ADVANCES IN IRRIGATION

Edited by

DANIEL HILLEL

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PREFACE

Advances in Irrigation is a serial publication aimed at fulfilling a widely perceived global need for periodically updated comprehensive elucidations of contemporary developments in the science and practice of irrigation. It provides an ongoing forum for the presentation of theoretical and technical innovations, analyses of problems, and critical reviews of relevant topics that from time to time appear to be ripe for publication. Ideally, such a presentation should not only summarize and encapsulate the state of our knowledge at any particular moment, but also assess its significance in relation to alternative approaches, and point to trends and prospects. Thus, we hope not only to inform of progress to date, but also to spur continued progress.

In the wake of the 1982 publication of Volume 1 in this series, and the favorable response which it has received, we were encouraged to proceed quickly toward publication of Volume 2. Once again, we have been fortunate in being able to enlist the participation of leading researchers in the field, whose contributions are embodied in the eleven contributions to this volume.

The order of the articles is somewhat arbitrary. An important contribution on irrigation scheduling and applied timing criteria is followed by an equally important one on the topical problem of energy utilization and management in irrigation. A subsequent article is devoted to a thorough examination of the relationship between irrigation requirements and crop response in terms of crop–water production functions. The global interest in the vital topic of irrigation development is exemplified in a highly informative chapter on irrigation in Australia, the driest of continents. A theoretical analysis of the application of a plant–environment model to problems in irrigation is followed by a discerning critical review of the vexing problem of soil variability in the field. Since in the final analysis irrigation must be an economical venture, we deemed it apt to include still another article on the economic analysis of on-farm irrigation using response functions of crops. The problem of irrigation scheduling is again addressed in a subsequent contribution from the point of view of a dynamic crop response model. Modeling plant growth and water relations is the topic of still another article which describes canopy development and root activity in relation to the concurrent processes of photosynthesis, transpiration, respiration, and soil–water dynamics. The plant is portrayed as a self-regulating dynamic system capable of responding optimally to concurrent changes in both the atmospheric and the soil environments. Techniques for estimating irrigation requirements and particularly the use of remote sensing methods for the monitoring of evapotranspiration constitute the topics of the concluding two articles.

Altogether, we believe that these contributions more than justify our initial expectations and constitute a volume fully commensurate in quality with its predecessor, Volume 1. As Editor, I must again express my deep gratitude for the exemplary cooperation of my colleagues who have taken time from their busy schedules to prepare and submit their contributions without (well, almost without) undue delay. I share their joy in the fruition of their efforts even as I already look forward to the task of preparing future volumes in this worthwhile continuing endeavor.

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I. Introduction

Many factors influence the decision-making process of determining when to apply irrigation water. Among them are climatic setting (arid, semiarid, etc.), water supply (constraints on availability), crop (flowering habit, harvest index, stress sensitivity of the current growth stage), irrigation system (degree of mechanization and control over application rate and amount), soils (profile textures, spatial variability), weather (current and short-term expected), and economics (profit-maximizing level of irrigation). Additional considerations may include electric load management, salinity control, crop quality at harvest, and the cultural or labor scheduling aspects of farming operations.

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Given these many factors (a partial listing at best), it is not surprising that the published literature in this subject area is voluminous. Recent expositions of irrigation scheduling and closely related subject matter are found in a number of monographs, for example, Kozlowski (1976), Lange *et al.* (1976), Barfield and Gerber (1979), Jensen (1980), Turner and Kramer (1980), Arkin and Taylor (1982), and Taylor and Jordon (1983). Symposium proceedings (American Society of Agricultural Engineers, 1981a,b) provide additional summaries.

The tone of this article reflects the generally perceived need to conserve, reduce, or more efficiently use water resources. Aquifer depletions, heightened competition between users, increasing energy costs, and the need to minimize adverse environment effects are frequently cited as reasons for efficiency improvements in irrigated agriculture. Initially, several developments and/or concepts are reviewed for their particular significance to applied irrigation scheduling. Thereafter, emphasis is given to the timing aspect of water application "on farm" ranging from traditional to more recent methods.

II. Fundamental Scheduling Concepts

A. Yield Responses to Irrigation Timing (General)

Early irrigation timing studies per se (thoroughly summarized by Salter and Goode, 1967) have widely demonstrated that stress sensitivity is generally greatest in the floral through pollination periods. Seed yields of determinate crops are typically least sensitive to mild stress in the early vegetative period. Stress sensitivity also diminishes in the latter part of the grain-fill period. In addition to the importance of timing effects, early studies also implicated that of stress duration and intensity. Thus there was a recognized need to define more quantitatively the degree of stress and its consequent effects.

Applied semiquantitative methods for irrigation timing have undergone varying degrees of development. Hiler and Clark (1971) introduced a stress day index (SDI) method which provides a decision-making procedure for initiating irrigations when a calculated SDI approaches defined critical levels in specified growth periods. The SDI is obtained from the product $SD_i \times CS_i$, where SD_i defines the degree and duration of plant water deficit in growth stage i and CS_i defines the crop yield susceptibility in a given growth stage to a given water deficit. Incomplete definition of yield susceptibilities as complete functions of stress indicators has hampered implementations. Illustrations of potentials for improved water efficiency and related developments concerning SDI methodology have been given by Hiler and Howell (1983).

Two types of experiments have been widely used in the past decade to study irrigation timing effects. For nonforage crops the growing season is usually divided into vegetative, flowering–pollination, and seed-fill periods. In arid climates a preseason irrigation is typically applied to return the soil profile water content to field capacity. In the first design, irrigation timing treatments may range from full irrigation [i.e., maintenance of potential or energy-limited evapotranspiration (ET) rates] in all growth periods (III) to a nonirrigated (000) treatment and all combinations (0II, 00I, 0I0, I0I, I00, and II0) in between. Stress imposition is normally limited to one growth period, with irrigations withheld either entirely or until a quantified degree of stress occurs (usually measured as the ET depression relative to the ET of the nonstress treatment). In these experiments the maximum seasonal yield (Y_m) is usually produced by the III treatment, which also accumulates the maximum seasonal evapotranspiration (ET_m).

Figure 1 illustrates results of Stewart *et al.* (1975) relating corn grain yields (normalized form, Y/Y_m) to accumulated seasonal ET (also normalized as ET/ET_m). These data created widespread interest regarding their implications to applied irrigation scheduling. First, they show that a wide array of yields can be associated with a given seasonal ET accumulation, not a surprising result, given the complex dynamics of the soil–plant–water–atmosphere system. The more important aspect, however, is that they

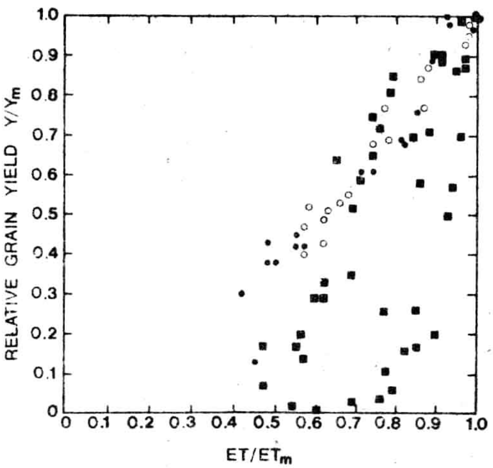

FIG. 1. Relative corn grain yield versus relative seasonal evapotranspiration, showing the probable existence of an upper-bound region of yields for any given ET/ET_m: (●) 1970; (○) 1971; (■) 1972. (From Stewart *et al.*, 1975.)

suggest the existence of an upper-bound yield–ET relationship; that is, for any given ET attainment (assuming also that other production inputs are at yield-optimizing levels), there exists an approximate maximum yield level. Also, the occurrence of yield–ET data all along the upper-bound relationship suggests that it is possible in most water supply situations to design management or timing regimes that ensure to a high degree an upper-bound yield attainment. These regimes would be the ones of primary interest.

Stegman *et al.* (1980) concluded that upper-bound yields are likely for a wide array of water management regimes. For example, yield–ET data for 000 regimes will often fall on the upper bound, but 00I data will fall to the right of the upper bound. Similarly, II0 and I00 data fall on the upper bound, but I0I data frequently fall to the right and below. These results imply that plants, through a survival mechanism, react to an imposed stress in an optimal way; that is, plants shed tillers, lose leaves, abort flowers, and so on, to achieve the maximum yield possible given the degree of drought severity that is imposed at a particular growth period. If, however, stress relief takes place later in the season, as with 00I or I0I treatments, irreversible damage to yield (usually a reduced number of fillable seeds) will have already taken place and the late season transpiration, resulting from irrigation, will cause a disproportionately large seasonal ET for the attainable yield. Thus 00I and I0I regimes very often result in suboptimal yields.

Yield–ET data for 0II regimes can fall somewhat above the position of regression-determined upper-bound yield functions (Stegman *et al.*, 1980). This plotting position occurs when early-season irrigations are successfully minimized to reduce evaporation loss but are in turn sufficient to maintain potential transpiration rates. Yields per unit of applied irrigation are frequently maximized by this management regime.

The 0I0 regime is often advocated as an optimal one (determinate seed yield crops) when the irrigation water supply is very limited. Reduced irrigation in the vegetative period reduces evaporation loss. If stress also reduces leaf area and plant size, these vegetative effects may in part be compensated (Hsiao, 1973) by greater canopy light penetration. Likewise negative stress effects, due to reduced irrigation in later seed fill may be partly compensated for by a translocation of dry matter from leaves and stems to the seed organ (Boyer and McPherson, 1975).

A second popular experimental design for the study of irrigation timing effects (Hanks *et al.*, 1976) uses a single-sprinkler lateral (line source) system to achieve a triangular distribution pattern perpendicular to the line. Irrigations are timed at frequent intervals (< 7-day interval) to simulate typical center-pivot system management. Irrigations maintain ET replacements varying from 100% at the line to 0% at the outer edge of the sprinkler pattern.

These high-frequency fractional ET replacement regimes are in effect variations of II0, I00, and 000 regimes. Resulting Y–ET relationships have been widely reported (Stewart *et al.*, 1977; Maurer *et al.*, 1979; Retta and Hanks, 1980) as being typically linear and usually devoid of Y–ET data as generated by 00I and I0I regimes. Hence high-frequency partial ET replacement regimes inherently achieve an optimal sequencing of ET deficits.

The two experimental designs described have therefore been helpful in defining likely timing effects. Resulting upper-bound production functions are, however, also dependent on a given set of production parameters (population, fertility, climatic setting, etc.). To consider a greater range of factors requires more complex methods of analysis. Thus plant response studies have evolved to the level of plant growth models (Baker *et al.*, 1972; Curry *et al.*, 1975; Childs *et al.*, 1977). Development, calibration, and verifications involve a long, complex, and laborious process. In a simulation mode they can, for example, be used to test the relative efficacies of differing irrigation timing strategies (Barfield *et al.*, 1977; Gilley *et al.*, 1980) over long periods of weather record. Their applied utility on a real-time basis still remains largely to be realized. It appears likely that simplified versions will be (in the not too distant future) adapted to microcomputer systems attached to irrigation systems. With appropriate peripherals and software, these computers will automatically control irrigation timing and the amount of water applied.

B. Maximizing Net Returns

Farmer–irrigators frequently assess profit potentials by conducting budget-type analyses in the preplanting period. These analyses result in decisions concerning crop and associated hybrid or variety selections, planting populations, fertilizer regimes, herbicide usage, tillage systems, and so on. For their economic survival farmers are committed to continually improving their production capacity and/or production efficiency. Thus farmer–irrigators can only afford an interest in water management regimes that are capable of producing acceptable or maximum net returns.

Figure 2 illustrates an observed (Stegman, 1982b) upper-bound production function for corn that rises linearly from a dry-land yield level to a maximum (Y_m – ET_m) level. A second function in Fig. 2 relates yield to the seasonal irrigation amount (IR). This latter relationship represents a least-squares fit to 3 years of data. The increasing curvature with increasing yield agrees with the generally expected curve shape, illustrating that non-ET losses increase as irrigation amounts approach the magnitudes and frequencies needed to achieve Y_m – ET_m levels. This particular curve reflects the efficiency potential of high-frequency irrigation timing ($<$7-day intervals) on sandy soils