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ASSESSING ADAPTIVE CAPACITY OF LARGE IRRIGATION DISTRICTS TOWARDS CLIMATE CHANGE AND SOCIAL CHANGE WITH IRRIGATION MANAGEMENT PERFORMANCE MODEL

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SUMMARY – We developed a new physical model called “Irrigation Management Performance Assessment Model (IMPAM)” for assessing irrigation district’s adaptive capacity towards climatic and social changes. It is a quasi three dimensional water balance model which represents the effects of irrigation, drainage canal networks and heterogeneous land use on agricultural production and water budget of the whole system.

We applied the IMPAM to the Lower Seyhan Irrigation Project in Turkey and tested the district’s adaptive capacity towards projected climate change in the 2070s. Due to the considerable decrease of precipitation in the winter time, the amount of irrigation demand is projected to increase (100-170mm) and the duration of irrigation to extend, from early spring to late autumn. Presently excessively high water table is projected to lower in the 2070s. Transition from gravity irrigation to drip irrigation in citrus gardens to adapt to water deficit would also enhance lowering of the water table. This study revealed that the problem of high water table was clearly the consequence of inefficient irrigation practice. For conserving adaptive capacity to possible, climate change, it is strongly recommended that water use efficiency be improved in this district.

Key words: IMPAM, Irrigation, drainage, climate change.

RESUME *- Nous avons développé un nouveau modèle physique appelé le Modèle d'Evaluation d'Exécution de direction D'irrigation (IMPAM) en vue dévaluer la capacité adaptive d’un quartier d’irrigation par rapport aux changements climatiques et aux changements sociaux. C'est un modèle d'équilibre d'eau quasiment tridimensionnel qui représente l'effet de l’irrigation et du réseau de canaux de drainage, selon les différentes terres hétérogènes en usage, sur la production agricole ainsi que le budget total de l'eau du système dans son entier.*

Nous avons appliqué le IMPAM au Projet D'irrigation du Bas-Seyhan en Turquie et ainsi évalué la capacité adaptive du quartier en vue du changement de climat prévu dans les années 2070. Due à la diminution considérable de précipitation en hiver, la quantité de demande d'irrigation a été projetée afin d’être augmentée (100-170mm) et la durée d'irrigation a été projetée pour s'étendre du début du printemps jusqu’à la fin de l'automne. L’actuelle excessivement haute table d'eau a été modélisée pour s’abaisser dans les années 2070. Selon cette étude, la transition entre une irrigation de gravité pour une irrigation de dégouttement dans les jardins d'agrume permettrait de compenser le déficit et également d’abaisser le niveau de la table d'eau. Cette étude a mis en lumière le fait que ce problème de la haute table d'eau était clairement la conséquence d’une pratique d'irrigation inefficace. Pour préserver la capacité adaptive du système aux différentes évolutions et aux changements de climat, il est fortement recommandé que l'efficacité de l’usage de l’eau sera améliorée dans ce quartier.

Mots-clès *: IMPAM, Irrigation, drainage, changement de climat*

INTRODUCTION

Changing environment of large irrigation projects

In the last half of the 20th century, many large-scale irrigation projects were launched for increasing and diversifying food production. Although most of the projects accomplished their mission, the long-term sustainability of these projects is now under question. While aging and degradation of infrastructure is inevitable, the degree of maintenance is largely dependent on the institutional (political and economical) environment and this has radically changed all over the world over the last two decades. Additionally, the inconsistencies between the initial design of management and gradually diversifying land use also bring conflict over water allocation. It is time for systematic assessment of their performance and diagnosis for sustaining productivity.

Need for specific modeling for irrigation district

The high level of diversity of irrigation systems arises from the fact that their form and attributes are a reflection of the landscape and cultural background of the region. For example, the average farm plot size, intensity of irrigation or drainage canals, topography and farm plot management may all vary. When focusing on farm plot level only, water dynamics can be fairly well-represented by a one-dimensional crop water balance model with special attention to soil-physical and crop-growth parameters. However for assessing the water budget at a district level, attention must also be paid to heterogeneous land use, properties of irrigation and drainage networks, topography and regional groundwater fluctuation. Only through good representation of this manmade environment with a model of appropriate scale, it would become possible to diagnose the combined effects of these properties on efficiency and sustainability of the whole system.

Irrigation Management Performance Assessment Model

The authors developed the “Irrigation Management Performance Assessment Model (IMPAM). A large proportion of the water brought into an irrigation district moves much faster than the Darcian flow: i.e. flow in a canal, leakage from canal recharging groundwater, and drainage flow etc. Whereas most one-dimensional crop water balance models mainly focus on soil water balance, the IMPAM is one of the first models to consider the spatial effect of an artificial water path. Another distinct character of the IMPAM is its ability to assess the effects of mixed land use because of its quasi-three-dimensional structure. The IMPAM is capable of assessing the influence of water management by representing water allocation rules and the states of canals.

Assessing the long-term changes

Once the model is calibrated to the water budget structure of a specific irrigation district, it can simulate the effect of climate change and a change in social conditions by using projected future climate data and by applying different scenarios of land use or technological advances. In this paper, we outline the structure of the model and show the case study of its application to the Lower Seyhan Irrigation Project on the Eastern Mediterranean coast of Turkey. We have tested the calibrated model with projected climate data of the 2070s and simulated crop growth and water balance. The aim of this study is not to accurately predict the possible changes, but rather to outline vulnerabilities in present irrigation management and assess the effect of possible adaptations.

MATERIALS AND METHODS

Irrigation Management Performance Assessment Model

Components of the model calculation

A distributed modeling approach is used in IMPAM as it has the capacity to take account of the effects of spatial information. Raster modeling has advantages in handling natural spatial information such as geology, topography and soil profile distribution. On the other hand, vector modeling, which is commonly used in the GIS, has advantages in expressing structure and nature of manmade environment such as boundaries of farm plots, canal branches and segments, which strongly influence water allocation. IMPAM therefore consists of three modules which include both "raster" and "vector" approaches:

- Water Distribution Module (WDM)
- Drainage Reuse Module (DRM)
- Water Movement Module for Irrigated Area (WMM).

The WDM and the DRM are vector-based models used for describing water allocation processes. The WMM is a grid-based hydrological model for the simulation of water dynamics. It also functions as a platform to integrate outputs of the WDM and the DRM, into a water dynamics simulation (Fig. 1). Inputs and outputs of IMPAM are indicated in Figure 2.

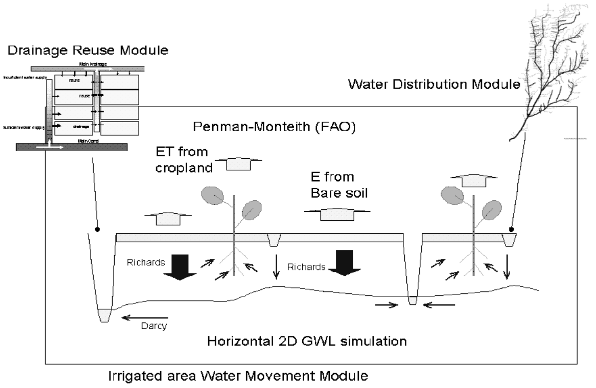


Fig. 1. Concept of calculation in the IMPAM

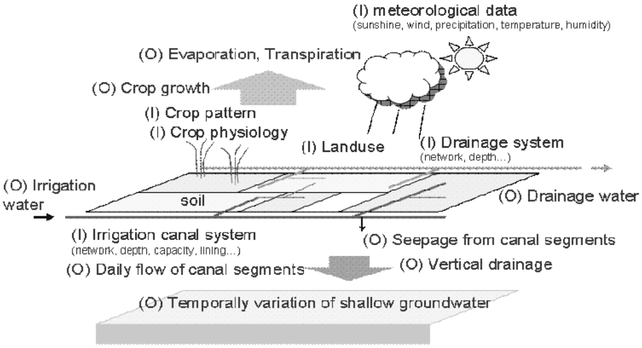


Fig. 2. Input (I) and output (O) of the IMPAM

Water Distribution Module (WDM)

The WDM calculates the daily discharge rate of each irrigation channel segment, taking the amount of seepage loss into account. The main input items to this module are; i) the topological structure of the irrigation channel network, ii) the capacity and loss rate of each channel segment, iii) the date and amount of irrigation for each farm plot, and iv) the cropping pattern, including the dates of sowing and harvesting. Details of dates and amounts of irrigation inputs are derived from reference tables prepared by local governmental organizations and research institutes, or can be calculated by the WMM. If the calculated daily discharge has fatal errors in estimation, for example, if it exceeds the channel capacity, the channel daily discharge is re-calculated with modified irrigation schedules.

Drainage Reuse Module (DRM)

The DRM calculates the total amount of drainage water from the irrigated area. The layout of the drainage channel network, the amount of drainage and reuse of drainage-water from each plot are the major input parameters to this module.

Irrigated Area Water Movement Module (WMM)

The hydrological processes incorporated in the WMM module are seepage from irrigation canals, groundwater flow to drainage, capillary rise of groundwater, deep percolation, evaporation from soil surface, transpiration or soil moisture extraction by plant roots and groundwater flow. Meteorology, irrigation schedule, land use, crop spatial distribution and the locations and dimensions of the irrigation and drainage canals are the main inputs of this module.

Horizontal water movement in unsaturated zones is relatively small and it can be considered negligible for modeling at this scale. Therefore, IMPAM adopted a quasi-3-dimensional modeling approach that employs a vertical one-dimensional crop-water interaction model for the unsaturated zone and a two-dimensional water balance model for the saturated zone. This has the advantage of reducing computational overhead.

Horizontal water movement in the saturated zone, where temporal and spatial variation of groundwater level is large, is expressed by the advection-dispersion equation (ADE): that is the differential equation to describe pressure head (h), time (t) and horizontal coordinates (x, y) (Eq.1). Resolution of the horizontal grid can be set freely from ten meters up to about one kilometer according to the purpose of simulations.

$$\frac{\partial h}{\partial t} = \frac{T}{S_S}\left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2}\right) + W \qquad (1)$$

In Equation (1), T is hydraulic conductivity coefficient and S_s is storage coefficient, respectively. The sink/source term W consists of flow to drainages, infiltration from irrigation canals and downward flux of the vertical one-dimensional module. Drainage rate is calculated from the groundwater level, the intensity of drainage and its depth. A table of canal segment properties gives infiltration rate and time-based information and the WDM shows the canal segments where infiltration occurs.

Methodologies of calculations of vertical one-dimensional water movement and transpiration are based on the theory used in SWAP (Van Dam *et al.*, 1997). Soil water movement is calculated with the partial differential equation developed by Richards (Eq.2). The top boundary condition is determined by the net flux resulting from irrigation, precipitation and evaporation from the soil surface. The bottom boundary condition is given by the distance from the ground water level (pressure head). Root water extraction is included in Eq.2 as the sink term (S(h)).

$$\frac{\partial \theta}{\partial t} = C(h)\frac{\partial h}{\partial t} = \frac{\partial\left(K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right)}{\partial z} - S(h) \qquad (2)$$

Potential soil surface evaporation flux and potential transpiration flux are calculated for each grid separately with the Penman-Monteith equation. Meteorological data is commonly available for a target area, and vegetation cover ratio, crop height and minimum canopy resistance are given for each plot. They are reduced by the effects of pressure head: the water conductivity (K(h)) of the soil surface and the root water extraction reduction coefficient α under dry conditions (Feddes et al., 1978).

Study Area: Lower Seyhan Irrigation Project

The Lower Seyhan Irrigation Project (LSIP) is one of the largest irrigation projects in Turkey, which extends to the delta plain of the Seyhan river basin with a total irrigated area of 133,000 ha (Fig. 3). Gravity irrigation is conducted with the water supply from the big reservoirs in the upstream. Annual precipitation is 744mm and this mostly falls during the winter. Before the implementation of the project in the late 1960s, cotton was cultivated during the summer exploiting only the residual soil moisture. Irrigation is mainly used for crop production during the dry summer months. Development of irrigation infrastructure was carried out in several phases over 30 years, and in areas of earlier development, degradation of facilities is quite serious. In 2004, the cultivation areas of maize, cotton, citrus, vegetables, and watermelon comprised 45, 9, 13, 4, and 6% of the total area, respectively.

Previous studies carried out in the area, such as those by Scheumann (1997) and Cetin and Diker (2003), suggested salinity and high groundwater as the main problems of the area. Donma et al. (2006) analyzed shallow groundwater fluctuation in the past two decades and revealed that salinity of shallow groundwater had decreased consistently, possibly due to introduction of irrigation and drainage systems. However high groundwater remained a problem due to leakage from deteriorated canals and low awareness of farmers about water conservation. The authors interviewed Water Users Associations in 2003 and learned that there were increasing conflicts among water users at peak irrigation season, in spite of maximum water intake at main canals. This also suggested possible increase of leakage from the canals.

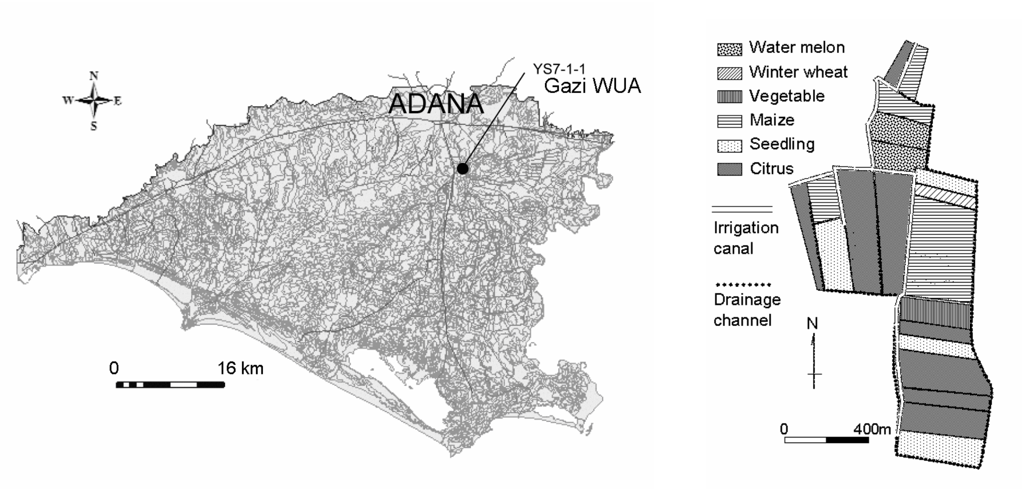


Fig. 3. Project area of the LSIP and the command area of YS7-1-1

The irrigation canal system of the LSIP consists of two conveyance canals, main canals, secondary canals, and tertiary canals. The two conveyance canals (YS0 and TS0) are diverted at the Seyhan Regulator. All of the main canals branch off these two conveyance canals except for YS1 and TS1, which are diverted directly from the Seyhan Reservoir. IMPAM was applied to the command area of the tertiary canal YS7-1-1 (Fig. 3), which is in the middle of the Seyhan Delta, on the left bank of the LSIP, and belongs to the Gazi Water Users Association. There are 21 plots in the area (total 90 ha), where maize, citrus, vegetables, and seedlings are cultivated. For the simulations, this area was divided into a 50 m x 50m grid. Drip irrigation is not used in Gazi, although it is rapidly spreading for citrus gardens in the LSIP area, for labor cost saving.

Scenarios for simulation

Simulations under three hypothetical scenarios and one actual situation were carried out (*Table 1*). In simulations 3 and 4, it was supposed that surface irrigation in citrus gardens would be completely replaced by drip irrigation. Usage of a drip irrigation option in the IMPAM also enables us to estimate how much irrigation demand would be changed by climate change, as the drip irrigation would be automatically activated to adjust soil moisture to a given condition in the model.

Table 1.Combinations of data for simulations

	Climate	Irrigation	Code
Simulation 1	Present	Surface	PCCSFI
Simulation 2	Projected	Surface	PWCSFI
Simulation 3	Present	Drip	PCCDRP
Simulation 4	Projected	Drip	PWCDRP

Assumptions and data for irrigation management

Irrigation in the LSIP is presently conducted from May to November. Regardless of rainfall in winter, almost the same amount of irrigation is applied every year under a fixed schedule. Data for irrigation and cropping management, such as amount of flow in irrigation canals, seepage rate, irrigation schedule, and cropping pattern were obtained from field observations (Nagano et al. 2005). The annual amount of irrigation for each crop applied in the fixed schedule irrigation scenarios and cropping patterns in this study area are shown in Table 2 and 3, respectively. The sum of seepage from the canal and application loss was assumed to be 170mm as area average to have best representation of groundwater fluctuation.

Table 2. Annual amount of irrigation for each crop

Crop	Irrigation (mm/year)
Maize	680
Vegetable	300
Watermelon	310
Citrus	770
Seedling	530

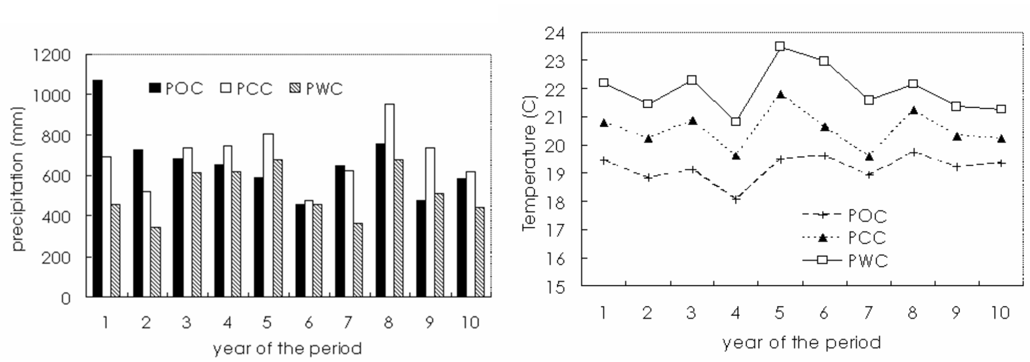
Table 3. Crop pattern in Gazi

Crop	Area (ha)	Plots
Citrus	40	8
Seedlings	13	4
Maize	24	4
Wheat + Maize	2	1
Vegetables	6	1
Watermelon	6	1

In the assumed drip irrigation scenarios, irrigation was applied immediately after citrus trees were stressed by dryness. When actual transpiration of trees decreased to 99% of the potential in 30% of a plot, 10 mm of irrigation was applied in the simulations. The source of drip irrigation in the LSIP is a deep aquifer. Groundwater withdrawal from this layer has little effect on shallow groundwater and unsaturated zones so the effect of withdrawal was ignored in the simulations.

Projected global warming data

The spatial resolution of the outputs of the Global Circulation Model is very low (often 2.5°) and often so different from actually observed data. Consequently the projection of "realistic" future changes is difficult. In this study, we used data downscaled with a special technique named "pseudo warming" (Kimura, 2005). Kimura (2005) first used the regional climate model RAMS (McQueen et al., 1997) with NCEP (National Centers for Environmental Prediction) reanalysis data as a boundary condition to represent the climate condition around the Seyhan Basin with a high spatial resolution (8.3 km). Then he added a climate change bias between the 10-year average of the 2070s and the 10-year average for the period 1994–2003 to this reanalysis data to produce a pseudo future boundary condition and generated the future climate by downscaling (Fig. 4). This method would make the regional climate much more representative, because the boundary conditions are close to the actually observed values. Currently, the CGCM2 by MRI/JMA (Yukimoto et al., 2001) was used with scenario A2 to calculate the climate change bias. According to the future projections by this method, the annual average temperature would rise 1.38C°, annual precipitation would decrease 177mm, and potential evaporation would increase in Adana.



POC: Present observed climate (1994–2003)
PCC: Present calculated climate (1994–2003)
PWC: Projected warmed climate (2070s)

(A) Annual precipitation (B) Annual average temperature

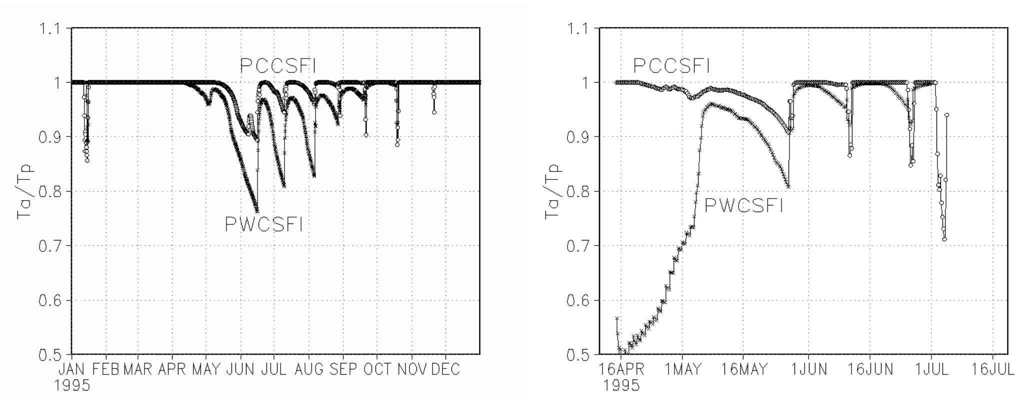
Fig. 4. Observed, calculated present, and calculated future climate

RESULTS AND DISCUSSIONS

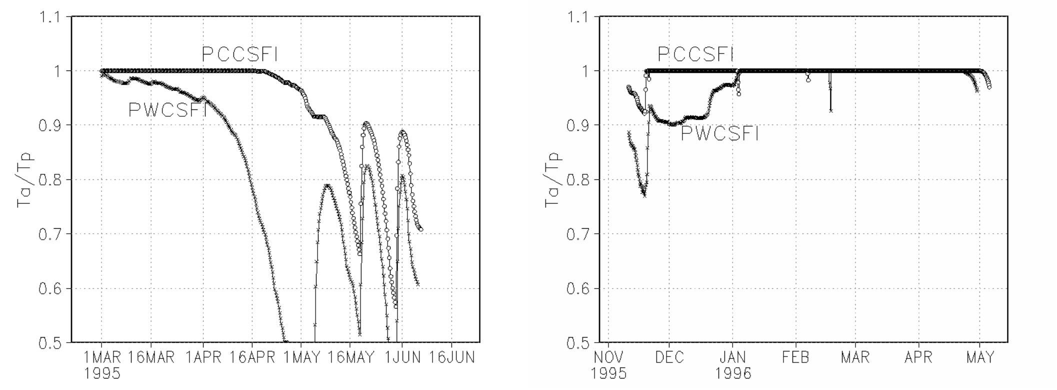
Impacts on crop growth and irrigation management

The ratio of actual transpiration amount to potential transpiration (Ta/Tp; 0–1) can be used as an indicator of water stress of the crops. Comparison between PWCSFI (the projected climate in 2070s with present water management) and PCCSFI (the present climate and water management) indicated that the water stress of crops would increase in the future because of the decrease in precipitation (Figs. 5 and 6). In figures 5 and 6, only the results from the second to third year of the simulation are shown as examples. Out of ten years' simulation period, these two years are not extreme but rather typical years in terms of the amount of precipitation (Fig. 7). Water stress mainly occurred in the spring and autumn, due to the significant decrease of precipitation in March and November (Fig. 8). Citrus, with its relatively deep roots, could draw soil moisture from deeper during the spring dry spell, and therefore exhibited stress later than maize and watermelons. With the present management, water deficit was unavoidable in the beginning of the growing season in early spring (Fig. A–C). However for winter wheat, precipitation in the beginning of the rainy season reset soil moisture deficit and did not bring high water stress at the time of planting (Fig.5D). Decreased precipitation in the mid-rainy season might not cause water stress, as potential evaporation is low in winter (Fig. 5 A and D).

According to the results of the drip irrigation scenario simulations, water demand for drip irrigation in the 2070s was 100–170 mm/year more than at present. While drip irrigation began in the middle of April and ended in the mid-November in the PCCDRP simulation, irrigation was applied throughout the later part of the year with some intermittent irrigation in the PWCDRP simulation (Fig. 9). Decrease in precipitation in the autumn and the resulting lower water table in the autumn raised the irrigation demand.



(A) Citrus (B) Maize



(C) Watermelon (D) Winter wheat

Fig. 5. Ta/Tp ratio at selected points (years 2–3 in the simulation periods) under surface irrigation scenarios (PCCSFI and PWCSFI)

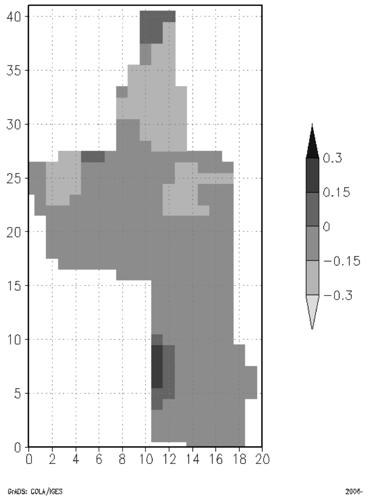
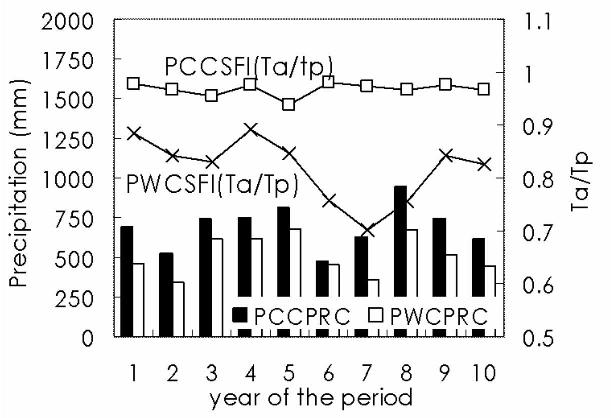


Fig. 6. Difference (PWCSFI – PCCSFI) of the Ta/Tp ratio. Annual average of the second years of the simulation periods



Precipitation
PCCPRC: Present calculated climate
PWCPRC: Projected warmed climate

Fig. 7. Area average Ta/Tp ratio (1994–2003 and the 2070s)

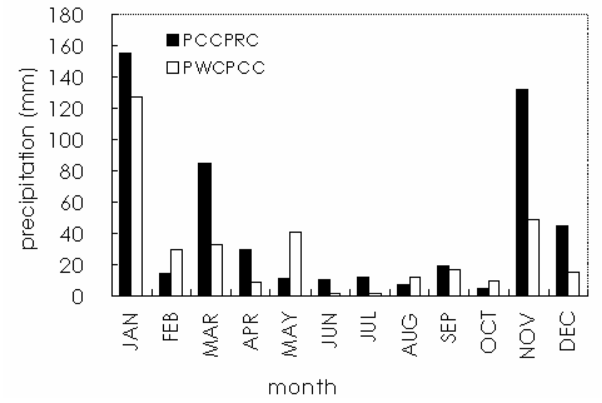


Fig. 8. Monthly precipitation in the second years of the simulation periods

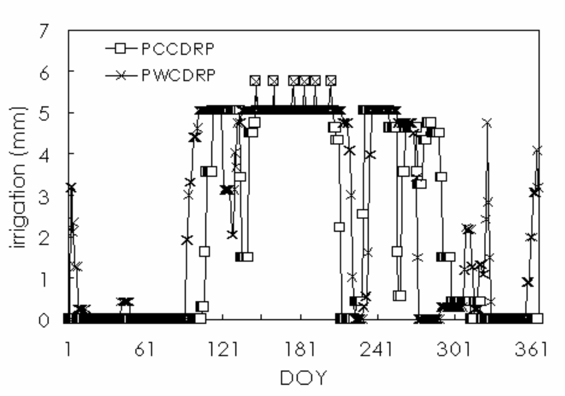


Fig. 9. Daily drip irrigation amount for citrus (all citrus plots average) in the PCCDRP and PWCDRP simulations

Impacts on the hydrological environment

The groundwater level generated by the PCCSFI simulation had a peak in winter, caused by precipitation, and this agreed well with the results of field observations. This peak vanished almost completely in the PWCSFI simulation (Fig. 10). Figures 5A and 11 show results at the same point in the same citrus plot. Although precipitation in winter in the 2070s was sufficient to prevent citrus trees from water stress, it was mostly extracted by tree roots as soon as it infiltrated, and a very little amount contributed for recharging to groundwater. In summer, however, the water table did not fall regardless of dryness in the root zone of citrus (Figs 5A and 10), indicating that the water table was low enough to have no interaction with water dynamics in the root zone.

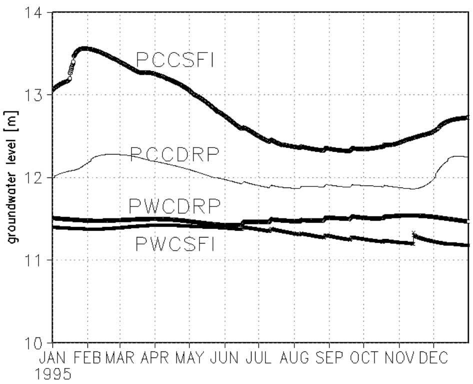


Fig. 10. Groundwater level in a citrus plot in the second years of the simulation periods (Ground surface is at 15.0 m elevation.)

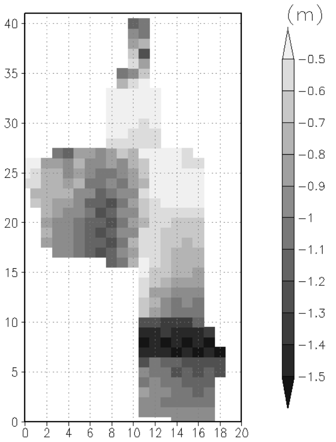


Fig. 11. Difference in groundwater level on 18 July 1995 (PCCDRP – PCCSFI)

The transition to drip irrigation also caused a drop in water table. The peak in winter decreased substantially even in the simulation using the present climate (PCCDRP, Fig. 10). Figure 11 shows the difference of water table level (PCCDRP-PCCSFI). In citrus garden plots and citrus seedling plots where the drip irrigation was introduced (see Fig. 3), water table dropped significantly. Consequently, water table in the adjacent plots also became lower. The areal average of seepage was reduced from 170mm to 100mm in PCCSFI with 100% application efficiency assumed for drip irrigation. This result suggests that presently high water tables are attributed to high rate of leakage and low application efficiency of gravity irrigation.

CONCLUSIONS

This study showed that irrigation demand would increase and irrigation period would become longer under the assumed climate change. The LSIP has two large-scale reservoirs in the upstream as water sources. Even though river discharge would decrease with climate change, resource-wise adaptive capacity would remain high. On the other hand, irrigation and drainage infrastructure is already aged and deteriorated so that carrying capacity would farther deteriorate without proper maintenance. Low transport and application efficiency are both contributing to high water table problems. Therefore management of the canal system would be the key factor determining adaptive capacity of the LSIP, system-wise. A shift to less water-consuming crops or diversifying cropping pattern for peak shaving are also effective, yet cropping pattern is not and would not be determined by water use aspect only.

At the end-users' side, there can be another adaptation by increased use of groundwater as source of irrigation. Farmers can apply water anytime without any negotiation with other farmers or associations. The spread of drip and sprinkler irrigation for cash crops is already enhancing this process in the LSIP. This study showed that water table would lower significantly with increased use of drip irrigation. However in many parts of the plane, deep aquifer is saline and degree of recharge is still questionable. In the coastal area, excessive exploitation of groundwater would surely enhance seawater intrusion. Use of river water with increased irrigation efficiency seems more desirable.

Acknowledgments

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