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# Remotely Sensed Evapotranspiration Data Assimilation for Crop Growth Modeling

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## 1. Introduction

The agricultural sector will require more water in the near future to provide more food, fibre and fuels (Molden et al., 2007). As population increases and development calls for increased demand of food, a change in diet due to increased prosperity, and a recent focus on biofuels. This population growth - coupled with industrialization and urbanization - will result in an increasing demand for water and will have serious consequences on the conservation of water resources. Therefore, a rational approach to best water management practices is needed to balance water supply and demand. One approach to check if the supply is adequate to meet the demand is to account for the respective components in the water balance. Doing so provides an opportunity to search for possible ways to save water from one application and allocate it to another. Simulation models are strong in this regard; they can simulate the processes in the real system and predict the state variables at every stage in the simulation.

The role of simulation models in understanding the processes in the soil-plant-atmosphere system has increased significantly in recent years. This is attributed to increased computing capabilities available today (Ines et al., 2002). Such mechanistic ecophysiological models integrate knowledge from data collection by various methods (e.g. GPS, field sampling, satellite remote sensing, radar etc.) and laboratory research. Simulations from such models are widely used to predict and simulate crop growth, yield, water requirements and greenhouse gas emissions. For monitoring agricultural crop production, growth of crops is modeled, for example, by using simulation models. Estimates of crop growth often are inaccurate for practical field conditions. Therefore, model simulations must be improved by incorporating information on the actual growth and development of field crops, for example, by using remote sensing data.

Numerous researchers have also used remotely sensed data in conjunction with crop growth models via data assimilation for the purpose of improving soil moisture estimation (Entekhabi et al., 1994; Van Dams et al., 1997; Reichle et al. 2001; Ines et al., 2002; Kamble et al., 2008). The objective of data assimilation is to obtain the best estimate of the state of the system by combining observations with the forecast model's first guess. Genetic algorithms (GA) are designed to search, discover and emphasize good solutions by applying selection and crossover techniques, inspired by nature, to supply solutions (Holland, 1975; Goldberg, 1989). GA operates on pieces of information like nature does on genes in the course of evolution. Changes in the genes of individuals from a given population allow selection of

certain groups of genes that are most important in fitting the environment pressures on the population. All individuals of one generation are evaluated by a fitness function. The strength of GA with respect to other local search algorithms is due to the fact that, in a GA framework, more strategies can be adopted together to find individuals to be added to the mating pool. Addition is made both in the initial population phase and in the dynamic generation phase. Thus, a more variable search space can be explored at each algorithm step. Based on the above biological evolution idea, a so-called "SWAP-GA" has been developed by Ines et al., (2002) to estimate input parameters of SWAP from remote sensing data. The SWAP-GA model was adopted and re-coded according to the objectives of this research. After recoding and recalibrating with local parameters simulation was then carried out for different generations and different populations.

Ines et al. (2002) developed an assimilation methodology for the Soil, Water, Atmosphere and Plant (SWAP) simulation model (Van Dams et al., 1997) with remote sensing data using a genetic algorithm (GA). Similar work was done by Chemin (2006), Kamble et al. (2006, 2008), Irmak et al. (2009) in which remotely sensed information was fed to SWAP-GA for optimization of soil hydraulic parameters. Proper evaluation of the water balance in the unsaturated zone depends strongly on the appropriate characterization of the soil hydraulic functions but direct measurement of soil hydraulic properties in the laboratory using soil core samples is the classic way to determine the soil hydraulic functions (van Genuchten et al., 1991). Unfortunately, direct measurement of these functions is impractical for most applications in research and management, especially for large-scale water management problems. The hydraulic parameters are mostly influenced by the water consumption by crop or evapotranspiration phenomenon which control the crop growth and water consumption and vice versa. Therefore, it may be useful to have a method that assimilate evapotranspiration in a hydrological model and use as a function of flexible boundary conditions and can also give the optimized hydraulic property.

This chapter introduces ET data assimilation scheme was implemented with a SWAP model and genetic algorithm to optimize crop growth parameters. The goal of this system was to provide realistic description of hydrological balance in an analytically tractable way, as a basis for quantitative understanding of soil moisture response to different hydraulic parameter which controls ET. In addition, this chapter introduces few implementation results from two case studies performed in India and USA with different conditions.

## 2. Evapotranspiration by energy balance model

Evapotranspiration is one of the most critical parameters and has a considerable impact on water losses. ET is usually the largest hydrological flux through during the summer months in Great Plains. The ability is required to accurately estimate the magnitude of this flux will, therefore, go a long way towards being able to compute the water balance and plan the water resources and regimes. It is, however, the most difficult flux to quantify (Peacock and Hess, 2004). Furthermore, quantification of this flux on a watershed or a regional scale is much more difficult. ET is highly dynamic in space and time because of the complex interaction of soil, vegetation and climate. In the last few decades, analysis of this biophysical phenomenon has received much attention (Burman and Pochop, 1994). After FAO 56 by Food and Agriculture Organization of the United Nations, last decade has witnessed many investigations of up-scaling the point-scale evapotranspiration (ET) to regional scale (Allen, 2000) and of quantifying ET either directly from remotely sensed

information (Bastiaanssen et al., 1998a, Bastiaanssen et al., 1998b, Schmugge et al., 2002, Su and Troch, 2003, Jia et al., 2003 Kamble et al., 2007 and Pan et al., 2008) or from simulation modeling.

These Land surface energy balance (EB)-based models convert satellite sensed radiances into land surface characteristics to estimate ET as a “residual” of the land surface energy balance equation. The Surface Energy Balance Algorithm for Land (SEBAL) was developed to quantify ET over large areas using remote sensing-based land surface energy fluxes (Bastiaanssen et al. 1998). It has been used to estimate riparian ET (Goodrich et al., 2000), basin wide ET (Bastiaanssen et al., 2002), mapping regional runoff and precipitation (Church et al., 1995), and developing crop coefficients (Singh and Irmak, 2009). Another satellite remote sensing model, the METRIC (Mapping Evapotranspiration at high Resolution using Internalized Calibration) was introduced by Allen et al. (2007a, b). The model originates from versions of SEBAL and is based on similar principles. Similar to SEBAL, METRIC models use near-surface temperature gradient ( $dT$ ) estimated as an indexed function of radiometric surface temperature, thereby eliminating the need for absolutely accurate surface temperature or air temperature measurements to estimate sensible heat flux ( $H$ ) in the computation of land surface energy balance.

Surface Energy Balance Algorithm for Land (SEBAL) was developed to quantify ET over large areas using satellite-based surface energy fluxes (Bastiaanssen et al. 1998). SEBAL is a one-source energy balance model that estimates the latent heat flux (evapotranspiration) as a residual of other energy balance components:

$$\lambda ET = R_n - G - H \quad (1)$$

where  $R_n$  is net radiation ( $W\ m^{-2}$ ),  $G$  is the soil heat flux ( $W\ m^{-2}$ ),  $H$  is the sensible heat flux ( $W\ m^{-2}$ ), and  $\lambda ET$  is the latent heat flux ( $W\ m^{-2}$ ).  $R_n$  is the difference between the incoming and outgoing fluxes, which is expressed as:

$$R_n = R_s \downarrow - R_s \uparrow + R_l \downarrow - R_l \uparrow - (1 - \varepsilon_s) R_l \downarrow \quad (2)$$

where  $R_s \downarrow$  is the incoming shortwave radiation ( $W\ m^{-2}$ ),  $R_s \uparrow$  is the outgoing shortwave radiation ( $W\ m^{-2}$ ),  $R_l \downarrow$  is the incoming longwave radiation ( $W\ m^{-2}$ ),  $R_l \uparrow$  is the outgoing longwave radiation ( $W\ m^{-2}$ ), and  $\varepsilon_s$  is the surface emissivity (unitless). Soil heat flux is mainly driven by a thermal gradient in the topsoil and this gradient is highly dynamic in space and time. The soil heat flux was estimated as a function of NDVI and  $R_n$  using the relationship developed by Singh et al. (2007) for south central Nebraska soil and crop management conditions:

$$G = [0.3811 \exp(-2.3187 NDVI)] R_n \quad (3)$$

$$H = \frac{\rho_a C_p dT}{r_{ah}} \quad (4)$$

where,  $\rho_a$  is the air density ( $kg\ m^{-3}$ ),  $C_p$  is the specific heat of air ( $J\ kg^{-1}\ K^{-1}$ ),  $dT$  is the near surface and air temperature difference (K), and  $r_{ah}$  is the aerodynamic resistance to heat transfer ( $s\ m^{-1}$ ). Once the instantaneous  $R_n$ ,  $G$ , and  $H$  are determined, the instantaneous evaporative fraction ( $\Lambda$ ) was calculated as:

$$\Lambda = \frac{\lambda ET}{R_n - G} \quad (5)$$

Finally, the daily actual ET ( $ET_c$ ) was estimated as:

$$ET_c = \frac{86400\Lambda(R_{n24} - G_{24})}{\rho_w \lambda} \quad (6)$$

where,  $ET_c$  is the daily crop ET ( $\text{mm day}^{-1}$ ),  $R_{n24}$  is the daily net radiation calculated on a daily time step ( $\text{W m}^{-2}$ ),  $G_{24}$  is the daily soil heat flux ( $\text{W m}^{-2}$ ),  $\lambda$  is the latent heat of vaporization ( $\text{J kg}^{-1}$ ), and  $\rho_w$  is the density of water ( $\text{kg m}^{-3}$ ).

The output from the SEBAL model is an actual ET map calculated on a 30-m grid resolution basis using SEBAL algorithms (Eq. 1. through Eq. 6). Further descriptions of the SEBAL methodology are discussed in detail in Singh et al. (2008). We ran the model for each of the seven Landsat images to quantify the spatial distribution of  $ET_c$ . After obtaining the  $ET_r$  (via geostatistics) and  $ET_c$  maps (via SEBAL), the spatial distribution of  $K_{cr}$  was calculated by dividing the  $ET_c$  map values by the  $ET_r$  map values.

### 3. Crop growth modelling and SWAP

An intermediate version of the SWAP model (SWAP) (fig. 1) was used in this study (Ines et al., 2005). The SWAP model is physically based one-dimensional model to simulate vertical transport of water flow, solute transport, heat flow and crop growth at the field scale level (Van Dam et al., 1997). It requires inputs including management practices and environmental conditions to compute a daily soil water balance and crop growth. The major processes taken into account are phenological development, assimilation, respiration, and ET. The SWAP uses Richard's equation to simulate vertical soil water movement in variable saturated soils is given as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ K(\psi) \left( \frac{\partial \psi}{\partial z} + 1 \right) \right] \quad (7)$$

where  $K$  is the hydraulic conductivity ( $\text{cm d}^{-1}$ ),  $\psi$  is the pressure head (cm),  $z$  is the elevation above a vertical datum (cm),  $\theta$  is the water content ( $\text{cm}^3 \text{ cm}^{-3}$ ), and  $t$  is time (d). The soil hydraulic functions in the model are defined by the Mualem-Van Genuchten (MVG) equations which describe the capacity of the soil to store, release and transmit water under different environmental and boundary conditions (Ines, 2002). Darcy's law is used to determine potential soil evaporation in wet soil conditions. Root water extraction at various depths in the root zone is calculated from potential transpiration, root length density and possible reductions due to wet, dry, or saline conditions (Eitzinger, 2000).

As SWAP simulates actual evaporation ( $E_a$ ) and transpiration ( $T_a$ ),  $ET_a$  can be taken as the sum of  $E_a$  and  $T_a$ . The Penman-Monteith approach (Allen et al., 1994) was used to estimate the potential ET rate,  $ET_p$ . The partitioning of  $ET_p$  into potential soil evaporation ( $E_p$ ) and potential transpiration ( $T_p$ ) is established according to soil cover fraction. In the case of wet soil,  $E_a$  is determined by the atmospheric demand and equals to  $E_p$ . When the soil dries out, the soil hydraulic conductivity decreases, which reduces evaporation. SWAP calculates the maximum possible evaporation rate ( $E_{max}$ ) according to Darcy's law and sets  $E_a$  equal to the minimum value of  $E_p$  and  $E_{max}$ . Hence,  $E_{max}$  is governed by the soil hydraulic



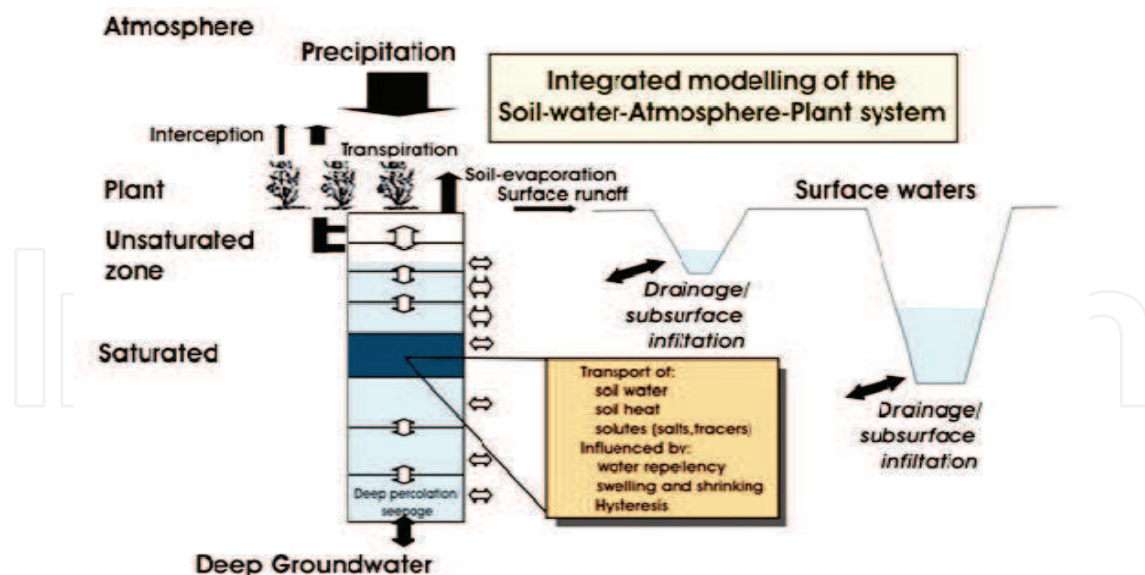


Fig. 1. Integrated modeling scheme of Soil Water Atmosphere Plant (SWAP) model

functions. The  $T_a$  is calculated using the root water uptake reduction due to water and/or salinity stress. Water requirements of a crop depend mainly on crop growth stage and environmental conditions. Different crops have different water-use requirements under the same weather conditions. For wheat, phenological stage was used along with the values of reference ET for computing the consumptive use at different growth stages by a water-balance approach.

#### 4. Data assimilation with genetic algorithm

The objective of data assimilation is to obtain the best estimate of the state of the system by combining observations with the forecast model's first guess. Genetic algorithms (GA) are designed to search, discover and emphasize good solutions by applying selection and crossover techniques, inspired by nature, to supply solutions (Holland 1975; Goldberg 1989). GA operates on pieces of information like nature does on genes in the course of evolution. Changes in the genes of individuals from a given population allow selection of certain groups of genes that are most important in fitting the environment pressures on the population. All individuals of one generation are evaluated by a fitness function. The strength of GA with respect to other local search algorithms is due to the fact that, in a GA framework, more strategies can be adopted together to find individuals to add to the mating pool, both in the initial population phase and in the dynamic generation phase. Thus, a more variable search space can be explored at each algorithm step.

Based on the above biological evolution idea, a so called "SWAP-GA" has been developed by Ines and Honda (2005) to estimate input parameters of SWAP from remote-sensing data. The proposed parameters were fed to SWAP by GA according to the evaluation of the difference processes between SWAP output ET and the target energy balance ET values. The GA searches for the optimum crop parameter set while SWAP tests the proposed parameters simultaneously by using them in forward simulations (Figure 2).

$$C = \sqrt{\left( \frac{ET_{METRIC} - ET_{SWAP}}{n} \right)^2} \quad (8)$$

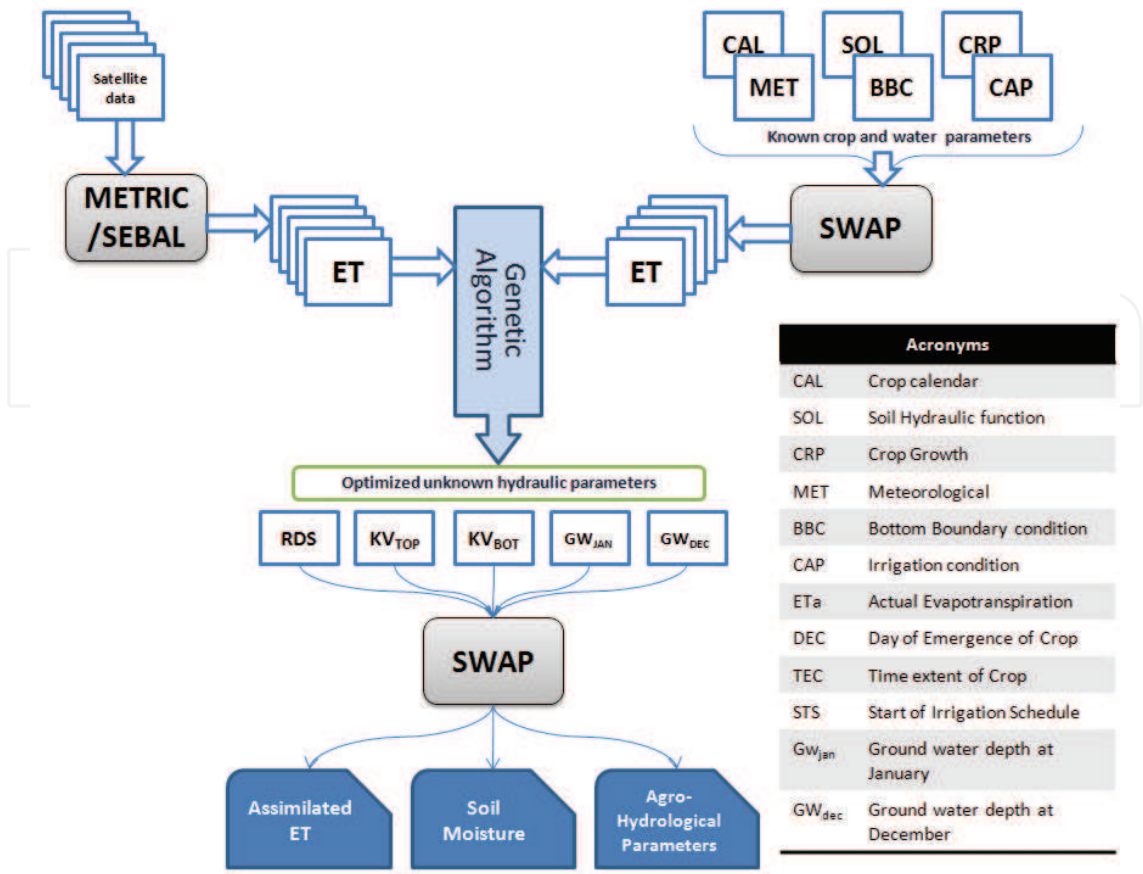


Fig. 2. SWAP-GA data assimilation framework

Consider  $C$  the cost function, and  $d$  is the satellite overpass date. where  $ET$  is estimated with energy balance model using remotely sensed data ( $cm$ ) and it was treated as observations.  $ET_{SWAP}$  is an estimated  $ET$  with  $SWAP$  ( $cm$ ),  $n$  is the time domain and  $C_{xy}$  is the objective function (root mean square error: RMSE) for the pixel at  $x, y$  location ( $cm$ ). When a minimum-difference defined threshold was reached,  $SWAP$  parameters were stored for reconstruction of  $ET$  for any required day in the cropping season. The fitness of an individual having  $x,y$  pixel location characteristics is the inverse of the cost function times the constraints aimed at minimizing the RMSE between  $ET_{SWAP}$  and target  $ET_{METRIC}$ .

$$F_{xy} = \frac{1}{\left(C_{xy} * (1.0 + \text{Constraint})\right)} \tag{9}$$

In Equation 13, the constraint is a function of the emergence date of the second crop (DEC) and the date of harvest:

$$\text{Constraint} = \text{Date of emergence} - \text{Harvest date} \tag{10}$$

Subject to the possible range of sowing dates:

$$b_{\min j} \leq sd_j \leq b_{\max j} \quad (j=1,\dots,6)$$

where  $b_{\min j}$  is the earliest possible sowing date,  $b_{\max j}$  is the latest possible sowing date, and  $sd_j$  is the actual sowing date. The units are day-of-year (ordinal day).

## 5. Research case studies

### 5.1 On-demand irrigations scheduling in Sirsa Irrigation Circle, India

The proposed approach was tested using a dataset on irrigated cotton field in the Sirsa Irrigation Circle for On-demand irrigation scheduling. Data used in this study was previously collected as part of comprehensive research conducted by the Wageningen Agricultural University, The Netherlands during 2002 for calibrating the SWAP model (Van Dam et al., 2003).

Figure 3 compares temporal distribution of SEBAL ET with predicted SWAP ET with SWAP-GA. Both SEBAL ET and SWAP-GA showed similar patterns of under and over estimations of actual ET. The SWAP-GA slightly overestimated ET early in the season when the soil surface was dry and underestimated late in the season when the soil surface was wet and covered by the crop which influences efficiency of water use, high water productivity and efficient farming activities.

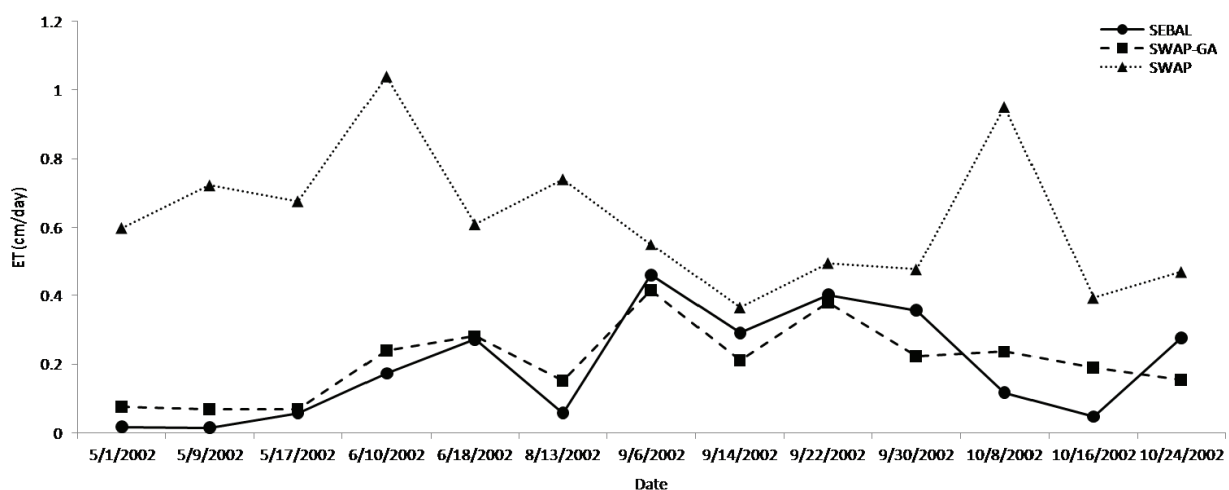


Fig. 3. Actual evapotranspiration (cm d<sup>-1</sup>) for the 2002 cotton growing seasons. Observed ET is based on SEBAL algorithms (SEBAL ET) on satellite overpass dates. ET predictions are with original SWAP and SWAP-GA models

Simulated and observed soil water content (cm<sup>3</sup>/ cm<sup>3</sup>) at 0-15 cm and 15-30 cm soil depths by SWAP-GA with optimized parameters, rainfall and irrigation amounts are shown in the figure 4. As per the scheduling criteria and its physiological stage, water uptake by crop changes, throughout season 50-60 percent of the total water uptake by the crop occurs over the first 90 cm depth, where more than 90 percent of the total root weight is found. It reveals that the top layer of the soil (0-15 cm and 15-30 cm) has greater fluctuations. It is because the top layer forms the sphere of life which receives moisture in pulses of rainfall and irrigation also the same water is eliminated through evaporation and transpiration by plants. The simulated and observed soil moisture levels show the increasing value from June to September, and then decreasing from September to November, which corresponds to the variation of irrigation and precipitation. But the dramatic difference between the simulated and observed soil moisture was found in July. The simulation has the lowest value in August due to the large relative contribution of ET (Fig. 3), whereas this phenomenon does not occur in the observation.



## 5.2 Optimization of hydraulic parameters and sensitivity analysis in Clay Center, Nebraska-USA

This study was conducted at the University of Nebraska-Lincoln South Central Agricultural Laboratory (SCAL) near Clay Center, Nebraska, USA (Latitude: 40° 34' N; Longitude: 98° 08' W; elevation: 552 m above MSL). In this research, the METRICTM was used to compute complete radiation and energy balances along with the resistances for momentum, heat, and water vapor transport for each pixel in the experimental area.

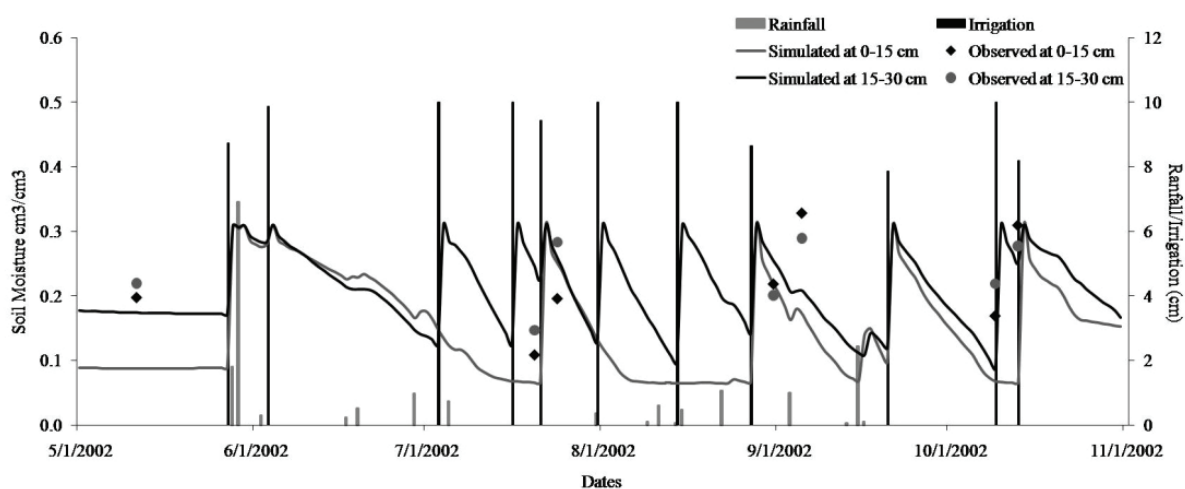


Fig. 4. Comparison of observed (SEBAL ET) and predicted evapotranspiration for the 2002 cotton growing seasons. The potential (dashed line) and actual (solid line) evapotranspiration were estimated by SWAP-GA with optimized parameters

Fourteen satellite images were selected from June through October in 2006 because these images were with a cloud cover less than 10%. The relative ET in this study was expressed as the reference ET fraction (ET<sub>r</sub>F) and was computed using the procedures outlined by Allen et al. (2007a and b). Figure 4a shows the ET for the MODIS satellite overpass on August 14, 2006. As expected, the ET was highly variable in south-central Nebraska due to variation in cropping practices, irrigation, and vegetation development. Furthermore, the ET values were usually lower for agricultural lands than rangeland/natural vegetation in August due to less green vegetation fraction because of crop maturity and harvest stages at this time. On the other hand, grazed rangeland/natural vegetation has green vegetation in August as evidenced by high NDVI on the scene. Higher ET values from grazed rangeland/natural vegetation pixels indicated that most of the available energy was used for transpiration. The spatial distribution of daily ET predictions on August 14, 2006 was between the range of 0.9-1.15 for agricultural lands and was as high as 0.13 for the natural vegetation/rangeland across the image (Fig. 4a). Figure 4b shows seasonal ET map corresponding to the 2006 season for the entire Clay, York, Hamilton Adams and Fillmore counties (Figure 1). Seasonal ET varied from 400 mm for bare soil to 950 mm for irrigated crops. Rain fed areas surrounding the Fillmore County (in the south east) had ET values around 400 mm which depicted the bare fields and fallow lands. The ET over Adams County showed the ET in between 400 mm to 650 mm, while ET values are for the SCAL fields in York and Hamilton Counties due to shallow water table, lateral seepage from the SCAL fields and an open network of irrigation canals. The ET map further showed a spatial gradient of increasing ET from the southern parts towards the northern parts of the

irrigation system except low ET in the Howard County due to settlements. All of these ET values are important for the agro-hydrological balance of the area as well as ground water modeling. According to table 1, average daily ET (ET) was  $0.426 \text{ cm.day}^{-1}$  with a mode and maximum values of  $0.75 \text{ cm.day}^{-1}$  and  $0.71 \text{ cm.day}^{-1}$ , respectively, for the study field. It is evident from the numerical figures in table that some crops are still developing on May and others are transpiring at higher rates. On June 23, all the crops in the area are established. This indicates the variability of sowing dates and water management practices as influenced by water availability.

The ET assimilation is carried out to obtain the best estimate of the state of the hydraulic system by combining observations with the forecast model at first guess. Figure 5 reveals the actual ET for the 2006 corn growing seasons. ET predictions are with original SWAP and SWAP-GA models. The result shows excellent fitness between the observed ET and simulated ET. There is a bias condition due to the comparison of point observation with model explicitly taken into account to prevent unnecessary forcing towards the biased observations.

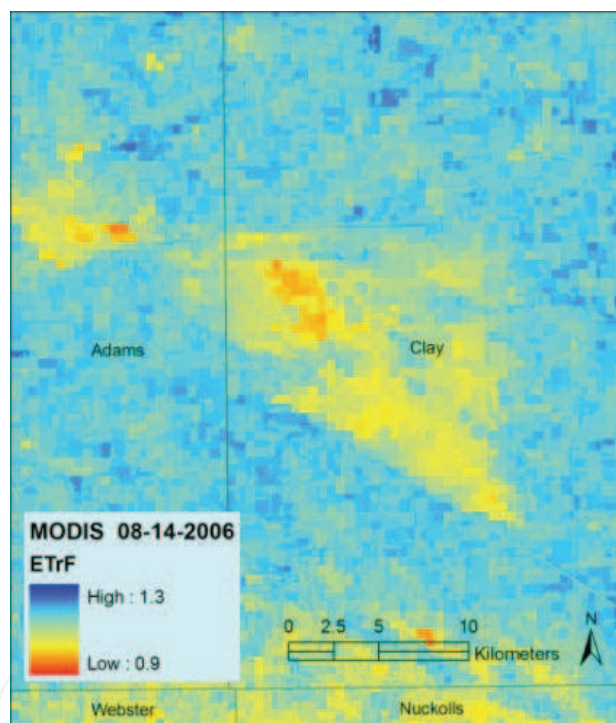


Fig. 6. MODIS derived spatial distribution of evapotranspiration (ET) (August 14, 2006) during the growing season in the study area

Figure 7 revised the relationship between the observed and predicted ET simulated by SWAP-GA (with data assimilation) and SWAP (without data assimilation) model for 2006 season. The independent regression analysis for two dataset shows the fitness of the SWAP-GA data with observed data and compares it with fitness of the SWAP data without data assimilation. This regression coefficient of SWAPGA (with data assimilation) provides good estimates than previously SWAP (without data assimilation). The relations obtained were statistically significant for ET data assimilation method. This fact indicates the strong need of assimilating observed data in crop growth model to minimize errors between simulation and real life crop growth.

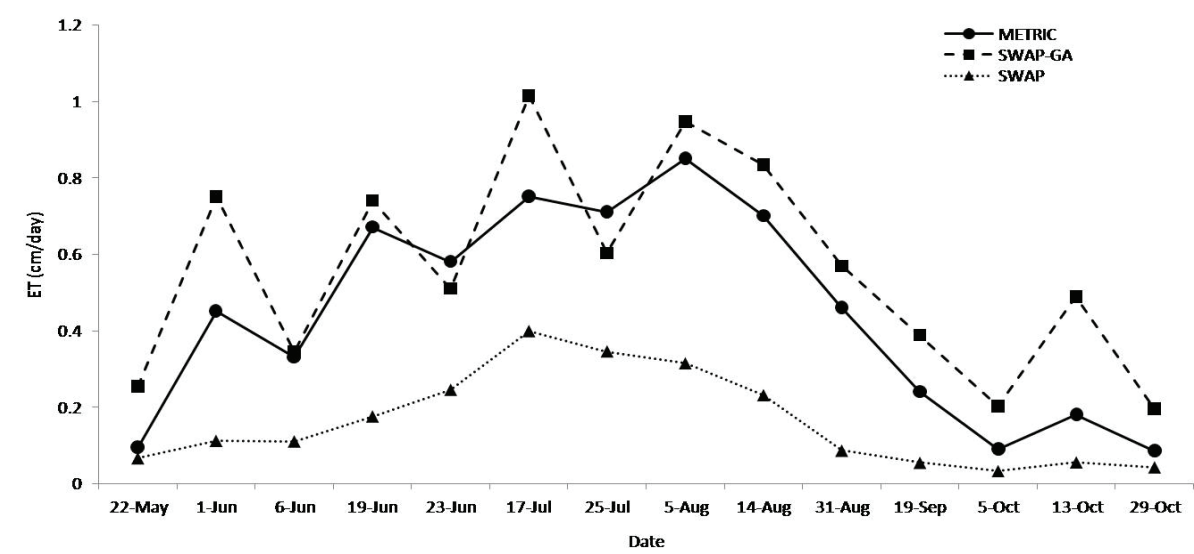


Fig. 7. Actual evapotranspiration (cm d-1) for the 2006 corn growing seasons. Observed ET is based on METRIC algorithms (METRIC) on satellite overpass dates. ET predictions are with original SWAP and SWAP

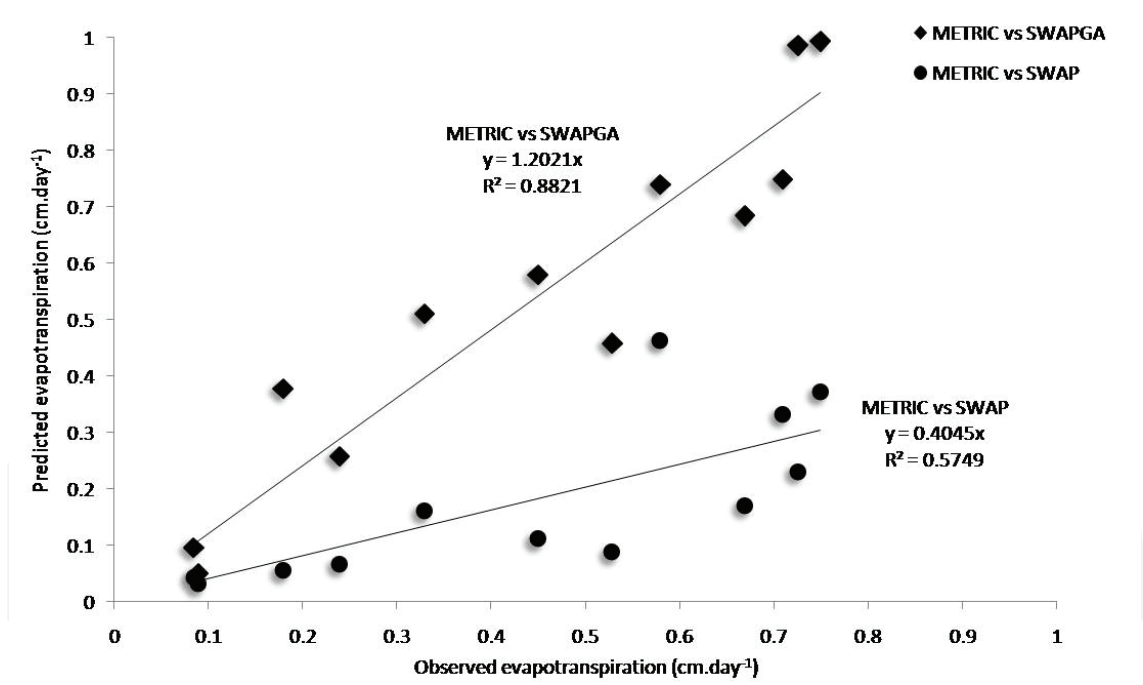


Fig. 8. Relationship between ET by remote sensing data and (observed) and Simulated ET from SWAPGA (with data assimilation) and SWAP (without data assimilation) model. The solid line corresponds to the 1:1 relation to the regression equation for the 2006 growing seasons

Optimization of crop growth parameters and sensitivity analysis

The optimized parameters were determined by minimizing the RMSE between SWAP-ET and the target METRIC-ET values. Generally, the actual remote sensing data contains errors due to atmospheric conditions, cloud cover, and errors in the remote sensing-based

models/algorithms used to estimate ET. Therefore, we tested the procedure assuming that some degree of error in remote sensing observations (METRIC ET) was present in the dataset. We compared the results from GA for different populations and different generations. Best results were obtained by applying the algorithm which was configured for 10 populations and 10 generations with up to nine variable parameters (three crop and six hydraulic parameters). The data inventory during the 2006 corn growing season was used to verify the optimized parameters from SWAP-GA simulation. Table 1 shows the values of optimized parameters as well as data from the experimental field. Best results are obtained by applying the algorithm which configured for 100 Population and 100 generation with up to nine variable parameters, which are selected according to the hydraulic sensitivity to water management problem and fitness function is based on crop parameter sensitivity. In simulations, hydraulic properties were based on measured values where possible; some values were altered slightly by optimizing the model to the local conditions until good agreement with measured ET was attained (fig 9).

Optimized parameters	Definition	Unit	Minimum value	Maximum value	Optimized value
GWjan	Groundwater at start of season	cm	100	160	120
GWdec	Groundwater at end of season	cm	100	160	130
BASEGW	Level of impervious layer	cm	170	230	185
KHBOT	horizontal hydraulic conductivity bottom layer	cm	15	30	25
KVTOP	Vertical hydraulic conductivity top layer	cm	5	20	18
RDS	maximum rooting depth allowed by the soil	cm	120	240	180

Table 1. Definition, unit, minimum, and maximum values of optimized parameters in SWAP-GA

The implementation of this sensitivity analysis after the estimation process aims at determining if the parameters estimated previously are well identified. Therefore, to examine the SWAP model response to changes of specific input data, i.e., to have an indication of the required accuracy at which each hydraulic parameter should be available; a sensitivity analysis of the model was performed (Figure 8). From the original dataset, obtained from field measurements and literature as explained above, the base simulation was established. From this, the sensitivity analysis was performed, assessing the effect produced by a given variation of the input data range on the SWAP output.

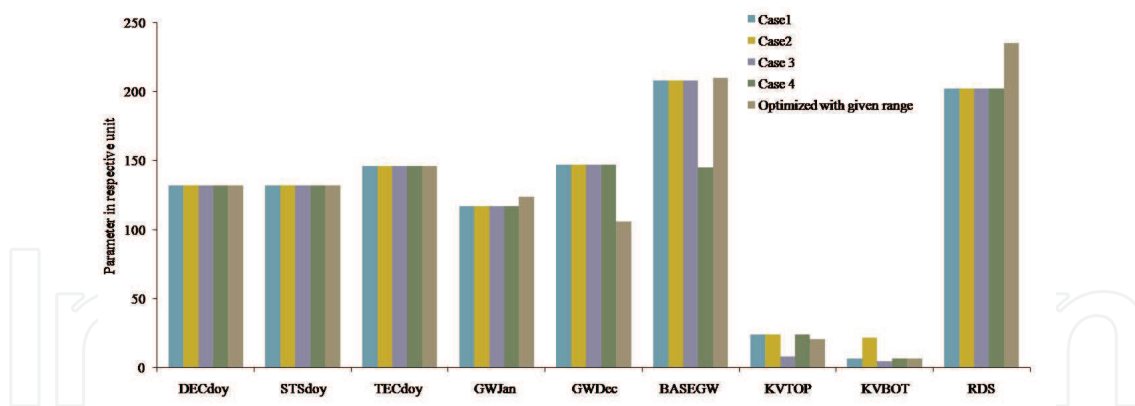


Fig. 8. Hydraulic parameter sensitivity analysis for 4 different cases according to change (+/- 20) in GW, BASEGW, KVTOP, KVBOT and RDS

## 6. Conclusion

We used remote sensing-based SEBAL and METRIC ET data to characterize our model via a stochastic data assimilation approach (GA), and the derived information was then used as inputs to SWAP. This methodology was evaluated in India and North American climatic conditions with different objectives. The methodology developed in this research to estimate hydraulic parameters and application to on-demand irrigation from calibrated crop model parameters gave good results. Parameter estimations were successful, and the ability of the model to produce similar ET values to the observed values (SEBAL ET) was promising, although, in general, the performance of SWAP-GA for on-demand irrigation can be described as reasonable. GA-based optimization retains the advantageous features of forward modeling, while reducing the number of required function evaluations to a level that is often much more computationally manageable. These conclusions suggest that it is indeed necessary to couple a remotely sensed ET with a pixel-based hydrological model in order to study and explore the water management options.

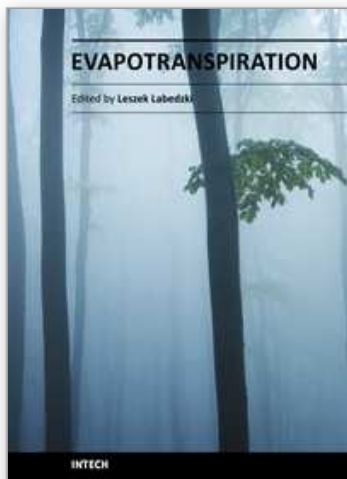
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## **Evapotranspiration**

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Evapotranspiration is a very complex phenomenon, comprising different aspects and processes (hydrological, meteorological, physiological, soil, plant and others). Farmers, agriculture advisers, extension services, hydrologists, agrometeorologists, water management specialists and many others are facing the problem of evapotranspiration. This book is dedicated to further understanding of the evapotranspiration problems, presenting a broad body of experience, by reporting different views of the authors and the results of their studies. It covers aspects from understandings and concepts of evapotranspiration, through methodology of calculating and measuring, to applications in different fields, in which evapotranspiration is an important factor. The book will be of benefit to scientists, engineers and managers involved in problems related to meteorology, climatology, hydrology, geography, agronomy and agricultural water management. We hope they will find useful material in this collection of papers.

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