI:	Cotton Research Institute, Uzbekistan
CSIRO:	Commonwealth Scientific and Industrial Research Organisation, Australia
DSIR:	Department of Scientific & Industrial Research, India
EEAD-CSIC:	Estación Experimental Aula Dei - Consejo Superior de Investigaciones Científicas, Spain
EMBRAPA:	Empresa Brasileira de Pesquisa Agropecuária, Brazil
FAO:	Food and Agriculture Organization of the United Nations, Italy
GRI:	Golan Research Institute, Israel
GRC:	Geisenheim Research Centre for Viticulture and Grapevine Breeding, Germany
IAM-B:	Mediterranean Agronomic Institute of Bari, Italy
IAEA:	International Atomic Energy Agency, Austria
IAS-CSIC:	Instituto de Agricultura Sostenible - Consejo Superior de Investigaciones Científicas, Spain
ICARDA:	International Center for Agricultural Research in the Dry Areas, Syria
ICREA:	Institució Catalana de Recerca i Estudis Avançats, Spain
ICRISAT:	International Crops Research Institute for the Semi-Arid Tropics, India
INIA:	Instituto Nacional de Investigaciones Agropecuarias, Chile
INRA:	Institute National de la Recherche Agronomique, France
INTA:	Instituto Nacional de Tecnologia Agropecuaria, Argentina
IRD CEFE-CNRS:	Institut de Recherche pour le Développement Centre d'Ecologie Fonctionnelle & Evolutive - Centre National de la Recherche Scientifique, France
IRRI:	International Rice Research Institute, Philippines
IRTA:	Institut de Recerca i Tecnologia Agroalimentaries, Spain

ISPA:	Istituto di Scienze delle Produzioni Alimentari, Italy
IVIA:	Instituto Valenciano de Investigaciones Agrarias, Spain
KESREF:	Kenya Sugar Research Foundation, Kenya
LARI:	Lebanese Agricultural Research Institute, Lebanon
LLNL:	Laurence Livermore National Laboratory, USA
SARDI:	South Australian Research and Development Institute, Australia
SASRI:	South African Sugarcane Research Institute, South Africa
SIA:	Servicio de Investigación Agraria, Spain
USDA-ARS:	United States Department of Agriculture – Agricultural Research Service, USA
WB:	World Bank, USA
VLIR-UOS:	Flemish Inter-University Council, Belgium
ZIS:	Zhanghe Irrigation System, China

List of principal symbols and acronyms

B	Dry biomass, of shoot for non-root crops, and of shoot plus storage root or tuber for root crops [tonne/ha or kg/m^2]
C_a	Mean atmospheric CO_2 concentration for the actual year [ppm]
$C_{a,o}$	Mean atmospheric CO_2 concentration for the year 2000 [ppm]
cc_o	Canopy size of the average seedling at 90% emergence [cm^2]
CC	Green canopy cover [percent or fraction]
CC*	Green canopy cover adjusted for micro advection [percent or fraction]
CC_{meas}	Canopy cover measured [percent or fraction]
CC_{sim}	Canopy cover simulated [percent or fraction]
CC_o	Initial canopy cover, canopy cover at 90% emergence [percent or fraction]
CC_{pot}	Potential canopy cover [percent or fraction]
CC_x	Maximum green canopy cover [percent or fraction]
CDC	Canopy decline coefficient [percent or fraction of canopy decline per unit time]
CGC	Canopy growth coefficient [percent or fraction of canopy growth per unit time]
CN	Curve number or surface runoff coefficient
[CO_2]	Carbon dioxide concentration of the atmosphere [ppm]
CWSI	Crop water stress index
d	Day
d_p	Plant density [plants per unit surface]
d_{ref}	Reference plant density [plants per unit surface]
D_r	Soil water depletion of the root zone [mm]
DAE	Days after emergence [day]
DAP	Days after planting [day]
DI	Deficit irrigation
DP	Deep percolation [mm per unit time]
DU	Distribution uniformity
E	Soil evaporation [mm per unit time]
E_{dz}	Surface evaporation from the rest of the soil surface outside the emitter wetting pattern [mm per unit time]
$E_{Stage\ I}$	Soil evaporation at Stage I (wet soil surface) [mm per unit time]
$E_{Stage\ II}$	Soil evaporation at Stage II (drying soil surface) [mm per unit time]
E_{wz}	Surface evaporation from the soil wetted by the emitters [mm per unit time]

ECe	Electrical conductivity of the saturated soil-paste extract [dS/m]
ECe_n	Electrical conductivity of the saturated soil-paste extract: lower threshold (at which soil salinity stress starts occurring) [dS/m]
ECe_x	Electrical conductivity of the saturated soil-paste extract: upper threshold (at which soil salinity stress has reached its maximum effect) [dS/m]
ET	Evapotranspiration [mm per unit time]
ET_a	Actual evapotranspiration [mm per unit time]
ET_c	Crop evapotranspiration under standard conditions [mm per unit time]
ET_x	Maximum evapotranspiration [mm per unit time]
ET_o	Reference evapotranspiration [mm per unit time]
f_{age}	Reduction coefficient describing the effect of ageing on $K_{c,Trx}$ [1/d]
f_{cc}	Fraction of the orchard ground surface occupied by the cover crop
f_{CO2}	CO_2 factor for atmospheric CO_2 normalization
f_{HI}	Adjustment factor for HIo
FC	Field capacity
FI	Full irrigation
FDR	Frequency domain reflectometry
FTSW	fraction of transpiring soil water
g_s	Stomatal conductance [m/s]
G	Ground cover fraction of the tree canopy
GDD	Growing degree days [°C d]
GIR	Gross irrigation requirement [mm or m3/ha per unit time]
GIS	Geographical information systems
HI	Harvest index [percent or fraction]
HI_o	Reference harvest index [percent or fraction]
I	Infiltration [mm per unit time]
K_c	Crop coefficient
K_{cb}	Basal crop coefficient representing Kc for a dry soil surface having little evaporation but full transpiration
K_{cc}	Cover crop coefficient
K_{ext}	Radiation extinction coefficient
K_p	Pan coefficient (for the pan evaporation method to determine ET_o)
$K_{r,t}$	Empirical coefficient relating the ET_c of an orchard of incomplete cover to that of a mature orchard
K_{sat}	Saturated hydraulic conductivity [mm per unit time]
$K_{s,e}$	Empirical soil evaporation coefficient
K_y	Yield response factor

$K_{c,Tr}$	Crop transpiration coefficient
$K_{c,Tr\,x}$	Crop transpiration coefficient for when the canopy fully covers the ground (CC = 1) and stresses are absent
Ke	Soil evaporation coefficient for fully wet soil surface
Ke_x	Soil evaporation coefficient for fully wet and non-shaded soil surface
Kr	Evaporation reduction coefficient
Ks	Stress coefficient
$Ks_{b,c}$	Cold stress coefficient for biomass production
$Ks_{pol,c}$	Cold stress coefficient for pollination
$Ks_{pol,h}$	Heat stress coefficient for pollination
Ks_{aer}	Water stress coefficient for water logging (aeration stress)
$Ks_{exp,w}$	Water stress coefficient for canopy expansion
Ks_{sen}	Water stress coefficient for canopy senescence
Ks_{sto}	Water stress coefficient for stomatal closure
LAI	Leaf area index [m^2 leaf area/m^2 soil surface]
LAI_{ref}	LAI of the same crop planted at a reference density
LWP	Leaf water potential [MPa]
NIR	Net irrigation requirement [mm per unit time or m^3/ha per unit time]
p	Fractional depletion of TAW
p_{upper}	Upper threshold of p (no water stress: Ks = 1)
p_{lower}	Lower threshold of p (maximum water stress: Ks = 0)
P	Precipitation or rainfall [mm]
PAR	Photosythetically active radiation [μmol per m^2 of surface per s]
PRD	Partial root drying
PWP	Permanent wilting point
RDI	Regulated deficit irrigation
RAW	Readily available soil water in the root zone [mm]
REW	Readily evaporable water at the top of the soil profile [mm]
RUE	Radiation use efficiency [Kg of biomass per MJ of intercepted solar radiation]
RO	Surface runoff [mm per unit time]
SDI	Sustained (or continuous) deficit irrigation
t	Time [GDD or d]
T	Air temperature [°C]
T_{base}	Base temperature (below which crop development does not progress) [°C]
T_c	Canopy temperature [°C]
$T_{max} = T_x$	Daily maximum air temperature [°C]

$T_{min} = T_n$	Daily minimum air temperature [°C]
$T_{n,cold}$	Minimum air temperature at upper threshold for cold stress affecting pollination [°C]
$T_{x,heat}$	Maximum air temperature at lower threshold for heat stress affecting pollination [°C]
T_{opt}	Crop optimal daily temperature [°C]
T_{upper}	Upper temperature (above which crop development no longer increases with an increase in air temperature) [°C]
Tr	Crop transpiration [mm per unit time]
Tr_{cc}	Cover Crop transpiration [mm per unit time]
Tr_x	Maximum crop transpiration (for a well watered crop) [mm per unit time]
TAW	Total Available soil Water (between FC and PWP), equivalent to the soil water holding capacity in the root zone [mm/m]
TDR	Time domain reflectometry
TE	Transpiration efficiency [Kg of biomass per unit of water transpired]
VPD	Air vapor pressure deficit [kPa]
wz	Fraction of the soil surface wetted by the emitters
Wr	Soil water content of the root zone expressed as an equivalent depth [mm]
WP	Crop biomass water productivity [tonne of biomass per ha and per mm of water transpired or kg of biomass per m^3 of water transpired]
WP*	WP normalized for ET_o and air CO_2 concentration [tonne /ha or kg/m^2]
$WP_{B/ET}$	WP as the ratio of biomass to ET [kg/m^3]
$WP_{B/Tr}$	WP as the ratio of biomass to Tr [kg/m^3]
$WP_{fresh\ Y/ET}$	WP as the ratio of yield measured as fresh biomass to ET [kg/m^3]
$WP_{lint/ET}$	WP as the ratio of lint (of cotton) to ET [kg/m^3]
$WP_{sucrose/ET}$	WP as the ratio of sucrose (for sugar cane) to ET [kg/m^3]
$WP_{Y/ET}$	WP as the ratio of yield (as dry matter) to ET [kg/m^3]
$WP_{Y/Tr}$	WP as the ratio of yield (as dry matter) to Tr [kg/m^3]
X	Irrigation depth [mm]
X_R	Required irrigation depth [mm]
Y	Yield [tonne/ha or kg/ha]
Y_a	Actual yield [tonne/ha or kg/ha]
Y_x	Maximum yield [tonne/ha or kg/ha]
Z_e	Effective rooting depth [m]
Z_x	Maximum effective rooting depth [m]
Z_n	Minimum effective rooting depth [m]
θ	Volumetric soil water content [m^3 of water / m^3 of soil]
Ψ_{stem} = SWP	Stem water potential [MPa]
Ψ_{leaf} = LWP	Leaf water potential [MPa]

Contents

1. Introduction

Food production and water use are inextricably linked. Water has always been the main factor limiting crop production in much of the world where rainfall is insufficient to meet crop demand. With the ever-increasing competition for finite water resources worldwide and the steadily rising demand for agricultural commodities, the call to improve the efficiency and productivity of water use for crop production, to ensure future food security and address the uncertainties associated with climate change, has never been more urgent.

To examine the pathways for increasing the efficiency and productivity of water use, the yield response of crops to water must be known. This relationship is complex in nature and various attempts have been made to provide simplified, though sound, approaches to capture the basic features of the response.

FAO's first publication that presented a relationship between crop yield and water consumed was *Irrigation and Drainage Paper* No. 33 *Yield Response to Water* (Doorenbos and Kassam, 1979). This approach, discussed in Chapter 2, is based on one single equation relating the relative yield loss of any crop (either herbaceous or woody species) to the relative reduction of water consumption, i.e. evapotranspiration, by way of a coefficient (K_y), which is specific for any given crop and condition. This approach has provided a widely-used standard for synthetic water production functions, still in use today. This simplification, however, made this approach more suitable for general planning, project design and rapid appraisal purposes, often providing a first-order approximation.

Over the last three and half decades, new knowledge has enlighten processes underlying the relationship between crop yield and water use and technology has improved. Further, novel needs have emerged related to the planning and management of water in agriculture, including those arising from climate change. FAO has, therefore, revisited the approach to quantify crop yields in response to water use and water deficit. The end product of this effort is a crop simulation model named *AquaCrop*, which balances accuracy, simplicity and robustness and is described in Chapter 3. The conceptualization and development of this modelling approach is the result of a number of years of consultation and collaboration with scientists, crop specialists and practitioners worldwide, consolidating the vast amount of knowledge and information available since 1979.

AquaCrop uses the original equation of Doorenbos and Kassam (1979) as a point of departure and evolves from it by calculating the crop biomass, based on the amount of water transpired, and the crop yield as the proportion of biomass that goes into the harvestable parts. An important evolution is the separation of the non-productive consumption of water (soil evaporation) from the productive consumption of water (transpiration). Furthermore, the timescale of the original equation is seasonal, or growth-stages that are weeks long in duration, while the timescale used in *AquaCrop* is daily, in order to better represent the dynamics of crop response to water. Finally, the model allows for the assessment of responses under different climate change scenarios in terms of altered water and temperature regimes and elevated carbon dioxide concentration in the atmosphere. *AquaCrop* simulates growth, productivity and water use of a crop day-by-day, as affected by changing water availability and environmental conditions. The results of calibration and testing of the model so far provide grounds for confidence in its performance.

The development of standard crop parameters has made the model accessible to several types of users in different disciplines and for a wide-range of applications. *AquaCrop* is mainly aimed at practitioner-type end users such as those working for extension services, consulting engineers, irrigation districts, governmental agencies, non governmental organizations, and various kinds of farmer associations for use in the development of irrigation schedules and management decisions. Economists and policy specialists can also use this model for planning and scenario analysis. In addition, research scientists should find the model valuable as a tool for analysis and conceptualization. Overall, *AquaCrop* allows proper investigation of strategic planning and management to improve the efficiency and productivity of water use in herbaceous crop production. It is not designed for use with trees and vines.

Chapter 3 not only describes *AquaCrop* but also provides samples of applications for specific purposes and guidelines for calibration.

Chapter 3 also provides the agronomic features of the sixteen crops for which the model has been calibrated and validated. The crops covered are: wheat, rice, maize, soybean, barley, sorghum, cotton, sunflower, sugarcane, potato, tomato, sugar beet, alfalfa, bambara groundnut, quinoa and tef. Additional crops will soon be calibrated and their agronomic features described. The goal is to provide an overview of each crop's physiology and agronomy for users interested in applying the model to a particular crop at a given location. Furthermore, the overview can serve as a reference when calibrating the model for different crop classes. The description of each crop includes crop growth and development, water use and productivity, responses to water deficits and expected yields.

Fruit production has risen in importance over the past decades for increasing the productivity and competitiveness of small-scale farmers around the world. Fruit not only provides better income opportunities for growers, but is also pivotal in providing more healthy diets to consumers. The yield response to water of fruit trees and vines forms the second major part of this *publication*, presented in Chapter 4. The complexity of tree crops resulting from carry-over effects from one year to the next and the large divergence among cultivars, however, precluded using a relatively simple modelling approach, as that used for herbaceous crops. Therefore, a *Guideline* is presented instead, which includes a *general section* on the irrigation of fruit trees and vines, and a special section covering physiological and agronomic features of each individual crop species. While the *general section* provides the technical background and guidelines for efficient irrigation management, the sections on individual crops give specific responses to water, with a common format, covering the following key items: growth and development, crop water requirements, yield response to water supply, and recommended strategies for deficit irrigation. The focus of Chapter 4, in fact, is to synthesize available data and to generate production functions to glean opportunities in many cases for reducing water supply without yield or net income penalties. Particular attention in this chapter is paid to safeguarding farmers' net income and, in some cases, to enhancing fruit quality. Crops covered in Chapter 4 include olive, citrus, apple, plum, almond, pear, peach, walnut, pistachio, apricot, avocado, sweet cherry, grapevine and kiwi. As more information becomes available, other fruit and plantation crops will be described and made available to users via the Internet.

Finally, Chapter 4 provides some closing remarks and the way forward from this FAO *I&D Paper* No. 66. A compact disc accompanies this publication, where the user will find most of the information products and guidelines relevant to her/his work.

This new publication will provide the practitioner with strengthened skills to: assess the effect of water shortages on crop production; investigate the impact of climate change on crop yield; compare the results of several water allocations plans; optimize irrigation scheduling (either full, deficit or supplementary); and enhance management strategies for increased water productivity and water savings.