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Inserting man's irrigation and drainage wisdom into soil water flow models and bringing it back out: how far have we progressed?

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Abstract

Half of the world food production originates from irrigated and drained soils. However, the future management of these systems must accept the paradigm shift away from managing abundant water supplies (with focus on conveyance and distribution) and toward the beneficial use of scarce water resources with the emphasis on deficit irrigation, sustainable groundwater exploitation and optimized crop water productivity. Mechanistic computer models – together with economic and social decision rules – have a key role to play in supporting water allocation decisions. Unfortunately, computer models for prediction and better understanding of unsaturated soil water flow processes have low operational focus, especially in many irrigation countries where they are most needed. Advanced models have the potential to contribute to the solution of relatively complex problems, provided that field data are available to calibrate and run them. Calibration techniques, especially with the help of GIS and remote sensing, have progressed rapidly, but the required level of expertise tends to make the application of sophisticated tools highly dependent on modeling experts. The challenge, now, is to reduce the gap between the abundant supply of advanced models and the low demand by the irrigation and drainage community. The likelihood of adoption by a broader user community will increase as models become more user- and data-friendly (or -tolerant) and heterogeneity-aware. The time to formulate and market the unsaturated-zone model as a necessary ingredient to the solution of crop water production problems and the time to equip users around the globe is now.

Introduction

Importance of irrigation and drainage in the food chain

The natural conditions for crop growth usually deviate from the ideal, and irrigation and drainage techniques are utilized to maintain soil moisture within a desirable range. These human manipulations increase the output from the natural resource via more food production and raise income and boost the economic

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development of poor rural areas. Approximately 350 million ha of land in this world is under irrigation. Presently, the total harvested agricultural area is about 1600 million ha. It is estimated that the potentially suitable cropland on Earth is some 3200 million ha (FAO 1996). Irrigation in developing countries (39%) and developed countries (11%) will produce half of the world's cereal production. The rain-fed agricultural systems in developed countries will be responsible for 20% of the cereal production, of which a large portion has drainage systems. Smedema, Abdel-Dayem and Ochs (2000) estimated that areas equipped with irrigation and drainage techniques are responsible for approximately 40% of the global food production, and areas equipped with drainage systems alone contribute another 10%.

If we are to meet the future demand for food that will be in pace with the 1.5% global population growth and if we are to meet the demands of the modern diet (Renault and Wallender 2000), the world food production will need an annual growth rate of about 3%. Rosegrant, Cai and Cline (2002) predicted the total world irrigated area to increase to 420 million hectare by 2025, representing a 16% increase as compared to 1995. Shiklomanov (1999) estimated that 27% more land needs to be brought under irrigation between 2000 and 2025 to meet future demands for food. According to Alcamo, Henrichs and Rösch (2000), a slowdown in dam building and irrigation investments, combined with the consequences of dropping groundwater tables, will limit the expansion of irrigated areas to 5 - 10% over a 25-year time span.

In semi-arid and arid zones having shallow groundwater tables, soil salinity can easily deteriorate fertile soils, and sub-surface drainage systems are needed as a remedy. About 45 million ha of irrigated land have salt-affected soils and 32 million ha of dryland agriculture are salt affected to varying degrees by human-induced processes (Oldeman, Hakkeling and Sombroek 1991).

The major irrigated areas of the world can be found in climates where potential evapotranspiration (ET_{pot}) exceeds net precipitation. Figure 1 (see Color pages elsewhere in this book) displays a map with 0.5° cells of the world showing the fractions equipped for irrigation around the period 1995 (Döll and Siebert 2000). This review paper on one-dimensional unsaturated soil water flow modeling for irrigation and drainage systems will focus on the regions displayed in Figure 1, i.e. where the technical potential offered by irrigation and drainage is deemed the highest. Since the authors are familiar with *swap* and its applications, there is a bias in the presentations and discussions towards this particular model. The examples can, however, be interpreted to represent nearly any Richards equation type of simulation model.

Development of soil water-flow models

The unsaturated zone is a complicated system governed by highly non-linear processes and interactions. Modern sensors are available to quantify flow processes; however, *in situ* instruments can be installed in a limited number of sites only, due to expense and labor requirements. Flow processes can alternatively be described by means of physical-mathematical models. Unsaturated-zone models can be used to simulate the timing of irrigations and irrigation depths, drain spacing and drain depth, and system behavior and response. The role of numerical models during the last 25 years has increased our understanding of irrigation and drainage processes in the context of soil–plant–atmosphere systems. Progress in modeling can be attributed to merging separated theories of infiltration, plant growth, ET and flow to drain pipes into a single numerical code. Modeling of soil moisture and solute transport in the unsaturated zone has been under development since the 1970s (e.g. Toksoz and

Kirkham 1971; Neuman, Feddes and Bresler 1974; Zaradny and Feddes 1979). Early soil water-flow models were further extended with routines for specific phenological and physiological development and solute transfer. The later developments for solute transfer came as a consequence of public environmental concern towards non-source point pollution. The majority of models are one-dimensional, although many two-dimensional models and some three-dimensional models exist.

A simulation model can be generally categorized into classes referred to as mechanistic, stochastic, empirical and functional. Some major names and categories of deterministic models are summarized in Table 1. Most of these models are dedicated to a certain process, such as *drainmod* to assist in drainage design, *leachm* for pesticide movement, *enwatbal* for distinguishing between soil evaporation, wet-leaf evaporation and crop transpiration, and *dssat* for crop–nutrient interactions. Each model has its strengths, weaknesses and data requirements and a universally appropriate and versatile model does not exist. The selection of a certain model should depend on the specific task.

Table 1. A selection of various categories of deterministic models for the unsaturated zone that are suitable to describe irrigation and drainage processes (the models and corresponding authors are listed in chronological sequence)

Model category	Example models	Sources
Bucket model	*sowatet, cropwat, salbal, saltmod, wsbm, opdm, cropsim*	Hanks and Cui (1991); Smith (1992a); Allen et al. (1998); Boumans and Croon (1993); Oosterbaan (1998); Droogers et al. (2001); Merkley (1996); Prajamwong, Merkley and Allen (1997)
Pseudo-dynamic	*must, simgro, faids*	De Laat (1976); Querner (1988); Roest, Abdel-Gawad and Abdel-Khalek (1993)
Richards equation	*swatre, drainmod, unsat2, worm, leachm, drainmod-s, isareg, opus, drainet, hyswasor, wave, mozart, swap, hydrus, dssat, cropgro, cropsyst, swms_3d, swat, simodis*	Feddes, Kowalik and Zaradny (1978); Belmans, Wesseling and Feddes (1983); Skaggs (1978); Neuman, Feddes and Bresler (1974); Van Genuchten (1987); Wagenet and Hutson (1989); Abdel-Dayem and Skaggs (1990); Kandil et al. (1995); Teixeira and Pereira (1992); Smith (1992b); Hundertmark et al. (1993); Yang and Zhang (1993); Dirksen et al. (1993); Vanclooster et al. (1994); De Leeuw and Arnold (1996); Van Dam et al. (1997); Šimůnek, Šejna and Van Genuchten (1998); Ritchie (1998), Hoogenboom, Jones and Boote (1992); Stockle et al. (2003); Šimůnek, Huang and Van Genuchten (1995); Arnold, Neitsch and Williams (1999); D'Urso (2001)
SVAT model	*micro-weather, cupid, enwatbal, swaps, unsat2e, isba, isba-ags, stics, rzwqm*	Goudriaan (1977); Norman (1982); Lascano et al. (1987); Ashby, Dolman and Kabat (1996); Allen and Ahmad (1992); Noilhan and Mahfouf (1996); Calvet et al. (1998); Brisson et al. (2003); Hanson (1998)
Multi-dimensional drainage models	*biwasa, sidra, cssri, hydrogeochem, sutra*	Nour-el-Din, King and Tanji (1987); Kiwan, Soliman and Bazaraa (1993); Kamra et al. (1991); Zimmer and Lorre (1993); Scientific Software Group (2000); Kelleners (2001)
Crop production models	*wofost, sucros, ceres, dssat, epic, oryza, sawah*	Van Keulen and Wolf (1986); Spitters, Van Keulen and Van Kraalingen (1989); Porter, Jamieson and Wilson (1993); Tsuji, Uehara and Bales (1994); Kropff, Van Laar and Ten Berghe (1993); Ten Berghe et al. (1995)

Soil–Vegetation–Atmosphere Transfer (SVAT) models include descriptions of the relatively rapid turbulent exchanges between vegetation and the atmosphere. Although SVAT models are meant for coupling with atmospheric models, they can be employed to study irrigation and ET processes in an off-line mode. The coupled energy and water balances computed for small time increments make SVAT models suitable for linkage to remotely-sensed data and techniques.

Some models combine processes originally held in separate models, such as the combination of *ceres* (Tsuji, Uehara and Bales 1994) and *dssat* (Ritchie 1998) to form a complementary model. Other examples are the extension of *drainmod* with options for nitrogen (N) and salinity (S) modeling (Abdel-Dayem and Skaggs 1990) and the combination of *swatre* (Feddes, Kowalik and Zaradny 1978; Belmans, Wesseling and Feddes 1983) and *wofost* (Van Keulen and Wolf 1986) into *swap* (Van Dam et al. 1997). For applications at the regional scale, one-dimensional soil water flow models are often combined with an irrigation-water distribution model and a groundwater model to specify or control the upper and lower boundary conditions, respectively (e.g. Abdel-Gawad et al. 1991; Kupper et al. 2002).

Intercomparison studies have assessed the performance of some soil water flow models and have provided guidelines to the potential user community on various 'to do' and 'not to do' aspects of specific models (e.g. McLin and Gelhar (1979), Feddes et al. (1988), Workman and Skaggs (1989), Clemente et al. (1994), Lorre, Lesaffre and Skaggs (1994), De Faria et al. (1994), Bastiaanssen et al. (1996) and Ines et al. (2001)). In general, most models perform well, provided detailed field and experimental data are available to calibrate them. The most complete and systematic collections of modeling examples have been compiled by special workshops dedicated to Crop–Water–Environment models under the auspices of the International Commission on Irrigation and Drainage (ICID), e.g. Drainage Research Institute (1990), Pereira et al. (1992), Lorre (1993), Pereira et al. (1995), Ragab et al. (1996) and Musi, Fritsch and Pereira (1999). Corwin, Loague and Ellsworth (1999) compiled an excellent review on the calibration and uncertainty aspects of solute-transfer models for the vadose zone. Their work emphasizes leaching of fertilizers and pesticides and the treatment of the soil system parameters in particular, which can also be utilized in modeling for irrigation and drainage systems. Olioso et al. (in print) compiled an excellent paper describing the parallel development and operational aspects of several French SVAT models.

The public expectations concerning environmental and water-resources management within irrigation and drainage projects are extremely high, so that computational tools are needed to assist human intuition in the management of these systems. Menenti (1994) argued for the use of models to help resolve conflicts between water-user groups and irrigation agencies, especially if user preferences are converted into a set of analytical definitions of water management.

Under-utilization of soil water flow models

Despite the promising progress made and the steady growth in modeling capacity and capability, the implementation of numerical models in irrigation and drainage systems has not really materialized to any substantial degree, neither in the irrigation research community and consultancy services, nor in the operation and evaluation of irrigation and drainage systems. Some of this underutilization is due to (i) poor education of local irrigation staff, (ii) insufficient awareness of technical capabilities of models, (iii) insufficient access to computers, (iv) absence of required soil, weather and crop data to operate a model, (v) steep learning curve for the first application, (vi)

natural unbelief that computer-based technology is useful for tackling practical irrigation and drainage problems, (vii) low priority assigned to technical solutions because social and institutional issues are more compelling, (viii) absence of validation opportunities, (ix) lack of calibration protocol so that multiple and contrasting results are often obtained, (x) poor justification for model use and wrong model selection in historic studies, (xi) models are not specific enough to solve site-specific problems and questions, (xii) assumptions and simplifications undertaken in the model are inadequate to sufficiently capture the intrinsic structure of the system being modeled, and (xiii) placement of more trust in field measurements than in model predictions.

An additional impediment to application of numerical models for planning and design is that applications must generally look across long time horizons and over large spatial areas. They must consider soil flow and cropping processes for many fields over multi-year periods and under management of many users, so that multiple simulations are necessary. Thus, users may need to assemble extensive field data for calibration, validation and operation, and construct large databases of information. Some of this data need can be reduced through employment of inverse modeling as described in section 'Progress in solution of technical and scientific issues'.

Model operators must contend with uncertainties in quantifying the heterogeneities associated with plant and soil properties. Uncertainties in model processes include subtle interactions among soil layering, root extraction, root density and plant morphology, differences in crop phenology and morphology within populations of the same crop variety (Tasumi et al. in press-a), the quantification of hydraulic parameters of soil (Ghidaoui and Prasad 2000), timing and amounts of water additions by the farmer and impacts of management on soil evaporation, and lack of energy-driven feedback between the evaporating surface and the aerodynamic boundary layer that are generally not encapsulated into the prediction of evaporative demand. These uncertainties and heterogeneities are surmountable, but only with invested time and resources or via the use of remote sensing as described in the section 'Inverse modeling for solving agricultural and irrigation practices'.

Most professionals involved in irrigation planning, design, operation and management today are able to run models that are adequately fitted to their programs. By far, one of the best success stories is *Cropwat* (Smith 1992a; Clarke, Smith and El-Askari 1998) because the model is simple to operate and understand and provides useful information regarding crop water requirements, irrigation scheduling and crop yield. It is interesting and useful to explore in more detail where and when relatively simple budget models such as *Cropwat* are good enough to answer common questions that concern the irrigation and drainage community.

The objective of this review paper is to make a Strengths–Weaknesses–Opportunities–Threats (SWOT) analysis of unsaturated-zone models and applications dealing with irrigation and drainage systems. The paper aims at describing the types of solutions that advanced models can provide and argues that with growing needs for more precise water management, model solutions should receive more attention from management. The SWOT analysis is made in the context of diminishing water resources in irrigated river basins. Because of the importance of crop yield response to water in irrigation and drainage management, some crop yield models and studies are reviewed as well. Modeling issues such as pesticide leaching and applications in rain-fed agriculture are not considered, as this is more related to environmental studies.

The unsaturated-zone modeling plaza

The demand side for quantified solutions

The number-one challenge for the irrigation sector is to produce more food from less water, meaning increased crop water productivity both in terms of kg m^{-3} and \$ m^{-3}, while simultaneously controlling soil salinity and groundwater contamination. Pesticide leaching must be reduced to a minimum to allow recycling of groundwater and allocation to other uses. The optimization of such management can be bolstered by an unsaturated-zone model coupled to a mechanistic crop growth model. For example, Droogers et al. (2003) used the combined *swap-wofost* model to compute water productivity for the Sirsa Irrigation District in Western Haryana, India, where nomographs were compiled between groundwater level, salinity of the irrigation water, crop water stress and water economics (productivity \$ m^{-3} and gross return in \$/ha). This application demonstrated how soil physics and basic economics in agricultural water management can be combined to produce management solutions (see Figure 2 on Color pages elsewhere in this book).

The glooming world water crisis has prompted many water policymakers to reassess the impacts and benefits of the huge water consumption of the irrigation sector. Worldwide, the agricultural sector withdraws 61% of diverted renewable water resources (Cosgrove and Rijsberman 2000). This percentage is projected to reduce to 59% by 2010 and to 54% by 2025 because of insufficient water to allocate to all thirsty crops. It therefore seems inevitable that irrigation schemes in river basins will receive progressively smaller river diversions, not only to meet the growing demands of domestic and industrial water users, but also to supply commitments of water resources to endangered species by enhancing river discharges, streamflows in creeks and (re-)hydration of natural wetlands. It also appears inevitable that sustainable water conservation programs will be introduced nearly everywhere and on a large scale. The often sounded solution for physical water shortage within a river basin is to increase the irrigation efficiency. At the river-basin scale, however, it is likely that the irrigation efficiency, whatever the exact meaning, is high already, especially where return flows are recaptured and drainage water is reused. This is generally the case in mid and upper portions of basins away from oceans.

In many irrigation schemes on alluvial plains with unconfined aquifers, leakage of irrigation water diverted from rivers or streams is a welcome feature to replenish declining aquifer systems – perhaps due to groundwater extraction for irrigation – and the percolation of water is not a 'loss' but only a displacement in time and space (Allen, Willardson and Frederiksen 1997). The introduction of modern and more precise irrigation technology is, under such circumstances, ineffective, if at the same time artificial recharge programs have to be initiated to bring a halt to rapidly declining groundwater tables. Where diversions are taken from confined aquifers, it may be important to hold percolation and runoff losses to a minimum.

The complex interactions between root-zone soil moisture flow, salinity build-up, dry-matter production, water quality degradation and opportunities to recycle water according to prevailing geo-hydrological and drainage conditions (see Figure 3), can no longer be appraised by simple (steady-state) concepts and FAO-type of analytical solutions. The real contribution of irrigation to overall water productivity and irrigation efficiency is unpredictable without detailed understanding of the system. Hence there is a clear demand for use of complex deterministic models that aid in the decision-making processes for basins struggling with competition for water.

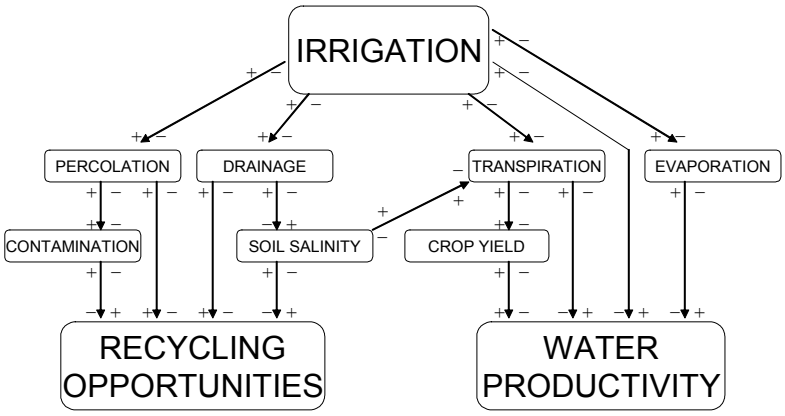

Figure 3. Process chain between irrigation water supply, water productivity and opportunities to recycle water. A plus sign indicates a positive relationship between the two combined processes and a negative sign implies a negative relationship

Groundwater is often used as a short-term remedy for shortages in surface-water supply for irrigation and environmental systems. As a consequence, basin-wide ET in dense irrigation schemes can exceed net precipitation of a basin indicating net water resources decline. During the last 10 to 20 years, there has been a substantial increase in the utilization of groundwater resources for agricultural irrigation, because of the widespread distribution and availability of groundwater and because of relatively low development cost (Clarke, Lawrence and Foster 1996). Today, the US, China, India and Pakistan are the largest consumers of groundwater and its use is still increasing (Postel 1997). The decline of water tables is essentially a function of tubewell extraction and return flow of irrigation diversions via percolation. Ahmad, Bastiaanssen and Feddes (2002), using a soil water flow model, found 28% of irrigation water in wheat–cotton systems in Pakistan returned back to groundwater as recharge and that the percentage increased to 42% for wheat–rice systems. Recycling of these water resources resulted in net irrigation efficiencies that were substantially greater than the nominal field-scale values. Without transient models that precisely describe moisture storage changes, this would be difficult to assess.

The interest in irrigation management is currently shifting from the supply side of water, where water supply should be managed to match the gross crop water requirement, to a system where the yield return and economic benefits to water use is maximized, i.e. the concept of water productivity (e.g. Molden, Sakthivadivel and Merrey 1999; Seckler, Molden and Sakthivadivel 2003). This paradigm shift requires new insights and analytical relationships between, for instance, irrigation supply, evaporative and transpirative components, deep percolation and crop yield. Water conservation programs in irrigation will, by definition, tend to make the root zone drier. The amount of empirical evidence is growing that deficit irrigation and regulated deficit irrigation (Goldhamer, Fereres and Salinas 2003) increases the water productivity for many crops (e.g. Al-Khaisi, Berrada and Stack 1997; Zhang et al. in press). Zhang et al. (1999) found empirical evidence in four irrigation schemes on the North-China plain that crop water productivity (crop yield per unit of depleted water) of wheat may increase from 0.95 to 1.35 kg m^{-3} if the irrigation application is reduced from 400 mm to 150 mm per season. Hargreaves (1975), in his compilation of data from Davis (California), Hawaii and Delhi (India), showed that the highest crop water productivity for cereals is obtained at a moisture adequacy (i.e. ratio of the actual

moisture available to the amount for which the yield is maximum) of 0.394, which suggests that significant water deficits enhance water productivity. Not all crops respond in this manner, however, and not all empirical evidence supports these findings. SVAT yield models must be able to simulate these processes with adequate precision.

Conjunctive use of groundwater and surface water is an accepted practice under water-short conditions. However, the safe yield of groundwater and disposal of any saline effluent from irrigated areas requires a long-term solution. The salinity of drainage systems and tube wells needs to be well described, especially in situations where water quality deteriorates with depth so that tube wells must be managed to skim fresh water to prevent salts from coming up. Solutions for these problems must be based on multiple-dimensional theory and require numerical models that solve both water and solute transport processes.

The supply side of analytical solutions

The FAO has played a prominent role in providing practical solutions to agricultural water management problems by assembling pieces of technology from numerous research laboratories and universities. This assemblage has culminated in the well-known series of Irrigation and Drainage Papers, out of which the FAO#24 (Doorenbos and Pruitt 1977), FAO#29 (Ayers and Westcot 1985), FAO#33 (Doorenbos and Kassam 1979) and FAO#56 (Allen et al. 1998) papers are most often cited. The basic features and application focuses of these practical technologies are summarized in Table 2.

Table 2. Workable considerations in solution of common and primary agricultural water management problems and decision-making needs promoted by FAO

Problem	Considerations for solution	Irrigation and Drainage Paper No.
Crop water requirement	Effective rainfall, reference evapotranspiration, crop coefficient	24, 56
Crop water stress	Root-zone water balance, readily available moisture fraction	33, 56
Crop salt stress	Electric conductivity, salt-tolerance factor, leaching fraction	29, 56
Crop production	Crop water stress, crop yield response factor	33, 56
Leaching requirement	Electric conductivity of water and soil, salt-tolerance factor	29
Drainage requirement	Leaching efficiency	29
Irrigation supply	Total season evapotranspiration, rainfall	24, 33, 56
Irrigation additions	Field capacity, wilting point, rooting depth, soil water-holding capacity	24
Irrigation scheduling	Root-zone water balance, evapotranspiration, rainfall, readily available water	24, 33, 56

These sets of ‘FAO tools’ have proven to be of high relevance and practical benefit because they are easy to understand and have a flat learning curve. The required data to operate these models can be obtained from simple field measurements (e.g. salinity of irrigation water vs. soil electric conductivity). The critical question to be posed is whether these solutions are good enough for solving our future challenges. The soil water potential at field capacity is, for instance, not a constant, but varies

according to the layered soil characteristics and soil moisture flow boundary conditions. Even so, an effective rule of thumb is to quickly estimate the maximum irrigation depth on the basis of soil water-holding capacity. The usual assumption of soil salinity being well mixed is more an exception than a rule, so that the concepts of leaching fraction and leaching efficiency are simplified representations of the real soil physical processes. The often used relationship between relative ET (ET_{act}/ET_{pot}) and relative yield (Y_{act}/Y_{pot}) – popular among economists – is a strong simplification, because the value of potential yield is controlled by farm management, quality of the seeds, the usage of pesticides, availability to credits etc. (Perry in print). Hence, accurate prediction of Y_{act} cannot be obtained merely from ET_{act}, ET_{pot}, Y_{pot} and the crop yield response factor K_y due to the myriad of interactions between timing and magnitude of stress, planting density, seed variety, conditioning, climate, soil and fertility. Hence, there are opportunities to use advanced simulation models to help to assess the errors associated with simple approaches.

The conditions for switching from simple solutions to advanced models depend on the problem to be solved in relation to the data and expertise available or that can be afforded relative to the economic cost posed by the problem. Menenti (1994) had as a working title of his paper "*Do irrigation agencies and farmers need computational decision support tools?*" Farmers who live and survive under the circumstances encountered in the field, have an objective (income generation) that differs from the water policymaker (sharing resources equally and productively). Menenti's view is that the debate about the practical relevance of computational tools should focus on the costs and added value for advanced decision-support systems vs. higher costs for water and loss of income. An example was recently demonstrated in the Sirsa Irrigation District, where Van Dam and Malik (2003) used remote sensing, Geographic Information System (GIS) and numerical models to show that the current gross return in a large irrigation system in Northwestern India is US$501 million per year, and that postponement of drainage interventions to arrest a rising groundwater table will reduce the gross return to $452 million per year.

What can advanced models really add?

This section presents a selected compilation of examples of interesting solutions to problems based on deterministic soil water flow models. The need for more sophisticated description of unsaturated-zone hydrology has motivated scientists to conduct studies to collect data and to develop more robust numerical models to interpret results. Once a model has been well calibrated, it can often be used to make predictions for a combination of events for which no empirical data have been collected or are available, such as impacts of changing row spacing of sub-surface drainage, use of more saline groundwater, installation of deeper sub-surface drains or impacts of weather anomalies. These extrapolations in application are only feasible if the model has a strong mechanistic character. Some examples primarily from developing countries are summarized in Table 3.

Baars and van Lochem (1993) investigated means to quantify farmers' desires regarding irrigation-water distribution in the Lower Tunuyan irrigation system in Argentina. Marketing techniques were used to develop a procedure in which farmers can actually participate in the design of an intervention. The client-oriented marketing approach consists of perception analysis, preference analysis and utility analysis. The outcome was a well-defined definition of an alternative system for water distribution, including irrigation interval, flow rate and allocation rules. The involvement of the water users follows well the paradigm shift to manage irrigation on the basis of

Table 3. Literature examples of applications of unsaturated-zone models in irrigation and drainage studies

Purpose	Country of application	Source
Irrigation supply and management	Pakistan, India, Zimbabwe, Egypt, Thailand, Argentina,	Smets et al. (1997); Singh and Singh (1997); MacRobert and Savage (1998); Merkley (1996); Prajamwong, Merkley and Allen (1997); Kupper et al. (2002)
Irrigation performance and water productivity	Argentina, India, Italy, Iran, The Netherlands, Turkey	Menenti, Azzali and D'Urso (1995); Singh and Singh (1996); D'Urso, Menenti and Santini (1999); Droogers et al. (2000); Hack-ten Broeke (2001); Droogers and Kite (2001); Singh, Van Dam and Jhorar (2003)
Irrigation strategic planning	Egypt, India, Pakistan	Abdel-Gawad et al. (1991); Agarwal and Roest (1996); Kuper (1997); Droogers et al. (2003)
Drainage of salt-affected soils	Australia, India, Pakistan, Italy, California	Cox, McFarlane and Skaggs (1994); Kamra, Rao and Singh (1995); Kelleners, Kamra and Jhorar (2000); Sarwar and Feddes (2000); Tedeschi and Menenti (2002); Ali et al. (2000)
Groundwater recharge from irrigated land	Pakistan	Beekma et al. (1995); Ahmad, Bastiaanssen and Feddes (2002)
Farmer perceptions	Argentina, India	Baars and van Logchem (1993); Van den Hoven (1997); Jacobs et al. (1997)
Water conservation	Egypt, Pakistan, California	Feddes and Bastiaanssen (1992); Sarwar and Bastiaanssen (2001); Burt et al. (2002)
Water harvesting and runoff	Israel, Argentina, Louisiana	Boers et al. (1986); Menenti (1994); Saleh (1994)
Land evaluation	The Netherlands	Feddes and Van Wijk (1990)
Irrigation system losses	Texas	Thompson (1997)
Tile drainage outflow	Minnesota, Louisiana	Ayars, McWhorter and Skogerboe (1981); Fouss, Bengtson and Carter (1987); Pohll and Guitjens (1994); Randall and Iragavarapu (1995); Manguerra and Garcia (1995)

utilization of water resources, rather than on the supply of water. The impacts of these user preferences and technical limitations in Argentina were studied using the *swap* model (Van den Hoven 1997). The model was able to determine that there were no hydrologic restrictions concerning proposed irrigation intervals and new allocation rules for the water distribution based on water users' preferences, and solute concentrations in irrigation water were recognized as an important consideration for improving the performance of the irrigation system.

Jacobs et al. (1997) quantified water-user preferences by head-end and tail-end farmers in India located along water courses having shallow groundwater table and proneness to soil salinity. Farmers, executive Irrigation Department staff, the State Government and academic agro-hydrologists were interviewed regarding remedial actions to be taken. The farmers were satisfied with the *warabandi* water distribution system that fits well with the existing social and institutional context, but they desired lining of canals. Physical criteria (crop yield, salinity, waterlogging), social criteria (equity in inter-distributary water quality, equity in intra-distributary waterlogging) and institutional criteria (O&M efforts, O&M costs) were associated with (i) flexible rotation distributary canals, (ii) shorter intervals between fixed rotation schedules, (iii) canal lining and (iv) construction of sub-surface drainage systems. Computer technologies were applied to evaluate the various scenarios, and optimum solutions were selected using a *swap* and the multi-objective analysis package *electre*.

Construction of sub-surface drainage systems was identified as the most desirable and cost-effective solution for meeting the physical, social and institutional criteria.

Management efforts to restore equilibrium between rainfall and ET at the basin scale must introduce ET-reduction programs that include deficit irrigation, changing planting dates, planting shorter-season crops or varieties, sowing crops at lower density, introduction of greenhouses, breeding waterstress-tolerant varieties, reducing consumptive non-transpirative losses, and reducing planted areas. ET-reduction programs should ultimately translate into sustainable groundwater tables and more discharge to natural streams, resulting in more surface water to coastal zones for maintaining aquatic ecology. Sarwar and Bastiaanssen (2001) used the *swap* model to predict the long-term effects of water-savings programs in the Punjab, Pakistan. The results indicate that, with good-quality irrigation-water supply, applications of 195 mm to wheat and 260 mm to cotton are required to maintain agricultural sustainability under both drained and undrained conditions. When farmers have no option other than conjunctive use or use of saline groundwater from tube wells, they should apply more water (325 mm for both wheat and cotton), assuming that there are no drainage constraints. If drainage systems are not present or are not performing well, then only salt-tolerant species should be cultivated. Thus it is not possible to implement water-savings programs, not even in the wheat belt of Asia if sub-surface drainage systems are not introduced on a large scale. It also demonstrates that water conservation programs have to include significant leaching requirements.

Droogers, Salemi and Mamanpoush (2001) gave a similar illustration with *swap* to the Rudasht irrigation project in the polluted Zayandeh Rud basin in Iran. The usual irrigation practice is to apply 900 mm of water having an average salinity level of 4 dS m^{-1}, yielding approximately 3300 kg ha^{-1} cotton with a topsoil salinity of 16 dS m^{-1}. If the total irrigation depth is decreased to 800 mm (thus by only 11%), the topsoil salinity is predicted to increase to 21 dS m^{-1} (31% increase) and the cotton yield to decrease to 2900 kg ha^{-1}. A water-savings program that supplies only 600 mm is predicted to decrease cotton yield to 2250 kg ha^{-1} and create a soil salinity of 26 dS m^{-1}. The findings from Pakistan and Iran suggest that water conservation practices under saline soil conditions are less effective, and practically infeasible to realize across large time frames incorporating the real weather variabilities. The outcome of these modeling exercises can assist the local policymakers in their decisions on the formulation and introduction of water conservation plans.

Progress in solution of technical and scientific issues

Inverse modeling for solving soil physical properties

In terms of data used in irrigation- and drainage-related modeling studies, there is an ongoing shift from utilizing locally-measured agro-hydrological data towards using globally-available data and from using conventional, non-remotely-sensed data to remotely-sensed data (Droogers and Kite 2002). Figure 4 shows the transition of commonly used types of data within this structure. It is expected that this shift will continue and that in the future more data will originate from remote sensing and will find their way into the public domain.

Inverse modeling is a procedure where a physically based model is used to compute physical parameters required by the model. This is generally done by fitting parameter values based on empirical observations and comparing and optimizing observed and modeled output. Inverse modeling differs from parameter estimation in that in inverse modeling, the 'optimized' parameters are physically-based. Examples

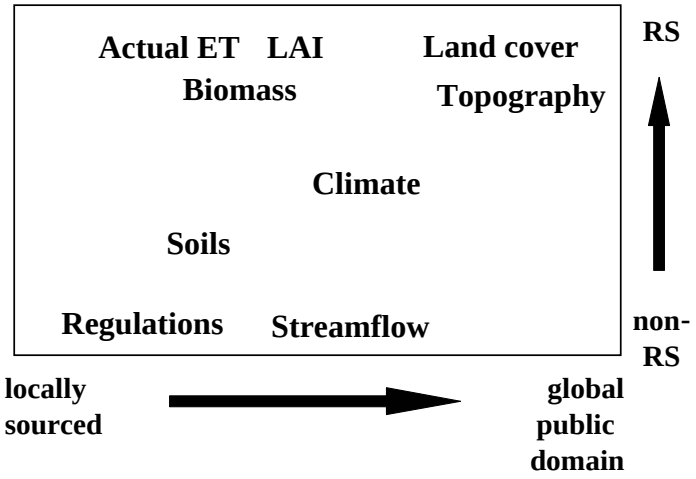

Figure 4. Data required for integrated hydrological modeling in a basin as a function of source and method of observation (RS is remote sensing)

are determination of soil water retention data or rooting depth via water balance computations.

The collection of needed data for model operation can be very costly and time-consuming. Different approaches have attempted to define the spatial variability of soil hydraulic properties (e.g. Van Genuchten and Leij 1992; Romano and Santini 1997; Ghidaoui and Prasad 2000). Recently, comprehensive archives have been constructed that relate laboratory observations of soil water retention and conductivity to other soil physical data derived from pedological surveys (e.g. Wösten 1999). These data make it possible to establish relationships between required soil hydraulic parameters and easily measurable data, such as soil texture, which can be found in regional soil maps (D'Urso and Basile 1997).

Two examples are presented in this section to demonstrate the power of innovative inverse-modeling approaches to data collection: (i) a procedure to estimate soil hydraulic functions, and (ii) an inverse-modeling approach to mimic agricultural and irrigation practices.

In this first illustration, the combination of lysimeter data, the *swap* model and a genetic algorithm is used to explore options to inversely obtain soil hydraulic characteristics from a lysimeter soil (Tyagi, Sharma and Luthra 2000) under a wheat crop (*Triticum aestivum*) in the vicinity of Karnal, India during the 1991-1992 Rabi season. The *swap* model was expanded to include a Genetic Algorithm (GA) to inversely estimate the soil hydraulic functions of the lysimeter (Ines and Droogers 2002b). GA is a global optimum-seeking algorithm (Zheng 1997) and the algorithm works by mimicking the mechanisms of natural selection to explore decision search space for optimal solutions (Goldberg 1989). GA approaches have been developed to overcome problems of non-uniqueness and local minimum solutions often experienced in highly non-linear processes found in the vadose zone. Obviously, as long as the amount of data available is sufficient in relation to the number of parameters to estimate, traditional optimization techniques based on gradients can be used (e.g. pest, Doherty, Brebber and Whyte 1994).

In a second study, Jhorar et al. (2004) studied the 23,000 ha Kheri Distributary irrigation canal, which is part of the Bhakra Irrigation system in Haryana (India), and derived sets of van Genuchten-Mualem parameters (θ_{res}, θ_{sat}, n, α, k_{sat}) that describe the irrigation hydrologic behaviour for 7 soil types in the area. Each soil type had 4 to

5 horizons. This is an example of a numerical experiment using the *pest* model for parameter estimation and the *swap* model to derive the water balance. Aerial average ET flux from the seven individual soil types and associated irrigation regime was computed according to soil type occurrence in the command area. Jhorar et al. concluded that actual soil evaporation could not be predicted accurately using the inversely determined soil hydraulic parameters due to the deviation of soil hydraulic properties among surface layers. They concluded that it was possible, however, to represent the seven spatially variable heterogeneous soil profiles with an equivalent single homogeneous soil profile and an empirical solution for the bare soil evaporation. The resulting water balance proved reliable (the reference *swap* run with 7 heterogeneous soils had evaporation of 106 mm, transpiration of 363 mm, and percolation of 185 mm; the *swap* run with 1 homogeneous soil had evaporation of 112 mm, transpiration of 365 mm, and percolation of 186 mm). This finding is of critical importance to applications that must discretize large-scale irrigation schemes into distributary canals (and smaller irrigation units).

One drawback of a numerical approach for evaluating soil and plant behavior is that it may not fully account for impacts of simplifications, assumptions and errors, which are implicitly part of any simulation model, on reducing the population variance and distribution of outcomes. Even the inclusion of generated random error terms in simulated 'observations', often seen as an ultimate solution in many studies for reproducing reality, has limitations. The strict replication of real population variance can only be achieved through the use of real field data. Thus, real remote-sensing data have been used in various inverse-modeling studies as summarized in Table 4.

Table 4. Selected examples of inverse-modeling studies in an irrigation and drainage context

Source	Numerical case	Experimental case	Country	Soil hydraulic properties	Agricultural water management
Tyagi, Sharma, and Luthra (2000)	ET, soil moisture	ET, soil moisture	India	Van Genuchten-Mualem	None
Jhorar et al. (2002)	E, T, ET, soil moisture		India	Van Genuchten-Mualem	None
Jhorar (2002)		ET, groundwater table	India	Soil water-holding capacity Saturated hydraulic conductivity	Groundwater extraction
Ines and Droogers (2002a; 2002b)		ET, soil moisture	India	Van Genuchten-Mualem	Irrigation supply, salinity irrigation water
Droogers and Bastiaanssen (2002)		ET, LAI	Turkey	None	Dates of sowing, irrigation supply, maximum LAI
Droogers (2002)		Groundwater table, ET	The Netherlands	Van Genuchten-Mualem	Forest Parc drainage design
Dorji (2003)		ET, LAI, soil moisture	Portugal	Van Genuchten-Mualem	Irrigation supply

Inverse modeling for solving agricultural and irrigation practices

In an investigation by Droogers and Bastiaanssen (2002), the model swap was used to explore options for improving water management in the Gediz Basin of Western Turkey, where cotton and grape crops cover more than 80% of the study area. One of the limiting factors in the study was the availability of accurate data on soils, planting dates and irrigation delivery schedules. The swap model contains several standard options for automatic irrigation scheduling, including supplying water when relative transpiration (T_{act}/T_{pot}) falls below a predefined threshold (Van Dam et al. 1997). The model automatically computes the timing and amount of water application. Spatial distribution of actual ET from the study area was obtained from the sebal remote-sensing algorithm (Bastiaanssen et al. in print) for two Landsat image dates, and these data were input to the inverse-modeling process for parameter development.

By increasing the standard deviation for the date of emergence from the original 10 days to 30 days, a similar pattern for ET as derived from *sebal* was obtained (Figure 5, bottom). For August 29, the standard deviation in the irrigation criterion (T_{act}/T_{pot}) was increased from 0.1 to 0.2 to obtain more variation in the ET predicted for this day. Simultaneously, an increase in the criterion itself, from 0.80 to 0.95, was made to prevent a decrease in the average predicted ET. Results of the parameter adjustment showed that average irrigation applications were between 400 and 600 mm for the season. The increase in standard deviation of the irrigation-scheduling criterion implied that farmers exhibited more farmer-to-farmer variation in their decision-making with regard to irrigation timing, perhaps due to their inability to demand and receive water when they most desired.

Dorji (2003) used the *swap-sebal* combination to elucidate the water balances and irrigation performances for two large farms in Southern Portugal where crops of grapes, olive, cotton, wheat and maize were irrigated. Similar to studies described earlier, Dorji calibrated the Van Genuchten-Mualem parameters using the *pest* (Doherty, Brebber and Whyte 1994) parameter estimation model against ET observed by *sebal* for three dates during the growing season (Figure 6, see Color pages elsewhere in this book). Dorji applied a first-order estimate of irrigation practices (timing and amounts) based on farmer interviews. Soil physical properties were calibrated based on data for 2001, and subsequently held constant. The irrigation regime was thereafter fitted using *pest* and limited farm records of accumulated flow readings from the drip-irrigation systems from 2002. The result was a calibrated irrigation-scheduling criterion for use in *swap* based on T_{act}/T_{pot}. The calibrated criterion was then compared against a theoretically optimal irrigation regime, and the new irrigation calendar – specified by day number and application depth – was given to the farmers for adapting irrigation attitudes. The advice resulted in an increase in seasonal irrigation applications to grapes from 123 mm to 265 mm, to olives from 125 mm to 213 mm, and to wheat from 147 mm to 165 mm, and to reduce the seasonal applications to maize from 772 mm to 662 mm and to cotton from 407 mm to 354 mm.

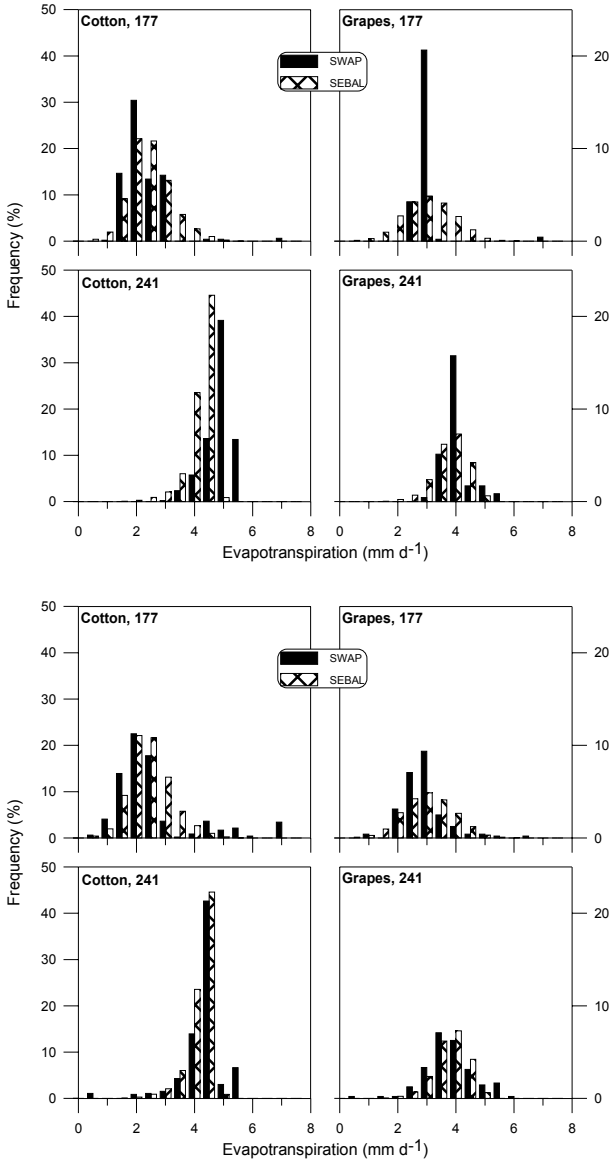

Figure 5. Comparison between modeled (swap) and indirectly observed (sebal) evapotranspiration estimates, before (top) and after (bottom) application of the inverse modeling approach in the Gediz River basin of Western Turkey. The numbers 177 and 241 refer to day numbers

For the Bhakra Irrigation System in the vicinity of Karnal, the spatial distributions for soil characteristics, irrigation practices and salinity of irrigation water were unknown. The *swap* model was applied to and validated for some representative fields, after which the entire irrigation system was modeled (Ines and Droogers 2002a). Comparison between simulated ET and ET derived from remote sensing was used to inversely obtain the spatial distribution of apparent salinity levels of irrigation water. This approach demonstrated clearly the value of inverse modeling and the approach for obtaining 'non-observable data'.

Jhorar (2002) investigated the application of the *faids* unsaturated zone model (Roest, Abdel-Gawad and Abdel-Khalek 1993) to describe the distribution of soil water and salt balance for a 500,000 ha area in the Sirsa District of Haryana State, India. The soil water-holding capacity and the thickness of the unsaturated zone – which are the soil physical parameters required by *faids* – were optimized using the

pest optimization package by comparing against ET fluxes derived from *sebal* using a series of NOAA-AVHRR satellite measurements (National Oceanic Atmospheric Administration – Advanced Very High Resolution Radiometer). For sub-areas where a match with physically realistic soil properties appeared to be unfeasible, unknown tube-well extractions were posed as an explanatory factor. Indeed, groundwater pumping is a common remedy for surface-water shortages in the Sirsa District. Jhorar (2002) used the satellite-based ET estimations and observations of the groundwater table to optimize the prediction of groundwater-pumping rates. This was a highly relevant and valuable exercise, as groundwater exploitation is extremely difficult to quantify from conventional field surveys of individual tube wells (Allen, Morse and Tasumi in print).

In conclusion, inverse modeling and data assimilation are promising techniques to solve for soil parameters and irrigation-system management, and in heterogeneous systems. Obviously, remote sensing, inverse modeling and data assimilation have accelerated data collection substantially because remote sensing can cover scales from 30 m pixels to complete irrigation systems and inverse modeling can efficiently create data sets for large numbers of soil families.

Modeling under data scarce conditions

Table 1 suggests that the model availability is not a limiting factor anymore, whereas data to feed these models in data-scarce environments are now the challenge. A major effort of UNESCO-IHP (PUB Science Steering Group 2003) focused on data-scarcity problems and development of innovative approaches to overcome them (PUB Science Steering Group 2003). One irrigation example and one drainage example are here referred to for simulation modeling under conditions of very limited data to explore options for the future. In Iran, two separate models over different spatial scales were first set up to overcome data limitations. In a second phase the models were jointly applied to construct scenario conditions (see Droogers et al. 2001). The second example is from a forested area in The Netherlands where waterlogging was a severe problem, but no detailed information was available to describe the drainage conditions (Droogers 2002).

Regional application of soil water-balance models

Soil water flow models have limited use in operational irrigation and drainage applications at the farm level. At larger aggregated levels, i.e. communities of farmers, irrigation agencies and advisory services, the required technical capacity and competence are more easily found and here more generic data can be used. However, application of soil water-balance models to composite areas such as regional districts, poses three different challenges: i) collection of data can be costly and time-consuming; ii) models are not suitable to any spatial scale; and iii) spatial variability of model parameters must be correctly represented.

The three challenges are intimately connected. The Richards equation can be applied in a three-dimensional domain of finite elements, once the required data and initial and boundary conditions (and their heterogeneities) have been specified (e.g. Paniconi and Wood 1993). Hence, application of Richards' equation at the pedon scale can be applied in a regional context in a semi-distributed way. In practice, however, this approach is nearly impossible due to the vastness of calculations and the complexity of required data. A viable solution to this dilemma is to consider water flow in the vertical direction only. This assumption can be made when unsaturated conditions prevail over large depth increments in the upper soil in areas having little

terrain slope. The extension to a larger area does not necessarily involve a scaling problem if an irrigation scheme can be schematized as a large set of single columns standing in parallel. This concept of regionalization has been applied in irrigation case studies in Italy (D'Urso, Menenti and Santini 1999) and Turkey (Droogers et al. 2000) by using the one-dimensional *swap* manner in a distributed fashion. It is not uncommon to schematize irrigated systems into (i) surface water distribution, (ii) vertical soil water flow and (iii) lateral groundwater movement (e.g. Querner 1988; Abdel-Gawad et al. 1991; Droogers and Kite 2001). A schematization concept for one-dimensionality is shown in Figure 7.

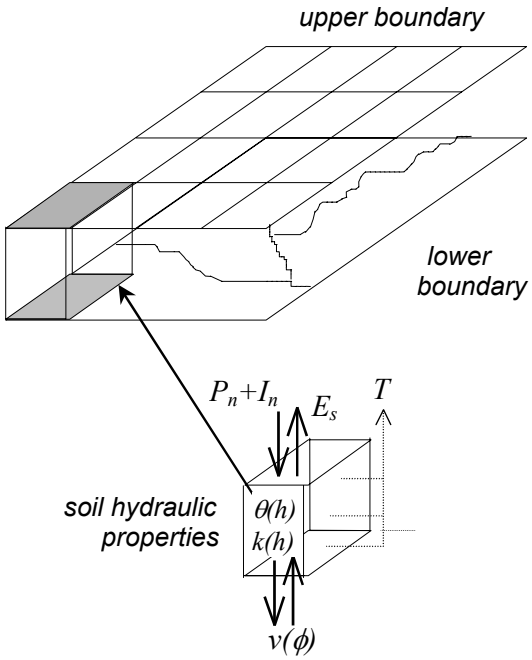

Figure 7. Compartmentalization of a one-dimensional water balance model in terms of a boundary condition problem (after D'Urso, Menenti and Santini 1999)

The upper boundary condition is dominated by the status of vegetation which can vary substantially over short distances (in the order of tens of meters) and within relatively short time frames (from a few days to few weeks). A common way to specify the upper limit for this boundary condition is via the potential water flux through the soil surface. This flux is dependent on the potential rates of transpiration and soil evaporation and on the amount of intercepted water. These quantities are a function of biophysical crop properties and climatic parameters. Remote sensing can be used to derive the spatial distributions of these canopy parameters – in particular the Leaf Area Index (LAI) and the fractional vegetation cover (e.g. Choudhury et al. 1994; Moreno, Menenti and Richter 2002). D'Urso (1999) varied the upper boundary condition in *swap* by applying the Penman-Monteith one-step equation with a minimum canopy resistance (e.g. Allen et al. 1998) and surface albedo derived from satellite data.

The lower boundary represents the exchange fluxes with the underlying groundwater system. The lower boundary has a much coarser variability in space and in time than the upper boundary, but identification of its boundary conditions is, nevertheless, very difficult in many situations. The boundary condition at the *bottom* can be defined in four ways: i) by specifying a value for the pressure head at the bottom; ii) by specifying a constant flux through the bottom; iii) by expressing a variable flux through the bottom as a function of groundwater depth and iv) as free drainage.

The first type of condition is often used when groundwater depth information is available. This type of boundary condition cannot be used in scenario simulations, unless the water-table depth is presumed to remain fixed at the imposed value, i.e. by a well or drainage network that keeps the groundwater table near the drainage base level. The second option may be taken when it is possible to identify an impermeable layer, which forces a 'zero' flux condition, or when the steady-state regional fluxes are known. The schematization of regional-scale irrigation-scheme models utilizes a finite-element groundwater model for the lower boundary condition. It is possible, using a GIS, to define the relationship between the flux and the water-table depth in each cell of the distributed model to be used as the lower boundary condition. In many situations, application of the conditions described result in unrealistic model behavior; often the soil profile is partially saturated at the lower boundary and there is a pronounced flux exchange with the underlying aquifer. The third type of condition was introduced to consider the influence of a drainage system on the soil water flow (Belmans, Wesseling and Feddes 1983) by relating the seepage per unit drained area to the average groundwater depth. For deep water-table conditions, free drainage can be assumed.

Following the population of the distributed model with data and boundary definitions, the spatial distribution of soil water deficit and corresponding irrigation water demands can be estimated. Scenario simulations in a case study in Italy have shown that the performance of an on-demand irrigation system near Naples could be significantly improved by reducing the average amount of water applied at the field level by 20%. If such a strategy were to be adopted by all farmers, the seasonal amount of water demanded by the entire district would be reduced by 6%, releasing important volumes of water to other competing uses.

Calibration problems

The spatial distribution of hydrology in irrigation systems is impacted by the type of irrigation system in place, by crop water use and by the behavior of farmers themselves. Hydrologic and management aspects of irrigation create different challenges during calibration of unsaturated soil water flow models used to: (i) simulate hydrologic processes under controlled conditions; (ii) derive irrigation decision-making processes.

Groundwater-table fluctuations have traditionally been used during calibration of soil water flow under specified drainage conditions. More detailed calibration procedures require well-controlled experiments where incoming water fluxes are measured or known. In the early years of model development, calibration and validation procedures were generally limited to highly specialized laboratories. Often these experiments were done with expensive instrumentation such as lysimeters, gamma rays and neutron probes. During recent years new measurement techniques and cheaper electronic instrumentation have enabled the validation and calibration of unsaturated soil water flow models in the field. At the local scale, the development of Time Domain Reflectometry in the early 1980s greatly expanded the means to monitor soil water content profiles (Topp, Davis and Annan 1980). With the development of simpler TDR-like instrumentations, the observation of soil water dynamics in the field is no longer confined only to research and specialized personnel, but also to lower-level technicians and to farmers. TDR techniques and soil water-potential measurement systems are now widely used to monitor irrigated soils operationally, similar to the use of standard agro-meteorological systems.

Ahmad, Bastiaanssen and Feddes (2002) calibrated the *swap* model in a groundwater recharge study in Recha Doab, Pakistan, by comparing against *in situ* measured soil moisture content at 35 cm depth intervals. They obtained RMSE values of 0.022 cm^3 cm^{-3} and 0.027 cm^3 cm^{-3} for Faisalabad and Pindi Bhattian application areas, respectively. They calibrated certain soil and crop parameters by means of ET fluxes measured by a Bowen ratio energy-balance station. Soil water flow models have been calibrated against measured stratifications of soil electric conductivity by Smets et al. (1997) and Van Dam (2000). Sarwar and Feddes (2000) calibrated *swap* against in situ measurements of soil water potential. The deviation of soil moisture was 0.019 cm^3 cm^{-3} for layers 30 cm thick. Bastiaanssen et al. (1996) calibrated *swap* against 25 cm depth intervals of soil moisture and salinity of an irrigated and drained vineyard near Mendoza, Argentina. The root mean-square errors for moisture and salinity were 0.03 cm^3 cm^{-3} and 1.0 mg cm^{-3}, respectively.

At the present time, research efforts are focusing on determining operational procedures for calibrating and validating soil water flow models applied at the regional scale. The availability of spatial information on agro-hydrological parameters and processes via remote sensing, including surface temperature, ET, dry-matter production, LAI and soil moisture, makes it feasible to apply data assimilation techniques. References are made to Houser et al. (1998), Schulz, Beven and Huwe (1999), Franks and Beven (1999) and Olioso et al. (1999).

The second type of model use relates to calibration procedures required to adapt simulation models to the actual operation of irrigation systems by comparing simulated and measured irrigation depths. In a simulation model, scheduling of irrigation is generally assumed to be dependent on the predicted soil water content and its assumed distribution in the soil profile. Parameters and criteria must be defined for identifying the starting times of applications using soil water-potential values in the root zone. To this end, the *simodis* procedure linking a distributed *swap* and a hydraulic model of the distribution system has been developed (D'Urso 2001; D'Urso and Santini 2002).

In the application of this procedure to the 3,000 ha Gromola Irrigation District in the vicinity of Naples (Southern Italy), the application day and best application volume were identified by comparing measured irrigation-water volumes to simulated values. The analysis indicated that irrigation volumes corresponded to 50% soil water deficit between 10 and 50 cm depths in the soil profile. Irrigation was applied when the soil water pressure was lower than a critical value corresponding to water stress for the specific crop type. As shown in Figure 8, the behavior and the habits of farmers in irrigation practice deviated from simulated daily values at the single field or irrigation unit level. These differences, which can be considered to follow a stochastic pattern, were much reduced when aggregated values in time or space were compared (i.e. for a time interval of one month or by combining irrigation applications of several irrigation units). Olioso et al. (in print) used a SVAT model to define iteratively the irrigation attitudes of farmers in France using remotely-sensed ET fluxes and LAI development as primary variables.

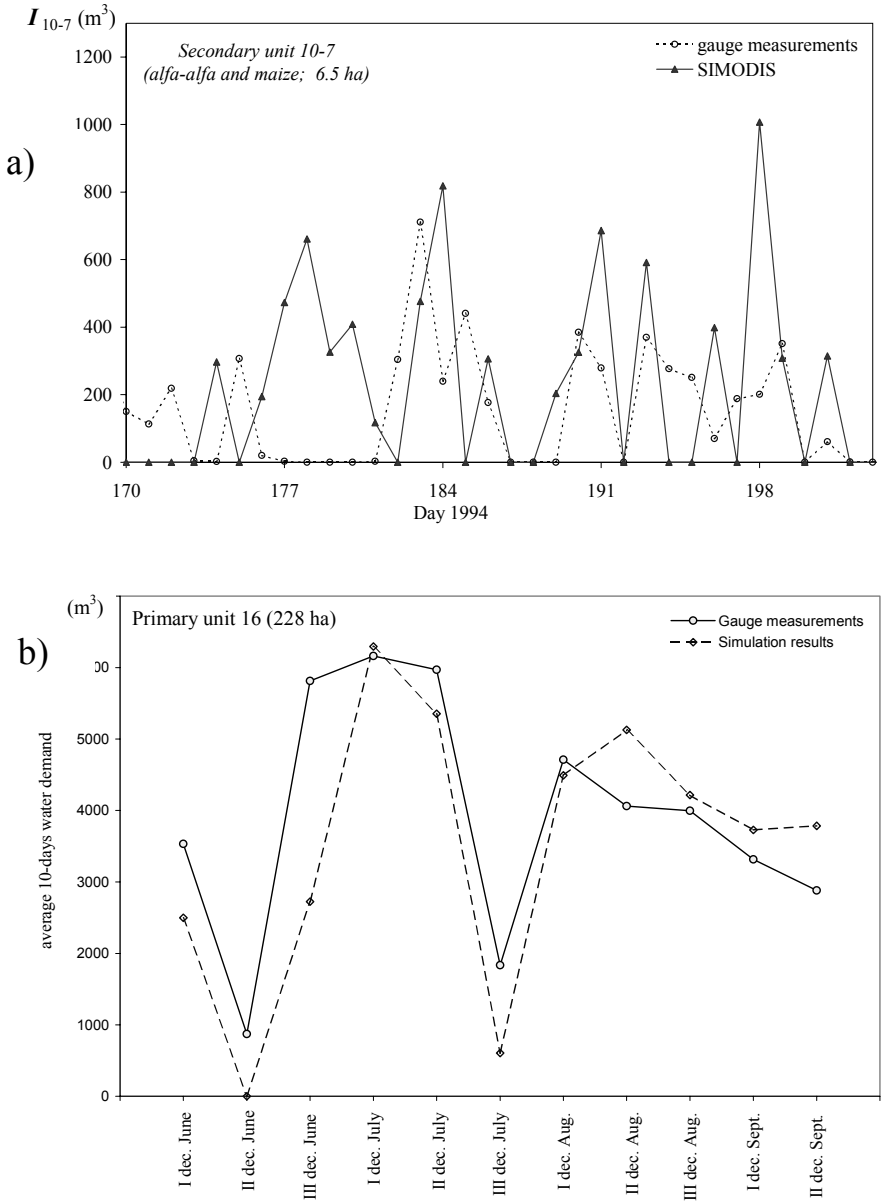

Figure 8. Comparison between simulated and measured irrigation volumes (a) for an irrigation unit of 6.5 ha and (b) for an irrigation sub-district with service area of 228 ha. The cumulative error in the first case is 54%, in the second case -12%

Strengths, Weaknesses, Opportunities and Threats (SWOT) Analysis

Strengths

Despite the fact that water flow in unsaturated soils beneath irrigated crops is highly dynamic due to large variations in infiltration rates and potentially fast sub-surface drainage outflow, advanced computation tools can now predict, with relatively high accuracy, the transient soil moisture and soil salinity profiles. Although computational power of computing systems has for a long time been a serious constraint for the application of advanced models, most countries now have sufficient in-house information technology and capacity. With the ability to describe physical processes more fully, it has become more feasible to quantify current operation conditions of irrigated systems and to assess effects of alternative management

solutions in a deterministic way. Simulation models can be used in conjunction with measurement tools – both *in situ* and via remote sensing, to (inversely) calibrate system properties such as soil properties, irrigation-scheduling patterns, groundwater extractions and dates of planting (see Table 4). Spatially-variable information describing ET, LAI and dry-matter production as derived from remote-sensing techniques (see Figure 4) can be used to populate the stochastic input data for one-dimensional column models across an irrigated region. ET is the major component of the water balance and is an integrator of the processes of the soil–water–plant–atmosphere continuum. Combined sensor–model methodologies have reached sufficient reliability to be applied for strategic evaluation of agricultural water management (see examples of India, Pakistan, Turkey, Iran) and in some cases for routine real-time irrigation scheduling (see example of Italy).

In view of the need of professionals in design and planning for information covering large numbers of processes and outcomes and the associated demand for spatial and temporal data, it would seem that SVAT models supported and driven by large spatial data bases would be a primary vehicle of use.

A strength of unsaturated SVAT models having a diurnal variation in surface fluxes is that they are more suitable for the evaluation of precision irrigation and the ET response and carbon assimilation for time periods in the order of hours, than are daily soil water flow models. The energy balance from SVAT models can be readily coupled with instantaneous ET fluxes derived from remote-sensing data. However, the uncertainties (perceived or real) associated with the various spatial and temporal data required to operate the SVAT models can be daunting, and may increase the appeal of the traditional, single-layer models that rely on simple crop coefficients or on single-layer ET equations. Often the reduced predictive accuracy in both ET and crop yield by simpler models is considered to be adequate when compared to their reduced data requirements.

The primary attraction to using simulation techniques lies in the possibility of varying one or more parameters and evaluating the results. Unsaturated soil water flow models form the core of decision-support systems for irrigation management at both local and regional scales. Simulation of different scenarios representing alternative water resource management criteria makes it possible to identify which strategy best matches project objectives.

The wide range of available models presents an almost luxurious situation for users during the selection of a tool for a specific application. Customers are, however, rarely guided during their selection process, and frequently select the wrong model, resulting in poor satisfaction in the end. For example, an agronomist may derive more benefit from a SVAT model containing detailed carbon assimilation than from a solute transport model. A ‘one-stop shop’ type of repository on the World-Wide Web supported with expert assistance by the international user community could facilitate the exchange of experience and provide guidance to new users.

Weaknesses

In contrast with the definition of upper boundary conditions in models, the description of lower boundary conditions for soil water flow has not progressed far enough. The largest weakness in unsaturated flow modeling is that models are often over-parameterized. The number of soil and plant parameters is often too high to permit obtaining a robust fit, and the solution of the calibrated parameter set is often non-unique. Considerable expertise is required to assess the type and amount of parameters that can be fixed *a priori*, and which parameters can be calibrated through

numerical optimization. If a particular model cannot fulfill certain calibration criteria (see for instance Metselaar (1999) for a method to quantify predictive quality), one should select a simpler model. The application of the most advanced irrigation and drainage models is only useful if sufficient *in situ* or remote-sensing data are available to calibrate them.

The larger impediment to application of soil-water computer models is that most applications in planning and design must look at a larger time and space horizon than a single simulation and outcome. They must consider soil flow and cropping processes in many fields over multi-year periods and under management of many users. Besides, differences in crop development occur among populations of even the same crop variety (e.g. Tasumi et al. in press-a).

Other modeling weaknesses involve hindrances to widespread model application, which were listed in the Introduction. The primary hindrances are i) steep learning curves for model theory, model operation and data assembly; ii) potential enormity of assembling spatially-variable data for large areas; and iii) difficulty in documenting and/or simulating farmer behavior, particularly with regard to actual timing and depth of water application. A fourth hindrance is the large uncertainty regarding knowledge of the population variances for characteristics of soils, vegetation, irrigation system and management, and corresponding uncertainty regarding the sufficiency of descriptions. However, as shown in earlier sections, inverse modeling can provide much insight into the appropriate degree of variability to build into parameters, especially when the modeling process is driven by remotely-sensed data for environments that are data-scarce.

Assumptions in the expected spatial variability may induce sufficient uncertainty in outputs of advanced models to reduce their applicability to the management under consideration. Simplified models, having fewer assumptions, may provide a comparable degree of certainty, but with less effort. An appropriate model configuration in terms of *structure*, *parameters* and *complexity* is required to advocate the more advanced model. Spatial variabilities in soil characteristics may call for different configuration set-ups of the model and consequently leave the debate open on which suite of model configurations to be used, depending on the conditions experienced. In order to promote the advanced model, the expected accuracies in its use under the different boundary and working conditions must be established.

It is difficult to afix '*cost–benefit*' values to the use of simulation tools within the context of irrigation systems. The implementation of these tools within real-time irrigation processes is considered to be feasible for high-value crops and high cost for irrigation water. Presently, however, irrigation water is not yet fully regarded as an economic good, even in areas with serious water scarcity.

Opportunities

Irrigation-water policymakers must accept the paradigm shift from managing abundant water supplies (with the focus on conveyance and distribution systems) to beneficial use of scarce water resources (with the emphasis on deficit irrigation, sustainable groundwater exploitation and crop water productivity). With the availability of new technology and a better understanding of the physical processes involved in the different components of irrigation systems, we can now describe the operation of such systems in an integrated, deterministic way. These methodologies have reached a sufficient degree of reliability to be utilized in practical applications. The availability of high-capacity and high-speed computing systems and high-speed

internet has made access to data bases, remotely-sensed data, software and experts possible at nearly all locations around the globe.

The main attractiveness in using simulation techniques lies in the possibility of tuning one or more management variables and evaluating the results. Unsaturated soil water flow models should represent the core of decision-support systems for irrigation management at both the local and regional scale. Simulating different scenarios representing alternative water resource management criteria makes it possible to identify which strategy best improves the level of satisfaction for all stakeholders. Simulation of a range of scenarios can derive quantitative information, i.e., water productivity and efficiency fractions, that can be used to assess priority criteria for irrigation management under water scarcity.

Considering the huge world-wide water management problems, one can conclude that socio-technical analyses and technology-based policy-making, in regard to implementation of water conservation and sustainable groundwater exploitation, are in their infancy and must grow. There is great opportunity for the scientific and commercial irrigation- and drainage-modeling profession to demonstrate how far the science has progressed and how to find optimal solutions with the various tools that are available. The development and improvement of methods for technology transfer from the research environment to the policy and management environment – especially between centers of research and potential users in developing countries – is crucial. Modeling studies showing impacts of water shortage on livelihood and identification of the best possible solutions, such as recently demonstrated by Alcamo et al. (2003), must become commonplace within the planning process at basin, scheme and water-user association levels.

A second opportunity is to participate in the development of electronic modeling plazas that contain guides for model selection and directions for obtaining more information; not only on the supply side of the chain, but also on good application practice. The unsaturated-zone hydrologic model as a strategic instrument for planning, design, operation and management needs to be better marketed. The groundwater-modeling community is in this sense better organized and has general information centers with web sites (e.g. http://www.mines.edu/igwmc/) that provide a broad range of illustrations of applied model studies by consultants.

Irrigation can impact the livelihoods of poor people in many ways. These include not only direct impacts on income, expenditures and nutrition, but also other dimensions that poor people themselves perceive as important aspects of poverty, including vulnerability to economic downturns, limited access to resources and social capital and the deprivation of status that comes from being informed and included in decision-making. It is unthinkable what the community situation would be in the Indus Plain or Nile Delta without irrigation systems in place. Prosperity also spread over the population of the Amu-Darya Delta when the Russians introduced large-scale irrigation systems. The same Amu-Darya Delta now illustrates that populations living in the lower reaches of irrigated river basins are vulnerable to poor water management upstream and the experience of adverse effects of water scarcity and low irrigation efficiencies. All in all, there is hope for poor men and women in improving livelihoods when irrigation and environmental systems both receive equal attention.

Threats

Tremendous effort must be invested to close the huge gap between complex expert systems in place in Western universities and research organizations and the application of these tools to irrigation and drainage systems in poor and water-short

countries. There is a steep learning curve for many of the deterministic models, and the duration of the learning and adoption process is expressed more in years than in months. This accessibility distance together with a lack of social-technical field data by which to populate soil water flow models is a direct hindrance to the operation of these technologies. A workable solution is one that will establish (or re-establish) extensive training programs and develop long-term relationships between model developers, modelers and recipient irrigation countries having few resources.

Apart from the economic-political problem, the threshold for initiating an extensive model application can be high and taxing, as in many cases a personal relationship with the model developer must be cultivated to support and facilitate the local implementation of the technology. There is little public support for obtaining self-reliance in the field of unsaturated-zone modeling. If model developers in universities do not work to change these requirements and 'ceilings', they may continue to create products primarily for their own satisfaction. The challenge nowadays is to make soil water flow models more versatile for different social-economic-physical conditions and for environments having poor or limited data availability. Otherwise, the irrigation and drainage community will continue to largely ignore some relatively powerful tools due to the high application threshold. The threat caused by mismatching model supply and model demand is real (see Figure 9), and efforts are necessary to increase implementation through international workshops and symposia. A primary threat to closing the gap between developer and user, however, is that those who devote time and effort to improving model implementation are not rewarded and valued to the same extent as those who develop the models.

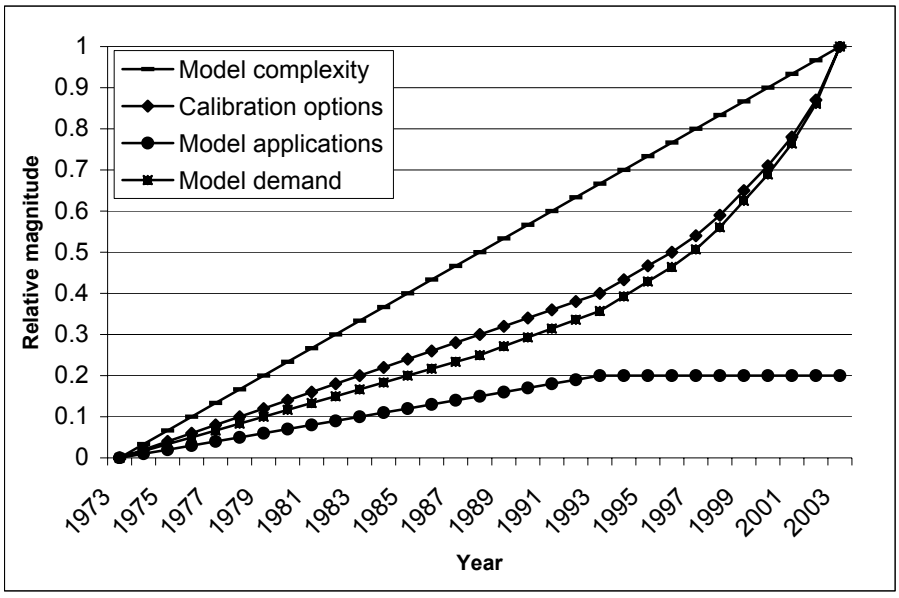

Figure 9. Historic evolution in the science and application of irrigation and drainage systems modeling on the basis of expert judgment of the authors. Model demand describes the need for numerical models and the applications reflect the number of studies executed

Conclusions

Models have progressed through advances in mathematics, science, and computer and information technology towards more accurate solution of increasingly complex equations, interactions between system parameters and difficult boundary conditions. Technical advances include more rigorous treatment of soil water flow, soil heat transport, solute and pesticide movement, energy fluxes, CO_2 assimilation and subsurface drainage, as well as the many interactions. The technical advances represent a major achievement. Modern models can simulate the performance of various irrigation and drainage designs and scenarios over long periods of time according to social and cultural traditions and needs, and can evaluate specified objective functions such as conserving water resources, tempering groundwater pumping, increasing crop water productivity and preserving the environment.

In the brief overview represented in this paper we have highlighted how existing knowledge and methodologies can favorably impact the application of unsaturated soil water flow models to the analysis of drainage and irrigation problems. If technicians and managers of irrigation and drainage agencies are encouraged to follow this application track, they may become more motivated to monitor and better measure disposition of water within their systems. In other words, they will learn, in a more objective and quantitative way, how their system works. The benefits will be an immediate positive feed-back to management, where subjective perceptions that currently govern decisions in irrigation and drainage problems both at field and regional scales are replaced by a 'measurement mentality' followed by a 'modeling mentality'.

The authors feel that model development – except for SVAT models – has reached a sufficient level at the beginning of the 21st century that more and better models are no longer an issue. Most theories in irrigation and drainage have been programmed into numerical codes. A wide spectrum of numerical models of the unsaturated zone are now available (see Table 1), and efforts should focus on making these models trustworthy and easy to use by outsiders who have critical attitudes toward purely technical solutions. Tremendous opportunities exist for model applications within social and economic studies that attempt to describe and improve the interaction between rural development, institutional arrangements, hydrology, decision-makers and livelihoods. The analytical descriptions required by social and technical evaluations can be greatly supported by appropriately calibrated models. Because water is a public and economic good that affects us all, it is unacceptable for any of us to ignore the potential and benefit of modeling applications to the irrigation sector. The irrigation and drainage-engineering profession must work more closely with the academic hydrologists, economists, sociologists and policymakers to establish this goal.

Good examples of utilizing numerical simulation models to solve complex issues exist (see for instance Table 3), but the overall track record of implementation during the last 25 years is poor. The rural communities' indigenous knowledge is often more finely tuned to the local conditions than is a numerical model. Nevertheless, the anticipated changes required for managing future scarce and expensive water resources cannot be determined using common sense alone, and the technical capacity for optimal solutions will become a necessity. Expectations of irrigation as a business will soon rank high on international political agendas, and models must be versatile enough and ready to answer questions concerning complicated optimization solutions

that contribute to the production of more food from smaller portions of the water resource, thereby enhancing human welfare in the poorer rural societies of this world.

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