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Research Report

Estimating Productivity of Water at Different Spatial Scales Using Simulation Modeling

Peter Droogers
and
Geoff Kite

International Water Management Institute

Research Reports

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Summary

Implementing real water saving measures in irrigated agriculture is only possible if all the components of the current water balance is clearly understood. However, measurement of all the terms in the water balance is infeasible on a spatial and temporal scale, but hydrological simulation models can fill the gap between measured and required data. To obtain all terms of the water balance for the Gediz Basin in western Turkey, simulation modeling was performed at three different scales: field, irrigation-scheme, and basin. These water balance numbers were used to calculate the Productivity of Water (PW) at the three scales. The four performance indicators considered were: $PW_{irrigated}$ (yield/irrigation), PW_{inflow} (yield/net inflow), $PW_{depleted}$ (yield/depletion), and $PW_{process}$ (yield/process depletion), all expressed in kg (yield) per m^3 (water). Of the two cotton fields evaluated at the field scale, the more upstream field performed better than the downstream field. This was partly attributable to the difference in climatic conditions, but was mainly due to the location of the two fields: upstream and downstream. At the irrigation-scheme scale $PW_{irrigated}$ was higher than at the individual cotton field scale, as nonirrigated crops were also included. Other PW values were lower than those at the cotton field scale, as crops more sensitive to drought were also found in the irrigated areas. As large areas of the basin were concealed with less-productive land cover, the basin scale PWs were lower than those at the irrigation-scheme scale and the field scale. It is concluded that performance indicators are useful ways of representing water dynamics, and that it is important to consider all the spatial scales at the appropriate scale of detail.

Estimating Productivity of Water at Different Spatial Scales Using Simulation Modeling

Peter Droogers and Geoff Kite

Introduction

Water is expected to be one of the most critical natural resources in the twenty-first century. Twenty-six countries are now classified as water deficient, and nearly 230 million people are affected with water shortages. And the prediction is that by 2025, one quarter of the world's population will face severe water shortages (Seckler et al. 1999). To avoid social and environmental chaos, there is a clear need for better management of the limited amount of water available. Because agriculture is the main consumer of freshwater, increasing irrigation efficiencies seem to be the practical way to "save" water. Measures like subsurface irrigation and trickle or micro-irrigation have been studied in detail, and may result in achieving greater efficiency in water management than the traditional methods. However, irrigation schemes are not isolated but are part of a whole basin with other water users. Water "savings" at one place are likely to reduce return flows to other users downstream in the basin (Seckler 1996). An integrated basin approach, considering all water users, is necessary to assess whether water "saving" actions are real or are only local "savings." The use of simulation models, at different spatial scales, is necessary for this integrated basin approach.

Recently, performance indicators have been developed that can be used to analyze the productivity of water with a few simple ratios (e.g., Molden 1997; Molden et al. 1998). These indicators were developed to replace the classical efficiencies used in irrigation engineering. These newly developed performance indicators have overcome two of the main limitations of the classical efficiencies: (i) nonagricultural water uses are included, and (ii) the interaction with other water users is more explicit. Data for these performance indicators are needed at different scales of detail, and mostly are not directly available. However, the use of simulation models at different spatial scales can be an effective means to fulfill this data need. A more detailed discussion on performance indicators is beyond the scope of this report, but can be found elsewhere (e.g., Burt et al. 1997; Droogers et al. 2000a).

An integrated basin modeling approach, including agricultural as well as nonagricultural usage of water was used to analyze water use for the Gediz Basin in western Turkey. A detailed description of the area and data used can be found in IWMI and GDRS 2000. At the smallest scale, the field, the detailed Soil-Water-Atmosphere-Plant (SWAP) (Van Dam et al. 1997) was applied to quantify the local water balance. Results at this scale are given as local water fluxes: transpiration, evaporation, drainage, irrigation, percolation, runoff, etc. Moreover, yield per unit water, diverted or consumed, can be estimated at this scale. At the intermediate scale, local-scale water fluxes were aggregated to describe the terms of the water balance at the irrigation-scheme scale. Finally, fluxes at this irrigation-scheme scale were integrated with the hydrology of the river basin. The river basin model, Semi-Distributed Land-Use Runoff Processes (SLURP) (Kite 1998), was used to evaluate the water supply and use of the entire basin, including agricultural and nonagricultural water users.

In summary, the objectives of this study were to: (i) simulate water balances at different spatial scales, (ii) use model results as data input for water productivity values, and (iii) compare these water productivity values at different spatial scales.

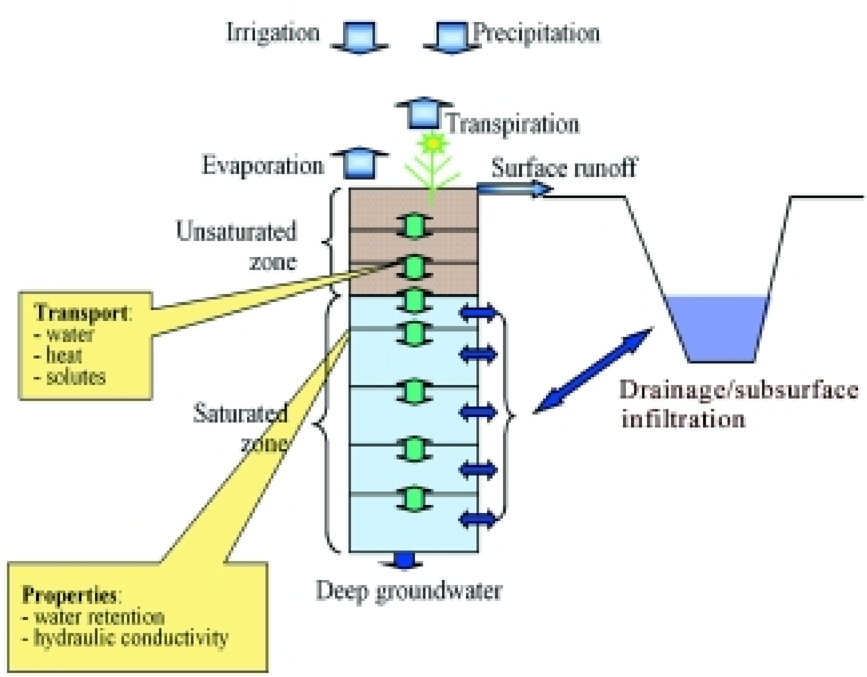
Materials and Methods

Applied Model: SWAP 2.0

The hydrological analyses at the field and irrigation-scheme scales 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. This model also includes modules for simulating irrigation practices and crop growth (figure 1). For this study, only the water transport and crop growth modules were used. The water transport module in SWAP is based on Richards' equation, which is a combination of Darcy's law and the continuity equation. A finite difference solution scheme is used to solve Richards' equation.

FIGURE 1.

Overview of the SWAP model.



Crop yields can be computed using either a simple crop growth algorithm based on the Food and Agriculture Organization's (FAO) approach (Doorenbos and Kassam 1979) or a detailed crop growth simulation module based on the partitioning of carbohydrate production between the different parts of the plant, taking into account the different phenological stages of the plant (Van Diepen et al. 1989). As detailed input data for crops were lacking, we elected to use the crop yield algorithm as described by Doorenbos and Kassam (1979), for this study. Yield response factors were applied in decomposed periods to account for different sensitivities throughout the growing season. One adjustment was made to this FAO approach; the ratio of actual transpiration to potential transpiration was used instead of simple evapotranspiration, following Hanks 1974. A distinction between soil evaporation and crop transpiration is desirable, as only the latter can be considered as a beneficial use of water in food production. The actual soil evaporation and plant transpiration are simulated based on the potential evapotranspirative demand and the leaf area index development. Actual soil evaporation and transpiration depend on the available soil water in the topsoil layer and the root zone, respectively. Irrigation practices can be simulated in two ways. First, the day that irrigation occurs can be defined as input. Second, the model can simulate that occurrence of irrigation is depended on a criterion, such as a defined soil moisture content or a defined plant stress. A detailed description of the model and all its components can be found in Van Dam et al. 1997.

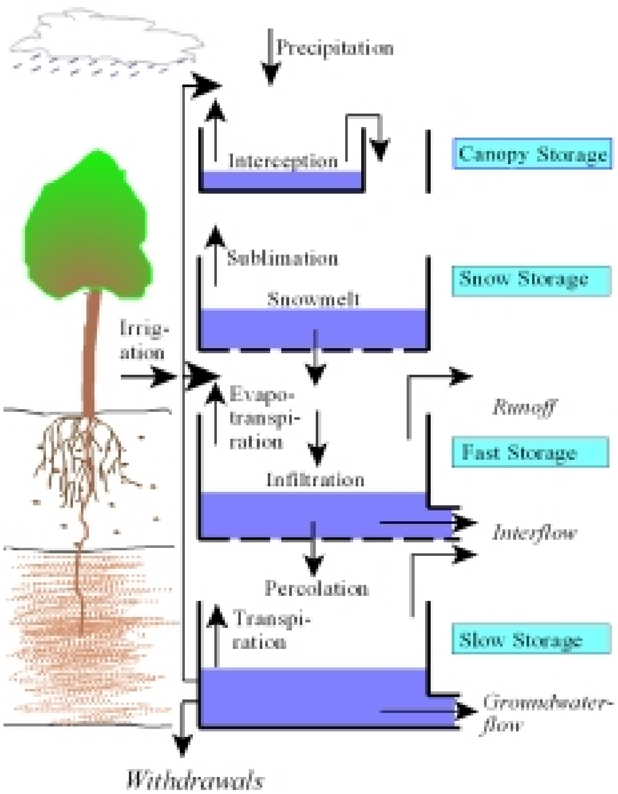
The first version of SWAP, called SWATRE, was developed more than 20 years ago (Feddes et al. 1978). Since then several research activities have been successfully conducted using the SWATRE model and its successors to study soil-water-atmosphere-plant relationships in many parts of the world (e.g., Feddes et al. 1988; Bastiaanssen et al. 1996). A validation of the performance of SWAP, focused on a comparison between simulated and observed soil moisture contents, for the particular conditions in western Turkey is given by Droogers et al. 2000b.

Applied Model: SLURP

The hydrological model, Semi-Distributed Land-Use Runoff Processes (SLURP) was applied at the basin scale (Kite 1998). SLURP is a continuous, semi-distributed, hydrological simulation model in which the parameters (interception coefficients, surface roughness, infiltration rate, snowmelt rates, soil moisture and groundwater storage characteristics) are related to the type of land cover (figure 2). The model divides a watershed into subareas known as aggregated simulation areas (ASA), and each ASA is subdivided into different land cover areas. During the simulation period, SLURP carries out a daily vertical water balance for each element of the matrix of ASAs and land covers. Each element is simulated by four reservoirs representing canopy interception, snowpack, rapid runoff, and slow runoff. The outputs from each vertical water balance include soil evaporation, crop transpiration, runoff, and changes in canopy storage, snowpack, soil moisture, and groundwater. Surface runoff, interflow, and groundwater flows are accumulated from each vegetation type within an ASA, and the combined runoff is converted to streamflow and routed through each ASA to the outlet of the basin. During this process, an account may be taken of diversions and regulatory structures. This large-scale model enables us to investigate irrigation schemes under basin-wide water management and water availability options, including changes in irrigation practice and climate variability and change options. A detailed description of the model can be found in Kite 1998. The model performance was previously tested, among other regions, in western Turkey (Kite and Droogers 1999).

FIGURE 2.

Overview of the SLURP model.



Performance Indicators

Performance indicators are based on the water balance approach using inflows and outflows. Such a water accounting system can be considered at different spatial scales: basin, subbasin, irrigation system or field. Molden (1997) has presented a conceptual framework for water accounting, based on inflows and outflows at different spatial scales, and this framework is mainly followed here. The generalized water balance for a certain area can be described as follows:

Water storage change = Precipitation + Irrigation + Capillary rise – Transpiration – Evaporation – Surface runoff – Drainage – Percolation.

Obviously, the change in water storage can relate to surface water, groundwater, as well as soil water. Care should be taken not to double count water, which can lead to fictitious water savings instead of real water savings ("dry" and "wet" savings in Seckler 1996). For example, the water balance of an entire basin should not include irrigation, as this water is already accounted for as inflow in the precipitation term. The following performance indicators were adopted from Molden 1997:

$PW_{irrigated}$ = Yield / Irrigation
PW_{inflow} = Yield / Net inflow
$PW_{depleted}$ = Yield / Depletion
$PW_{process}$ = Yield / Process depletion

For the three spatial scales distinguished here, different definitions apply to the performance indicators (table 1). Irrigation is defined as the real amount of water brought to the field. $PW_{irrigation}$ is not applicable to the whole basin, as production will also include nonirrigated areas as well as nonagricultural areas such as forests and natural vegetation used for grazing. Net inflow for the basin also does not include capillary rise, as this is zero for a basin as a whole. The amount of water depleted for a certain area depends on the location of the area considered. Drainage water and water percolated to groundwater can be utilized by downstream users, as long as the water quality is not limiting. However, outflow from coastal areas should be considered as depleted as this is not used any further. Therefore, the definition of depletion depends on the location of the area considered. Finally, process depletion is defined as the amount of water transpired by the crop.

In this study, PW is expressed only in terms of yields per unit supply (kg m^{-3}), while ignoring the economics and water needs of domestic users, industry, and nature reserves. A comprehensive discussion of these points can be found in Molden 1997.

TABLE 1.

Terms of the water balance used to calculate the Productivity of Water indicators (PW) for the three spatial scales considered.

	Field	Irrigation scheme	Basin
$PW_{irrigated}$	Irrigation	Irrigation	Not applicable
PW_{inflow}	P + I + dS + Cap	P + I + dS + Cap	P + dS
$PW_{depleted}$	*Upstream location:* E + T *Downstream location:* E + T + Drainage + Percolation + Surface runoff	*Upstream location:* E + T *Downstream location:* E + T + Drainage + Percolation + Surface runoff	E + T + Outflow
$PW_{process}$	T	T	T

Notes: P = precipitation, I = irrigation, dS = change in soil water storage, Cap = capillary rise, E = actual evaporation, and T = actual transpiration.

The four PWs indicate different performances, and a combination of PWs shows the performance of the system considered. A detailed interpretation of the meaning of PWs is given in the results section, but in general, a higher PW indicates a better-performing system. $PW_{irrigation}$ can be considered as a classical indicator (Droogers et al. 2000a), and should be used in combination with the other indicators to show the effectiveness of irrigation. PW_{inflow} can also be regarded as a more classical indicator, but is less irrigation-focused and considers the whole balance. $PW_{depleted}$ is the best indicator to show the actual performance of crops: irrigated, nonirrigated as well as nonagricultural crops. In general, this indicator is the most important one to assess the performance of an entire system. Finally, $PW_{process}$ explains how well a specific crop is performing in terms of crop water use efficiency.

To avoid results valid only for a specific year, a period of 9 years (1989–1997) was used for all simulations and analyses at field and irrigation-scheme scales. In addition to the long-term analyses, a dry year (1989) and a wet year (1995) were selected to evaluate the impact of different climatic conditions on the performance indicators.

Field Scale

A cotton field was selected in each of the two large irrigation schemes, Salihli Right Bank (SRB) and Menemen Left Bank (MLB) (figure 3). Although both fields are located on loamy soil, and irrigation inputs are similar, the fields require different water management to increase productivity of water. SRB is located in the middle of the basin and water leaving the system through drains and deep percolation is used by downstream users. For the cotton field in MLB, the situation is completely different. As it is located at the tail end of the basin near the Aegean Sea, surface runoff, drainage, and percolation to groundwater flow to the sea and, therefore, this water cannot be used for other purposes. As a result of this difference in location, the definition of the amount of water depleted is different for the two fields (table 1). Obviously, the definition upstream does not relate to the actual location, but to the existence of downstream users, which is the case for SRB, where depletion includes only actual soil evaporation and actual crop transpiration while for MLB total depletion includes surface runoff, drainage, and percolation.

Climate data for the two fields were collected in the vicinity of the fields. Potential evapotranspiration was calculated using the Penman-Monteith approach. Instead of calculating one combined potential evapotranspiration for the soil and the crop, two separate potentials were obtained by varying the values for crop resistance, crop height and albedo.

Irrigation inputs were not constant during the period considered. In 1987, two years prior to the selected dry year, a severe drought occurred in the basin resulting in reduced inflows to the main reservoir in the Gediz Basin. As a consequence of this, from 1989 onwards less water was released for irrigation purposes. After this dry period, the climate improved somewhat and gradually more water became available in the reservoir for irrigation. Also, more wells were dug, which resulted in a further development of conjunctive use of surface water and groundwater.

Irrigation-Scheme Scale

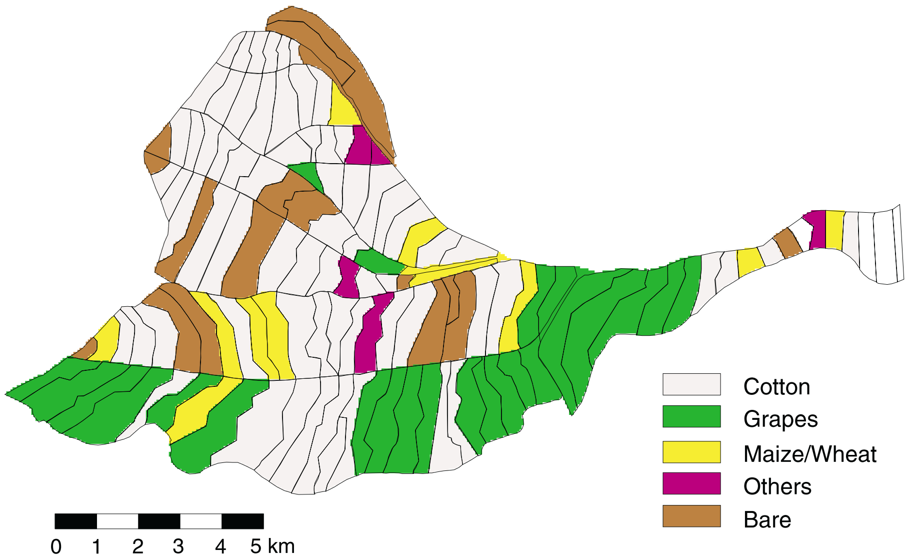
SRB was selected to demonstrate the method developed at the irrigation-scheme scale (figure 3). The SWAP model used at the field scale was also applied at the irrigation-scheme scale, but in a aggregated way. The entire study area was divided into subareas denoted as Land Use Systems (LUS) (FAO 1976), and each LUS was assumed to be homogenous in soil and

FIGURE 3.

Map of Turkey showing the Gediz Basin and the Salihli Right Bank (SRB) and Menemen Left Bank (MLB) irrigation schemes. (Crosses [x] indicate the locations of the two fields studied in detail.)

FIGURE 4.

Tertiary units for Salihli Right Bank (SRB) and associated predominant crops.



hydrological behavior. Within each LUS different crops can occur. These LUSs are considered to be the building blocks for the simulations, i.e., the whole SRB is treated as a set of homogenous areas. Details of this approach can be found in Droogers et al. 2000b.

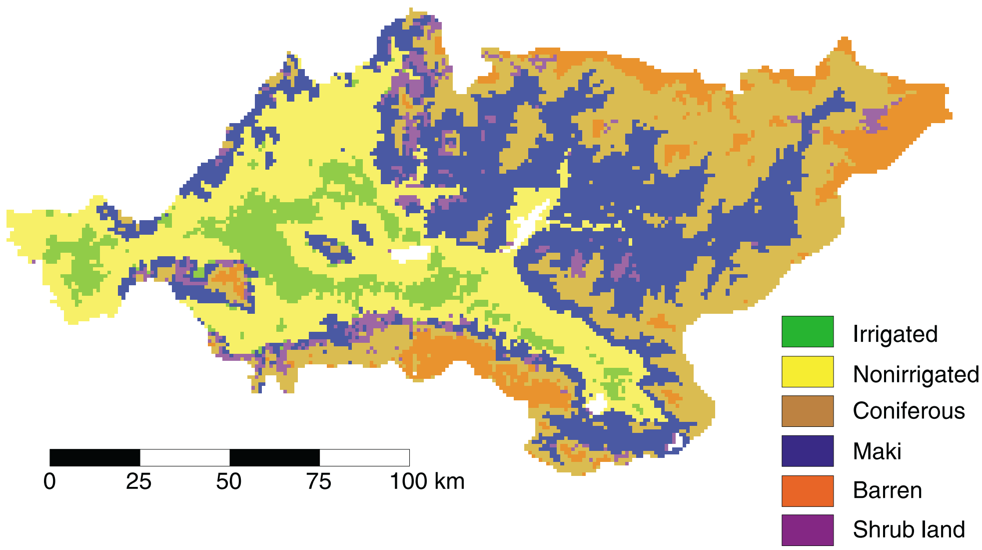
A comprehensive database describing cropping patterns was built up using the 125 tertiary irrigation canals as units (figure 4). The gross area and the area per crop for each tertiary unit were known. The main crops grown were cotton (60%), grapes (10%) and a combination of maize and wheat (10%). Twenty percent of the area was left bare. The wheat was seeded in autumn and harvested in spring and it was succeeded by maize, resulting in two yields from the same field. The winter wheat was never irrigated. As information for four tertiaries (201 ha) was not available, similar cropping patterns to the neighboring tertiaries were assumed. Climate conditions and irrigation inputs were similar to those described earlier for the cotton field in SRB.

Basin Scale

The basin-scale analyses were performed using the SLURP hydrological model (Kite 1998). As described earlier, the whole basin was divided into ASAs using a digital elevation model and a topographic analysis package. The land cover map of the whole basin, using National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer (NOAA-AVHRR) satellite images, is displayed in figure 5 (Droogers et al. 1998). Climatic data (precipitation, temperature, radiation, wind, and humidity) were collected at five climate stations, and the weighted average values for each specific area of the basin were obtained using Thiessen polygons. As SLURP is a parametric model, a calibration was carried out using observed streamflows to derive parameters for the fast and slow store as well as for some of the hydraulic properties. Details of this calibration can be found in Kite and Droogers 1999.

FIGURE 5.

Land cover map of the Gediz Basin, based on NOAA-AVHRR satellite images.



Note: Maki is a typical Mediterranean land cover with a mixture of shrubs and small trees.

At the basin scale, in addition to the agricultural use of water, water transpired by forests, natural vegetation, as well as the urban and industrial water supply, was analyzed. In the productivity of water at the basin scale, the assumption was made that the only non-beneficial uses of water were soil evaporation and outflow to the sea. All other water consumptions were considered to be beneficial. The latter is clearly true for agricultural use and forests but we considered all the urban extractions too as beneficial. For natural vegetation, the situation is more complicated. Parts of these are used for grazing and are thus beneficial but, owing to inaccessibility resulting from physical constraints, other parts are unsuitable for grazing. As more detailed information was lacking, we considered all the actual transpiration from natural vegetation as beneficial.

The performance indicators described above are all related to crop yields. Basin-scale crop yields were calculated using the ratio of actual crop transpiration to potential crop transpiration and multiplying this by the maximum possible yield (table 2). This maximum possible yield is assumed to be 4,000 kg ha^{-1} for the irrigated areas, which is the weighted average of most common crops in the area, as reported by local experts. The potential yields for the other land covers were defined using some general and local expertise.

TABLE 2.

Maximum possible yields for the land covers used at the basin scale.

Land cover	Potential yield kg ha^{-1}
Irrigated	4,000
Nonirrigated	2,000
Coniferous	1,000
Maki	500
Barren	0
Shrubs	500

Results

Field Scale

Simulated cotton yields for the two fields are displayed in figure 6. The dry period starting in 1989 had a dramatic adverse impact on the crops causing an almost 50 percent drop in cotton yields. The crop yields increased in later years as a result of an improvement in the climatic conditions as well as the use of irrigation water from groundwater extractions. The two fields differed somewhat in the yields obtained although the soil type and crop were identical. Generally, the MLB field has lower yields, mainly due to different climatic conditions in terms of greater evaporative demand by the atmosphere resulting from higher wind speeds.

The Productivity of Water (PW) indicators are given in table 3 as average values over the period considered. All PW values are higher for the SRB field in comparison with the MLB field. This cannot be explained only by the higher yields for the SRB field. For the SRB field, yields by 22 percent and PW values by 63 percent, respectively are higher than those for the MLB field. The difference in the $PW_{process}$ values indicates that the climatic conditions for SRB field are more favorable than for the MLB field. An analysis of the meteorological conditions of the two sites showed a substantial difference in wind speed, with much higher values for the MLB field. This difference is a consequence of the different locations of the two fields; MLB in the Gediz Plain near the Aegean Sea and SRB in the main valley surrounded by mountains.

However, the big difference in the $PW_{depleted}$ originates not from these differences in climate but from the different positions of the two fields in the basin: MLB at the tail end of the basin

FIGURE 6.

Simulated yields for the two cotton fields. MLB is located at the tail end of the basin, SRB in the middle of the basin.

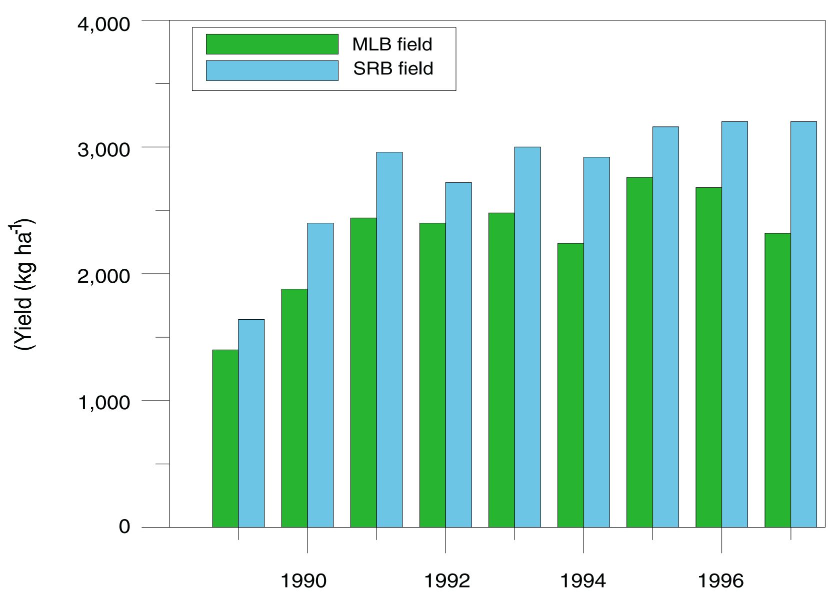


TABLE 3.

Performance indicators for the three scales considered. (The MLB field is located at the tail end of the basin, the SRB field in the middle of the basin, both cotton. A definition of the four Productivity of Water [PW] indicators is given in the text. Data are averages over the 9-year period 1989–1997.)

	Yield*	$PW_{irrigated}$	PW_{inflow}	$PW_{depleted}$	$PW_{process}$
	kg ha^{-1}	———	kg m^{-3}	———	
Field (MLB)	2,289	0.47	0.24	0.24	0.38
Field (SRB)	2,800	0.57	0.30	0.39	0.54
Irrigation scheme	2,614	0.75	0.30	0.32	0.40
Basin	874	-	0.16	0.16	0.21

*Yield is the simulated yield and refers to cotton for the field scale, to irrigated crops for the irrigation scheme, and to agricultural and nonagricultural production for the basin scale.

and SRB at the middle of the basin. As a consequence of this difference, $PW_{depleted}$ is only defined in terms of actual evapotranspiration for the SRB field while for the other field surface runoff, percolation, and drainage are also included. The PW_{inflow} and the $PW_{depleted}$ for the MLB field must be almost equal as the difference is only imposed by the change in soil water storage, which is normally minimal on a year-to-year basis.

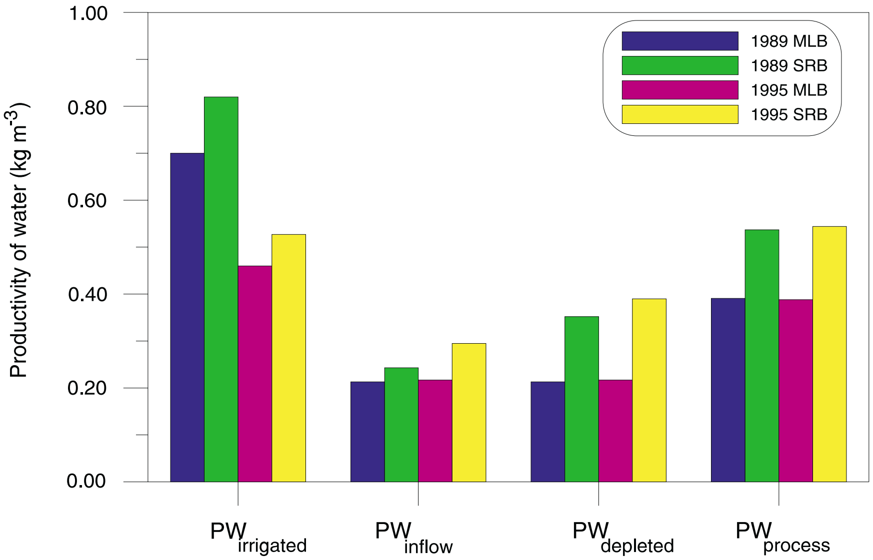
Table 3 indicates only the long-term average values. As described earlier, a severe drought started a few years before 1989 resulting in a dramatic drop in irrigation inputs. A detailed analysis of the periods before and after the drought is interesting, as the irrigation system, during these two periods, could be considered as "demand-based" and "supply-based," respectively. Figure 7 shows the four PWs for a year directly after the drought (1989) and for a later year when the irrigation input had recovered (1995). Clearly, all the values for the SRB field were higher than those for the MLB field, as explained earlier. PW_{inflow} and $PW_{depleted}$ are similar for MLB as the difference in these factors depends only on the changes in soil water storage, which is very low over a 1-year time span. $PW_{irrigated}$ was, as expected, higher for the low irrigation input year (1989) than for the higher irrigation input year (1995). This seems to be a justification for applying deficit irrigation; lower irrigation inputs increase the productivity of water. However, as mentioned earlier, water usage must be considered in a broader sense instead of only as water applied for irrigation. $PW_{process}$ should be seen as a real indicator of whether water has been saved. It appears that during the dry year $PW_{process}$ was similar to that of during the wet year, indicating that deficit irrigation is questionable. It should be emphasized that the crop growth module used here is an empirical one, which might be less accurate for these dry conditions.

Irrigation-Scheme Scale

Table 3 shows the long-term average yield and PW values for the irrigation scheme. Yields are somewhat higher than those for the two fields described earlier, as other crops, with higher yields such as grapes and wheat, are grown in the area too. On the other hand, some areas without crops were also included in the overall figure. The yield also includes nonirrigated winter wheat resulting in high $PW_{irrigated}$ values. The other PW values are lower (or similar) in comparison

FIGURE 7.

Productivity of water for the two cotton fields in a dry year (1989) and a wet year (1995).



with the values for the individual SRB cotton field as described in the previous section. $PW_{depleted}$ is lower as approximately 20 percent of bare soil was included in this PW value. From these areas water leaves the system through soil evaporation, without producing any crop. $PW_{process}$ is relatively low in comparison with the cotton field, especially during the dry period, as some of the other crops grown here are more sensitive to drought than cotton.

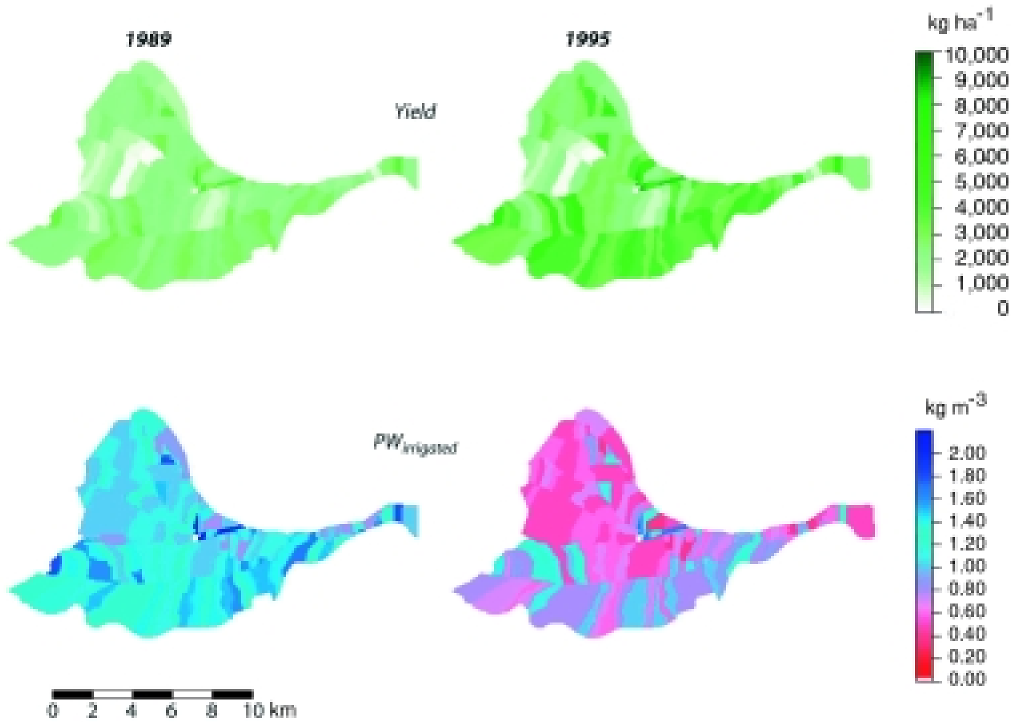
Areally distributed values of yield and $PW_{irrigated}$ are shown in figure 8 for a dry year (1989) and a wet year (1995). The yields show a lot of spatial variation, with high values in areas that are dominated by a combination of maize and wheat and, low values in areas with a high percentage of uncropped land. Yields were lower in 1989 as a consequence of the lower irrigation inputs, although the maize and wheat areas suffered to a lesser extent from the drought as they were totally rain-fed. The grapes, too, suffered less from the drought as the deeper roots induced a higher capillary rise from the groundwater. Differences in the $PW_{irrigated}$ between the 2 years were very high, with much higher values in the dry year 1989 than in 1995, and with areal average values for $PW_{irrigated}$ of 1.11 kg m^{-3} and 0.76 kg m^{-3} for 1989 and 1995, respectively. The lower values in 1995 occur despite higher yields as a result of substantially higher irrigation inputs. Again, areas with a higher percentage of grapes and a combination of maize and wheat show higher $PW_{irrigated}$ values.

Basin Scale

Average basin yields as well as PW values for the 9 years considered are given in table 3. Yields as well as the three PWs are lower in comparison with the other two scales considered. The reason for this is that only part of the basin is used for agricultural production (8% is irrigated and 25% is nonirrigated), while the main area is covered with less-productive vegetation. As a result we did not apply $PW_{irrigated}$ at the basin scale.

FIGURE 8.

Areal distribution of yield and productivity of water for Sahili Right Bank (SRB) during a dry year (1989) and a wet year (1995).

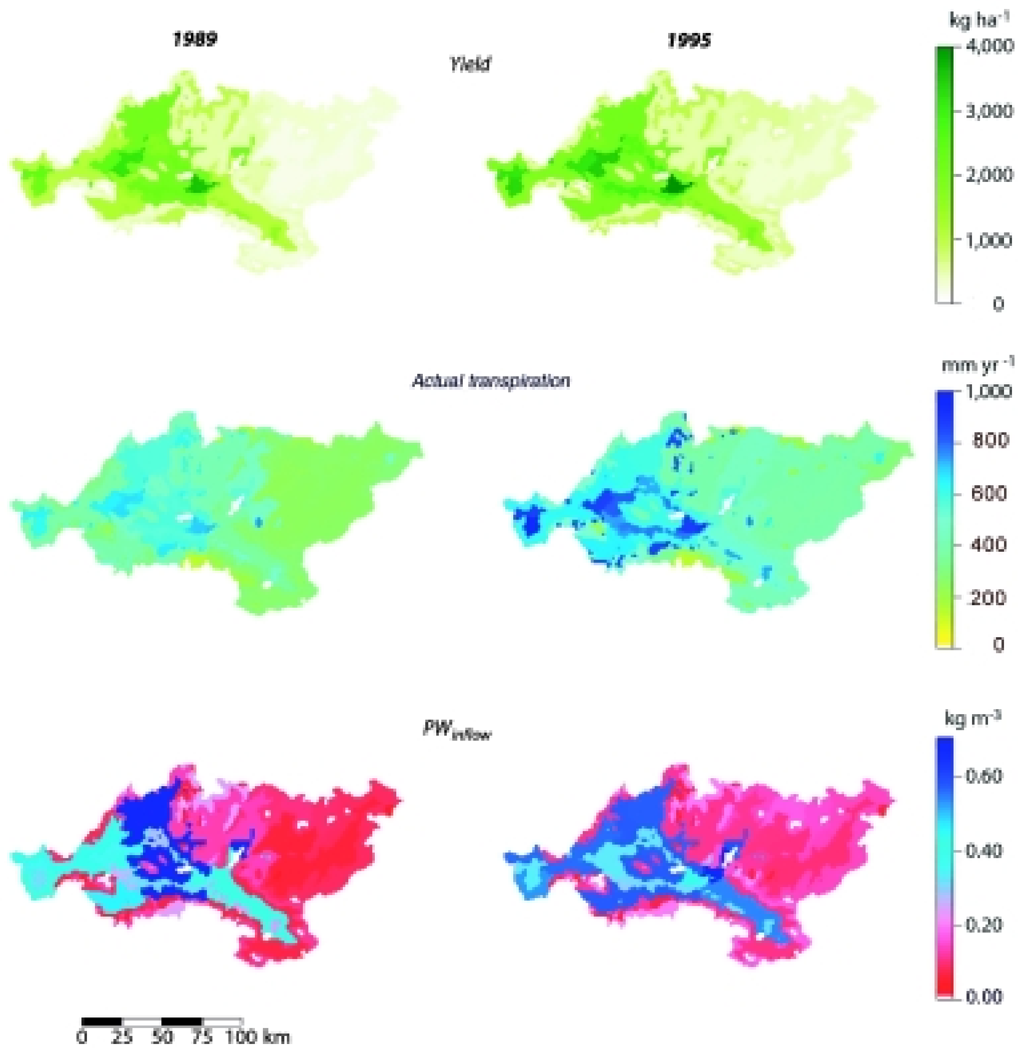


PW_{inflow} and $PW_{depleted}$ are similar as the difference is only governed by the change in soil water storage, which is normally low when considered over a whole year.

Yield, actual transpiration and PW_{inflow} for the whole basin for the dry and the wet years (1989 and 1995) are shown in figure 9. Clearly, the irrigated areas have higher transpiration rates than the nonirrigated and naturally vegetated areas, inducing higher crop yields. Areally averaged yields were 790 kg ha^{-1} and 1,005 kg ha^{-1} for 1989 and 1995, respectively. It is interesting to note that the irrigation schemes upstream perform better than those downstream. The areal averages of PW_{inflow} for the 2 years are comparable, 0.18 kg m^{-3} and 0.14 kg m^{-3} for 1989 and 1995, respectively. However, a large areal variation, with lower values for the nonagricultural areas and higher values for irrigated and nonirrigated land covers, exists. Values for nonirrigated areas are higher than those for the irrigated areas, as yields are reasonably high while inflows are limited.

FIGURE 9.

Yield, actual transpiration, and $PW_{process}$ for the whole Gediz Basin for a dry year (1989) and a wet year (1995).



Conclusions

- Water productivity indicators (PWs) and the combination of PWs, are a useful means to evaluate the use of water in a simple manner. PWs were used here successfully to intercompare different areas, and to assess the effect of changes in water supply at different spatial scales.
- Simulation models can be used to derive the data needed to calculate these performance indicators. Some of these required data are difficult to measure in terms of spatial or temporal resolution or in processes such as soil evaporation in comparison to crop transpiration and capillary rise.

- The models used in this study were applied reasonably quickly because of their extensive validations during many other studies and the availability of existing datasets. For areas where local data are limited or lacking, the growing number of available global datasets can be utilized.

- Deficit irrigation needs to be studied in a total water-balance context, instead of concentrating only on irrigation inputs.

- Considering that all the spatial scales are important to evaluate water resources at the appropriate scale of detail, detailed soil-water-balance analyses although less appealing for natural vegetation or forests, are important for irrigated areas.

- The location of the area considered within the basin is an important characteristic in the context of the desired water management, for example, upstream users and the downstream users. This can be clearly noticed from the differences in the depletion indicator for the two cotton fields considered.

- Results obtained can be used for an economic analysis where PWs can be expressed in US$ m^{-3} instead of kg m^{-3}.

- The methodology described can also be used to assess the impact of different scenarios on the productivity of water. Such an assessment can be easily made by changing the appropriate input, running the simulation models, calculating the PWs, and comparing these for the different scenarios.

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