by Daniel Hillel

For many centuries, the standard mode of irrigation consisted of the diversion of water from rivers via channels to level beds located in valleys. Much water was lost in excess seepage, which tended to raise the water table and waterlog and salinize the soil. The situation improved somewhat with the use of pumps and metal pipes and the application of water under pressure via sprinklers, but the efficiency and sustainability of irrigation still left much to be desired.

About 40 years ago, a revolutionary change occurred in the science and art of irrigation, and it now seems appropriate to review its origin and current status and to consider its future prospects. Fittingly, this revolution took place in the Middle East, the region where irrigation first began. However, the initiators were themselves newcomers to the practice who were able to turn the disadvantage of their inexperience to the advantage of a fresh approach. The new mode of irrigation started in Israel within two decades of its birth in the middle of the 20th century, as the nascent state needed to develop its agriculture under extreme conditions of water scarcity and capital constraints.

Having participated in that seminal development, I can describe it directly. It was a rare and heady experience for a young scientist to be present and active at the birth of an innovation that had both fundamental and practical importance and has since proven to be globally applicable. I refer to the advent and evolution of high-frequency, low-volume, partial-area irrigation techniques, including drip/trickle and microspray irrigation. What began as a re-examination of the guiding principles of irrigation management (Hillel, 1971, 1972; Rawlins and Raats, 1975; Bresler, 1977) eventually led to a complete change of paradigm, an inversion of traditional premises, and the elaboration and widespread adoption of an entirely new set of technologies (Hillel, 1982, 1987, 1990, 1997; Dasberg and Bresler, 1985; Bucks and Nakayama, 1986).

OPPOSITE PAGE: *Left*—**The "head" of an early drip irrigation system—control valves, filter, and fertilizer injector. SOURCE: March 1971 *Crops & Soils* magazine.** *Right*—**Technician Ernest Yoder checks water flow instrumentation on a subsurface drip irrigation system used for peanuts, cotton, and corn crops. Photo by Peggy Greb (USDA-ARS).**

Conventional Approach Based on 'Equal Availability'

The conventional approach to irrigation management, presumably bolstered by research done in the early decades of the 20th century,

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was based on the hypothesis that soil moisture remains equally available to crops until plant roots deplete it to some residual low value called "the permanent wilting point" (Veihmeyer and Hendrickson, 1950). In practice, this hypothesis justified a regimen of infrequent irrigation designed to wet the soil periodically to its maximal "field capacity" and then to let crop roots deplete soil moisture almost to the "wilting point" of the plants before irrigating again to replenish the "soil moisture reservoir." The conventional irrigation scheme thus consisted of repeated short episodes of watering, followed by extended periods of soil moisture extraction by the crop.

Accordingly, the rooting zone was periodically wetted to saturation, a maximal content that deprived the roots of aeration, leached nutrients, and raised the water table. Then the soil was allowed to dry gradually to a minimal water content that subjected the plants to increasing stress. Practical limitations on the frequency of irrigation by the conventional methods of surface-flooding, furrow, and sprinkler irrigation made it difficult to test alternative strategies to avoid such wide fluctuations by maintaining an intermediate (optimal) level of soil moisture and aeration continuously.

The low-frequency mode of irrigation seemed to make economic sense because most of the conventional systems were more expensive to run at a higher frequency, lower delivery rate, and longer duration. For example, where the cost of portable tubes was a major consideration, it was economical to make the least amount of tubing serve the greatest area by shifting available tubes successively to as many tracts of land as possible before returning to the same tract for the repeat irrigation. The question was, therefore, how dry can the soil become before crops experience a "significant" reduction in yield?

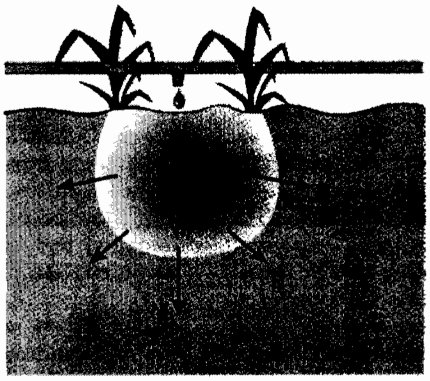
LEFT: Early drip irrigation system in newly planted avocados. The flexible vinyl hose has three emitters per tree. SOURCE: March 1971 *Crops & Soils* magazine. BOTTOM: Before drip irrigation, the conventional irrigation scheme consisted of brief episodes of watering to the soil's maximal "field capacity" followed by extended periods of extraction of soil moisture, as shown here in Post Falls, ID in the 1940s. SOURCE: October 1949 *Crops & Soils* magazine.

The hypothesis of undiminished soil moisture availability to crops until they come close to wilting is an example of the human tendency to contrive theoretical justification for what may seem convenient in given circumstances. To be sure, the "equal availability" principle was questioned by some leading scientists (Richards and Wadleigh, 1952), but at the time, they had no way of disproving it conclusively. There was simply no practical or economical way to establish and maintain a nearly constant soil moisture regime in the root zone of a field throughout the growing season so as to show that plants growing in a continuously moist soil outperform plants growing in a soil that is periodically near the lower end of the so-called "availability range."

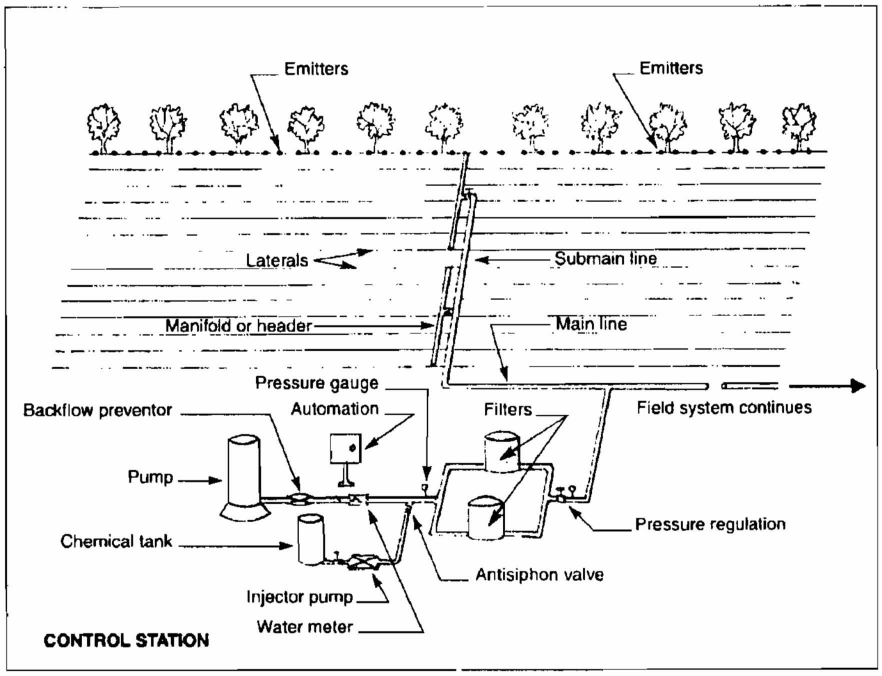
A New Paradigm Emerges

Gradually, the contradictions of the old theory became too obvious to ignore. Evidence accumulated that soil moisture is not equally available but rather less and less readily available to crops as it is progressively depleted. Therefore, it occurred to some of us that we ought to try the opposite approach: to irrigate as frequently as possible but with very small volumes of water (Hillel and Guron, 1973). For the traditionalists, our unorthodox approach seemed foolish. Irrigate more often in an arid environment? That, they said, would increase water use per unit area. But lower water use per unit area never should have been an end in itself. A better criterion is water use per unit of production (i.e., crop yield), termed "water use efficiency."

And this is how the new approach proved itself. Rather than ask crops to go thirsty without diminished performance, we began to ask crops how much better they could perform if they were grown in a constantly moist soil and prevented from ever suffering stress. When we tried that, we soon discovered that crops often show a pronounced increase in yield when irrigation is provided in sufficient amount and frequency that water never becomes a limiting factor,



TOP: The pattern of soil wetting under a drip emitter placed between closely spaced rows of a crop. RIGHT: A basic trickle irrigation system. SOURCE: FAO. 1997. Small-scale irrigation for arid zones: Principles and options. FAO Development Series 2. FAO, Rome.



especially if nutrients are supplied along with the water (Rawitz and Hillel, 1974; Howell and Hiler, 1975; Hillel, 1987).

But could that condition be accomplished in a practical way? What had not been feasible in former decades became so with the advent of low-cost, weathering-resistant plastic tubes that could be fitted with variously designed porous sections or spaced emitters so as to ooze or drip water into the root zone at a slow rate, either continuously or in frequent pulses. Such tubes could be laid on the ground or placed below the surface to conform to crop rows and the spacing of plants within the rows. To prevent clogging of narrow-orifice emitters (by suspended particles, algae, or precipitating salts),