Tesis Doctoral

Empleo de técnicas de teledetección con diferentes niveles de resolución para la mejora de la gestión del riego

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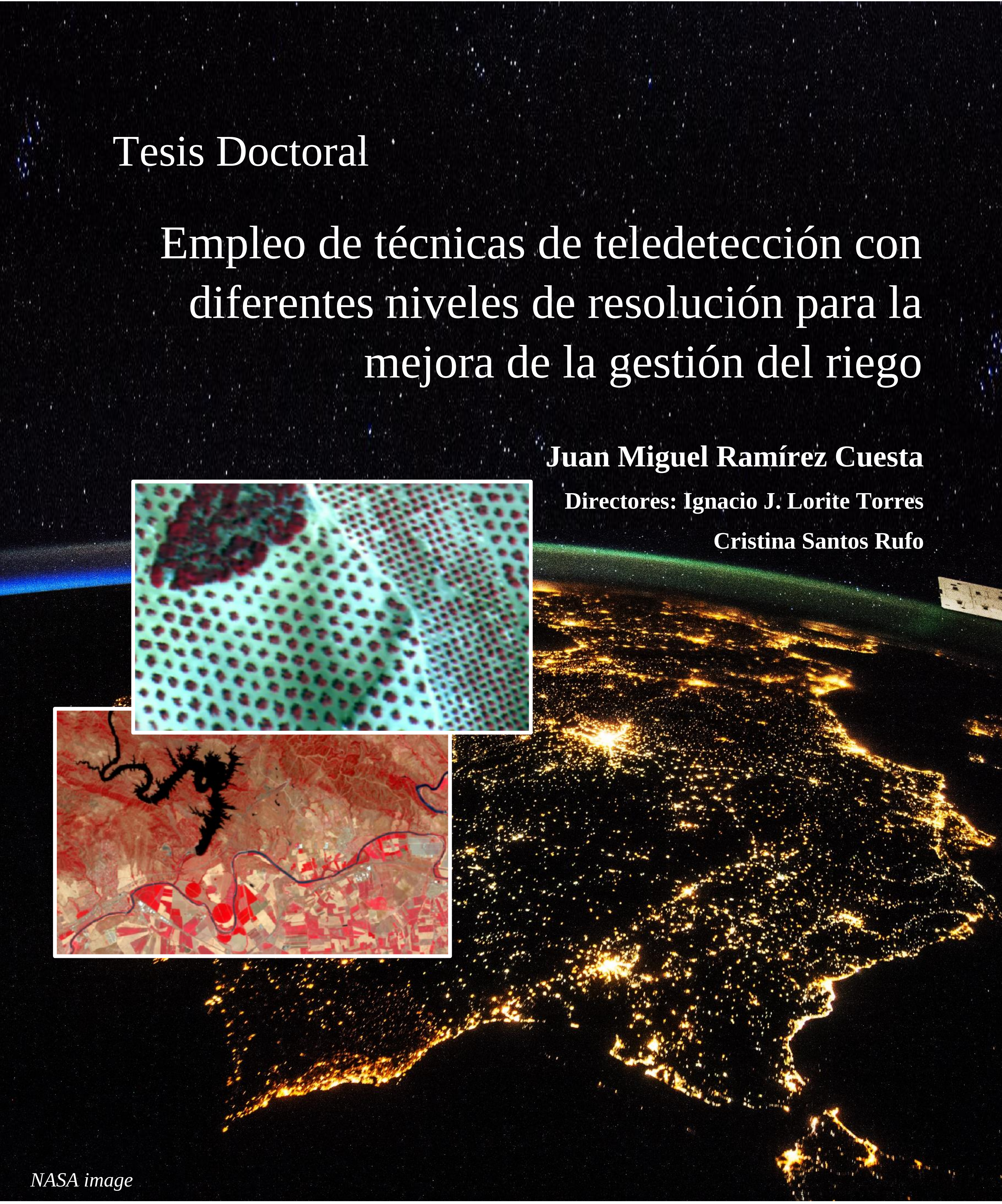

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TITULO: *Using remote sensing techniques at different resolution scales for enhancing irrigation management*

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TESIS DOCTORAL

Empleo de técnicas de teledetección con diferentes niveles de resolución para la mejora de la gestión del riego

Using remote sensing techniques at different resolution scales for enhancing irrigation management

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MINISTERIO
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TÍTULO DE LA TESIS: "Empleo de técnicas de teledetección con diferentes niveles de resolución para la mejora de la gestión del riego"

DOCTORANDO/A: Juan Miguel Ramírez Cuesta

INFORME RAZONADO DE LOS DIRECTOR/ES DE LA TESIS

(se hará mención a la evolución y desarrollo de la tesis, así como a trabajos y publicaciones derivados de la misma).

La evolución de la tesis titulada "Empleo de técnicas de teledetección con diferentes niveles de resolución para la mejora de la gestión del riego" ha sido muy satisfactoria y se ha desarrollado según el plan previsto inicialmente.

La tesis se ha estructurado en 4 artículos científicos publicados en revistas incluidas en la Colección principal de Web of Science (Clarivate Analytics). Así, el artículo "Assessing reference evapotranspiration at regional scale based on remote sensing, weather forecast and GIS tools" de Ramirez-Cuesta et al (2017) fue publicado en la revista International Journal of Applied Earth Observation and Geoinformation (55:32-42) y cuenta en la actualidad con 5 citaciones, el artículo "Evaluating the impact of adjusting surface temperature derived from Landsat 7 ETM+ in crop evapotranspiration assessment using high-resolution airborne data" de Ramirez-Cuesta et al. (2017) fue publicado en la revista International Journal of Remote Sensing (38, 14:4177-4205) y cuenta en la actualidad con 4 citaciones, y el artículo "Using weather forecast data for irrigation scheduling under semi-arid conditions" de Lorite, Ramirez-Cuesta et al. (2015) fue publicado en la revista Irrigation Science (33, 6:411-427) y cuenta en la actualidad con 10 citaciones. Finalmente, el artículo "Impact of the spatial resolution on the energy balance components on an open-canopy olive orchard" de Ramirez-Cuesta et al. (2019), con fecha de aceptación 3 de Septiembre de 2018 se ha publicado en la revista International Journal of Applied Earth Observation and Geoinformation (74, 88-102).

En todas las publicaciones que forman la tesis doctoral el doctorando es el primer autor, con excepción de la publicación en Irrigation Science que es segundo, si bien su contribución ha sido esencial para la realización del citado artículo.

Además de las publicaciones en revistas internacionales, los resultados más relevantes del doctorando han sido publicados en revistas nacionales y en múltiples congresos nacionales e internacionales.

Muchos de estos trabajos se iniciaron en la estancia predoctoral que el doctorando realizó en la Universidad de Nebraska – Lincoln bajo la supervisión de la doctora Ayse Kilic en el periodo 2/3/2015 al 2/9/2015. Esta estancia ha permitido que esta tesis cumpla uno de los requisitos establecidos en el artículo 35 de la Normativa de Doctorado de la Universidad de Córdoba para conseguir la Mención Internacional. La realización de esta estancia fue decisiva para el buen desarrollo de la tesis y ha sido fundamental para la obtención de muchos de los resultados publicados.

Por todo ello, se autoriza la presentación de la tesis doctoral.

Córdoba, 21 de septiembre de 2018

Firma de los directores

Fdo.: Ignacio J. Lorite Torres　　Fdo.: Cristina Santos Rufo

Mención de Doctorado Internacional

Esta tesis reúne los requisitos establecidos en el artículo 35 de Normativa de Doctorado de la Universidad de Córdoba para la obtención del Título de Doctor con Mención Internacional:

- Estancia internacional predoctoral de 6 meses (2 Marzo de 2015 – 2 Septiembre de 2015) en University of Nebraska Lincoln, School of Natural Resources and Civil Engineering (Nebraska, EE.UU). Supervisora: Dra. Ayse Kilic.

La tesis cuenta con el informe previo de dos doctores externos con experiencia acreditada pertenecientes a alguna institución de educación superior o instituto de investigación distinto de España:

- Dr. Ricardo Trezza. University of Idaho (EE.UU). Department of Water Resources.

- Dra. Isabel Poças. University of Porto (Portugal). Department of Geosciences, Environment and Spatial Planning.

Un doctor perteneciente a alguna institución de educación superior o centro de investigación no español forma parte del tribunal evaluador de la tesis.

- Dr. Giuseppe Ciraolo. Università degli Studi di Palermo (Italia). Dipartimento di Ingegneria Civile, Ambientale, Aerospaziale, dei Materiali.

La Tesis se ha redactado en inglés y será presentada en dos idiomas: castellano e inglés.

El doctorando

Fdo. Juan Miguel Ramírez Cuesta

Tesis por compendio de artículos

Esta tesis cumple el requisito establecido en el artículo 24 de Normativa de Doctorado de la Universidad de Córdoba para su presentación como compendio de artículos. Está constituida por cuatro artículos publicados o aceptados en revistas incluidas en los tres primeros cuartiles de la relación de revistas del ámbito de la especialidad y referenciadas en la última relación publicada por el Journal Citations Report (SCI y/o SSCI).

Publicaciones:

I. Lorite, I. J.; Ramírez-Cuesta, J. M.; Cruz-Blanco, M.; Santos, C., 2015. Using weather forecast data for irrigation scheduling under semi-arid conditions. Irrigation Science, 33: 411–427. https://doi.org/10.1007/s00271-015-0478-0.
JCR 2015: índice de impacto 1.948; posición 18/83 y 1er cuartil en el área temática Agronomy.

II. Ramírez-Cuesta, J. M.; Cruz-Blanco, M.; Santos, C.; Lorite, I. J., 2017. Assessing reference evapotranspiration at regional scale based on remote sensing, weather forecast and GIS tools. International Journal of Applied Earth Observation and Geoinformation, 55: 32-42. https://doi.org/10.1016/j.jag.2016.10.004.
JCR 2017: índice de impacto 4.003; posición 7/30 y 1er cuartil en el área temática Remote Sensing.

III. Ramírez-Cuesta, J. M.; Kilic, A.; Allen, R.; Santos, C.; Lorite, I. J., 2017. Evaluating the impact of adjusting surface temperature derived from landsat 7 ETM+ in crop evapotranspiration assessment using high-resolution airborne data. International Journal of Remote Sensing, 38: 4177–4205. https://doi.org/10.1080/01431161.2017.1317939.
JCR 2017: índice de impacto 1.782; posición 11/27 y 2º cuartil en el área temática Imaging Science & Photographic Technology.

IV. Ramírez-Cuesta, J. M.; Allen, R. G.; Zarco-Tejada, P. J.; Kilic, A.; Santos, C.; Lorite, I. J., 2019. Impact of the spatial resolution on the energy balance components on an open-canopy olive orchard. International Journal of Applied Earth Observation and Geoinformation, 74: 88-102.

JCR 2017: índice de impacto 4.003; posición 7/30 y 1er cuartil en el área temática Remote Sensing.

El doctorando

Fdo. Juan Miguel Ramírez Cuesta

Actividades del plan de formación realizadas

A continuación se numeran las actividades del plan de formación realizadas por el doctorando:

- Asistencia a la Jornada "Seguridad Alimentaria y Pequeña Agricultura" correspondiente a la actividad "Seminarios de actualidad sobre los retos de la investigación en la ingenieria agraria, alimentaria, forestal y del desarrollo rural sostenible" (Año 2013/2014).

- Impartición del seminario titulado "Aplicación de técnidas de teledetección a diferentes escalas para la mejora de la gestión de los recursos hídricos" en el centro IFAPA, Alameda del Obispo, (Año 2013/2014).

- Movilidad en Universidad de Nebraska-Lincoln (Nebraska, USA) bajo la supervisión de la Dra. Ayse Kilic (Año 2014/2015).

- Asistencia a la Jornada del día 27 de Noviembre de 2015 correspondiente a la actividad "Mejora de la empleabilidad y orientación laboral" impartida por APROINN CONSULTORES (Año 2015/2016).

- Asistencia a la Jornada "Retos de la Alimentación Sostenible" correspondiente a la actividad "Seminarios de actualidad sobre los retos de la investigación en la ingenieria agraria, alimentaria, forestal y del desarrollo rural sostenible" (Año 2016/2017).

- Visita a la empresa Limagrain Ibérica S.A. como parte de la actividad formativa "Visita a centros, grandes instalaciones y laboratorios de investigación del sector privado y del público" (Año 2016/2017).

- Organización del Seminario de Actualidad denominado "La innovación como base del crecimiento empresarial en el sector Agro. Programa de mejora en la empresa EUROSEMILLAS", correspondiente con la actividad "Seminarios de actualidad sobre los retos de la investigación en la ingenieria agraria, alimentaria, forestal y de desarrollo rural sostenible" (Año 2016/2017).

- Asistencia a la Jornada "La innovación como base del crecimiento empresarial en el sector Agro. Programa de mejora en la empresa EUROSEMILLAS" correspondiente a la actividad "Seminarios de actualidad sobre los retos de la investigación en la ingenieria agraria, alimentaria, forestal y del desarrollo rural sostenible" (Año 2016/2017).

Resultados relacionados con la formación investigadora, aunque no directamente de la tesis

Participación en congresos nacionales e internacionales

- 2 Presentaciones Orales en XXX International Horticultural Congress. Istanbul (Turquía), 12-16 Agosto 2018.

- Presentación Poster en International Geoscience and Remote Sensing Symposium (IGARSS 2018). Valencia (España), 22-27 Julio 2018.

- Presentación Oral en VIII Conference on Soil Use and Management: Gestión Sostenible de Suelos y Aguas. A Coruña (España). 25-27 Junio 2018.

- Presentación Oral en IV Remote Sensing and Hydrology Symposium (RSHS 2018). Córdoba (España). 8-10 Mayo 2018.

- Presentación Oral en III Symposium Nacional de Ingeniería Hortícola, I Symposium Ibérico de Ingeniería Hortícola. Lugo (España), 21-23 Febrero 2018.

- 3 Presentaciones Poster en III Symposium Nacional de Ingeniería Hortícola, I Symposium Ibérico de Ingeniería Hortícola. Lugo (España), 21-23 Febrero 2018.

- Presentación Oral en XVII Congreso de la Asociación Española de Teledetección. Murcia (España), 3-7 Octubre 2017.

- Presentación Poster en Tübingen Atmospheric Physics Symposium: Scintillometer and Applications. Tübingen (Alemania), 7-9 Octubre 2013.

Realización de cursos

- ESA-EO Summer School. Frascati (Italia). 30 Julio 2018 – 10 Agosto 2018. Organizado por European Space Agency.

- Notion de Teledetection – Application aux Images Sentinel 1. Toulouse (Francia). 12-15 Marzo 2018. Organizado por Université Toulouse III.

- Unmanned Aerial Vehicle Pilot. Madrid (España). Febrero 2016. Organizado por Aeromax.

- Generación de script con Python en ArcGIS 10.1. Online. 12 Julio 2014 – 11 Agosto 2014. Organizado por ESRI España Geosistemas.

- Hyperspectral Remote Sensing. Online. 27 Enero 2014 – 07 Marzo 2014. Organizado por Faculty of Geo-Information Science and Earth Observation of the University of Twente.

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- Ramírez-Cuesta, J. M.; Vanella, D.; Consoli, S.; Motisi, A.; Minacapilli, M., 2018. A satellite stand-alone procedure for deriving net radiation by using SEVIRI and MODIS products. International Journal of Applied Earth Observation and Geoinformation, 73: 786-799.

- Ramírez-Cuesta, J. M.; Mirás-Avalos, J. M.; Cancela, J. J.; Intrigliolo, D. S., 2018. Integración de la ecuación universal de pérdida de suelo (RUSLE) y técnicas de teledetección para la determinación de la variabilidad espacial de la erosión. En: García-Tomillo, A.; Lado-Linares, M.; Vidal-Vázquez, E.; da Silva-Dias, R.; Mirás-Avalos, J. M.; Paz-González, A., 2018. VIII Conference on Soil Use and Management: Abstract book (I. S. B. N.: 978-84-9749-684-1).

- Intrigliolo, D. S.; Moreno, M. A.; Jiménez-Bello, M. A.; Ramírez-Cuesta, J. M., 2018. Aplicaciones de drones y satélites en la gestión de cultivos en climas semi-áridos. En: Cancela-Barrio, J. J.; González-Vázquez, X. P., 2018. Actas de Horticultura 78: Colección de Actas de Horticultura (I. S. B. N.: 978-84-697-9314-5).

- Ramírez-Cuesta, J. M.; Rubio-Asensio, J. S.; Mirás-Avalos, J. M.; Intrigliolo, D. S., 2018. Implementación del modelo de coeficiente de cultivo dual en una toolbox en ArcGIS para su utilización con imágenes de satélite. En: Cancela-Barrio, J. J.; González-Vázquez, X. P., 2018. Actas de Horticultura 78: Colección de Actas de Horticultura (I. S. B. N.: 978-84-697-9314-5).

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- Ramírez-Cuesta, J. M.; Rodríguez-Santalla, I.; Gracia, F. J.; Sánchez-García, M. J.; Barrio-Parra, F., 2016. Application of change detection techniques in geomorphological evolution of coastal areas. Example: Mouth of the River Ebro (period 1957–2013). Applied Geography, 75: 12-27.

- Cruz-Blanco, M.; Santos, C.; Ramírez-Cuesta, J. M.; Lorite, I. J., 2013. Evaluación de variables agrometeorológicas mediante teledetección y su aplicación a la optimización del uso del agua. Ambienta, 105: 28-39.

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Esta tesis es vuestra.

Resumen

Actualmente existe un interés creciente por la mejora de la gestión del agua en la agricultura mediterránea debido a las previsibles consecuencias del cambio climático y a la competencia con otros sectores como el medioambiental. Por este motivo en esta tesis se han evaluado diferentes metodologías para incrementar la eficiencia en el uso del agua en la agricultura andaluza por medio de la mejora en la estimación de las necesidades de riego de los cultivos, empleando diferentes técnicas de teledetección y análisis espacial. De este modo, en este trabajo se abordó el estudio de los dos principales parámetros involucrados en la determinación de la evapotranspiración de cultivo: la evapotranspiración de referencia (Capítulos 1 y 2) y el coeficiente de cultivo (Capítulos 3 y 4).

Más específicamente, en el Capítulo 1 se evaluaron diferentes métodos de interpolación de información obtenida desde estaciones meteorológicas para determinar cuál de ellos proporcionaba unas estimaciones de evapotranspiración de referencia (ET_o) más precisas. Las estimaciones de ET_o obtenidas con dichos métodos de interpolación se compararon con los valores de ET_o proporcionados por Land Surface Analysis Satellite Application Facility (LSA SAF), a partir de la radiación solar diaria derivada de Meteosat Second Generation (MSG) y de las prediciones de la temperatura del aire a 2 m proporcionadas por European Centre for Medium-range Weather Forecasts (ECMWF). Adicionalmente, se propusieron técnicas para la mejora en la estimación de la ET_o en zonas sin estación meteorológica cercana, basadas en el análisis de localización espacial de las estaciones meteorológicas y en la evolución temporal de ET_o en las mismas.

Relacionado también con la estimación de la ET_o y su aplicación práctica para la gestión del riego, en el Capítulo 2 se presenta una innovadora metodología para la realización de calendarios de riego fácilmente utilizable por agricultores y técnicos, utilizando predicciones meteorológicas para la estimación de ET_o proporcionadas por la Agencia Estatal de Meteorología (AEMET) y por el ECMWF. Además, se analizó el efecto de la consideración de diferentes métodos para la estimación de la ET_o sobre las necesidades de riego y sobre el rendimiento del cultivo simulado utilizando el modelo AquaCrop.

Una vez determinados valores fiables de ET_o mediante las metodologías desarrolladas en los Capítulos 1 y 2, para la correcta estimación de las necesidades de riego de los cultivos, es preciso obtener valores de coeficiente de cultivo ajustados al estado de los mismos. Esta cuestión se trató en el Capítulo 3, donde se aplicaron diferentes correcciones atmosféricas sobre imágenes del satélite Landsat 7, con el objetivo de eliminar el efecto que la atmósfera causa durante el proceso de adquisición de las mismas. De este modo, se consiguió obtener unas medidas de temperatura superficial mucho más precisas, para finalmente conocer el efecto de las diferentes correcciones atmosféricas sobre la determinación del coeficiente de cultivo del olivar.

Sin embargo, el efecto de la atmósfera en el proceso de adquisición de imágenes de satélite analizado en el Capítulo 3 no es el único aspecto a tener en cuenta al emplear técnicas de teledetección. Así, la resolución espacial también es un factor clave para la correcta aplicación de estas técnicas en la gestión del riego. Es por ello que en el Capítulo 4 se evaluó la influencia de la resolución espacial sobre los diferentes componentes de balance de energía estimados mediante el modelo de balance de energía METRIC, prestando especial atención a la evapotranspiración del cultivo.

Summary

Currently there is a growing interest in improving water management in Mediterranean agriculture due to the foreseeable results of climate change and to the competition with other sectors such as the environmental. For this reason different methodologies have been evaluated in this thesis to increase water use efficiency in Andalusian agriculture by means of the improvement in the estimation of crop irrigation water requirements, using different remote sensing techniques and spatial analysis. In this work the two main parameters involved in crop evapotranspiration determination were addressed: reference evapotranspiration (Chapters 1 and 2) and crop coefficient (Chapters 3 and 4).

More specifically, in Chapter 1, different interpolation methods were applied to meteorological data and results were assessed in order to determine which of them provided the most accurate reference evapotranspiration (ET_o) estimates. The ET_o estimates obtained from the interpolation methods were compared with the ET_o values provided by the Land Surface Analysis Satellite Application Facility (LSA SAF), based on the daily solar radiation derived from Meteosat Second Generation (MSG) and air temperature at 2 m forecasts provided by European Center for Medium-range Weather Forecasts (ECMWF). Additionally, new techniques were proposed for ET_o estimation improvement in areas without a nearby weather station, which were based on the analysis of the spatial location of the weather stations and the temporal evolution of ET_o.

Also related to ET_o estimation and its practical application for irrigation management, Chapter 2 presents an innovative methodology for performing irrigation schedules easily usable by farmers and technicians, using weather forecasts provided by the National Meteorological Agency (AEMET) and by ECMWF for ET_o estimation. In addition, the effect that the different methods for ET_o estimation has on the crop water requirements and on the crop yield simulated using the AquaCrop model was also assessed.

Once accurate ET_o values were determined by means of the methodologies developed in Chapters 1 and 2, it is necessary to determine crop coefficient values for the correct estimation of the crop water demands. This issue was addressed in Chapter 3, where different atmospheric corrections were applied to Landsat 7 satellite images, with the

aim of eliminating the effect that the atmosphere causes during the image acquisition process. In this way, it was possible to obtain much more accurate surface temperature measurements, in order to assess the effect of the different atmospheric corrections on the determination of the olive crop coefficient.

However, the effect that atmosphere has on the satellite images acquisition process analyzed in Chapter 3 is not the only issue to be taken into account when using remote sensing techniques. Thus, spatial resolution is also a key factor for the application of these techniques in irrigation management. Therefore, in Chapter 4 the influence of spatial resolution on the different energy balance components estimated by the METRIC energy balance model was evaluated, paying special attention to crop evapotranspiration.

Glossary

ACCESS-G: Australian Community Climate and Earth System Simulator.

AEMET: Agencia Estatal de METeorología.

AHS: Airborne Hyperspectral Scanner.

ALADIN: Aire Limitée Adaptation dynamique Développement InterNational.

ANOVA: ANalysis Of VAriance.

ASCE-EWRI: American Society of Civil Engineers - Environmental and Water Resources Institute.

ASTER: Advanced Spaceborne Thermal Emission and Reflection radiometer.

ATM: Airborne Thematic Mapper.

ATMCORR: ATMospheric CORRection parameter calculator.

AVHRR: Advanced Very High Resolution Radiometer.

CINN: Correction Index based on the closest weather station.

CITS: Correction Index based on the weather station with the most similar ET_o trend.

C_p: Air specific heat at a constant pressure.

CV: Coefficient of Variation.

CWSI: Crop Water Stress Index.

D0: Same-day forecast.

D1: 1-dayahead forecast.

D2: 2-dayahead forecast.

D3: 3-dayahead forecast.

D4: 4-dayahead forecast.

D5: 5-dayahead forecast.

D6: 6-dayahead forecast.

DA: Differences in ET_o caused by the use of different methodology for ET_o assessment.

DAIS: Digital Airborne Imaging Spectrometer.

DEM: Digital Elevation Model.

DN: Quantized calibrated pixel value.

DOY: Day Of Year.

dT: Near surface temperature gradient between two near surface heights.

EC: Eddy Covariance.

ECMWF: European Centre for Medium-range Weather Forecasts.

e_a: Actual vapour pressure.

EROS: Earth Resources Observation and Science.

e_s: Saturation vapour pressure.

($e_s - e_a$): Saturation vapour pressure deficit.

ETM+: Enhanced Thematic Mapper Plus.

ET: Evapotranspiration.

ET_c: Crop evapotranspiration.

ET_{inst}: Instantaneous evapotranspiration.

ET_o: Reference evapotranspiration.

ET_oLSASAF: Reference evapotranspiration map provided by the LSA SAF.

ET_oRIA$_i$: Reference evapotranspiration map generated by each interpolation approach with data from 57 RIA weather stations.

EUMETSAT: EUropean organization for the exploitation of METeorological SATellites.

FAO: Food and Agriculture Organization of the United Nations.

F_c: Vegetation fraction cover.

FOV: Field Of View.

FPA: Focal Plane Array.

FWHM: Full Width Half Maximum.

G: Soil heat flux.

GCP: Ground Control Point.

GERB: Geostationary Earth Radiation Budget.

GIS: Geographic Information System.

GMT: Greenwich Mean Time.

GRG: Generalized Reduced Gradient.

H: Sensible heat flux.

HAR: Hargreaves equation.

HARMONIE/AROME: HIRLAM ALADIN Research on Meso-scale Operational NWP in Europe/ Application of Research to Operations at Mesoscale.

HC: Regionally Calibrated Hargreaves equation.

HIRLAM: HIgh Resolution Limited Area Model.

IDW: Inverse Distance Weighting.

IE: Errors generated by the interpolation of RIA values.

IG: Stomatal Conductance Index.

IMU: Inertial Measuring Unit.

IR: Infrared.

IS-A: Irrigation scheduling A (Table 2.1).

IS-B: Irrigation scheduling B (Table 2.1).

IS-C: Irrigation scheduling C (Table 2.1).

IS-D: Irrigation scheduling D (Table 2.1).

K_1: Constant for Landsat images.

K_2: Constant for Landsat images.

K_{co}: Crop coefficient.

LAI: Leaf Area Index.

L1T: Landsat Standard Terrain Correction.

L_6: Spectral radiance of band 6 of Landsat 7.

L7: Landsat 7 ETM+.

LE: Latent heat flux.

$L_{max,\lambda}$: Radiance at sensor that are scaled to Q_{calmax}.

$L_{min,\lambda}$: Radiance at sensor that are scaled to Q_{calmin}.

LPSO: Landsat Project Science Office.

LSA SAF: Land Surface Analysis Satellite Application Facility.

LST: Land Surface Temperature.

MAE: Mean Absolute Error.

MAK-Adv: Advection-revised Makkink equation.

METRIC: Mapping Evapotranspiration with Internalized Calibration.

MM5: Fifth-Generation NCAR/Penn State Mesoscale Model.

MODIS: MODerate resolution Imaging Spectroradiometer.

MSG: Meteosat Second Generation.

MVIRI: Meteosat Visible and InfraRed Imager.

NCEP: National Centers for Environmental Prediction.

NDVI: Normalized Difference Vegetation Index.

NN: Closest weather station.

NOAH-OSU: NOAH-Oregon State University.

NWP: Numerical Weather Prediction.

p: p-value, probability value.

OC: Ordinary Cokriging.

OCASP: Ordinary Cokriging using aspect as secondary variable.

OCDEM: Ordinary Cokriging using DEM as secondary variable.

OCDSA: Ordinary Cokriging using DEM, slope and aspect as secondary variables.
OCSLP: Ordinary Cokriging using slope as secondary variable.
OK: Ordinary Kriging.
PM-FAO56: Standardised Penman–Monteith equation.
PSU/NCAR: Pennsylvania State University / National Center for Atmospheric Research.
Q_{calmax}: Maximum quantized calibrated pixel values corresponding to $L_{max,\lambda}$.
Q_{calmin}: Minimum quantized calibrated pixel values corresponding to $L_{min,\lambda}$.
r: Pearson’s correlation coefficient.
R^2: Coefficient of determination.
R_a: Water equivalent of the extraterrestrial radiation.
r_{ah}: Aerodynamic resistance to heat transfer.
RAW: Readily Available soil Water.
R_c: Corrected thermal radiance from the surface.
RIA: Agroclimatic Information Network of Andalusia.
RMSE: Root-Mean-Square Error.
R_n: Net radiation.
R_p: Path radiance in the approximately 10.4–12.5 μm band.
rRMSE: Relative Root-Mean-Square Error.
RS: Remote Sensing
R_s: Solar radiation.
$R_{S\downarrow}$: Incoming shortwave radiation.
$R_{L\downarrow}$: Incoming longwave radiation.
$R_{L\uparrow}$: Outgoing longwave radiation.
R_{sky}: Narrow band downward thermal radiation from a clear sky.
SAVI: Soil Adjusted Vegetation Index.
SD: Standard Deviation.
SEB: Surface Energy Balance.
SEBS: Surface Energy Balance System.
SEBAL: Surface Energy Balance Algorithms for Land.
SEVIRI: Spinning Enhanced Visible and Infrared Imager.
SCASP: Simple Cokriging using aspect as secondary variable.
SCDEM: Simple Cokriging using DEM as secondary variable.
SCDSA: Simple Cokriging using DEM, slope and aspect as secondary variables.
SCSLP: Simple Cokriging using slope as secondary variable.

SCK: Simple Cokriging.

SK: Simple Kriging.

SMARTS: Simple Model of the Atmospheric Radiative Transfer of Sunshine.

S-SEBI: Simplified Surface Energy Balance Index.

SSEBop: Operational Simplified Surface Energy Balance model.

T_{2m}: Near-surface air temperature.

T_{air}: Air temperature.

TAW: Total Available soil Water.

T_c: Canopy temperature.

TD: Total Difference.

TIRS: Thermal InfraRed Sensor.

T_m: Mean daily air temperature.

TM: Thematic Mapper.

T_{max}: Daily maximum temperature.

T_{min}: Daily minimum temperature.

TPS: Thin Plate Splines.

T_s: Surface temperature.

$T_{s,Airborne}$: Surface temperature derived from airborne.

$T_{s\ datum}$: Surface temperature adjusted to a common elevation datum using a digital elevation model and a specified lapse rate.

$T_{s,Landsat}$: Surface temperature derived from Landsat 7.

TS: Most similar weather station.

TS-ET_o: Temporal signatures of reference evapotranspiration.

u_2: Wind speed at a height of 2 m.

UAV: Unmanned Aerial Vehicle.

UCSB: University of California, Santa Barbara.

UK: Universal Kriging.

USGS: United States Geological Survey.

VI: Vegetation Index.

VIS: VISible.

VNIR: Visible and Near-InfraRed.

W_b: Weighting coefficients for albedo calculation.

WRF: Weather Research and Forecasting.

α: Surface albedo.

α: Hargreaves equation empirical coefficient.

Δ: Slope of saturated vapour–pressure curve.

ΔT: Average daily range air temperature.

ε_{NB}: Surface behavior for thermal emission in the relatively narrow thermal band of Landsat.

ε_0: Surface thermal emissivity.

λ: Latent heat of vaporization.

ρ: Air density.

$\rho_{s,b}$: At-surface reflectance for band b.

ρ_w: Water density.

τ_{NB}: Narrow band transmissivity of air.

γ: Psychrometric constant.

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General Introduction

In recent years, the interest in improving agricultural water management, especially in arid and semi-arid conditions, has grown as consequence of the effects of climate change and the increased competition for water resources with other sectors such as the environmental. This new scenario has resulted in the development of several actions intended for increasing water use efficiency, such as the promotion of irrigation advisory services for the accurate assessment of irrigation water requirements (Lorite et al., 2012) or the development of deficit irrigation strategies to reduce the volume of water applied without affecting production (Fereres and Soriano, 2007). Additionally, significant advances in modelling and sensors have also contributed to the improvement of water management in many areas around the world (Allen et al., 2007a; Steduto et al., 2012). Thus, sensors have improved the characterization of the agriculture, and crop simulation modelling has increased our understanding of how agricultural systems function (Marsal and Stocke, 2012). These advances have allowed to assess optimal agronomic practices that increase water productivity and optimize irrigation management at both farm (García-Vila and Fereres, 2012) and district level (Lorite et al., 2007).

In order to increase water use efficiency, crop water demands must be taken into account. Consequently, it results critical to accurately estimate crop evapotranspiration (ET_c), defined as the sum of soil surface evaporation and crop transpiration, and reference evapotranspiration (ET_o), defined as the evapotranspiration from a hypothetical grass reference crop without water stress (Allen et al., 1998). Lysimetry under reference conditions is the only way to accurately measure these variables (Vaughan et al., 2007). As an alternative, methods based on field measurements of soil water balances (Chávez et al., 2009; De Bruin et al., 2010), energy balances (Todd et al., 2000; Villa-Nova et al., 2007) or micrometeorology techniques (Er-Raki et al., 2009; Chávez et al., 2009) have been developed.

Regarding reference evapotranspiration (ET_o), there are simple estimation methods which use numerical approaches based on measured weather data. Among the wide range of available approaches, Allen et al. (1998) established the Penman-Monteith equation as the reference method for ET_o assessment to standardize ET_o estimation in different climates. Several authors have found the Penman-Monteith model as the most accurate method under different climatic conditions (Jensen et al., 1990; Allen et al., 1998; Berengena and Gavilán, 2005; Irmak et al., 2003, 2008; Hargreaves and Allen, 2003; ASCE-EWRI, 2005; Temesgen et al., 2005; Allen et al., 2006, Jabloun and Sahli, 2008; Trajkovic and Kolakovic, 2009; Martinez and Thepadia, 2010; Xystrakis and Matzarakis, 2011; Azhar and Perera, 2011; Tabari et al., 2011). All these studies highlight the crucial role that acquisition of high-quality weather data has. Thus, the weather data acquisition must meet strict rules concerning the location and the physical conditions of the field where the weather station is located (Temesgen et al., 1999; Gavilán et al., 2006) which, together with the high costs of maintenance and data collection, have restricted the growth of weather station networks (Exner-Kittridge and Rains, 2010; Collins, 2011). As consequence of even nowadays most modern weather station networks do not fulfill such requirements, uncertainties and overestimations in ET_o assessment are reported (Cruz-Blanco et al., 2014a). Additionally, weather station data refer to local measures, being representative of only a very limited area which may not be valid for even nearby regions. This situation gets worse when the number of weather stations composing the network is limited and vast areas are located far from well-managed weather stations (Voogt, 2006; Collins, 2011).

In order to face the above mentioned limitations, alternative approaches have been developed, highlighting (i) the use of simplified equations with reduced data requirements (Allen et al., 1998; Gavilán et al., 2006; Khoob, 2008); (ii) the use of interpolation approaches (Alves et al., 2013; Walsh et al., 2013); (iii) the use of weather forecast data for ET_o estimation for the development of real-time irrigation scheduling (Mariño et al., 1993; Cai et al., 2007; Xu et al., 2012); and (iv) the use of remote sensing techniques, providing high-quality and fine-resolution weather characterization for extensive areas (Cristobal and Anderson, 2012; Cruz-Blanco et al., 2014a, 2015; Rahimikhoob and Hosseinzadeh, 2014).

Since climatic parameters are the only factors affecting ET_o, the lack of accurate weather data is one of the main limitations for the application of Penman-Monteith equation (Pereira et al., 2002; Popova et al., 2006; Jabloun and Sahli, 2008). Alternatives equations requiring less climatic parameters than the reference established standardized Penman–Monteith equation (Allen et al., 1998) have been developed for using where complete weather data are lacking. Among these approaches the most worldwide used are those developed by Trabert (1896), Thornthwaite (1948), Makkink (1957), Romanenko (1961), Turc (1961) , Schendel (1967), Mahringer (1970), Hansen (1984), Priestley and Taylor (1972), Hargreaves and Samani (1985), Trajkovic (2007), Ravazzani et al. (2012), Valiantzas (2013). More recently, some of these equations have been adapted for being use in different climates from those they were created for. This is the case of the study by Camargo et al. (1999) for Thornthwaite equation (Thornthwaite, 1948); the study by Oudin et al. (2005) for the approach described in Romanenko (1961); the studies carried out by De Bruin (1987), De Bruin et al. (2012) and Cruz-Blanco et al. (2014a) for Makink equation (Makink, 1957); and the developed by Gavilán et al. (2006) and Berti et al. (2014) considering the Hargreaves and Samani equation (Hargreaves and Samani, 1985).

Despite several authors have demonstrated the good performance of the above mentioned improved approaches for different climate conditions (Hargreaves and Allen, 2003; Utset et al., 2004; Yoder et al., 2005; Gavilán et al., 2006; Sentelhas et al., 2010; Espadafor et al., 2011; De Bruin et al., 2012; Fisher and Pringle III, 2013; Raziei and Pereira, 2013; Cruz-Blanco et al., 2014a, b; Djaman et al., 2015, 2017) it is recommended to avoid the use of alternative ET_o calculation procedures when inaccurate or missing meteorological data are detected (Allen et al., 1998). Thus, it is advisable to estimate first the missing meteorological data and then to calculate ET_o using the standard FAO Penman-Monteith method. Some procedures have been proposed in the Manual FAO56 (Allen et al., 1998) for deriving missing climatic parameters based on their relationship with other meteorological variables. These procedures focus on estimating missing humidity, radiation and wind speed data; whereas air temperature cannot be reliably estimated when it is missing, considering this parameter as the minimum data requirement to apply correctly the FAO Penman-Monteith approach. Such procedures for estimating missing data have been evaluated in different countries and climates to test their feasibility (Stöckle et al., 2004; Popova et al., 2006; Jabloun and Sahli, 2008).

Alternatively, there are other approaches focused on the estimation of weather data based on the values of nearby weather stations, on weather forecast data or in remote sensing techniques. Thus, the second approach for overcoming the limitations of ET_o estimation can be found in the use of interpolation methods. The interpolation of data from weather stations emerges as a promising approach for assessing ET_o (Alves et al., 2013). The use of interpolation methods has increased as result of the technological advances made in recent decades, mainly related with the development of Geographic Information Systems (GIS) (Irmak et al., 2010).

Many different interpolation methods could be considered, as Inverse Distance Weighting, Thin Plate Splines, Kriging or Cokriging approaches. A full description of the interpolation approaches can be found in Li and Heap (2008, 2011). However, the choice of an interpolation model depends on available weather stations density, spatial distribution and surface complexity, the desired degree of accuracy and the available technological resources (Lam, 1983).

Most of the interpolation approaches have already been applied to the assessment of weather variables with very satisfactory results around the world (Martínez-Cob, 1996; Nalder and Wein, 1998; Hart et al., 2009; Li and Heap, 2011), although non consensus has been achieved for identifying the most accurate interpolation methods for climatic variables estimation (Mardikis et al., 2005; Li and Heap, 2008, 2011; Di Piazza et al., 2011; Keblouti et al., 2012) possibly caused by the important limitations in the procedure of validation of the results provided by the interpolation approaches.

Another approach for assessing crop water demands is the use of weather forecast data at short and medium-term. Around the world, public and private institutions provide accurate, daily, online weather forecasts, and in most cases these are freely accessible to all. These weather forecast services are based on complex numerical models. In Europe, the two main consortiums that provide weather forecast data are HIRLAM (HIgh Resolution Limited Area Model; Unden et al., 2002) and ALADIN (*Aire Limitée Adaptation dynamique Développement InterNational*; ALADIN, 1997). In 2006, both European consortiums collaborated in the development of high-resolution systems with a spatial resolution of less than 1 km. The resulting system is called HARMONIE/AROME (HIRLAM–ALADIN Research towards Meso-scale Operational NWP in Europe/Application of Research to Operations at Mesoscale; Seity et al., 2011) and will be the successor to HIRLAM (Gronsleth and Randriamampianina, 2012). In addition to these, the European Centre for Medium-Range Weather Forecasts (ECMWF; Persson, 2011) also provides weather forecasting services for Europe and North Africa, that are used in conjunction with the HIRLAM system (Navascués et al., 2013). Other models such as Weather Research and Forecasting (WRF), MM5 (PSU/NCAR mesoscale model) or Australian Community Climate and Earth System Simulator (ACCESS-G) provide atmospheric research and operational forecasting for North America, South America and Australia (Done et al., 2004; Silva et al., 2010; Perera et al., 2014).

Numerous studies have been carried out using weather forecast data for agriculture applications. Some studies have evaluated the use of those data for ET_o estimation when data from weather stations were not available (Er- Raki et al., 2010; Xu et al., 2012; Perera et al., 2014; Luo et al., 2014; Tian et al., 2014), while others have focused on the impact of real-time weather forecast data, mainly rainfall, on irrigation scheduling (Cabelguenne et al., 1997; Gowing and Ejieji, 2001; Wang and Cai, 2009; Bergez and Garcia, 2010; Cai et al., 2011; Mishra et al., 2013). Also related to irrigation scheduling, numerical weather data have been used for soil water content assessment (Venalainen et al., 2005; Cai et al., 2009; Tian and Martinez, 2014) with satisfactory results. Finally, the integration of forecasting tools with remote sensing techniques has provided spatially distributed weather data information with very satisfactory results (De Bruin et al., 2010; Cristobal and Anderson, 2012; Cruz-Blanco et al., 2014a, b).

Remote sensing techniques have contributed significantly to the improvement of water management by providing an accurate estimation of crop evapotranspiration (Bastiaanssen et al., 1998; Allen et al., 2007a, b; Santos et al., 2008, 2010). Remote sensing approach represents an efficient and economic technology that can be employed to determine ET since it provides actual ET estimations of large areas, allowing the assessment of the spatial ET variability (Norman et al., 1995b; Bastiaanssen et al., 1998; Allen et al., 2001; Su, 2002; Anderson et al., 2003; Allen et al., 2007a).

The most common approaches for ET estimation from remotely sensed imagery are the vegetation indexes (VI) based models and the surface energy balance (SEB) models. VI-based approaches are intended on deriving ET from the fraction of ground cover or shaded by vegetation derived from vegetation indexes (for example, the normalized difference vegetation index, NDVI, or the soil-adjusted vegetation index, SAVI). However, VI reflect the actual vegetation cover conditions for estimating actual K_{cb}, but requiring an additional approach, normally a water balance model, to estimate K_e (Allen et al., 1998, Mateos et al., 2013; Paço et al., 2014), and therefore K_c and ET_c. Numerous examples of VI-based approaches are reported in literature for both homogeneous and heterogeneous crops (Bausch and Neale, 1987; Calera et al., 2005; Hunsaker et al., 2005; González-Dugo and Mateos, 2008; Campos et al., 2010; Johnson and Trout, 2012).

Nevertheless, most VI-based methods are unable to observe the impact of soil water shortage, salinity or disease on K_c, requiring the use of SEB models for solve this limitation, since uniquely they are able to assess K_c under stress conditions. Thus, some authors have proposed to compare VI-driven K_c with those derived from SEB models in order to estimate reductions caused by water or salinity stress, disease or fertility (Zwart and Bastiaanssen, 2007).

Energy balance models (SEB) take advantage of the relationship between surface radiances and energy balance components to derive crop evapotranspiration (ET). Latent heat flux (LE; W m^{-2}), and therefore ET, is computed as the residual component of the SEB at the time of satellite overpass by subtracting the soil heat flux (G; W m^{-2}) and sensible heat flux (H; W m^{-2}) from the net radiation (R_n; W m^{-2}) at the surface. Net radiation represents the actual radiant energy available at the surface and is computed as the difference between incoming and outgoing radiation of both short and long wavelength (Allen et al., 2007a). Soil heat flux is the energy storage into the soil and vegetation due to conduction, being positive when the soil is warming and negative when the soil is cooling. Sensible heat flux accounts the rate of heat loss to the air by convection and conduction and is a function of the temperature gradient above the surface, surface roughness and wind speed.

In all SEB models, surface temperature data play a critical role in crop water requirements estimation. The emergence and improvement of satellites and airborne sensors has provided a useful and global way to estimate surface temperature over large areas. These sensors provide various scales of application and decreasing spatial resolution ranging from kilometers to a few centimeters. Some examples are the Advanced Very High Resolution Radiometer (AVHRR; Pozo-Vázquez et al., 1997), Moderate Resolution Imaging Spectroradiometer (MODIS; Sobrino et al., 2003), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER; Sepulcre-Cantó et al., 2009), Landsat Thematic Mapper (TM; Sobrino et al., 2004b), Landsat Enhanced Thematic Mapper Plus (ETM+; Suga et al., 2003), Landsat Thermal Infrared Sensor (TIRS; Jiménez-Muñoz et al., 2014), Airborne Hyperspectral Scanner (AHS; Sobrino et al., 2006), Airborne Thematic Mapper (ATM; Callison et al., 1987), and Digital Airborne Imaging Spectrometer (DAIS; Sobrino et al., 2004a). The measure of the sensors could be impacted by uncertainty in sensor calibration, atmospheric attenuation and sourcing, surface emissivity, view angle, and shadowing (Norman, et al., 1995a; Irmak et al., 2012), generating errors in surface temperature (T_s), ranging in some cases from 3 to 5 K (Kalma et al., 2008). Then, the calibration and validation of thermal sensor measurements is crucial to the accurate determination of surface temperature from remote sensing.

The consideration of the previously described platforms such as Landsat or MODIS providing medium-high spatial resolution data, has allowed developing and validating models for ET assessment. Satellite-based SEB models include Surface Energy Balance Algorithm for Land (SEBAL; Bastiaanssen et al., 1998), Mapping Evapotranspiration at high Resolution using Internalized Calibration (METRIC; Allen et al., 2007a, b), Surface Energy Balance Index (SEBI; Menenti and Choudhury, 1993), Simplified Surface Energy Balance Index (S-SEBI; Roerink et al., 2000), Surface Energy Balance System (SEBS; Su, 2002), Two-Source Energy Balance (TSEB; Kustas et al., 2004), and Simplified Two Source-Energy Balance model (STSEB; Sánchez et al., 2008), among others. The spatial resolution of these approaches varies according to the selected sensor. Thus, although the spatial resolution from satellites in the visible and near infrared (VNIR) has improved significantly in the last years, the thermal domain remains at the same (or even lower) spatial resolution than the one provided by the satellites in the early eighties (for example thermal band resolution for Landsat 7 was 60 m while for the most recent satellite of the Landsat series the resolution has been reduced to 100 m). Due to the relevance of spatial resolution in the final results obtained by SEB (Su et al., 1999; McCabe and Wood, 2006; Tian et al., 2012; Sharma et al., 2016), it may be necessary to evaluate these models to other spatial scales different from those targeted in their development (Yang et al., 2014; Zipper and Loheide II, 2014; Bisquert et al., 2016; Ortega-Farias et al., 2016, 2017), as the change in the spatial resolution could impact on the turbulent heat fluxes calculation, resulting in a spatial scale discrepancy (Su et al., 1999).

Several authors have studied the effect of the spatial resolution of input satellite data on crop ET estimation. Thus, Su et al. (1999), Hong et al. (2009), Gebremichael et al. (2010), Long et al. (2011) and Tang et al. (2013) analyzed spatial resolution effect on SEBAL model. McCabe and Wood (2006), Ershadi et al. (2013) and Sharma et al. (2016) performed studies with the same objective than the previous ones, but based on SEBS model, whereas Tian et al. (2012) focused on the effect on METRIC model. Kustas et al. (2004) performed a similar research by using a two-source energy balance model (Norman et al., 1995b). All these studies were mainly focused on the range from Landsat to MODIS spatial resolutions and found that a good agreement exists between ET estimated from these satellites, especially when simple averaging approach is used for spatial input aggregation. In addition, these authors also pointed out the critical role that extreme pixels selection, which are used to calibrate the sensible heat flux at the pixel-level; and land surface heterogeneity play, which can cause significant errors in the ET estimation. However, they did not assess the effect of high-resolution image pixel sizes (from few meters to Landsat spatial resolutions) on the crop ET estimation, especially when non-homogeneous crops are evaluated.

To sum up, although FAO56 approach (Allen et al., 1998) provides a standard procedure to determine crop water requirements, this procedure suffers from important limitations when climatic and vegetation characteristics differ from the ones considered by FAO, promoting the evaluation of alternative approaches. In this work, some of these above-mentioned approaches have been deeply addressed and its suitability for accurately estimate crop water demands tested. Results and conclusions derived from this work based on remote sensing techniques are intended for solving actual concerning on agricultural water management in Mediterranean environments.

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Objectives

The main objective of this work was to develop and validate new methodologies and to adjust previous ones, for improving irrigation management and thus, increasing water use efficiency, based mainly on remote sensing and geographic information technologies. This main objective has been addressed from four specific objectives:

(i) To evaluate the use of geographic information systems for reference evapotranspiration estimation considering interpolation approaches, weather forecast tools and remote sensing techniques (Chapter 1).

(ii) To assess the use of weather forecast data for ET_o assessment, irrigation scheduling and yield estimation by comparing the results with those generated with measured data by automatic weather stations (Chapter 2).

(iii) To develop and to test different atmospheric corrections to be applied on surface temperature imagery obtained from airborne, assessing how they affect evapotranspiration estimation (Chapter 3).

(iv) To assess the effect of spatial resolution on each component of the energy balance equation estimated in open-canopy olive orchards, using METRIC energy balance model, paying special attention to crop evapotranspiration (Chapter 4).

Chapter 1: Assessing reference evapotranspiration at regional scale based on remote sensing, weather forecast and GIS tools

1.1. Abstract

Reference evapotranspiration (ET_o) is a key component in efficient water management, especially in arid and semi-arid environments. However, accurate ET_o assessment at the regional scale is complicated by the limited number of weather stations and the strict requirements in terms of their location and surrounding physical conditions for the collection of valid weather data. In an attempt to overcome this limitation, new approaches based on the use of remote sensing techniques and weather forecast tools have been proposed.

Use of the Land Surface Analysis Satellite Application Facility (LSA SAF) tool and Geographic Information Systems (GIS) have allowed the design and development of innovative approaches for ET_o assessment, which are especially useful for areas lacking available weather data from weather stations. Thus, by identifying the best-performing interpolation approaches (such as the Thin Plate Splines, TPS) and by developing new approaches (such as the use of data from the most similar weather station, TS, or spatially distributed correction factors, CITS), errors as low as 1.1% were achieved for ET_o assessment. Spatial and temporal analyses reveal that the generated errors were smaller during spring and summer as well as in homogenous topographic areas.

The proposed approaches not only enabled accurate calculations of seasonal and daily ET_o values, but also contributed to the development of a useful methodology for evaluating the optimum number of weather stations to be integrated into a weather station network and the appropriateness of their locations. In addition to ET_o, other variables included in weather forecast datasets (such as temperature or rainfall) could be evaluated using the same innovative methodology proposed in this study.

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Chapter 2: Using weather forecast data for irrigation scheduling under semi-arid conditions

2.1. Abstract

A new methodology based on the use of weather forecast data from freely and easily accessible online information for determining irrigation scheduling has been developed. Firstly, reference evapotranspiration (ET_o) was determined with a user-friendly procedure that does not require previous local calibration, knowledge of data acquisition or processing, or a nearby weather station. The comparison of ET_o based on short-term (sameday) and long-term (6-day-ahead) weather forecast data with measured data for 50 locations in southern Spain during 2013–2014 season indicated that differences in ET_o were relatively low with root-mean-square error (RMSE) equal to 0.65 and 0.76 mm d^{-1}, respectively. The procedure was tested for a wide range of weather conditions in the development of irrigation schedules and yield simulations for maize crop during 2013–2014 season. Irrigation water depths provided by irrigation schedules based on ET_o obtained from daily and weekly forecasts and from measured data showed differences of around 1.5 and 0.9 %, respectively. Likewise, yield simulation with irrigation scheduling based on forecast and measured data provided equal averaged values, with a relative RMSE of below 5 %. This similarity of irrigation scheduling and yield estimation based on forecast and measured data has proved the optimal performance of the proposed approach.

This chapter has been published in:

Lorite, I. J.; Ramírez-Cuesta, J. M.; Cruz-Blanco, M.; Santos, C., 2015. Using weather forecast data for irrigation scheduling under semi-arid conditions. Irrigation Science, 33: 411–427.

Chapter 3: Evaluating the impact of adjusting surface temperature derived from Landsat 7 ETM+ in crop evapotranspiration assessment using high-resolution airborne data

3.1. Abstract

Surface temperature (T_s) is an essential parameter in many land surface processes. When T_s is obtained from remotely sensed satellite data the consideration of atmospheric correction may be needed to obtain accurate surface temperature estimates. Most atmospheric correction methods adjust atmospheric transmissivity, path radiance and downward thermal radiation coefficients. Following a standardized atmospheric correction of Landsat 7 thermal data, some differences were found between these corrected data and surface temperature derived from very-high resolution airborne thermal data. Five different methods for determining atmospheric correction were evaluated comparing atmospherically corrected Landsat 7 data with airborne data for an area of olive orchards located at Southern Spain. When using standard default Landsat 7 calibration coefficients T_s differences between satellite and airborne observations ranged from 1 to 6 K, highlighting the need to perform more robust atmospheric correction. When applying the customized values for semi-arid temperate climate in Idaho, USA, and the values based on the National Centers for Environmental Prediction (NCEP) T_s differences ranged from 1 to 4 K, indicating that additional local calibration may be appropriate. Optimal coefficients were determined using the Generalized Reduced Gradient (GRG) approach, a nonlinear algorithm included in Solver tool, obtaining T_s differences around 1–3 K. In order to evaluate the impact of considering the proposed correction approaches, assessment of the evapotranspiration and crop coefficient values derived from the Mapping Evapotranspiration with Internalized Calibration (METRIC) energy balance model provided maximum errors of around 4%, indicating that the METRIC model does not require a robust atmospheric correction. However, the localized calibration approaches are proposed as useful alternatives when absolute land surface temperatures values are required, as in the case of the

determination of crop water stress based on differences between canopy (T_c) and air temperature (T_{air}).

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Chapter 4: Impact of the spatial resolution on the energy balance components on an open-canopy olive orchard

4.1. Abstract

The recent technical improvements in the sensors used to acquire images from land surfaces has made possible to assess the performance of the energy balance models using unprecedented spatial resolutions. Thus, the objective of this work is to evaluate the response of the different energy balance components obtained from METRIC model as a function of the input pixel size. Very high spatial resolution airborne images (≈50 cm) on three dates over olive orchards were used to aggregate different spatial resolutions, ranging from 5 m to 1 km. This study represents the first time that METRIC model has been run with such high spatial resolution imagery in heterogeneous agricultural systems, evaluating the effects caused by its aggregation into coarser pixel sizes. Net radiation and soil heat flux showed a near insensitive behavior to spatial resolution changes, reflecting that the emissivity and albedo respond linearly to pixel aggregation. However, greater discrepancies were obtained for sensible (up to 17%) and latent (up to 23%) heat fluxes at spatial resolutions coarser than 30x30 m due to the aggregation of non-linear components, and to the inclusion of non-agricultural areas in such aggregation. Results obtained confirm the good performance of METRIC model when used with high spatial resolution imagery, whereas they warn of some major errors in crop evapotranspiration estimation when medium or large scales are used.

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General Conclusions

Water management must be based on detailed and advanced characterization of the agricultural systems. Thus, the assessment of the evaporative demand of the atmosphere (named reference evapotranspiration) and the crop water demand, that considers crop evapotranspiration and crop water stress terms, are critical components that frequently are not correctly measured at field level and generate large uncertainties to develop a correct irrigation water management.

Remote sensing and GIS-based techniques appeared a few decades ago, and their use has increased exponentially in the last years as consequence mainly of the quick development that computer science has experienced. Thus, the combination of data from weather station networks together with remote sensing and GIS-based techniques has allowed to solve all limitations that weather station networks present. This is the case of the interpolation methods or tools combining weather forecast and remote sensing techniques, which estimate ET_o in locations where no meteorological information is available. In Chapter 1 of this thesis, spatially distributed ET_o values for the Andalusian region were estimated from some commonly-used interpolation methods and other GIS tools based on innovative approaches combining weather forecast and remote sensing techniques. Among all evaluated methods, Thin Plate Splines (TPS) and Inverse Distance Weighting (IDW) methods performed best since they provided the best agreement with the values derived from Land Surface Analysis Satellite Application Facility (LSA SAF) (i. e. the lowest interpolation error). Additionally, alternative approaches were developed for ET_o estimation based on the closest weather station to each location (NN) and on the most similar weather station according to temporal signatures of reference evapotranspiration (TS) which improved considerably the results obtained with the previous approaches. These contributions have allowed obtaining accurate values of ET_o, improving water management at the field scale by the development of accurate irrigation scheduling adapted to local conditions, a key component in the sustainability of irrigation schemes, especially under semi-arid conditions.

The accurate estimation of crop evapotranspiration in semiarid regions allows determining crop water demands with the development of site-specific irrigation schedules that could be easily implemented by farmers and technicians. Currently, most irrigation schedules are based on past weather data, that may not reflect the weather condition of the period when the water is applied, inducing crop water stress or over irrigation. To solve this limitation and for better reflecting the future weather conditions, in Chapter 2 a new methodology that includes the use of weather forecast data for ET_o assessment is evaluated. Thus, different approaches for ET_o calculation based on weather forecast data were tested, using both short-term and long-term (until 6 days ahead) weather forecast data. Comparing ET_o estimated from short-term weather forecast data and measured in the weather station, the Penman–Monteith approach provided the best results, while using long-term data, Hargreaves approach and its regionally calibrated form achieved the best performance. The satisfactory results obtained in this study demonstrate that the development of accurate irrigation scheduling using weather forecast data is an easy task using free available data and simple well-known approaches.

Similar importance to carry out a correct ET_o assessment is the characterization of the crop water demand by the study of crop coefficients and crop water stress indexes. Recently, remotely sensed derived images have enabled the spatial assessment of physical parameters, including crop evapotranspiration and surface temperature, among others. However, a proper calibration is required for considering atmospheric attenuation and sourcing, surface emissivity, view angle and shadowing. Therefore, in Chapter 3 the effect of surface temperature (T_s) calibration was assessed, comparing atmospherically corrected surface temperature from satellite Landsat 7 using five different approaches with surface temperature obtained from an aircraft. All the approaches considered improved surface temperature retrieval, obtaining discrepancies of less than 1K when Generalized Reduced Gradient (GRG) non-linear algorithm calibration derived parameters (the most accuracy approach) were used. In addition, crop evapotranspiration obtained from the energy balance model METRIC, using T_s from the different calibration methods were compared, concluding that energy balance models based on endmember pixels (such as SEBAL or METRIC) do not require an intensive atmospheric correction since they are based on relative T_s differences.

Once the calibration issue was studied, another question was to evaluate how the spatial resolution impacts on the results obtained from energy balance models for calculating crop evapotranspiration. Most of these models have been developed and validated using medium-high spatial resolution data such as Landsat or MODIS. However, the increase in the use of aircrafts and drones in the last decades has favored the improvement of spatial resolution. Therefore, to check how these models behave at different spatial resolutions, encompassing pixel sizes from a few meters to one kilometer, has been a pending task. Thus, in Chapter 4, the effect of pixel size on energy balance components estimated by METRIC model was assessed, obtaining that coarse spatial resolutions result more critical than high-resolution scales. Analyzing individually each energy balance component, net radiation and soil heat flux estimations showed a near scale-insensitive behavior, whereas for sensible and latent heat fluxes more pronounced discrepancies at coarse spatial resolutions were observed. These results illustrate the good performance of METRIC model when is used with very high-resolution images (spatial resolutions around 5-30 m), whereas some major errors occur when medium or large scales are used (> 60 m).

Therefore, new remote sensing and GIS techniques have been proved as useful tools for estimating spatially distributed reference and crop evapotranspiration, base for the development of accurate irrigation scheduling. In the near future, these novel techniques will be incorporated into the daily life of farmer and technicians for decision making on the management of agricultural fields. However, some aspects must be considered when using these approaches, such as the effect of the temporal and spatial resolution or the pre-processing of the remotely-sensed acquired images. It implies that users of these technologies should have the enough knowledge of how to properly use them, Unfortunately, it is not an easy task, so a few years are needed in order to totally include these approaches into the field management activities, The implementation of the innovate tools evaluated in this study would improve the irrigation efficiency at field and irrigation district scale and constitutes excellent instruments to develop decision support systems to farmers and technicians. It acquires special relevance under the climate change scenario, since less water will be available for agriculture, requiring the adoption of different techniques, as those described in this work, to increase water use efficiency.

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