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Quantifying the agricultural landscape and assessing spatio-temporal patterns of precipitation and groundwater use

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Abstract

Quantitative agricultural landscape indices are useful to describe functional relationships among climatic conditions, groundwater dynamics, soil properties and agricultural land use for mathematical models. We applied methods of regression statistics, variance component estimation and a Geographical Information System (GIS) to construct indices describing crops and soils and to establish functional relationships among these variables. This paper describes the development of indices and the partitioning of the spatial and temporal variation in groundwater models using the data from Tulare County, California, which was selected as the study area. Indices of ground surface elevation, total crop water demand, soil water infiltration rate, and soil production index explain 91% of the variation in average spring groundwater level. After relating spatial patterns of groundwater use to indices of crop and soil properties, we found that mean groundwater use is positively related to total crop water demand and soil water infiltration rate while the variation in groundwater use was negatively correlated with the crop water demand and soil water infiltration rate and positively related to soil water holding capacity. The spatial variation in groundwater use was largely influenced by crops and soil types while the temporal variation was not. We also found that groundwater use increased exponentially with decreasing annual precipitation for most townships. Based on these associations, groundwater use in each township can be forecast from relative precipitation under current methods of agricultural production. Although groundwater table depth is strongly affected by topography, the statistically significant indices observed in the model clearly show that agricultural land use influences groundwater table depth. These simple relationships can be used by agronomists to make water management decisions and to design alternative cropping systems to sustain agricultural production during periods of surface water shortages.

Introduction

Landscape ecology is concerned with spatial and temporal patterns and how these relate to ecosystem processes (Levin 1992). The complex interactions between physical and biological processes over time and space in the agricultural landscape are sometimes more difficult to interpret because of human activity (Risser 1987). Most ecological models focused on temporal changes while assuming spatial homogeneity in the landscape (Costanza et al. 1986). Clearly spatial heterogeneity is the norm in agricultural systems, with abrupt discontinuities in crop type, cover, and growth stages among nearby land units. Variation in the agricultural landscape is introduced by microclimate, topography, physical properties of soils, crop diversity, and management patterns (Ryszkowski and Kedziora 1987). Almekinders et al. (1995) showed that poor management of agricultural systems through failure to understand this variation threatens sustainability of the agricultural resource. One approach to characterize and quantify patterns is to use physical indices that simplify spatial and temporal variation and

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integrate complex environmental functions. The objectives of this study were: (1) to derive indices that describe spatial patterns of crops and soil types with regard to water use, and (2) to understand the temporal and spatial relationship of precipitation, groundwater use, crops and soils in the agricultural area by functionally relating these indices to groundwater table depths.

A number of studies used spatial indices landscape patterns in agricultural systems or to contrast them with natural systems (O'Neill et al. 1988; Gustafson and Parker 1992; Hulshoff 1995; Riitters et al. 1995). Medley et al. (1995) used spatial indices in a Geographic Information System (GIS) to examine multi-decadal land use change in an agricultural watershed. Although these and other papers have shown the usefulness of indices to integrate textural properties of landscapes, none has linked physical processes like climate or water use to agricultural landscape characteristics. Understanding environmental processes at a regional scale requires quantification of the spatial and temporal variations in abiotic factors, like precipitation, irrigation, groundwater, and biotic factors like crop water use. The dynamics of spatial and temporal patterns of precipitation and groundwater use in an agricultural landscape is critically important for crop management but difficult to measure or predict with current methods. The integration of these complex phenomena is best described through the development of new quantitative indices and the relationships.

Groundwater is one of the most precious natural resources in California agriculture. Normally, groundwater provides about 40 percent of the State's water supply; during droughts, groundwater may provide up to 60 percent of the supply (California Department of Water Resources 1991). Agriculture usually uses 90% or more of the water supply in California (Howitt and M'Marete 1991). The long and severe drought in California during the period from 1987 to 1993 profoundly affected the water supplies to natural reserve systems, agriculture (crops, livestock, fish and wildlife, and forestry), recreation, municipalities and industry. Groundwater storage, to some extent, delayed the impact of the extended seven-year drought on agriculture until the end of 1990 (Gleick and Nash 1991). California Department of Water Resources (1991) estimated that drought-idled acreage totaled > 184,000 ha in 1991 and that the economic loss in agriculture in 1990 was about \$ 455 million. At the same time, despite less actively farmed acreage than in water abundant years (i.e., during mid 1980s), the groundwater table declined dramatically in the San Joaquin Valley due to over-pumping (Gleick and Nash 1991). For example, Figure 1 shows declines in groundwater table depth for Tulare County. California during the recent drought. Tulare County was selected as our study county and the general information of the county was described in the study area section.

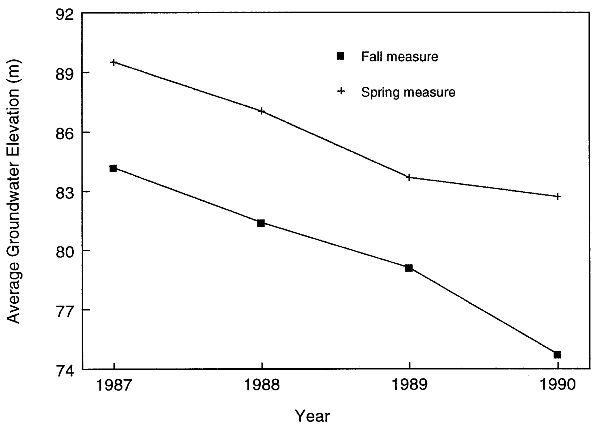

Figure 1. The average groundwater elevations in Tulare County from 1987 to 1990 in spring and autumn.

Declining water levels increase costs because greater energy consumption is required for water dumping. In addition to immediate costs, declining groundwater levels might cause other problems, e.g., land subsidence or intrusion of sea water into fresh water aquifers in coastal regions of California (California Department of Water Resource 1991). However, these are not the immediate problems for Tulare County. Rapid groundwater over drafting and slow recharge have led to significant land subsidence in the past (U.S. Geological Survey 1970; California Department of Water Resources 1974). Parts of the Central Valley, including Tulare County, are potential candidates for subsidence.

Therefore, understanding the dynamics of groundwater movement and its interaction with regional climate is extremely important to sustain ample water resources for agricultural production in a water-limited environment. Because cropping systems and soil types influence groundwater levels, the construction of quantitative indices that describe their spatial patterns are a logical first step in modeling groundwater dynamics (O'Neill et al. 1988; Gustafson and Parker 1992). Such indices quantitatively integrate the interactions from the multiple variables in a system that otherwise make comparisons among complex systems difficult.

Generally, groundwater and rainfall complement each other as irrigation sources (Howitt and M'Marete 1991). Rainfall directly contributes to available surface water. Because surface water is the main irrigation source, groundwater has to be pumped to meet water demand if surface water is limited. Therefore, groundwater pumpage is inversely related to rainfall without additional surface water supplies. Moreover, precipitation intensity also affects the groundwater recharge rate (Water Resources Center of the University of Minnesota 1983). Similar patterns were observed by Boone et al. (1983) in the eastern Sierra Nevada. Computer and statistical techniques are often applied to management problems related to groundwater use (Andersson and Sivertun 1991; Barringer et al. 1987; Tan and Shih 1990).

Hydrologic inputs originate from precipitation, stream flow, and irrigation while system outflows are derived from evapotranspiration, runoff, and subsurface/groundwater flow. A complete water budget for each township in the agricultural region of Tulare County would include all water inputs and outflows as follows:

$$\mathrm{I} + \mathrm{P} + \mathrm{GW}_{\mathrm{in}} - \mathrm{GW}_{\mathrm{out}} + \mathrm{Pump}_{\mathrm{in}} - \mathrm{Pump}_{\mathrm{out}} - \mathrm{ET} = \Delta \mathrm{S}_{\mathrm{gw}} + \Delta \mathrm{S}_{\mathrm{unsat.\ zone}}$$

where I is irrigation supplied from canals plus groundwater sources, P is annual precipitation, GW is the groundwater flow into and out of the township, Pump is the groundwater pumpage in and out of the township, ET is actual evapotranspiration, estimated for each crop weighted by area. ΔS_{gw} is the change in groundwater storage over the season and $\Delta S_{\mathrm{unsat.\ zone}}$ is the change in water storage in the unsaturated zone. In formulating this relationship we assumed that the lateral groundwater transport between townships for this study is near zero, the net seasonal pumpage is near zero, and the change in water storage in the unsaturated zone is also near zero. Therefore the equation can be simplified as:

$$\mathrm{I} + \mathrm{P} - \mathrm{ET} = \Delta \mathrm{S}_{\mathrm{gw}}$$

To maintain ET when I and P are limited, such as during drought conditions, groundwater storage must decrease, i.e., ΔS_{gw} is negative. The water is pumped out of the groundwater storage and into the cropping systems. Thus, ET and ΔS_{gw} will cancel. In this system, we had direct monthly measures of precipitation but no independent measure of irrigation and surface (canal) flows, which requires flow gauges on the wells or irrigation channels. In terms of outflows, we have seasonal estimates of potential evapotranspiration for specific crops in Tulare County, but no direct measure of runoff or subsurface flow. Because of the relatively flat topography, we assumed that there was minimal net seasonal lateral surface and subsurface flows between townships. This provides a boundary condition for the assumption that the seasonal ratio in groundwater depth (spring groundwater depth/autumn groundwater depth) is due to irrigation pumpage. As stated before, groundwater use ranges between 30–90% of the total evapotranspiration demand, depending on the availability of surface water.

Materials and methods

Study area

The 384,460 ha irrigated agriculture (Figure 2) of the western part of Tulare County (35–36 ° N, 118–119 ° NW), California, was chosen for this research because of its high agricultural productivity, the diversity of its agricultural commodities and its dependence on summer irrigation. The county is located in the southeast San Joaquin Valley and produces more than 44 commodities (Tulare County 1990). The terrain is largely flat valley bottom land although the eastern side of the agricultural land marks the transition into the lower foothills of the Sierra Nevada range, which are managed as rangeland. The Kaweah and Tule are the major rivers of the county, both running across the county from the Sierra Nevada range on the east to the San Joaquin River on the west. The Friant-Kern irrigation canal runs through the valley floor, from north to south, in the center of the agricultural region. About 90% of the land has less than 6% slopes with an additional 24,282 ha of rolling land between 6 and 20% slopes. All land in 47 townships is used for agriculture. The average distance to surface water varies depending on the distance to the rivers or the canal. Average annual precipitation in the county is 268 mm while water use is about 1062 mm. During the 1987–1993 drought period, groundwater use accounted for 70 to 90% of the total water consumption in the county, while only 33% of the water supply is from groundwater in normal years (Curtis 1988).

The township was chosen as the base mapping grid unit for Tulare County due to the resolution of the available data; well site and other point data were aggregated to townships for statistical analysis. Townships are a common administrative unit in the western

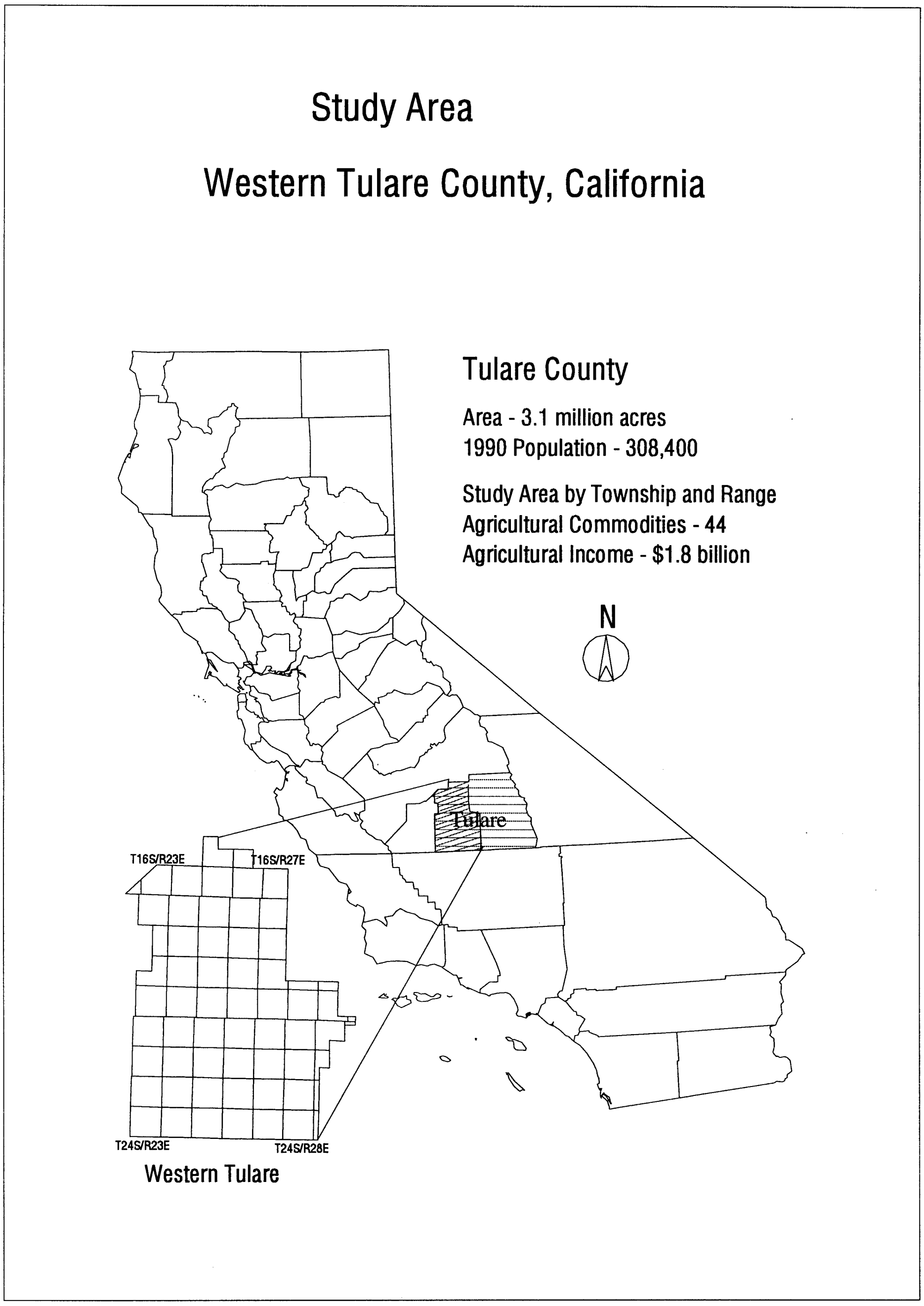

Figure 2. Study area of Tulare County, California. Map also shows the distribution of townships as each grid (9.8 m^2 in size) in the county.

United States which are a survey grid of 9.8 km^2 ($\sim$6 mi^2) numbered from a north-south base line and an east-west meridian. Each township and range (square grid shown in Figure 2) is further divided into 36 subgrid sections ($\simeq$0.27 km^2) ($\sim$1 mi^2). In addition, most public and private U.S. agencies that collect and maintain agricultural databases use the township as their base unit for their studies.

Data sources

U.S. Bureau of Reclamation data on groundwater elevation (ground-to-water depth distance) between 1970 and 1990 were obtained for 1219 wells in unconfined aquifers. The number of wells per section ranged from a minimum of 3 to close to 100, mostly from 20–40. These wells were distributed over the agricultural region with higher densities in the east and fewer wells in the west. The data were screened for outliers (Rousseeuw 1987) and small sample size before the analysis. Wells with < 9 years continuous measurements were omitted from the data set (< 100 wells were eliminated). Land use maps (1:24,000) for 1985, were interpreted from aerial photos, obtained from San Joaquin Water District, California Water Resources Department. Though crop types could vary from year to year, the cropping system in Tulare County is rather stable due to the perennial orchard and vine crops, large scale of farming, and irrigation systems. Interannual cropping patterns are largely driven by the available water supply. Therefore, the land use map was used to estimate crop type distribution for the study. Soil maps (1:63,360) were obtained from the University of California Cooperative Extension, Tulare County. Approximately 92 soil types occur in the agricultural region of the county. The descriptions of depth, moisture content, and the production index of soils were obtained from the soil database. Twenty years monthly mean precipitation data were obtained from Tulare County weather stations (five stations are located in the valley – Delano, Lemon Cove, Lindsay, Porterville and Visalia, and two stations in the foothills – Ash Mountain and Grant Grove). These seven weather stations are representative of the county and used to compute the County precipitation average. The precipitation values are similar among the valley stations and somewhat higher at the two foothill stations. Because spatial variation in precipitation is small, the county average was used for all the townships. Crop evapotranspiration information was obtained from the California Department of Water Resources (1974) and University of California Cooperative Extension (1990) and were used to estimate crop water demand in the county.

Methods

Frenzel (1985) reviewed three methods for estimating groundwater pumpage: from relationships between volume of water pumped and power consumption at the wells, from estimates of crop-consumptive use, and from measures of instantaneous discharge. Although these measures provide accurate estimates for individual wells, because of the small number of wells where these data are recorded, we could not develop spatial estimates of volume of water pumped. Instead we used a surrogate measure, the change in water table depth between spring and autumn. Such an estimate is possible because of the negligible summer precipitation in California. The quantity of groundwater pumpage (GWP) was measured as the ratio of ground-to-water depth in the autumn to ground-to-water depth in the spring of the same year. A value > 1 indicates extensive groundwater pumpage; a value of ≈ 1 indicates that little or no net groundwater was pumped; and a value of < 1 shows that more surface water percolated into the groundwater than was used, which for irrigated agriculture indicates that more water was applied than required to replace water lost by ET (evapotranspiration), assuming that all other pathways of water transport are minimal. The irrigation sources can be from both surface water and groundwater depending on the weather conditions of the year. Relative precipitation (RP) is the ratio of the average annual precipitation of the year i to the 20 year average. A value of 1 represents average rainfall, < 1 indicates a dry year below the long-term average, and > 1 indicates a wet year. The relative precipitation indicates the proportion of average rainfall.

Both land use and soil maps were digitized using the ARC/INFO GIS (ESRI 1990). TINLATTICE surface modeling with 200 m grid-cell resolution used to interpret the groundwater level in Arc/Info GIS. Analyses of variance were performed to determine the variation in groundwater level between years within townships, and between townships within years. Using these results, the total variance in the groundwater level for each season was partitioned into temporal and spatial components. The average groundwater pumpage (or groundwater use) for a township was estimated from the ratio of seasonal groundwater table depth over 20 years. The variance around the mean groundwater pumpage was partitioned into temporal and spatial components. Finally, multiple regression analysis was used for model development. Temporal variation in a township was also characterized by the regression coefficients. The integration of temporal and spatial variation in the water use was depicted by a secondary correlation among the regression coefficients, mean groundwater pumpage and the indices of crops and soils. Because of the county topography, east-west, north-south trends were examined for the parameters in the study. East-west trend is related to elevational gradient in the groundwater flow direction and north-south trend is somewhat related to the availability of survey water, because the location of the Central Valley Project canal, the primary source of irrigation water, runs from north to south across the County.

Results and discussion

Indices for quantifying agricultural landscape processes

The first step in the analysis was to relate water use and crop and soil water related properties in Tulare County. The indices describing crop and soil types were derived from spatial distributions of land use and soil type maps in the ARC/INFO GIS database. The definitions and formulas of the indices are summarized in Table 1. These indices are described in more detail below.

Crop indices
The 1985 land use map is shown in Figure 3. The crops were more dense and diverse (number of crops/ha) and field size was smaller in the northwest. Because of the relatively uniform and low relief terrain, the different cropping patterns observed across the county may primarily relate to the availability of surface water and the soil hydrologic properties. Spatial distributions of orchards and vineyards are consistent between years. Changes in row crop distribution are expected between years although the number of planted hectares per crop is relatively consistent from year-to-year. Two representative transects, located near the central axis of the grid, were selected for comparison across the major topographic and cropping gradient in the county. The relative number of crops (R) was the ratio of the actual number of crops grown in a township to the number of crops grown in the county. Only actively farmed acreage was included. Urban areas, farmstead, dairy and feedlots, and all abandoned crop lands of each township were excluded. The relative number of crops, highest in the northwest, decreased from north (Township 15S) to south (Township 24S). The relative number of crops increased from west (Range 23E) to east (Range 26E), then decreased east of Range 27E and 28E (Figure 4a). The percent crop coverage in a township (AC) was the sum of the area of each crop divided by the total township area. The percent crop coverage was higher in the middle of the county, but for all townships, the percent crop coverage was much higher in Range 23E to 26E than farther east, at Range 27E and 28E (Figure 4b).

Crop water demand was based on the crop type and total acreage for each type following the relationship defined in Table 1. Relative total crop water demand in a township (TWD) was estimated from the summation of the ratio of crop water demand to the maximum water demand of a crop grown in the county (California Department of Water Resources 1974). The relative total crop water demand decreased southward across the county and increased eastward up to Range 26E, but decreased afterwards (Figure 4c). Ground elevation decreased westward while changing slightly southward (Figure 4d). These patterns correspond with the topographic features in the county. Lands in the west and central part of the county have a higher relative number of crops, higher percent crop coverage, a greater diversity index, and have the highest relative total crop water demand. This pattern may occur because those townships are closer to surface water sources, receive more abundant water for irrigation, and have highly productive soils as indicated by soil production index.

Examining the correlation coefficients among the indices showed ground elevation was negatively correlated with percent crop coverage ($r = -0.47$, $p < 0.01$) and soil water holding capacity ($r = -0.65$, $p < 0.01$), while ground elevation was positively correlated with total crop water demand ($r = 0.42$, $p < 0.01$) and soil infiltration rate ($r = 0.30$, $p < 0.05$). Because of the crop type differences, the total crop water demand was correlated with the percent crop coverage ($r = 0.47$, $p < 0.01$), but not as strongly compared to the relative number of crops ($r = 0.94$, $p < 0.01$). Figure 4 showed similar directional trends for the relative number of crops and total crop water demand (Figure 4a, 4c), while percent crop coverage had a different directional distribution (Figure 4b). Generally, relative numbers of crops and crop total water demand decreased from north to south and increased from west to east up to Range 26 east and then decreased after that. Values for each township were based on summarizing all the ranges across the township (usually Range 23E to Range 27E; refer to the county township grid for sample size).

Soil indices
Soil water holding capacity for each soil type was estimated from soil moisture contents for each layer and soil depth (Roe 1950). The total soil water holding capacity (SAWT) in a township was summed from each soil type in a township and weighted by its area. The soil water holding capacity increased from west

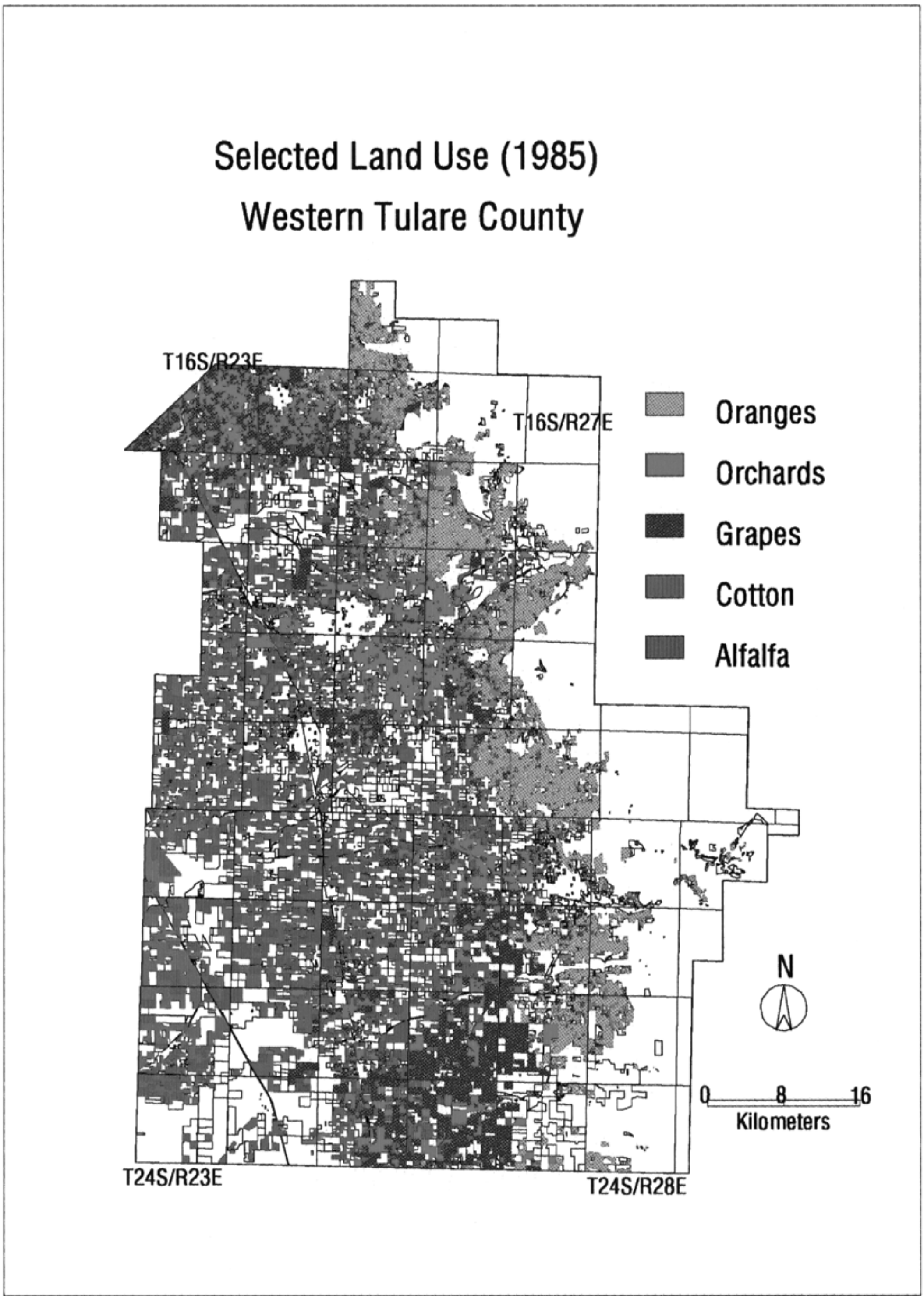

Figure 3. Land use map of major crop type distributions in 1985 for Tulare County. Although many commodities are grown in the county, these represent a small proportion of the total acreage. Water use requirements generally follow patterns similar to one of these general crop types.

Table 1. Main indices of crops and soils with regard to water in a township.

1.	Relative number of crops (R)	$R = \frac{S}{S_{max}}, S = \Sigma I_i$	where S is the number of the crops in a township and S_{max} is the maximum number of commodities in the county I = 0, 1; i = 1,... n crops.
2.	Percent crop cover (AC)	$AC = \sum \frac{Ci}{TA}$	where C_i is the area of *i*th crop, and TA is the area of a township.
3.	Relative total crop water demand (TWD)	$TWD = \sum \left[\frac{CWD_i}{CWD_{max}} * I_i \right]$	where CWD_i is the annual water of *i*th crop in a township, and CWD_{max} is the maximum water demand of a crop in the county.
4.	Soil water holding capacity (SAWT)	$SAWT = \frac{\Sigma SAW * SA}{\Sigma SA} * 2.54$	where SA = the area of each soil type;
			SAW = soil water holding capacity for each soil type;
			M_{eq} = the moisture equivalent at a soil depth;
		$SAW = \frac{(M_{eq} - W_p) * A_s * D_s}{100}$	W_q = wilting coefficient ($W_q = M_{eq}/1.84$);
			A_s = apparent specific gravity;
			D_s = thickness of soil horizon, cm;
			and
		$A_s = 2.65 \left(1 - \frac{S}{100}\right)$	S = soil pore space.
		$S = 27 + 0.7M_{eq}$	
5.	Soil production index (SPIT)	$SPIT = \frac{\Sigma PIN * SA}{\Sigma SA}$	SPIT is the soil production index in a township where PIN is the production index of each soil type.
6.	Soil water infiltration rate (SIRT)	$SIRT = \frac{\Sigma IR * SA}{\Sigma SA}$	SIRT is the soil infiltration rate in a township where IR = water infiltration rate of a soil type.

to east across Township 15S to 24S, while it decreased from Range 23E to 26E and then increased westward (Figure 4e). It is clear that highest soil water holding capacity occurred in the eastern part of the county agricultural land. Higher soil water holding capacity was found in the southwest area than on the east side of the county. The soil water infiltration rate in a township (SIRT) was weighted by area and estimated based on the water infiltration rate for each soil type. The spatial patterns of soil water infiltration rates were inversely related to soil water holding capacity. Higher soil water infiltration rates occurred in the northeast. The potential infiltration rates decreased between Township 15S to 24S, and increased from Range 23E to 28E (Figure 4g). The weighted soil production index (SPIT) in a township was estimated without considering possible soil salinity. Higher values of the soil production index were found in the western and the central parts of the county (Figure 4f). Soil production index was not correlated with soil water holding capacity, but negatively correlated with soil infiltration rate ($r = 0.42$, $p < 0.01$).

Table 2 shows the range of the values of each index and most of the indices (relative number of crops, total crop water demand, and soil water holding capacity) had normal distributions. However, the values of some indices such as percent crop coverage in a township was uniformly high at Range 26E. These values ($AC \approx 0.7$) indicated that the crops in most townships were equally intense in terms of water use (Figure 4b). Not all indices were independent of each other and to a certain extent overlapping or redundant information. Based on the correlation coefficients of the indices, the representative indices (ground elevation, total crop water demand, the soil production index, and soil water infiltration rate) were selected as the most independent (although not completely orthogonal) for further analyses with regard to water use and groundwater model development.

Other authors have developed integrated indices of spatial variables to describe complex phenomena. For example, Hulshoff (1995) found combined indices provided more meaningful information about landscape structure in an intensively managed agricultural system than single indices. Riitters et al. (1995) found six orthogonal factors that integrated 26 spatial metrics and accounted for 87% of the variation in landscape structure and condition. These studies provides justifications for the approach to developing simple multivariate factors to represent the more complex landscape functions. Furthermore, our result on integrated crop and soil indices combined with the topographic elevations, support findings of Medley et al. (1995) who observed that local farm level practices,

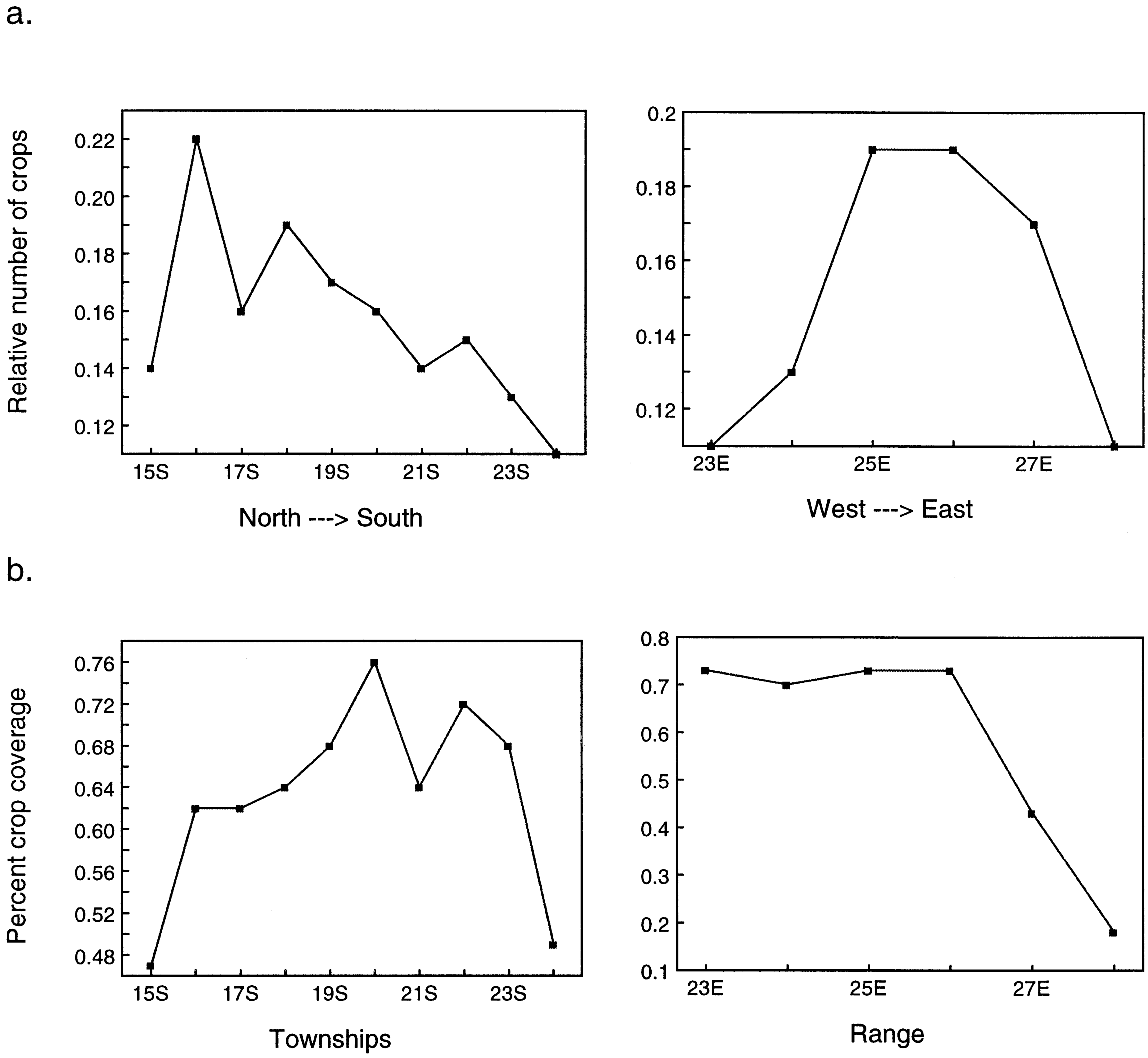

Figure 4a,b. Spatial distribution of several physical variables across the townships (north-south direction) or ranges (west-east direction) in Tulare County. a. Relative number of crops grown per township. b. Percent crop cover.

Table 2. The basic statistics of the indices

Indices	N	Minimum	Maximum	Mean	Standard deviation
Ground elevation (m)	47	60.00	187.00	105.00	31.0
Relative number of crops (unitless)	47	0.04	0.29	0.15	0.06
Percent of crop cover (% cover)	47	0.11	0.93	0.65	0.24
Total crop water demand (unitless)	47	3.51	21.87	13.19	4.74
Soil water holding capacity (cm)	47	2.63	12.22	7.36	1.93
Soil production index (unitless)	47	0.23	0.86	0.50	0.17
Soil water infiltration rate (cm/hr)	47	0.81	15.30	4.27	3.23

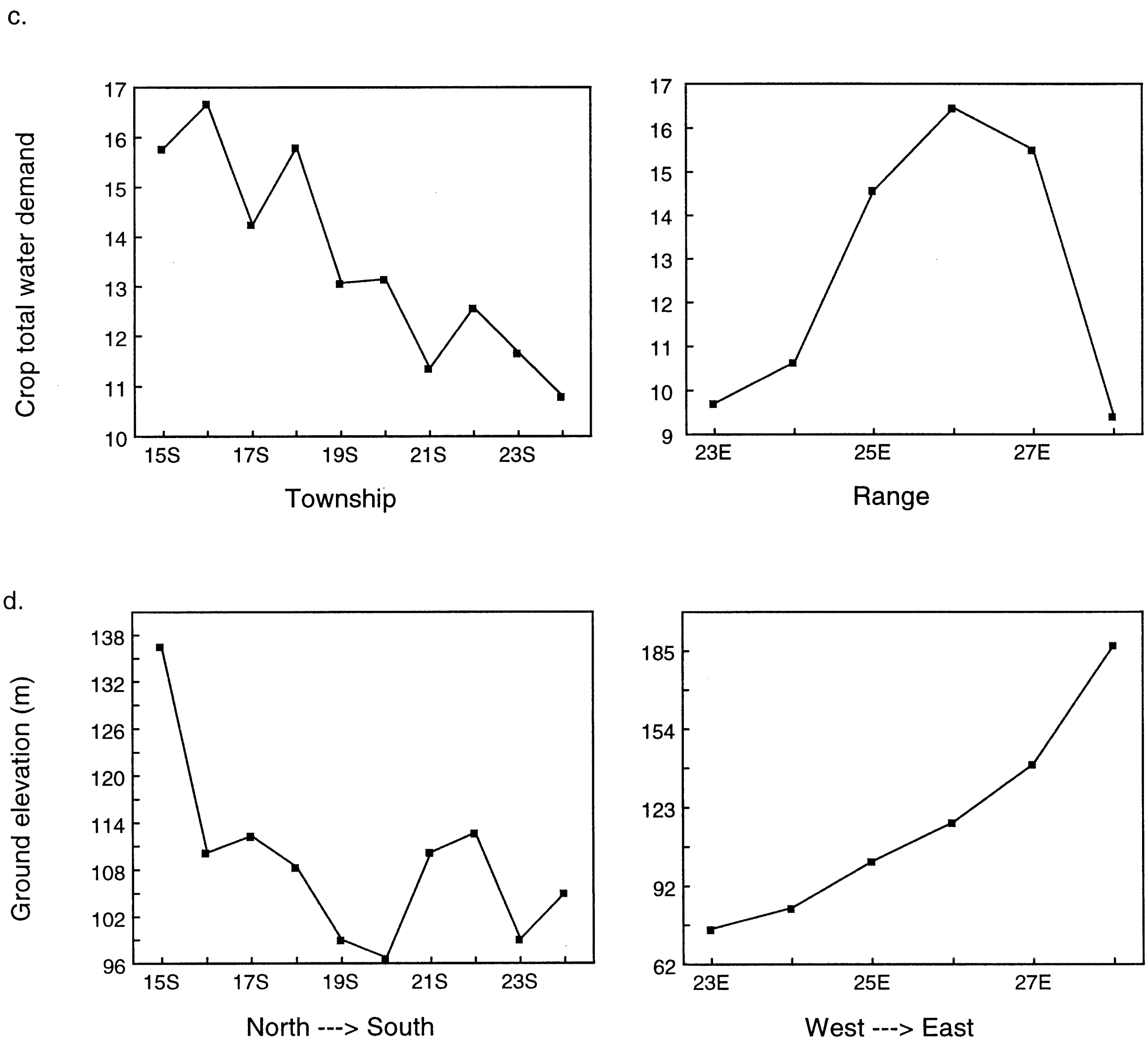

Figure 4c,d. Spatial distribution of several physical variables across the townships (north-south direction) or ranges (west-east direction) in Tulare County. c. Relative total crop water demand. d. Ground elevation.

combined with regional climate variation were more closely linked to landscape patterns than patterns were to socio-economic factors or governmental policies.

Groundwater depth and crop/soil relationships

The two-way analysis of variance showed that both sources of variation between townships (spatial variation, $F = 1392,66$, $p < 0.01$) and between years (temporal variation, $F = 142.33$, $p < 0.01$) were significant for groundwater levels. The spatial variation showed that the groundwater level changed at the scale of the township. Many factors contributed to spatial variation, including different soil depth and texture characteristics, cropping systems, and ground elevation in each township. Because variation in interannual rainfall and the rates of groundwater pumpage, the groundwater level changed significantly between years. Analysis of variance for interannual variation within townships indicated that 33 out of 47 townships had significant yearly variation in groundwater level at least at the 5% level. The significant variation in interannual groundwater variation was evident even with the large inter-township variation.

The townships with non-significant interannual variation were analyzed for soil types, cropping systems and/or topographic elevation patterns. Table 3 shows the average values of indices having significant and non-significant yearly variation in the ground-

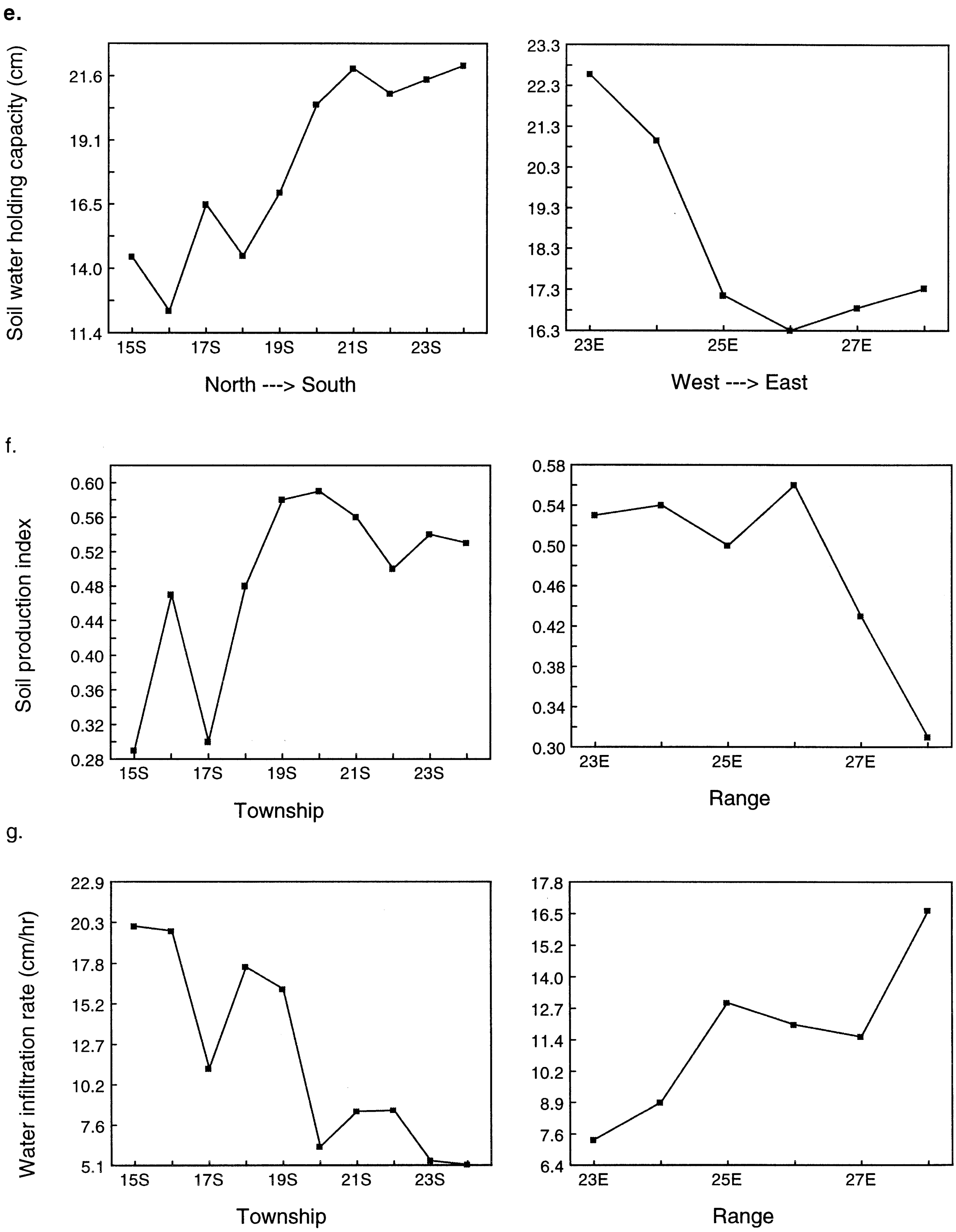

Figure 4e,f,g. Spatial distribution of several physical variables across the townships (north-south direction) or ranges (west-east direction) in Tulare County. e. Soil water holding capacity. f. Soil production index. g. Soil water infiltration rate.

Table 3. The average values of indices calculated using a significance level criterion (5% or non-significant) in yearly variation in groundwater depth using data from spring ground-to-water depths as an example. Refer to Table 1 for definitions of the indices.

Indices	Yearly variation, sign. at 5% level	Non-sign.
Ground elevation (m)	106.5	130.3
Percent crop cover (%)	0.76	0.40
Total crop water demand (unitless)	14.35	10.45
Soil water holding capacity (cm)	17.5	22.1
Soil production index (unitless)	0.6	0.6

water level. These selected indices represented crops and soil water characteristics. More townships with non-significant variation were located along the Sierra Nevada foothills or close to the foothills on the east side of the agricultural region where ground surface elevation was somewhat higher. Less groundwater was pumped in these townships as the land was more frequently managed for grazing and rangeland than irrigated agriculture. The distribution of citrus seen on Figure 3 marks the transition between the agricultural lands of the valley floor and the foothills. These eastern Tulare County townships have soils with low production index values and reduced crop coverage, hence lower water demand. In the southwest corner of the county, heavy clay soils were found in some townships having non-significant index values. These soils have better water holding capacity but the soil production index is lower, thus crop coverage was smaller for these townships, and water demand was less than average. Thus, sites with non-significant interannual variation in groundwater table depth were those with less water demand.

Generally, the twenty-year average groundwater level in the spring is lowest in the southwest and the southern part of the county (Figure 5a). Spatial patterns in autumn are similar to spring, but the water table is lower. This observation may result from a combination of lower surface water availability, groundwater flow patterns, which are generally from the east to the west, and local topographic elevation. The townships in the southwestern regions are furthest away from local rivers and streams and the Central Valley Project canal, therefore, less surface water is available than townships located in the eastern and the middle parts of the county. This suggests that in the southwestern part of Tulare County, less groundwater is recharged from rivers, streams and unlined water canals than other parts of the county.

The correlation analysis showed that average groundwater level was positively correlated with ground surface elevation ($r = 0.78$, $p < 0.001$), total crop water demand ($r = 0.41$, $p < 0.01$) and water infiltration rates ($r = 0.57$, $p < 0.01$) but was negatively correlated with percent crop coverage ($r = -0.40$, $p < 0.001$), soil water holding capacity ($r = -0.51$, $p < 0.01$), and soil production index ($r = -0.37$, $p < 0.01$). Similar patterns have been reported by Ryszkowski and Kedziora (1987) for agricultural sites in Poland. The interannual direction of groundwater flow was from higher elevations in the east to the lower elevations in the west, so groundwater levels increased with elevation. Because groundwater is mainly recharged through irrigation return flows (Schmidt 1987), larger soil water infiltration rate and total crop water demand contribute to the higher groundwater table.

Average groundwater level in spring was predicted from ground surface elevation, total crop water demand, soil production index, and water infiltration rate in soils ($R^2 = 0.91$). The model used standardized regression coefficients (which were adjusted by variation in groundwater levels by the direct contribution of each independent variable to the dependent variable) as:

$$\text{Groundwater level} = 0.709\text{AVGELEV} + 0.1811\text{TWD} - 0.106\text{SPIT} + 0.199\text{SIRT}.$$

The coefficients indicated that the average groundwater level increased when ground surface elevation, total crop water demand and the water infiltration rate in soils increased. The average groundwater level decreased when the soil production index increased. The ranked magnitude of contribution to the groundwater depth were ground surface elevation, water infiltration rate in soils, total crop water demand, and the soil production index. The tolerance value (an indicator for acceptance of the model) for each variable in the model is greater than 0.6, which is acceptable (the minimum acceptable value is 0.1) (Draper and Smith 1981). Therefore, the spatial groundwater levels in Tulare County were satisfactorily predicted from the multiple regression equation relating elevation, crop water demand, and soil properties (Figure 5b). The close spatial patterns of Figure 5a and Figure 5b demonstrate the ability of the model to closely predict spatial distributions of groundwater level consistent

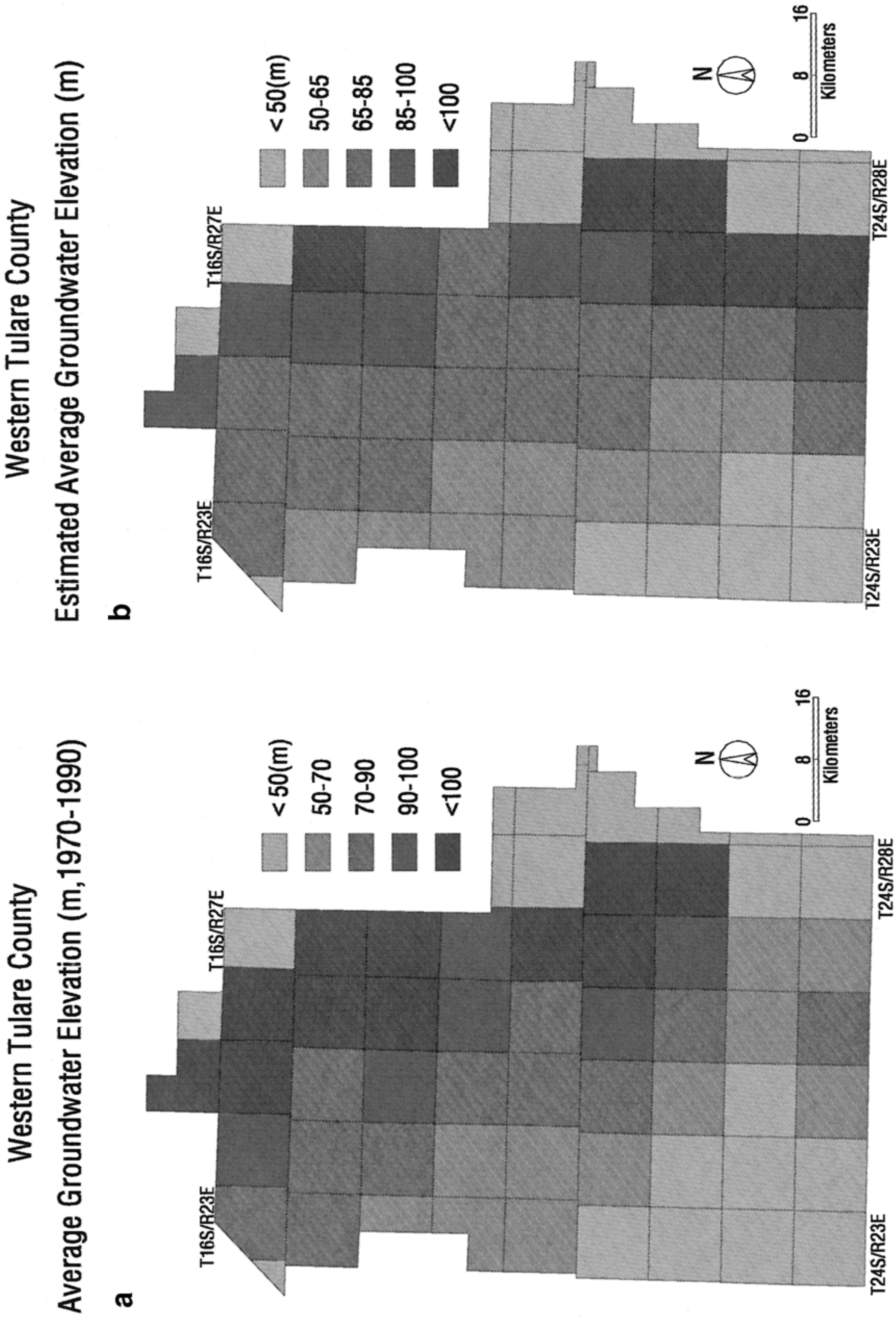

Figure 5. a. Average groundwater elevation (m, 1970–1990). b. Estimated average groundwater elevation (m).

with the measured groundwater levels. This spatial information should be useful reference for predicting potential problems associated with unusually high or low groundwater levels and allow managers to plan alternatives.

In addition, the standard deviation of variation in groundwater level was positively correlated with ground surface elevation ($r = 0.5$, $p < 0.01$) but negatively correlated with the percent crop coverage ($r = -0.29$, $p < 0.05$), total crop water demand ($r = -0.34$, $p < 0.01$), and water infiltration rate ($r = -0.32$, $p < 0.01$). Despite the relatively low proportion of the total variation explained by each of the variables, a clear pattern emerged. The total variation of groundwater level was not only influenced by ground surface elevation, but also affected by crop conditions and soil types.

After partitioning the spatial variance component of groundwater, the temporal component of groundwater level variation was related to the ground surface elevation ($r = -0.63$, $p < 0.01$), the percent crop coverage ($r = 0.59$, $p < 0.01$), total crop water demand ($r = 0.56$, $p < 0.01$), and the soil production index ($r = 0.57$, $p < 0.01$). The spatial variation within a township was correlated with ground elevation ($r = 0.54$, $p < 0.01$), the percent crop coverage ($r = -0.32$, $p < 0.05$), and total crop water demand ($r = -0.37$, $p < 0.05$). In other words, crop cover and topography in a township appear to be the principal factors determining temporal variation in groundwater level. Soil water holding capacity and water infiltration rates within a township did not exhibit much variation. In summary, the average groundwater level increased with increased water infiltration rates and with elevated topography, and decreases with increasing crop water demand. The variations in groundwater level among townships were largely determined by crops and ground surface elevation.

Patterns of groundwater use

The next step of this study was to relate groundwater use with precipitation patterns in Tulare County. The average groundwater pumpage in the county varied annually (Figure 6), depending on the availability of surface water supply. During dry years, the relative average groundwater pumpage increased, such as values of 1.30 for 1977 and 1.31 for 1990 as shown in Figure 6a. During wet years, groundwater pumpage was minimal and excess surface water irrigation was sufficient to partially recharge the

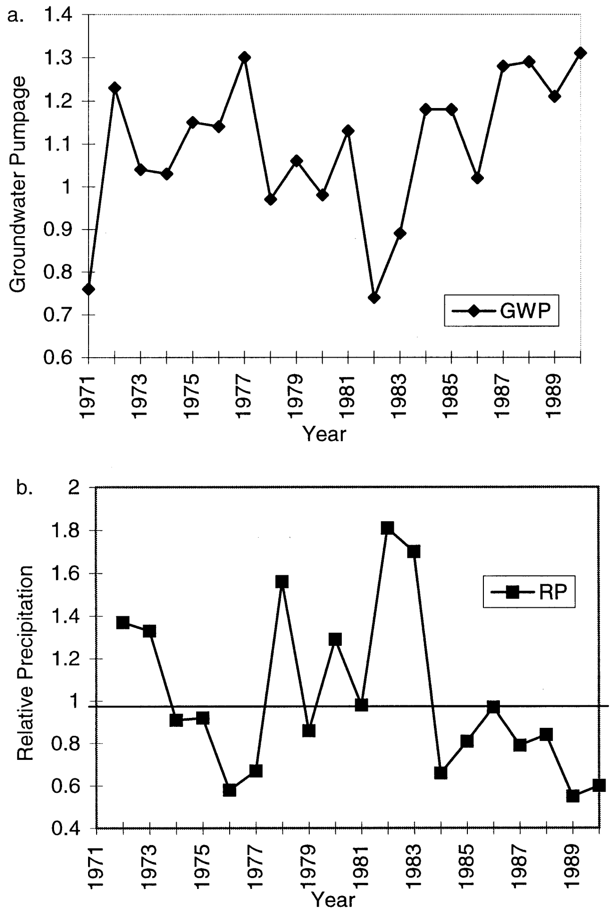

Figure 6. a. The average annual groundwater pumpage (GWP), b. Relative precipitation (RP).

groundwater (Howitt and M'Marete 1991). Although interannual variations in groundwater pumpage differed among townships, the 20 year averages were similar except for Townships 23S and 24S. The average groundwater pumpages were always highest for these two townships because surface water was less accessible to them.

The average groundwater pumpage was positively correlated with average ground elevation ($r = 0.34$, $p < 0.05$) and total crop water demand ($r = 0.35$, $p < 0.05$), but negatively correlated with soil water holding capacity ($r = -0.36$, $p < 0.05$). In other words, groundwater pumpage was greater when crop water demand was higher and/or soil water holding capacity was lower. The relatively low, but significant correlation coefficients were possibly due to the complex water transport systems in the agricultural landscape. However, the townships having significant coefficients indicated that the groundwater pumpage was mediated through crop water use and soil types in this agricultural landscape system.

The standard deviations (STD) of the average groundwater pumpages were negatively correlated with the relative number of crops ($r = -0.31$, $p < 0.05$) and crop total water demand ($r = -0.33$, $p < 0.05$), but positively related to soil water holding capacity ($r = 0.22$, $p < 0.1$). Thus, townships with diverse crops, higher crop water demand, and sandy soils pumped more water each year than townships with fewer crops, low water demand, and clay soils. The effect of crop and soil properties on the magnitude of groundwater pumpage variation, in contrast to the sign of variation, is opposite to this pattern. These results are consistent with accepted management practices for groundwater pumpage, supporting the validity of the constructed indices (Almekinders et al. 1995).

For each township, the variance of average groundwater pumpage was further partitioned into year-to-year variance (STD between years, temporal component) and site-to-site well variance (STD within townships, spatial variation within township) components. The temporal variance component of groundwater pumpage was negatively related to average ground surface elevation and total crop water demand ($r = -0.3$, $p < 0.10$). The within township spatial variance in groundwater pumpage was negatively correlated with the relative number of crops ($r = -0.33$, $p < 0.05$) and crop total water demand ($r = -0.38$, $p < 0.01$), and was positively correlated with soil water holding capacity ($r = 0.47$, $p < 0.01$). Therefore, a combination of crops and soil types are critical elements in determining the spatial variation in groundwater pumpage within townships. However, less temporal variation in groundwater pumpage was found for areas of higher ground surface elevations close to the mountains where surface water was more available and where crop production was less intense. In summary, the average groundwater pumpage increased when surface water availability decreased and where total crop water demand by crops was high. Larger soil water holding capacity is associated with larger variations in pumping. The sign of the correlations between average groundwater pumpage and the indices was opposite to the sign of the correlations between the variation in groundwater pumpage and the indices. Thus, as mean groundwater pumpage increases, the interannual variation in pumpage decreases.

We also investigated the variation in groundwater pumpage and precipitation. The long-term (40 year) mean annual precipitation in the valley floor of Tulare County is 268 mm, with a high of 508 mm and a low of 75 mm and a standard deviation 90 mm. Relative precipitation for the period of 1970 to 1990 is shown in Figure 6b. In about a third of the years of record, the relative precipitation was greater than 1, and in almost a third of the years it was below 0.8.

During the critical drought years, groundwater pumpages increased significantly to meet the water demand when precipitation decreased. The exponential function

$$\mathrm{GWP} = \mathrm{b}_0 \mathrm{e}^{(-\mathrm{b}_1\mathrm{RP} - \mathrm{b}_2\mathrm{RP}^2)}$$

describes the relationship between groundwater pumpage (GWP) and relative rainfall satisfactorily for most townships based on a Mean Square Error (MSE) criterion (Myers 1987). In the equation, b_0, b_1 and b_2 are the exponential regression coefficients and RP is the relative precipitation. The coefficient, b_0, in the model estimates the maximum groundwater pumpage in the township when $e^{(-b_1RP-b_2RP^2)} \leq 1$, where RP $\leq -b_1/b_2$. Because the values of relative rainfall were between 0.6 and 1.8, any rainfall value below 0.6 implies that b_0 does not represent the maximum value of GWP. Therefore, in some townships (8 out of 47), b_0 has no meaning regarding the maximum groundwater pumpage. Moreover, RP for a maximum value of GWP was at $-b_1/2b_2$. This solution was estimated when the first derivative of the function was set to zero and the second derivative of the function was negative. GWP had a minimum value at the value of RP when the second derivative was positive. Therefore, the derivatives produced two types of curves between GWP and RP.

Relating these regression coefficients to the indices of crops and soils, the maximum pumpage (b_0) increased with increasing relative number of crops ($r = 0.3$, $p < 0.05$) and total crop water demand ($r = 0.3$, $p < 0.05$) in a township. The coefficient, b_0, for those townships when RP < 0.6 (i.e., where b_0 did not estimate the maximum groundwater pumpage) did not correlate with any indices. These results support the expectation that a larger number of high water demand crops require greater water use, and possibly leads to greater maximum groundwater pumpage when surface water supply is limited.

Conclusions

Efficient water use and conservation requires irrigation scheduling with consideration of specific crop water demand and soil-water properties. Therefore, to reduce groundwater pumpage we must understand the interactions among the major factors influencing water use in agriculture. Because of the large spatial scale and long temporal periodicity of groundwater systems, conservation of water resources requires an integrative approach. Information technologies such as Geographic Information System (GIS) used in this analysis can not only provide spatial water crop and soil data which are not readily available, but assist in local and regional management decisions on crop irrigation scheduling. One issue in using a GIS approach is the appropriateness of the data resolution to the models being applied. Since environmental processes are scale dependent, aggregating at the township level may not be appropriate nor may be aggregating at seasonal and interannual comparisons (Levin 1992). Pierce and Running (1995) examined the impact of aggregation on the prediction of net primary productivity in grasslands and forests and showed relatively better fits when models are run with DEMs, climate, and leaf area index resolved at fine spatial scales (e.g., 1 km^2 vs. 10 km^2 or more) and longer temporal periods (e.g., annual vs. daily, weekly or monthly). Sections approximate this spatial scale and time periods were biannual or interannual. Ryszkowski and Kedziora (1987) also show that energy flux estimates are higher and more realistic when calculated for smaller individual ecosystems than for entire watersheds or landscapes. Although individual farm units may be larger than sections and less than a township, the aggregating of major crops distributions in Tulare County (Figure 3) suggests that the township scale is realistic for land cover classes. Because the availability of the data and common unit of township by government agencies, these findings support the appropriateness of the scales used in this study.

The soil and crop indices we developed provided useful expressions that integrated crop water use and soil-water properties. Although conceptually similar to integrated indices like those of Riitters et al. (1995) and Hulshoff (1995) this study related spatial and temporal patterns of water availability and use rather than structural land use patterns. This study also demonstrated an integrated analysis between GIS and statistical methods at a regional scale, and provided an approach to the landscape ecology of agricultural systems. Use of the indices provides simple measures to evaluate the seasonal and interannual impact of changing water demand and use in a complex spatial landscape. Such measures can be used to develop site specific management of agricultural systems.

Through derived indices, we found that the groundwater table depth can be predicted at an accuracy of 91% through knowledge of topographic elevation, total crop water demand, soil infiltration rate, and soil production rank. Groundwater use can be predicted through an exponential function defined by relative annual precipitation for each township. Townships with diverse crops, higher crop water demand and sandy soils consistently pumped more water each year than townships with fewer crops, low water demand, and clay soils while the effects on the variation of groundwater pumpage is just the opposite. The rate of groundwater use can be estimated from the relationships between crop water, soil water holding capacity and ground surface elevations.

These results demonstrate that a better understanding of the interactions among cropping systems and soil types can be used to predict spatial and temporal variation in groundwater dynamics. Over-pumping of groundwater in Tulare County, especially during consecutive drought years, may lead to a serious depletion of groundwater resources. Better management methods are essential to understand these dynamics. Information on this spatial distribution of groundwater table depth, may suggest sites and conditions where alternative cropping systems should be used to avoid the risk over-pumping groundwater during droughts. Where groundwater tables are high, farmers can use groundwater as a sustainable resource to alleviate drought without changing cropping patterns. Because of the long-term consistency in groundwater elevation, it should be possible to predict the magnitude of interannual and seasonal groundwater availability on a township and estimate long-term impacts on groundwater resources. It is clear that sustainable agriculture and environmental quality depend on a balance among the physical and biotic agricultural landscape elements.

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