Estimation of root-zone soil moisture by combining the FAO-56 dual crop coefficient model with land surface temperature and vegetation index data for irrigation management

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Abstract: By controlling the plant transpiration, the root-zone soil moisture (RZSM) plays a crucial role in meteorological modeling and hydrological studies over vegetated areas. In agriculture, RZSM can be used to detect the onset of crop water stress to trigger irrigations. The crop water requirements have been commonly estimated from FAO-56 dual crop coefficient (FAO-2Kc) model by simulating evapotranspiration (ET) and its two main components: soil evaporation (E) and plant transpiration (T). FAO-2Kc is a water balance model driven by meteorological forcing variables and the water supply (precipitation and irrigation) to simulate the soil water availability for ET. Given that the main limitation of FAO-2Kc for operational irrigation management over large areas is the unavailability (over most irrigated areas) of irrigation data, this study investigates the feasibility to constrain the FAO-2Kc RZSM from land surface temperature (LST) and vegetation index (VI) data. In practice, the vegetation and soil temperatures retrieved from LST/VI data are used to estimate the FAO-2Kc vegetation stress coefficient (Ks) and soil evaporation reduction coefficient (Kr), respectively. The methodology proposes to retrieve irrigation amounts and dates from LST-derived estimates and precipitation only and then to estimate the RZSM on a daily basis at the field scale. The modeling and remote sensing combined approach is tested over a wheat crop field in central Morocco by using ground-based measurements along the agricultural season. The total irrigation depth (67 mm) is correctly estimated and is very close to the actual effective irrigation (69.8 mm) applied by the farmer. Daily RZSM is estimated with an R^2 value of 0.68 and a RMSE value of 0.034 m^3m^{-3} by forcing FAO-2Kc using the retrieved irrigation (from LST/VI data and precipitation only). Since spaceborne LST data are currently not available at both high-spatial and high-temporal resolution, a sensitivity analysis is finally undertaken to assess the potential and applicability of the proposed methodology to temporally-sparse thermal data.

Keywords: Root-Zone Soil Moisture, Irrigation, FAO-56 model, Land Surface Temperature, Vegetation Index

Introduction & Objective

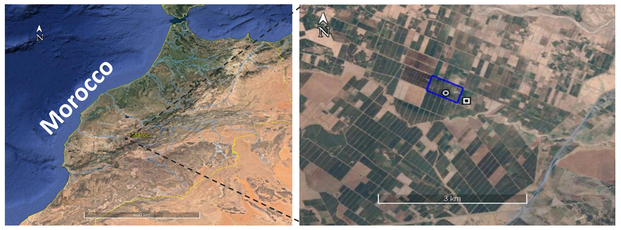
•The FAO-56 dual crop coefficient (FAO-2Kc) model has been extensively used to estimate the crop water requirements by means of the simulated ET

•ET critically depends upon the RZSM, which is hence paramount to determine the crop water requirements

• Issues in the operational application of FAO-2Kc to large scale :
➢ unavailability of irrigation data at the field scale

OBJETIVE :
- **Proposing an original approach to better constrain the water budget components of FAO-2Kc from LST and VI data.**
- **Estimating RZSM on a daily basis at field scale**

Study Area, Data

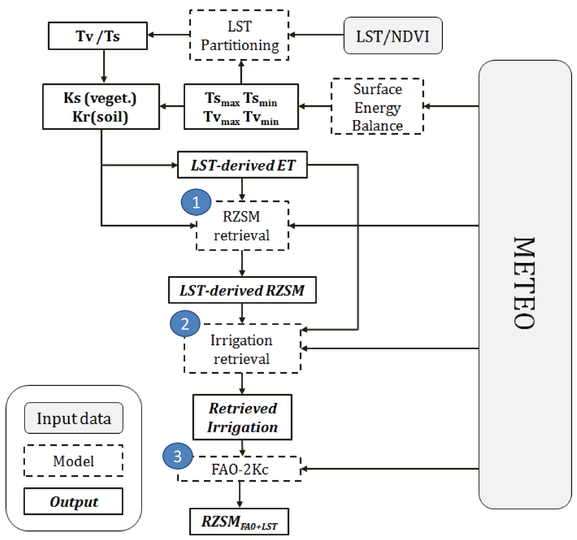


Wheat field EddyCov station (EC) Meteorological station

Data	
Meteorological data	**Ta – Rg – u – RH – P**
Flux data	**EC (H + LE) – Rn – G**
Soil Moisture (TDR)	**5 – 10 – 20 – 30 – 50 – 100 cm**
Irrigation data	**4 Flood irrigation (24 mm)**
Surface Temperature	**Thermal radiometer (LST)**
Fractional green and total vegetation cover	**Surface reflectance (NDVI) Hemispherical canopy photo**

INPUT :
30-min between the period 10 – 14 h

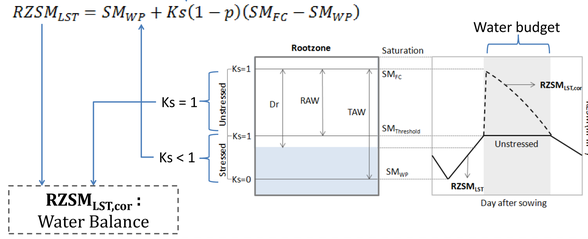
Method



1 RZSM retrieval

$$RZSM = SM_{WP} + \left(1 - \frac{D_r}{TAW}\right)(SM_{FC} - SM_{WP})$$

$$RZSM_{LST} = SM_{WP} + Ks(1-p)(SM_{FC} - SM_{WP})$$

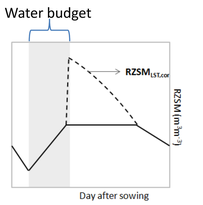


$RZSM_{LST,cor}$: Water Balance

2 Irrigation retrieval

Irrigation events are detected based on a significant increase in first-guess LST-derived RZSM

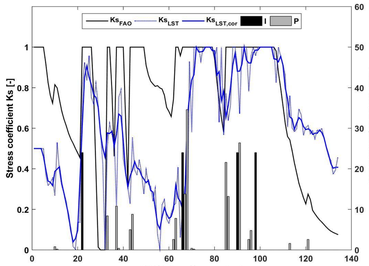
$$I_{inv} = DP + ET_{LST} + \Delta RZSM_{LST} - P$$



Results & Discussion

• Ks_{LST} detects stress periods and responds well to the water inputs, even though its estimation is fully independent of a daily water balance.

• Ks_{LST} simulates stress conditions in a more pronounced way, except for the late season



•ET_{LST} is better estimated than ET_{FAO}. RMSE is improved in 19% (from 0.84 to 0.68 mm d^{-1})

Fig. R1. Ks from FAO-2Kc method according to Allen et al. 1998 (Ks_{FAO}), LST-derived Ks from daily ground-based LST/VI (Ks_{LST}) and the smoothed Ks_{LST} ($Ks_{LST,cor}$).

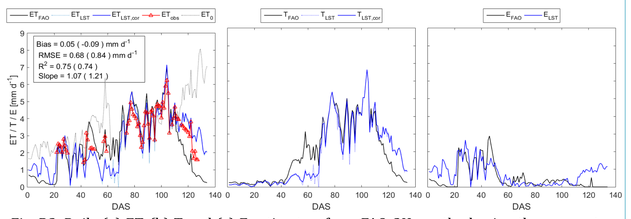
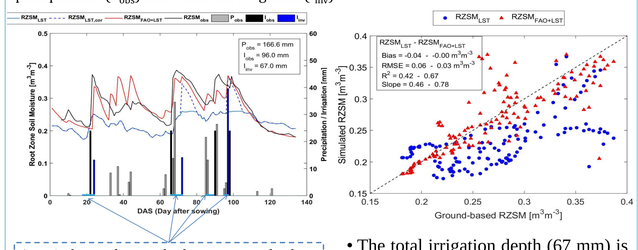


Fig. R2. Daily (a) ET, (b) T and (c) E estimates from FAO-2Kc method using the parameters given by Allen et al (1998) forced by observed irrigation, and from Ks_{LST} (ET and T) and Kr_{LST} (E) and from the $Ks_{LST,cor}$ (ET_{cor} and T_{cor}, respectively). The statistical parameters of ET_{cor} (ET_{FAO}) versus EC observations are shown in the box of (a).

Fig. R3. Daily RZSM from Ks_{LST} ($RZSM_{LST}$), corrected ($RZSM_{LST,cor}$) through a water budget for unstressed periods (Ks=1) and RZSM simulated by the FAO-2Kc ($RZSM_{FAO+LST}$) forced by precipitation (P_{obs}) and retrieved irrigation (I_{inv}).



4 periods are detected where a water budget is applied to estimate the Irrigation (I_{inv})
The 4 periods correspond to the actual I_{obs}

• The total irrigation depth (67 mm) is correctly estimated and is very close to the actual effective irrigation (69.8 mm, applied by the farmer – drainage.

Sensitivity Analysis

• Daily ET and RZSM are estimated for all days in the growing season irrespective of the observation frequency used (1 – 16 days)

• Good performance and acceptable errors by increasing the time revisit frequency.

• Cycle revisit up to 10 days :
  - MAE total Irrig < 15 mm (relative MAE: 21%)
  - $R^2 > 0.5$
  - RMSE < 0.04 m^3m^{-3}

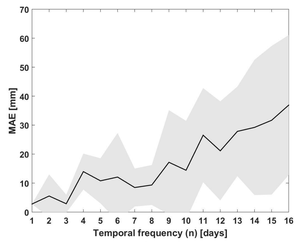


Fig. S1. Sensitivity of total irrigation water supply constrained from ET_{LST} and $RZSM_{LST}$ to different frequency of thermal data observations. The shaded area represents its standard deviation.

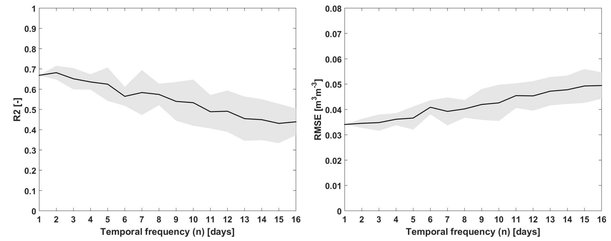


Fig. S2. Sensitivity of $RZSM_{FAO+LST}$ (simulated from FAO-2Kc forced by P and I_{inv}) to different frequency of thermal data observations. Average R^2 and RMSE are presented for each temporal frequency by running the model n times by changing the first day of observation from 1 to n. The shaded area represents its standard deviation.

Conclusions

•A new approach in the calculation of water budget components and for irrigation scheduling (when and how much to irrigate) is developed by integrating LST/VI data into the FAO-2Kc model.

•The first-guess RZSM is significantly improved when FAO-2Kc is implemented by using the retrieved irrigation **(RMSE from 0.06 to 0.03 m^3m^{-3})**

•It is demonstrated that the irrigation amounts and dates can be estimated, allowing us to run FAO-2Kc for estimating RZSM (and ET) along the season on a daily basis.