A conjunctive use model for the Tule River groundwater basin in the San Joaquin Valley, California

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Abstract A conjunctive use model of the Tule River basin, California, USA, has been developed. We present the conceptual model of the basin hydrology and hydrogeology, and a description of the model components consisting of geographical information system (GIS)-based surface water and land-atmosphere interface and unsaturated zone (LAIUZ) models, and a GIS-linked groundwater flow model. The surface water model computes surface water allocations to each district and aquifer recharge from the major channels. For each land unit, LAIUZ computes the water budgets of the soil root and deep vadose zones, allotment of delivered surface water, pumpage required to meet the balance of its applied water demand, and aquifer recharge from surface applied water. The groundwater flow model computes groundwater levels in response to pumping and recharge. Crop consumptive use is adjusted to match the modelled basin hydrological budget to the measured one for an error of less than 1% annually.

Key words conjunctive use; crop water budget; GIS; groundwater; hydrogeology; land use; numerical modelling; surface water; vadose zone

INTRODUCTION

The Tule River groundwater basin is located in the southwest quarter of Tulare County in the San Joaquin Valley, California, USA (Fig. 1(a)). Approximately 68% of the basin is under agricultural production. Many basin farmers receive a significant portion of irrigation as surface water through the federally managed Central Valley Project (CVP) Friant Unit. Conjunctive use management of groundwater and surface water resources by Friant service area districts has ensured a sustainable irrigation supply for wet and dry years. However, implementation of the 1992 Central Valley Project Improvement Act may result in severe reductions in future CVP surface water deliveries and a subsequent increase in groundwater pumping. This may jeopardize the ability of Friant districts to manage their water resources conjunctively.

Our primary objective is to develop a conjunctive use model to simulate groundwater storage changes when pumping is required to supplement inadequate surface water deliveries. The model consists of three sub-models: (a) a surface water model; (b) a land-atmosphere interface and unsaturated zone (LAIUZ) model; and (c) a groundwater flow model developed using MODFLOW (McDonald & Harbaugh,
The model also includes an extensive hydrological and hydrogeological database. To efficiently organize the database and process simulated outputs, a secondary objective is to link the input data, the model, and the model outputs using state-of-the-art software for database management and pre- and post-processing. The databases are organized in a GIS and in GIS-linked spreadsheets. We used Argus Open Numerical Environments (ONE®) with a MODFLOW graphical user interface (Shapiro et al., 1997) to build the groundwater flow model according to the conceptual hydrogeology, to link it with the surface water and LAIUVZ models, and to post-process outputs in a GIS format.

PROJECT AREA DESCRIPTION

The Tule River groundwater basin encompasses 2250 km$^2$, is delineated into 9289 land units (Zhang, 1993), and includes 25 municipal, irrigation, or water districts, several small cities, and other unincorporated areas of land (Fig. 1(b)). The basin is bounded by the foothills of the Sierra Nevada mountains to the east, by shallow watershed divides to the north and south, and by the Tulare lakebed to the west. To the south and west, the project area boundaries coincide with the county boundary.

The basin has a semiarid, Mediterranean climate with an average annual evapotranspiration of 850 mm and precipitation of 230 mm. Most of the local precipitation occurs from December through to April. The largest supply of irrigation water comes from the Friant-Kern Canal (Fig. 1(b)), which delivers CVP water from Millerton Reservoir located more than 100 km northwest of the Tule River basin. From the Friant-Kern Canal, water is delivered to the districts either directly or by diversion into an intricate conveyance system of rivers, creeks, sloughs, ditches and canals (Fig. 1(b)). The Tule River basin itself contains three major natural surface water channels discharging into the basin from the Sierra Nevada: Tule River, Deer Creek and White River. Surface water inflows into the project area are monitored by stream gauges. Practically all surface water is consumed within the basin and in most years no surface water leaves the project area.
The basin is conceptualized as an unconfined aquifer in the eastern half and a confined aquifer underlying an unconfined aquifer in the western half. In the western half, distal alluvial fan deposits interfinger lacustrine and marsh deposits associated with the Tulare lakebed. There, a relatively continuous lacustrine clay layer, known as the Corcoran Clay Member of the Tulare Formation, forms a regional aquitard separating an upper semi-confined aquifer from a lower confined aquifer. The thickness of the Corcoran Clay in the project area is greatest along the western boundary and diminishes near the mid-point of the basin. Depth to the Corcoran Clay ranges from 180 m along the western boundary to 48 m where its thickness diminishes. The unsaturated zone profile consists of an approximately 1.8 m thick soil root zone overlying a deep vadose zone, ranging in thickness from 15 to 50 m. A shallow water table exists near the Tulare lakebed along the western boundary of the model domain.

CONJUNCTIVE USE MODEL


Surface water model

The purpose of the surface water model is to estimate monthly district surface water deliveries and monthly aquifer recharge from channel seepage ("channel" here refers to the rivers, creeks, streams, canals, or other surface water conveyance conduits). Channel seepage is a significant source of aquifer recharge in the Tule River basin. Channel flows and diversions of surface water for delivery to the districts are measured at numerous gauge stations and diversion points, respectively. The distance between consecutive stations or points defines a channel segment. The combined seepage and evaporative losses along each segment is the difference between measured inflow and outflows at consecutive gauge stations or diversion points. We assume that seepage accounts for 95% of the total loss with evaporation accounting for the remaining 5%. In addition, we assume that seepage loss is distributed uniformly along the length of individual segments. Seepage is also assumed to directly recharge the unconfined aquifer and thus calculated long-term changes in unsaturated zone storage are considered negligible. Groundwater return flows into the channels are also considered negligible due to the deep water table throughout most of the modelling area. Surface and groundwater flow models are operated independently.

The surface water model outputs are the monthly water deliveries to each district and the monthly aquifer recharge from channel seepage. The recharge is then input into the groundwater flow model and the surface water deliveries to each district are input into the LAIUZ model. In Fig. 2 we present the estimated annual total surface water deliveries and channel seepage for the basin from 1970–1985.
Land–atmosphere interface and unsaturated zone (LAIUZ) model

The LAIUZ model estimates the monthly precipitation, crop consumptive use, applied water demand, soil root and deep vadose zone water contents, applied surface water, and aquifer recharge from surface applied irrigation, for each of the 9289 land units. Due to the lack of groundwater pumping data, LAIUZ also estimates the monthly groundwater pumping as the difference between the applied water demand and the applied surface water. The recharge from surface applied water and the pumpage rates are the main output of LAIUZ and are input into the groundwater model.

To estimate recharge and pumpage, LAIUZ first computes the surface water available for irrigation to each land unit. Surface water allocation to each land unit is a function of its acreage, crop consumptive use, the total surface water delivered to its district, and the total district irrigated acreage. The crop consumptive use $ET$, or evapotranspiration, is defined as the cumulative amount of water (volume of water per unit area) transpired by the crop, retained in its plant tissue, and evaporated from adjacent soil surfaces during the growing season (Fio, 1994). For each crop, the monthly consumptive use is the product of the monthly crop coefficient $Kc$ and the monthly reference crop consumptive use $ETo$, $ET = Kc \times ETo$. The monthly crop coefficient is a weighting factor used to compute the fraction of the monthly reference consumptive use required for growth by the crop under consideration. In this study, the reference crop is grass. From 1970 to 1999, annual grass consumptive use varied from 103 cm in 1978 to 138 cm in 1987 with an overall average of 122 cm. In the project area, 12 crop types account for nearly 95% of the agricultural acreage. These crops are: cotton, grains and grass hay, citrus, vines, alfalfa hay, silage corn, olives, almonds, field corn, plums, walnuts, and pistachios.

A crop's applied water demand is estimated by first dividing the crop consumptive use by its irrigation efficiency. The applied water demand is then adjusted for the available root zone soil moisture. If, in any given month, the total amount of delivered water to the district is equal to or in excess of its total applied water demand, then no
pumping is needed to supplement irrigation. Surface water in excess of applied water demand is distributed uniformly among the agricultural land units within the district. If, however, the total surface water supplies are less than the total applied water demand, then all land units receive the same fraction of their applied water demand from available district surface water supplies. The remaining deficiency is met by pumping. The actual pumping rate varies from land unit to land unit. Pumping occurs in the unconfined or lower confined aquifers and is proportional to screen lengths and depths typical for wells within the vicinity of the land units.

Since water level changes in the unconfined aquifer are much smaller than the thickness of the vadose zone, we assume that fluxes through the vadose zone are independent of groundwater level changes. LAIUZ is consequently independent of the groundwater model. Water flow through the soil root zone is computed on a mass balance basis. Percolation into the vadose zone is equal to the available root zone moisture in excess of its field capacity. In contrast, percolation from the vadose zone into the unconfined aquifer is computed as a nonlinear function of the average soil moisture in the vadose zone and saturated hydraulic conductivity. The computed monthly pumpage and aquifer recharge for each land unit are then input into the groundwater model. The spatial distributions of the average annual pumpage and recharge from 1970–1986 are shown in Fig. 3.

**Groundwater flow model**

The saturated zone consists of an unconfined aquifer, an aquitard, and a confined aquifer. In MODFLOW, each is modelled by a single layer of finite difference cells. In the eastern half of the basin, the three layers represent a single unconfined aquifer and are assigned identical hydrogeological properties. Horizontal cell dimensions of the finite difference grid are 1000 m. The base of the modelled aquifer system is 40 m below the ground surface at the eastern boundary and rapidly dips westward to 500 m.

![Fig. 3 Average groundwater pumpage and surface applied recharge (cm per year) from 1970–1985.](image)
The aquifer stresses are pumping, aquifer recharge from irrigation, and channel seepage. Recharge is applied to the unconfined aquifer while pumping is distributed among the unconfined and lower confined aquifers. Importation of model stresses as GIS coverages is performed using the functionality of ArgusONE®. Due to the relatively flat basin topography and low monthly precipitation, overland flow and runoff are assumed negligible at the spatial resolution of the model.

The boundary conditions consist of no-flow on the northern, southern, and eastern boundaries and a general-head on the western boundary. The general-head boundary conditions were derived from a much larger, coarse-gridded regional model of the San Joaquin Valley. The initial conditions are the 1970 spring-measured hydraulic heads. The calibration period is from 1970–1985 and the fiscal water year is divided into four seasonal stress periods: October–November, December–March, April–May, and June–September.

**HYDROLOGICAL BUDGET ANALYSIS**

Basin groundwater storage changes are estimated using measured hydraulic heads. Due to its relatively flat topography and large size, major basin storage changes likely result from irrigation and pumping stresses rather than net outflow at basin boundaries. These stresses are a function of crop consumptive use and available surface water. Consequently, measured long-term basin storage changes should be similar to the net recharge computed using the surface water and LAIUZ models. Given this, groundwater storage changes from 1970 to 1986 were estimated from spring-measured hydraulic head-generated contour data. These were then compared to the net recharge computed using the surface water and LAIUZ models for the same 16-year period. The difference between measured and modelled storage changes was 11.7 ha-cm ha⁻¹. For the 16-year period, the annual average is 0.6 ha-cm ha⁻¹ year⁻¹ or, assuming a specific yield of 10%, a 7 cm difference in hydraulic head per year. The close agreement...
validates the basin hydrological budget as calculated from the surface water and LAIUZ models. The model errors of the budget on a district level for the un-calibrated groundwater flow model are presented in Fig. 4. Currently, we are using an automated technique to calibrate the flow parameters to match target storage changes on the district level. Once completed, we will then perform a transient calibration followed by a model validation for the period of 1986–1999.

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REFERENCES


