Irrig Sci (2000) 19: 139–145

ORIGINAL PAPER

Peter Droogers · Geoff Kite · Hammond Murray-Rust

Use of simulation models to evaluate irrigation performance including water productivity, risk and system analyses

Received: 3 June 1999

Abstract Worsening water scarcity will increase pressure to use water more productively. In the classical view of irrigation research, some important aspects are often ignored: the total water balance approach, productivity of water, food security, and irrigation-system level analyses. These four approaches were evaluated using a detailed agro-hydrological model applied to an irrigation system in western Turkey. Emphasis was placed on the two dominant crops in the area: cotton and grapes. According to the classical point of view, the only result would be to irrigate the cotton with 1000 mm and the grapes with 800 mm. From the water productivity point of view, however, the water productivity of grapes appeared to be maximal without any irrigation; while for the cotton, irrigation at 600 mm maximizes water productivity. To minimize risks and increase yield stability, grapes perform better than cotton. Finally, from the irrigation system point of view, decisions can be made about the desirable cropping pattern and the distribution of water between crops. With limited amounts of water available for irrigation, a cropping pattern consisting mainly of grapes is desired; while with higher water availability, a mixture of cotton and grapes is preferable. The methods presented provide a clear methodology with which to achieve the most productive use of water.

Introduction

Water scarcity is and will continue to be a real threat to millions of people in arid and semi-arid areas. Growing populations and an expected higher standard of living will increase the demand for water dramatically in the near future. As irrigation is a large consumer of water resources, much effort will be put into finding a more productive use of this resource. Traditionally, research has focussed on irrigation–yield relationships, referred to here as the 'classical approach'. Although it is known that this 'classical approach' has serious short comings, much research is still done in this way and many papers are still published describing field experiments where the irrigation–yield relationship was studied on small plots (e.g., Camp et al. 1996; Saeed and El-Nadi 1998). Despite the valuable and applicable results of these experiments, especially in conditions where water is not yet a serious constraint, some important aspects are ignored in these studies.

First of all, these experiments often focus only on the amount of water applied by irrigation, ignoring other important water sources such as rainwater, capillary rise and depletion of groundwater. Only an approach that includes all aspects of the water balance is able to derive real water-saving measures. The apparent local water savings and real water savings are referred to as 'dry' vs 'wet' water savings by Seckler (1996).

Secondly, attempting to attain the highest yield is not the same as attempting to achieve the highest productivity of water expressed as the yield per unit volume of water. Molden (1997) advocates a water-use analysis based on productivity of water consumed, instead of on yield. Recently, a set of performance indicators have been developed that can be used to analyze the productivity of water with a few simple calculations (e.g. Molden 1997; Molden et al. 1998). These indicators were developed to replace the classical efficiencies used in irrigation engineering.

A third aspect which is often neglected is variation in yields and associated risks. Irrigation recommendations are often based on field trials performed over a limited period of time, ignoring any temporal variability. In terms of food security, achieving a long-term average lower yield, while keeping the associated risks lower, might be preferable to a somewhat higher long-term yield with high between-years variation. This is especially true for developing countries where no buffer

P. Droogers (✉) · G. Kite · H. Murray-Rust
International Water Management Institute, PO Box 2075,
Colombo, Sri Lanka
e-mail: p.droogers@cgiar.org
Tel.: +94-1-867404; Fax: +94-1-866854

exists in terms of food or money in case of a less productive year.

Finally, at the irrigation system level, two important issues must be considered: what will be the most productive cropping pattern and what will be the most productive distribution of water between the different crops.

Simulation models are an attractive tool for overcoming these problems, as all terms of the water balance are evaluated and long-term simulations can be performed easily. Nowadays, a broad range of well-tested models exists with different degrees of physical realism and spatial resolution (Camase 1996).

To investigate the problems described earlier, long-term simulations were performed using a physically based model for the unsaturated–saturated zone of an irrigated area in western Turkey. In this irrigation system, a shift in cropping pattern from cotton to grapes has been observed. A simulation model was used to analyze the effects of this shift, taking into account the four points already mentioned: (1) the total water balance approach, (2) productivity of water, (3) risk, and (4) system-wide analyses.

Materials and methods

Study area

Menemen Left Bank (MLB) irrigation system is located at the tail end of the river Gediz in western Turkey and extends over an area of 16 500 ha (Fig. 1). Soils are mainly alluvial deposits. Average annual temperature is 17 °C and average precipitation is 510 mm. The main crops are cotton and grapes and, to a lesser extent, orchards, cereals and vegetables. There is a tendency in the basin for a shift in cropping patterns, with an increase in grape cultivation at the expense of cotton. This shift appears to be related to a decrease in water availability for irrigation after a severe drought which started in 1989 (Fig. 2). Recently, climatic conditions have improved and simultaneously a small increase in the cotton area can be observed.

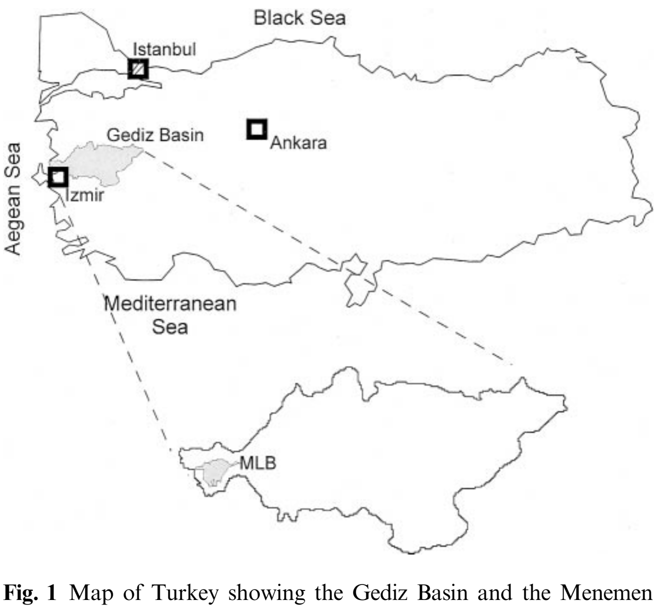


Fig. 1 Map of Turkey showing the Gediz Basin and the Menemen Left Bank (*MLB*) irrigation scheme

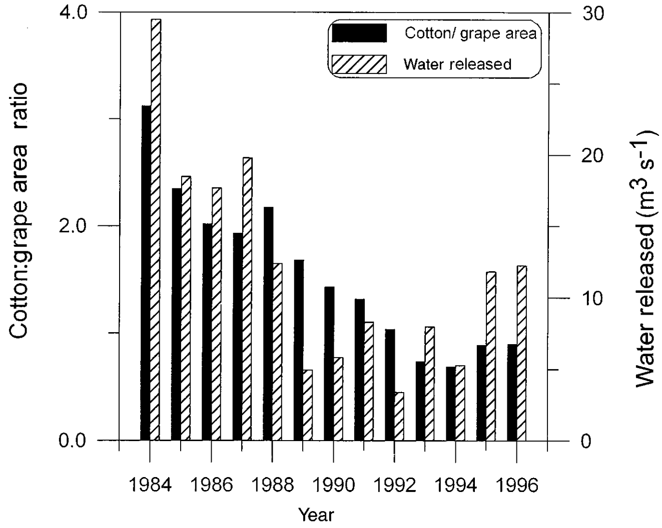


Fig. 2 Relationship between water released from the main reservoir (m^3 s^{-1}) and the ratio between cotton area and grape growing area

Irrigation was mainly applied by using surface water, originating from the main reservoir in the basin. As a result of a severe drought in the upstream part of the basin prior to 1989, releases of water dropped substantially. Farmers started to drill wells, resulting in a mixed groundwater–surface water irrigation system. In recent years climatic conditions have recovered, resulting in an increase in water delivered for irrigation purposes.

Simulation model

The hydrological analyses were performed using the SWAP 2.0 model (Van Dam et al. 1997). SWAP is a one-dimensional, physically based model for water, heat and solute transport in the saturated and unsaturated zones, and also includes modules for simulating irrigation practices and crop growth. For this specific study, only the water transport and crop growth modules were used. The water transport module in SWAP is based on the well-known Richards' equation, which is a combination of Darcy's law and the continuity equation. A finite difference solution scheme was used to solve Richards' equation.

Crop yields can be computed using a simplified crop growth algorithm based on that of Doorenbos and Kassam (1979) or by using a detailed crop growth simulation module that partitions the carbohydrates produced between the different parts of the plant as a function of the different phenological stages of the plant (Van Diepen et al. 1989). In this specific case, the first method was applied as detailed crop measurements were not available. Potential evapotranspiration is partitioned into potential soil evaporation and crop transpiration using the leaf area index. Actual transpiration and evaporation are obtained as a function of the available soil water in the top layer or the root zone for soil evaporation and crop transpiration, respectively. Finally, irrigation can be prescribed at fixed times, scheduled according to different criteria, or by using a combination of both. A detailed description of the model and all its components is beyond the scope of this paper, but can be found in Van Dam et al. (1997). A practical application of the model to analyze the effects of drought on an irrigation system in the same basin is given by Droogers et al. (2000).

Input data

Daily meteorological data were obtained from a station located in the irrigated area. Annual average rainfall over the last 30 years was 510 mm, and ranged from 334 mm in 1992 to 731 mm in 1981. Over the last 10 years the average annual rainfall was 50 mm below the long-term annual mean. Average annual temperature is 17 °C and shows little year-to-year variation. Average temperatures in January and July are 8 °C and 26 °C, respectively.

A period of 30 years was used in the analyses, assuming that these 30 years represent stable weather conditions. This allows the possibility of analyzing results in terms of frequencies rather than in fixed values. Such an approach has already been used successfully to estimate the risk of nitrogen leaching to the groundwater (Droogers and Bouma 1997).

Daily potential evapotranspiration was calculated using the Penman-Monteith approach (Monteith 1981). Instead of using crop factors (Doorenbos and Pruitt 1977) to account for differences in soil cover and crop development stage, a more physically based approach was used. Three reference evapotranspirations were calculated: wet crop completely covering the soil, dry crop completely covering the soil and bare wet soil. Using different values for canopy resistance, crop height and albedo in the Penman-Monteith equation, maximum possible evaporative fluxes were computed. The leaf area index and canopy storage were then used to determine the weight of each of the three reference evapotranspiration terms in the total reference evapotranspiration. Actual evapotranspiration was then simulated depending on the soil moisture status of the root zone. Details of this method are given by Van Dam et al. (1997).

The most common crops in the area, cotton and grapes, were included in the analyses. As detailed crop growth measurements would be required in order to apply a sophisticated crop growth model, we chose to apply the more general model as described by Doorenbos and Kassam (1979), despite its known drawbacks for some specific cases. Input data for this approach for the two crops considered are given in Table 1. The maximum potential obtainable yields are specified using local knowledge from farmers and extension services and this is defined as the maximum yield if no limitations, such as water stress, fertilizer, pests and diseases, occur.

Soil data were obtained from a 1:200 000 soil map of the entire Gediz Basin (Topraksu 1974). The main area is covered by alluvial soils that were formed from deposits by streams. They have a medium texture, good drainage conditions, and are very productive. A representative profile was taken and, for each horizon, texture, bulk density and organic matter content were derived in the laboratory (Topraksu 1974). For simulation purposes, soil hydraulic functions, water retention and hydraulic conductivity properties are required. Pedo-transfer functions can be used to derive these difficult-to-measure soil hydraulic functions from easily obtainable data such as texture and bulk density (Tietje and Tapkenhinrichs 1993). Recently, Wösten et al. (1998) developed a set of pedo-transfer functions using a comprehensive soil database including data from 4030 horizons. These pedo-transfer functions were used to obtain the soil hydraulic properties required.

Results

Classical view

In the more classical way of evaluating the results, only the relationship between irrigation inputs and yields is considered. Average simulated yields, using the period of 30 years of climatic data, were calculated for irrigation inputs between 0 and 1400 mm. Obviously, a clear relationship between the amount of water applied as irrigation and crop yields exists for both cotton and grapes (Fig. 3, top). When no irrigation is applied, grape yields are much higher than those for cotton. At very high irrigation inputs, grape yields are still higher than those of cotton, as the maximum obtainable yield is higher for grapes (5000 vs 4000 kg ha^{-1}). Increasing the irrigation amount above 600 mm has almost no effect on grape yields, and irrigation inputs higher than 1000 mm

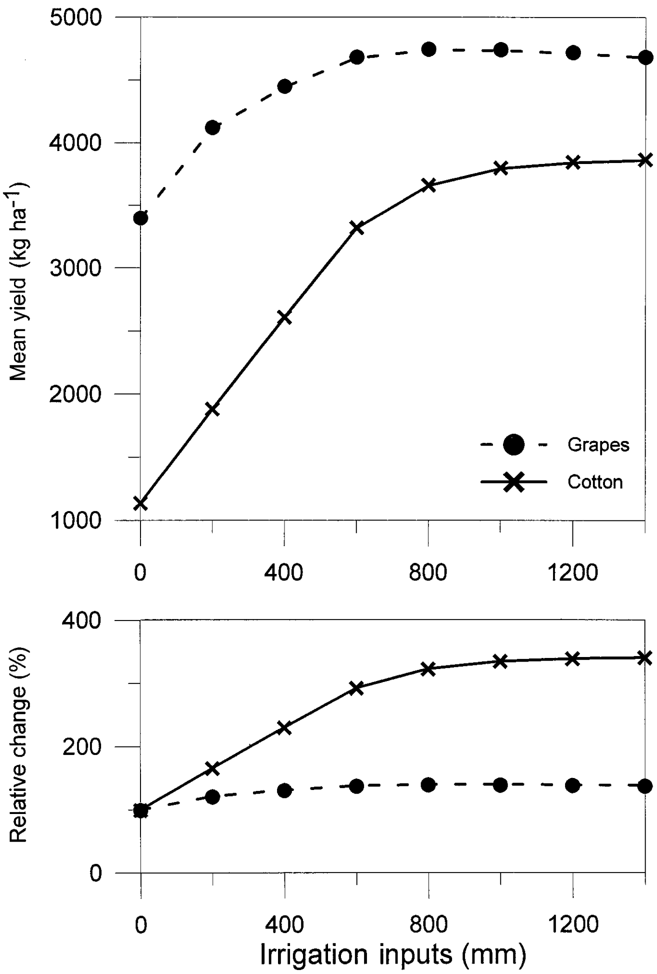


Fig. 3 Crop responses on irrigation inputs given as means over a period of 30 years of weather records

Table 1 Yield response factors (k_y) from Doorenbos and Kassam (1979) and length of development stages (days) from local information

Crop	Start of growing season	Development stage (length (d) | k_y)					Days	Harvest date	Maximum rooting depth (cm)	Maximum yield (kg ha^{-1})
		1	2	3	4	5				
Cotton	1 May	15 | 0.2	35 | 0.2	40 | 0.5	40 | 0.5	20 | 0.3	150	1 October	60	4000
Grapes	1 March	10 | 0.2	30 | 0.5	45 | 0.8	70 | 0.2	45 | 0.2	210	1 October	200	5000

will even decrease these yields as a result of waterlogging.

The responses of the two crops to an increase in irrigation are quite different. In Figure 3 (bottom) this increase in irrigation inputs is plotted against the increase in yields in percentages. In the transition zone between low and high irrigation inputs, cotton benefits more than grapes from an increase in irrigation.

These differences between grapes and cotton originate from different crop characteristics interacting in a complex soil–water–plant system. Grape roots are deeper, inducing a higher capillary flux from the groundwater into the root zone. The shallower rooting system of cotton allows a quicker response to an irrigation event. The sensitivity to drought is different at similar growing stages for the two crops and also the total length of the growing season is different. The characteristics determining the evaporative demand, such as crop duration, crop resistance, albedo and leaf area index, are also different. All these differences interact with each other and are taken into account in the SWAP model.

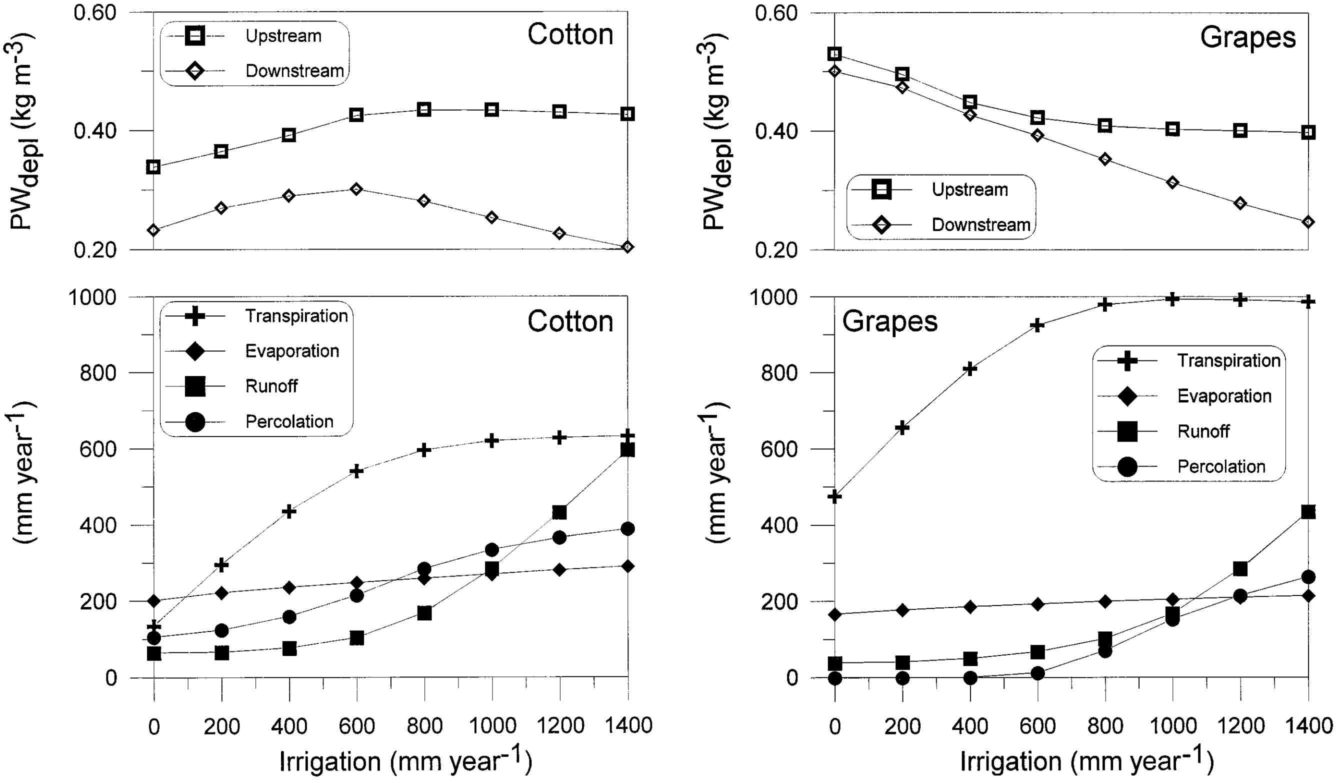
Water productivity view

As emphasized earlier, analyzing the effects of irrigation water alone on yields is not appropriate, as other water sources must also be included. The productivity of water, expressed here in terms of yield per amount of water depleted (PW_{depl}), was calculated following Molden (1997). The amount of water depleted depends on the location of the fields considered. For upstream areas the amount of water depleted is only the amount of evapotranspiration, as water 'losses' by runoff and percolation can be reused by downstream users. On the other hand, these water losses by runoff and percolation for downstream users should be considered as real losses.

The four terms of the water balance relevant to the calculation of the PW_{depl}, as well as the PW_{depl} itself for downstream and upstream situations, are displayed in Fig. 4. The general pattern for the water balance terms is similar for cotton and grapes: an increasing amount of irrigation inputs increases all the depletion factors. For cotton, soil evaporation, runoff and percolation are somewhat higher, while crop transpiration is considerably higher for grapes.

The resulting PW_{depl} shows large differences between cotton and grapes (Fig. 4 top). For cotton the most productive use of water is reached with about 600 mm of irrigation. Although the amount of depleted water increases, yields increase more at this level of irrigation application, resulting in a higher productivity. Higher application rates will hardly reduce the productivity for upstream situations as this will mainly effect the amount of depleted water that can be reused by other users. For grapes a zero irrigation application is the most profitable in terms of productive use of water. Increasing irrigation

Fig. 4 Productivity of water per amount of water depleted (*PW_{depl}*) for (left) cotton and (right) grapes for a downstream and an upstream situation. *At the bottom* the four terms of the water balance relevant to depletion are shown



applications increases the yield, but depletion is proportionally greater.

Yield stability view

In terms of food security, or in this case with cash-crops 'yield stability', variations in expected yields must be considered. By applying the model for a historical climatic series of 30 years, probability analyses were performed assuming that this historical range represents future weather conditions in the short term. Figure 5 shows, for the two crops considered, the expected yields with their associated probability at various irrigation inputs. Clearly, variation in yields is higher for cotton than for grapes.

From Fig. 5 some distinct points were extracted and inserted in Table 2 to show the use of these figures. For example for cotton, the chance of obtaining 50% of potential yield is only 32% with an irrigation application of 200 mm per year, while for grapes this is 100%. Applying 600 mm of irrigation the chance of obtaining 90% of potential yield is 24% and 93% for cotton and grapes respectively. Clearly, grapes guarantee higher yield stability than cotton.

Irrigation system view

For an irrigation system as a whole, the question arises as to what the appropriate cropping pattern is, given a certain amount of water available. In this case cotton and grapes were compared in terms of growing area as well as irrigation distribution between the two crops. As a distinguishing factor the relative yield, defined as actual over potential yield, was used. In other words, if, for example, on average 600 mm of irrigation water is available, what is the optimum area for cotton and for grapes and what is the optimum distribution of this 600 mm between the two crops.

In Fig. 6 these relationships are plotted for different amounts of water available for irrigation. Obviously, some combinations of area and irrigation applications are impossible. For example if an average amount of 200 mm water is available and 60% of the area is covered by cotton, applying 600 mm on this 60% is impossible. In this case a maximum amount of $200/0.6 = 333$ mm can be applied, leaving no water for the grape area. On the other hand, a practical constraint is that no more than 1400 mm of water can be applied. For example if 1200 mm of water is available for irrigation and there is a cotton area of 60% an application of 600 mm on the cotton is impossible. The grapes must receive in this case $(1200 - 600 \times 0.6)/0.4 = 2100$ mm which is higher than the threshold value of 1400 mm.

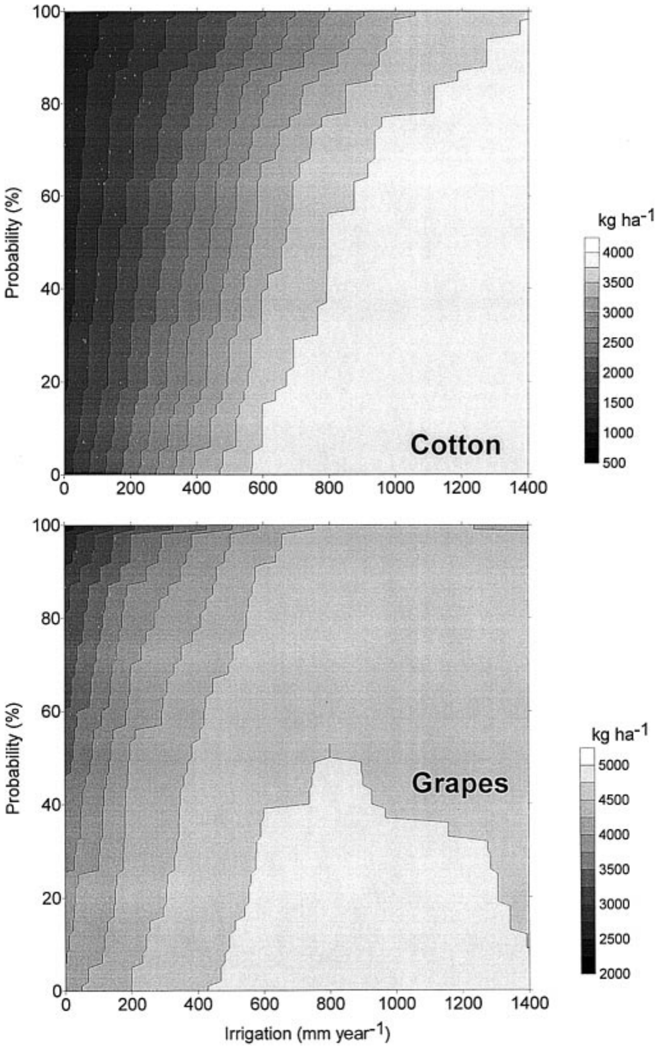


Fig. 5 Expected yields of cotton and grapes with their associated probability for different irrigation inputs

Table 2 Probability (%) of obtaining a specified amount of yield for different irrigation applications to cotton and grapes. Y_{act}/Y_{pot} is the amount of actual over potential yield

Irrigation (mm)	Cotton			Grapes		
	Y_{act}/Y_{pot}			Y_{act}/Y_{pot}		
	50%	75%	90%	50%	75%	90%
200	32	0	0	100	86	12
400	95	15	0	100	100	41
600	100	79	24	100	100	93
800	100	99	59	100	100	100

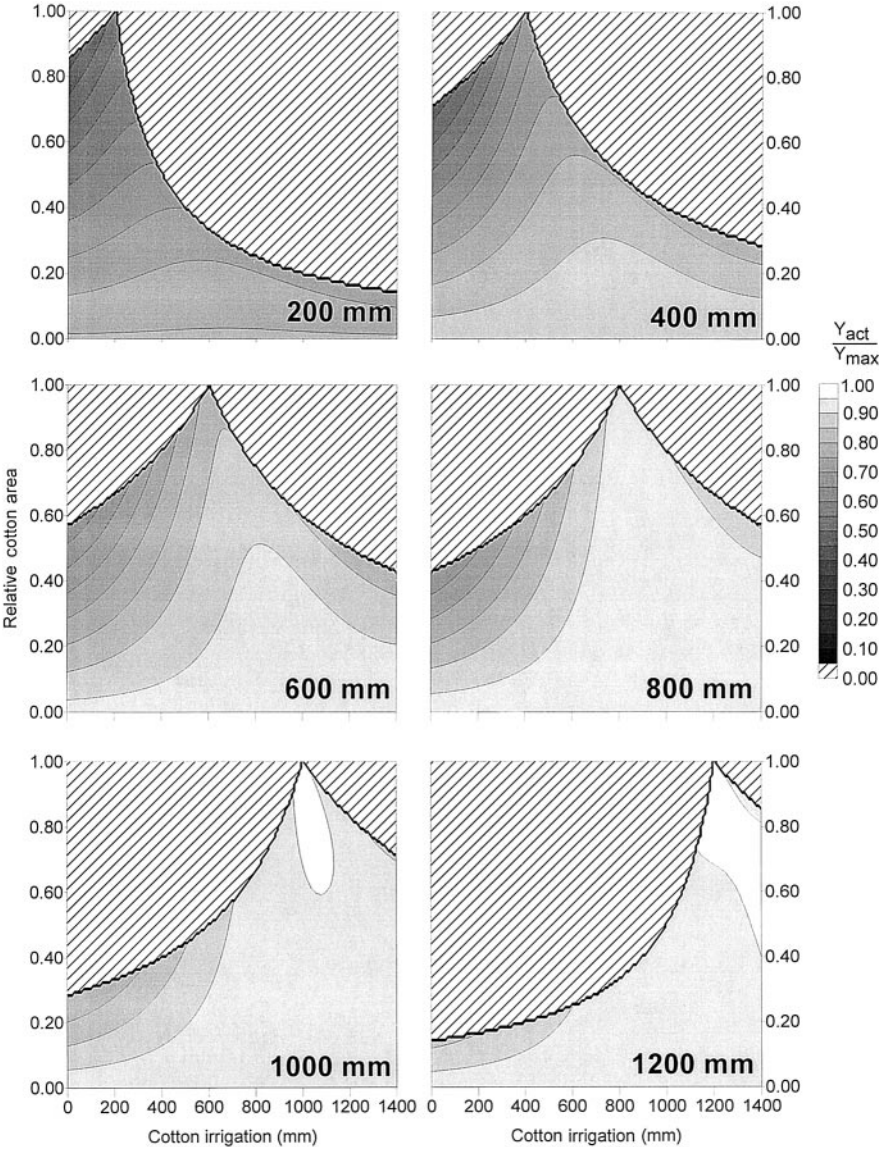


Fig. 6 Expected total relative yields for different combinations of cotton–grape areas and irrigations. *Hatched areas* indicate impossible combinations

Figure 6 can be used for several purposes. In existing situations, where cropping patterns are known and a limited amount of water is available for irrigation, the distribution of this water can be optimized. In conditions with a limited amount of water available, irrigation must be applied in favor of grapes. If water availability is higher than 800 mm, water must be distributed evenly between the two crops or at exceptionally high values, more water must be delivered to cotton.

If the amount of irrigation water is fixed, a deliberate decision can be made about the optimal cropping pattern. From Fig. 6 it is obvious that at low levels of water availability a cropping pattern with mainly grapes is preferable, while at higher levels a mixture is better.

Discussion and conclusions

From the four points of view described above, some clear conclusions can be drawn. From the classical point of view, only statements about the crop water requirements for the different crops would be made. In this case it would be advisable to irrigate grapes with about 800 mm and cotton with 1000 mm. The results can also be used to predict the average yield given a certain amount of water available for irrigation. The results clearly indicate that if water is limiting, cotton benefits more from water than grapes. An advantage of using models to estimate crop water requirements over the more traditional field experiments is that the results presented here represent an average over 30 years of climatic conditions, instead of merely the few years that would be normally considered in field experiments.

The water productivity view shows that zero irrigation should be considered as the most productive use of water for grapes with about 0.5 kg grapes produced per m^3 of water depleted. For cotton a completely different situation pertains, where the most productive use of water is reached with about 600 mm of irrigation. Situations with lower irrigation inputs are less productive.

This figure is close to the water requirements as considered from the classical view. The differences between upstream and downstream-located areas are only relevant with higher irrigation applications for grapes, while for cotton the PW_{depl} is distinct for all irrigation inputs.

The water productivity figures are based on annual depletions and not on irrigation season values alone. The latter can be considered as a more classical approach, ignoring water sources other than irrigation. The extent to which outside irrigation season water can be managed, depends on the specific conditions in the area studied. A basin approach is necessary to evaluate this (Droogers and Kite 1999). In this case, farmers have adapted to this outside irrigation season water by shifting from cotton to grapes, and thus increasing the use of available soil moisture due to the deeper rooting system of grapes.

In terms of yield stability the message is clear; grapes are preferable to cotton for the whole range of possible irrigation inputs. The use of relative yields is an attractive way of analyzing this yield stability. The results of these analyses can be extended with by the use of an economic analysis; in order to change from looking at yield stability to assessing income stability. Such an analysis is beyond the scope of this paper.

Finally, the irrigation system view can be considered as a management tool to make decisions about the desirable cropping pattern and distribution of water for a particular amount of water available for irrigation. With limited amounts of water available for irrigation, a cropping pattern mainly of grapes is desired, while with greater water availability a mixture of cotton and grapes is preferable.

Putting all these views together, the general conclusion can be drawn that with a limited amount of water availability, grapes are advantageous over cotton: yields are higher, productivity of water is higher, and income stability is more secure. If more water is available, a mixture of cotton and grapes is advantageous and the results in Fig. 6 can be used to estimate the optimal cropping pattern and water distribution.

The economics and profitability analyses of the two crops are beyond the scope of this study, but can be deduced relatively easily using the results presented here (see Ray and Gül 2000). Other topics ignored in this study, such as additional water requirements for leaching to avoid salinity, soil fertility and diseases, were not relevant for this specific case. Winter rains are sufficient for flushing salts and farmers apply fertilizers and pesticides to avoid problems with soil fertility and diseases. However, in cases where these topics are relevant, they can be included in the models and the same analyses as described here can be applied.

Acknowledgments This study was conducted as part of a collaborative research program between the General Directorate of Rural Services (GDRS) in Turkey and the International Water Management Institute (IWMI) and is funded by the Government of Turkey as part of the World Bank assisted Turkish Agricultural Research Plan (TARP).

References

Camase (1996) Register of agro-ecosystems Models Eds: [Plentinger MC and Penning de Vries FWT (eds)]. AB-DLO Wageningen, The Netherlands (http://www.co.dlo.nl/camase)

Camp CR, Sadler EJ, Yoder RE (Eds.) (1996) Evapotranspiration and irrigation scheduling. In: Proceedings of the International ASAE Conference, November 3–6. San Antonio, Tex., 1166p.

Doorenbos J, Kassam AH (1979) Yield response to water. FAO irrigation and drainage paper 33. Rome, Italy

Doorenbos J, Pruitt WO (1977) Crop water requirements. FAO irrigation and drainage paper 24. Rome, Italy

Droogers P, Bouma J (1997) Soil survey input in exploratory modeling of sustainable soil management practices. Soil Sci Soc Am J 61: 1704–1710

Droogers P, Kite G (1999) Water productivity from integrated basin modeling. Irrig Drain Syst 13: 275–290

Droogers P, Bastiaanssen WGM, Beyazgül M, Kayam Y, Kite G, Murray-Rust H (2000) Distributed agro-hydrological modeling of an irrigation system in western Turkey. Agric Water Manage 43/2: 183–202

Molden D (1997) Accounting for water use and productivity. SWIM Paper 1. International Irrigation Management Institute, Colombo, Sri Lanka

Molden D, Sakthivadivel R, Perry CJ, de Fraiture C, Kloezen WH (1998) Indicators for comparing performance indicators of irrigated agricultural systems. Research Report 20. International Water Management Institute, Colombo, Sri Lanka

Monteith JL (1981) Evaporation and surface temperature. Q J Royal Soc 107: 1–27

Ray I, Gül S (2000) Reducing canal water supply and demand in agriculture: a case study of the Gediz Basin, Turkey. Irrig Drain Syst (submitted)

Saeed IAM, El-Nadi AH (1998) Forage sorghum yield and water use efficiency under variable irrigation. Irrig Sci 18: 67–71

Seckler D (1996) The new era of water resources management. Research report 1. International Irrigation Management Institute, Colombo, Sri Lanka

Tietje O, Tapkenhinrichs M (1993) Evaluation of pedo-transfer functions. Soil Sci Soc Am J 57: 1088–1095

Topraksu (1974) Gediz havzasi topraklari. Toprak etütleri ve Haritalama Dairesi. Report 86. Ankara, Turkey

Van Dam JC, Huygen J, Wesseling JG, Feddes RA, Kabat P, VanWalsum PEV, Groenendijk P, van Diepen CA (1997) Theory of SWAP version 2.0. Technical Document 45. Wageningen Agricultural University and DLO Winand Staring Centre, The Netherlands

Van Diepen CA, Wolf J, Van Keulen H, Rappoldt C (1989) WOFOST: a simulation model of crop production. Soil Use Manage 5: 16–25

Wösten JHM, Lilly A, Nemes A, Le Bas C (1998) Using existing soil data to derive hydraulic parameters for simulation models in environmental studies and in land use planning. Report 156. DLO Winand Staring Centre, The Netherlands