Computers & Geosciences ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

ArcE: A GIS tool for modelling actual evapotranspiration ☆

Salvador España [a,*], Francisco J. Alcalá [b,c], Ángela Vallejos [a], Antonio Pulido-Bosch [a]

[a] Departamento de Hidrogeología, Universidad de Almería, 04120 Almería, Spain
[b] Geo-Systems Centre/CVRM, Instituto Superior Técnico, 1049-001 Lisbon, Portugal
[c] Estación Experimental de Zonas Áridas (EEZA-CSIC), 04120 Almería, Spain

ARTICLE INFO

Article history:
Received 26 April 2010
Received in revised form
10 January 2011
Accepted 19 March 2011

Keywords:
Actual evapotranspiration
GIS
ArcObjects
Semiarid climate
SE Spain

ABSTRACT

This paper introduces ArcE, a GIS tool for modelling actual evapotranspiration (E_A) from an undefined number of meteorological stations. From daily data of precipitation and temperature, ArcE uses ArcObjects as the programming language to incorporate equations and hydrological boundary conditions, in order to calculate E_A at monthly and yearly time steps. Because weather data are often missing, ArcE is programmed to use non-global models such as Hargreaves for potential evapotranspiration (E_P) and Budyko for E_A. In arid regions, where results from global and non-global models are expected to deviate, ArcE allows for the segregation of low-divergent areas suitable for interpolating E_A from those that should be excluded for mapping the variable. In the semiarid Almanzora River basin, a heterogeneous region with contrasting climate in SE Spain, divergence in lowlands with a higher aridity index was about 15% with respect to an accurate estimate of E_A from the Penman–Monteith equation. Evaluating E_A is a first step for mapping the non-evaporative fraction of precipitation as the difference in P and E_A.

1. Introduction

After precipitation (P), evapotranspiration (E) is the largest component in the terrestrial hydrological budget, of decisive relevance for water resources evaluation and sustainable water management policies (Dalezios et al., 2002; Arora, 2002). E is a large uncertainty water balance term, difficult to calculate and compute, which depends largely on the availability of water and energy, and thus it is site-specific (Milly and Eagleson, 1987). E may be yielded at different spatiotemporal scales, from short-term local estimates for agronomical uses (Allen et al., 1998; Droogers and Allen, 2002) and ecological purposes (Domingo et al., 2001), to long-term areal values for groundwater resources evaluation (Contreras et al., 2008; Alcalá et al., 2011) and climate predictions (Sobrino et al., 2007; Chenini and Ben Mammou, 2010).

A great number of formulae are available, which use some of the physical knowledge; the choice depends on what can be observed and which data are actually measured (Droogers and Allen, 2002; Dalecios et al., 2002). Non-global models for potential E (E_P) are based on (1) precipitation and temperature data; (2) solar radiation; (3) direct measurements in evaporimeters; etc. (Allen et al., 1998; Arora, 2002). Based on precipitation and temperature data, Hargreaves (1994)'s is a widely used model when weather data are missing, although models of everywhere - or global models - based on energy balance and aerodynamics components such as Priestley Taylor, Penman–Monteith, etc. are recommended (Allen et al., 1998). Global models for actual E (E_A) should be based on aerodynamic and canopy resistance parameters supported with soil moisture field data, direct measures from lysimeters (López-Urrea et al., 2006), or direct data from Eddy Covariance towers (Alcalá et al., 2011). Since on occasions, only temperature and precipitation are available, Turc (1961) and Budyko (1974) continue to be widely used non-global formulae for preliminary E_A. Arora (2002) and Gerrits et al. (2009) analyse advantages and limitations of some of these methods in different climates, and they recommend Budyko (1974)'s model for preliminary E_A. Non-global models function reasonably well if the aridity index is low-to-moderate and there is no significant snow cover in the catchment. Monthly time steps are often used for water balance tasks from daily records of precipitation and temperature (Milly and Eagleson, 1987).

In Mediterranean semiarid regions, knowledge about E_A rates continues to be poor (Detto et al., 2006; Gavilán et al., 2006; Weiß and Menzel, 2008) because of the difficulty in evaluating it accurately, since all weather variables range over very large intervals, and because of the heterogeneity in land-use and vegetation (Sobrino et al., 2007). Because E_A is usually close to P, accurate E_A estimates recorded in well-equipped stations are needed to compute water balances (Domingo et al., 2001; Alcalá et al., 2011). Nevertheless, weather data are often limited and E_A should be estimated

☆ Code available from: http://www.iamg.org/CGEditor/index.htm.

* Corresponding author. Tel.: +34 950 014 012; fax: +34 950 015 465.
E-mail address: salvaes@ual.es (S. España).

0098-3004/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cageo.2011.03.008

using simple models as a proxy of global models. The divergence can be only measured when there are well-equipped reference stations (Arora, 2002; Weiß and Menzel, 2008).

GIS has become a powerful tool for integrating and processing large amounts of spatial information, such as the environmental variables needed for evaluating water balance terms (Ludwig and Mauser, 2000; Portoghese et al., 2005). Experience has been gained on the development of non-coupled GIS models for evaluating E_A that function as stand-alone applications (Dalezios et al., 2002). These models work mainly with raster files, and they require a long computation time and an advanced knowledge of programming languages, like Visual Basic, Python, Java, C+, etc. (ESRI, 2000). Large data series are manually selected before mapping, principally using kriging techniques for spatial interpolation. Uncertainty due to gaps in the series and interpolating errors may remain unnoticed in the results.

ArcObjects is a component library that includes all the functions of ArcGIS® (ESRI, 2004), which permit any spatially distributed variable, such as E_A, to be manipulated through the application programming interfaces before interpolation (Chang, 2008). This is in contrast to certain non-coupled models in GIS that require the information to be processed before it is introduced into the software (Cherkauer, 2004; Batelaan and De Smedt, 2007). The use of ArcObjects as a programming language allows access to data in their original format and so reduces the tasks that need to be programmed using other programming languages (Stevens et al., 2007).

The experience of computer programming to evaluate actual evapotranspiration over large areas reduces to basic applications, without the ability for an undefined number of meteorological stations under variable climate conditions to be managed spatially. Software programmed in several languages as ENWATBAL.BAS (Evett and Lascano, 1993), TSAR (Chen et al., 2006), and DAILYET (Hess, 1996), allows combining global and non-global models depending on available data, with limited possibility of managing large spatially distributed geodatabase. Using ArcObjects as the programming language (Chang, 2008), a new model – ArcE – is created to automate the sequential calculation of E_A from E_P from an undefined number of meteorological stations with variable hydrological boundary conditions. The Hargreaves (1994) and Budyko (1974) formulae have been programmed for estimating E_P and E_A in monthly time steps from daily data of precipitation and temperature. This research is part of a larger study designed to evaluate water resources in semiarid basins.

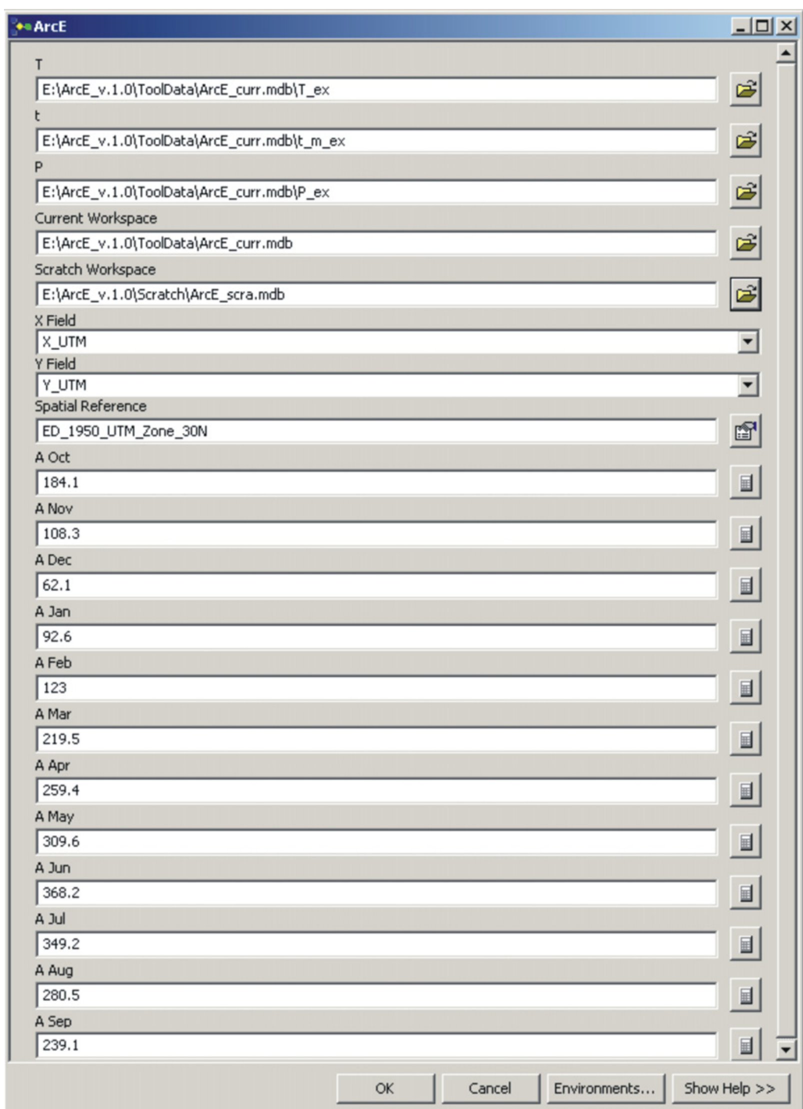

Fig. 1. ArcE interface used to estimate E_P, E_A, and R_T.

Please cite this article as: España, S., et al., ArcE: A GIS tool for modelling actual evapotranspiration. Computers & Geosciences (2011), doi:10.1016/j.cageo.2011.03.008

2. Methods

2.1. Basis for calculating water balance terms

Hargreaves (1994)'s model is used to calculate daily E_P as

$$E_P = 0.0023t^{0.5}A(T+17.8) \tag{1}$$

where t is the daily range of air temperature (°C); T is the average daily air temperature (°C); A is the daily extraterrestrial radiation (mm). Data were uploaded from the *FAO Corporate Document Repository* website [http://www.fao.org/docrep/X0490E/x0490e0j.htm#annex_2._meteorological_tables], although they can be calculated alternatively using the formulation of Duffie and Beckman (1981) as

$$A = 1440G\pi^{-1}d[(\omega\sin\varphi\sin\delta)+(\cos\varphi\cos\delta\sin\omega)] \tag{2}$$

where G is the solar constant (1367 W m^{-2}); d is the factor of relative sun-earth distance; δ is the sun declination (radians); φ is the latitude (radians); ω is the hour angle (radians).

Budyko (1974)'s model is used to calculate daily E_A as

$$E_A = [(1-\cosh(\phi)+\sinh(\phi))(E_P P\tanh(\phi^{-1}))]^{0.5} \tag{3}$$

where P is the daily precipitation (mm); $\phi = E_P P^{-1}$, and E_P is derived from Eq. (1).

$R_T = P - E_A$ is a proxy of the non-evaporative fraction of precipitation (mm) (Sobrino et al., 2007). For a sufficiently long period, such as one hydrological year, R_T means the potential availability of surface water and groundwater resources (Budyko, 1974; Arora, 2002).

Table 2
Input parameters used to compute monthly and yearly E_P, E_A, and R_T in ArcE for any hydrological year.

Parameter	Description
T	Table of mean monthly temperature data, in °C
t	Table of t data, in °C
P	Table of mean monthly precipitation data, in mm
A	Extraterrestrial radiation, in mm
Scratch workspace	Place or file where the intermediate results of the model are stored
Current workspace	Place or file where the final model results will be stored
X_UTM	Latitude of the meteorological station
Y_UTM	Longitude of the meteorological station
Spatial reference	System of reference of coordinates for the fields Y_UTM and X_UTM. This will be the output layer's coordinate system (ED 1950 30 N)
E_P	Table of mean monthly and yearly E_P data (in mm) derived from Eq. (1)

Table 1
Format for monthly P (mm), T (°C), and t (°C) input data used in ArcE (The UTM coordinates system is ED 1950 30 N).

OID	ID	Station	Coordinates		P											
			X_UTM	Y_UTM	P_OCT	P_NOV	P_DEC	P_JAN	P_FEB	P_MAR	P_APR	P_MAY	P_JUN	P_JUL	P_AUG	P_SEP
1	1	Albox	575,758	4,138,224	9	54	21	14	121	38	69	63	10	0	0	0
2	2	Huercal Overa	597,029	4,138,445	16	71	9	7	166	38	20	31	38	28	4	122
3	3	Cuevas del Almanzora	599,610	4,128,304	32	67	11	12	112	39	24	42	1	0	0	0
4	4	Puerto Lumbreras	599,140	4,147,100	21	49	7	98	26	4	5	72	0	0	14	21
5	5	Purchena	556,731	4,140,847	19	78	19	18	152	27	8	64	20	0	0	0
6	6	Águilas	625,291	4,140,054	12	54	10	2	69	19	6	56	0	0	3	2
7	7	Lubrín	583,205	4,118,878	33	93	22	3	239	28	10	82	0	0	0	2
8	8	Uleila del Campo	570,342	4,115,525	17	76	2	3	98	33	8	46	0	0	9	0
9	9	Vera	601,158	4,122,466	47	67	15	6	169	31	46	31	2	0	0	1
10	10	Benizalón	567,472	4,118,920	114	142	3	96	118	151	17	21	1	0	0	62
11	11	Macael	562,125	4,131,976	20	50	23	25	222	39	4	83	13	0	0	0
12	12	Rambla Honda	555,096	4,109,443	18	89	6	3	115	115	8	38	0	0	0	0
					T											
					T_OCT	T_NOV	T_DEC	T_JAN	T_FEB	T_MAR	T_APR	T_MAY	T_JUN	T_JUL	T_AUG	T_SEP
1	1	Albox	575,758	4,138,224	15.5	12.6	11.9	10.5	10.3	14.5	16.4	19.4	23.6	26.5	27.7	23.2
2	2	Huercal Overa	597,029	4,138,445	17.5	13.9	10.4	7.1	9.6	15.3	16.2	19	23.7	25.9	27.1	21.3
3	3	Cuevas del Almanzora	599,610	4,128,304	19.1	15.6	13	10.5	10.6	13.1	15.8	19.9	22.3	24.6	28.8	21.9
4	4	Puerto Lumbreras	599,140	4,147,100	19.2	13.2	9.7	8.3	7.8	13.6	15.6	16.6	20.9	23.2	24.3	19.4
5	5	Purchena	556,731	4,140,847	15.8	14.1	9.9	9	7.9	11.9	14.4	17	22	24	25.1	21
6	6	Águilas	625,291	4,140,054	19.6	16.1	15.5	12	12	14.9	16.8	20.8	23.9	26.9	28	22.8
7	7	Lubrín	583,205	4,118,878	17.4	14.5	11	8.6	8	11	13.7	16.5	21.1	25.6	26.7	20.4
8	8	Uleila del Campo	570,342	4,115,525	17.8	13.6	12.3	10.4	10.9	7.1	15.9	18.4	22.8	26.4	31.2	21.1
9	9	Vera	601,158	4,122,466	18.8	15.7	12.4	9.9	9.4	12.1	14.8	18.2	21.9	24.7	26.1	21.9
10	10	Benizalón	567,472	4,118,920	15.9	14	4.9	8.4	8.4	12.3	14.9	17.5	22.7	26.6	25.6	22.3
11	11	Macael	562,125	4,131,976	17.6	16.4	13.6	9.4	9.4	14.2	16.5	18.2	22.1	22.6	23.5	19.9
12	12	Rambla Honda	555,096	4,109,443	15.5	13	9.3	7.3	7.3	10.2	13	16	21.3	23.8	24.6	19.8
					t											
					t_OCT	t_NOV	t_DEC	t_JAN	t_FEB	t_MAR	t_APR	t_MAY	t_JUN	t_JUL	t_AUG	t_SEP
1	1	Albox	575,758	4,138,224	11.9	11.6	8.1	12.5	8.8	11.8	13.2	13.2	13.2	12.5	13.3	13.3
2	2	Huercal Overa	597,029	4,138,445	13	11.4	10.1	11.5	10	13	12.2	12.7	12.4	12.4	13.8	11.1
3	3	Cuevas del Almanzora	599,610	4,128,304	11	10.6	9.3	11.8	6.9	10.2	11.9	10.8	11.6	10	13.7	10.4
4	4	Puerto Lumbreras	599,140	4,147,100	12.6	9.1	12.7	12.7	9.3	12.1	13.8	9.7	9.6	10.7	10.5	8.4
5	5	Purchena	556,731	4,140,847	12.2	11.8	8.8	13	10.1	13.7	13.6	13.7	14.6	13.5	14.1	15.5
6	6	Águilas	625,291	4,140,054	6.9	7.8	6.7	9.3	7.1	8.8	8.4	7.3	7.4	5.9	6	7.7
7	7	Lubrín	583,205	4,118,878	17.4	14.5	11	8.6	8	11	13.7	16.5	21.1	25.6	26.7	20.4
8	8	Uleila del Campo	570,342	4,115,525	11.1	10.7	7.6	4.4	7.3	3.8	6.1	7.9	10	9.7	9.5	8.2
9	9	Vera	601,158	4,122,466	10.6	11	9.1	10.8	9.1	10.7	11.4	10.5	10.8	10	9.8	10.7
10	10	Benizalón	567,472	4,118,920	10.4	10.2	4	14.5	9.3	12.2	13.4	11.8	13.5	12.7	11	14
11	11	Macael	562,125	4,131,976	24.1	19.3	18.4	18.1	17	20.7	24	19.3	20.1	19.3	21	20.1
12	12	Rambla Honda	555,096	4,109,443	16	11.2	11.2	10.3	9.6	13.2	13	10.8	12.2	13.1	16.5	12.8

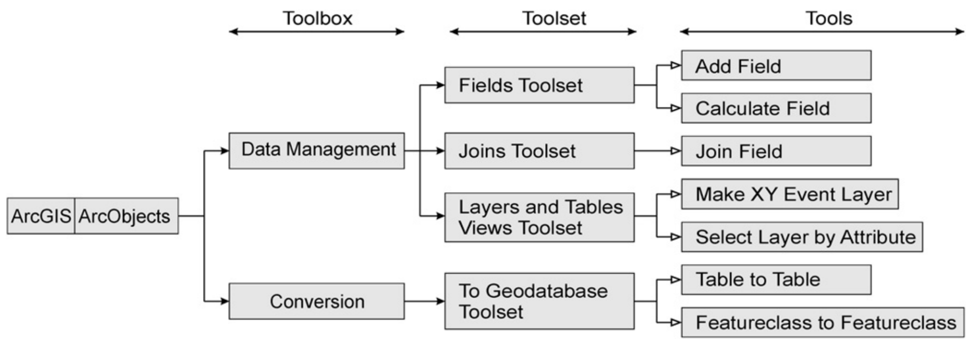

Fig. 2. Toolboxes, Toolsets, and Tools used in ArcE.

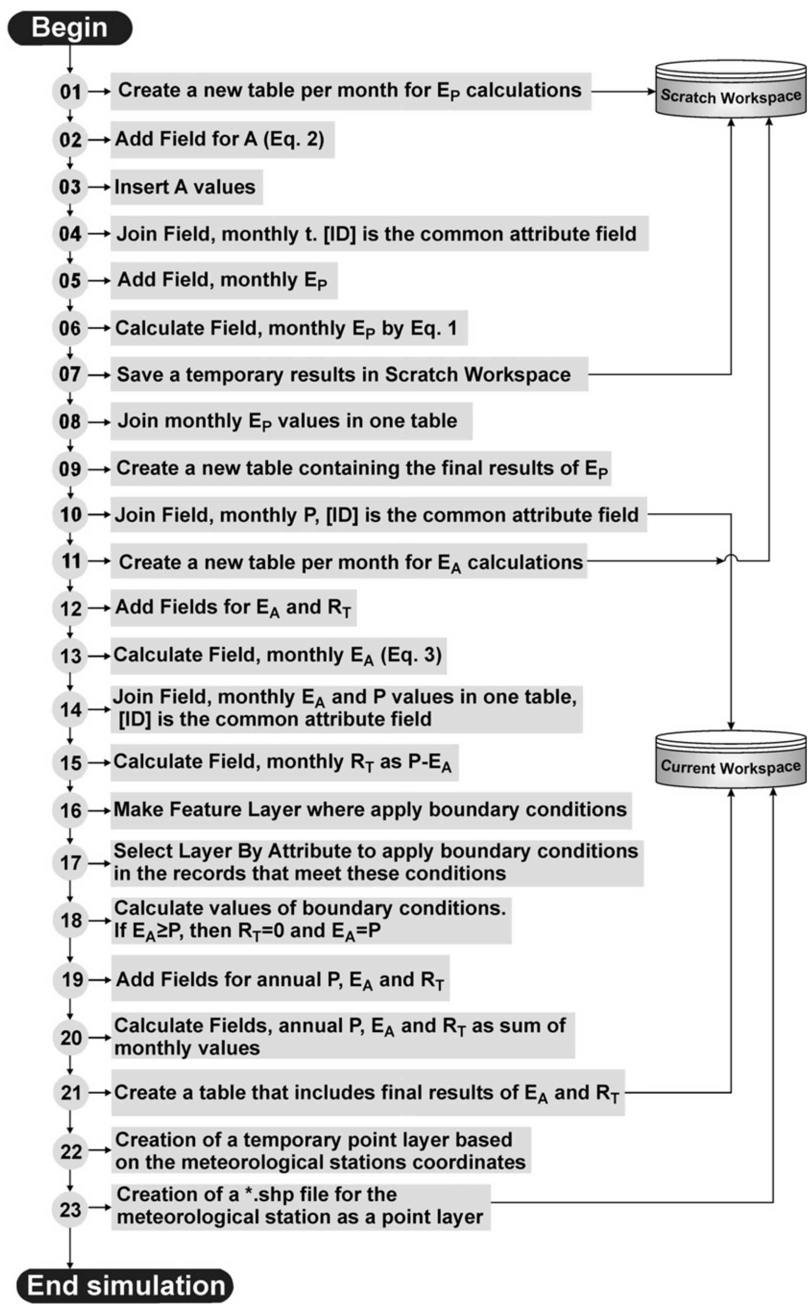

Fig. 3. Design of the ArcE structure for calculating E_P, E_A, and R_T.

Please cite this article as: España, S., et al., ArcE: A GIS tool for modelling actual evapotranspiration. Computers & Geosciences (2011), doi:10.1016/j.cageo.2011.03.008

2.2. ArcE-tools implementation and operation

ArcE is a modelling tool programmed using ArcObjects that uses tables of P, T, and t as input data. Adding and calculating new attributes, copying tables and records, creating relationships between tables and reports, etc., are tedious tasks avoided by ArcE to deliver a layer of points with attributes of source data that contain the spatial position of each station and their values of E_P, E_A, and R_T.

When P and T values are absent from the time series data, R_T calculation from E_P and E_A must be adjusted by programming two reasonable boundary conditions: (1) if annual E_P=null, then $E_P=0$; (2) if E_A=null, then $E_A=0$. Two other boundary conditions were programmed to respect hydrological premises: (1) if $E_A > P$, then $E_A=P$; (2) if R_T=null or $R_T<0$, then $R_T=0$.

The operation of the ArcE interface includes three steps (Fig. 1): (1) The routes to the input data for P, T, and t (Table 1), and other parameters (Table 2) are introduced to compute E_P, E_A, and R_T for each station; (2) The model is run; (3) The results are saved as a table and as a point feature class in a geodatabase.

Data Management Toolbox and Conversion Toolbox are toolboxes used to add new fields to the source tables and calculate variables needed to estimate E_P, E_A, and R_T (Fig. 2). In addition, Fields Toolset, Joins Toolset, Layers and Tables Views Toolset, and To Geodatabase Toolset are used to develop the ArcE, according to the flow diagrams shown in Fig. 3. The intermediate calculations and final results are stored in geodatabases previously defined by the user. The position of each meteorological station and its coordinates must be specified in the input table, as shown in Table 1.

2.3. Study site

ArcE was implemented for the Almanzora River basin, a 2651 km^2 semiarid basin in southeastern Spain surrounded by ranges (peak elevation 2168 masl. at Calar Alto), that flow to the Mediterranean Sea (Fig. 4). This basin typifies the large geological, topographic, and climatic heterogeneity of SE Spain, one of the most arid regions of southern Europe.

Yearly precipitation ranges from 200 mm along the coast to 500 mm in the highlands, with a surface-elevation-weighted value of 298 mm and a coefficient of variation of 0.41 for the period 1975–1995. Rainfall generation is mainly controlled by entering western Atlantic weather fronts favoured by the west–east orientation of the basin. Most of the rainfall occurs during the autumn (108 mm) and spring (84 mm), and derives from Mediterranean convective storms of short duration and high intensity. In winter, cold northern and wet westerly winds predominate, whilst in summer and autumn a maritime wind blows mainly from the S and SE (Summer et al., 2000). The annual temperature

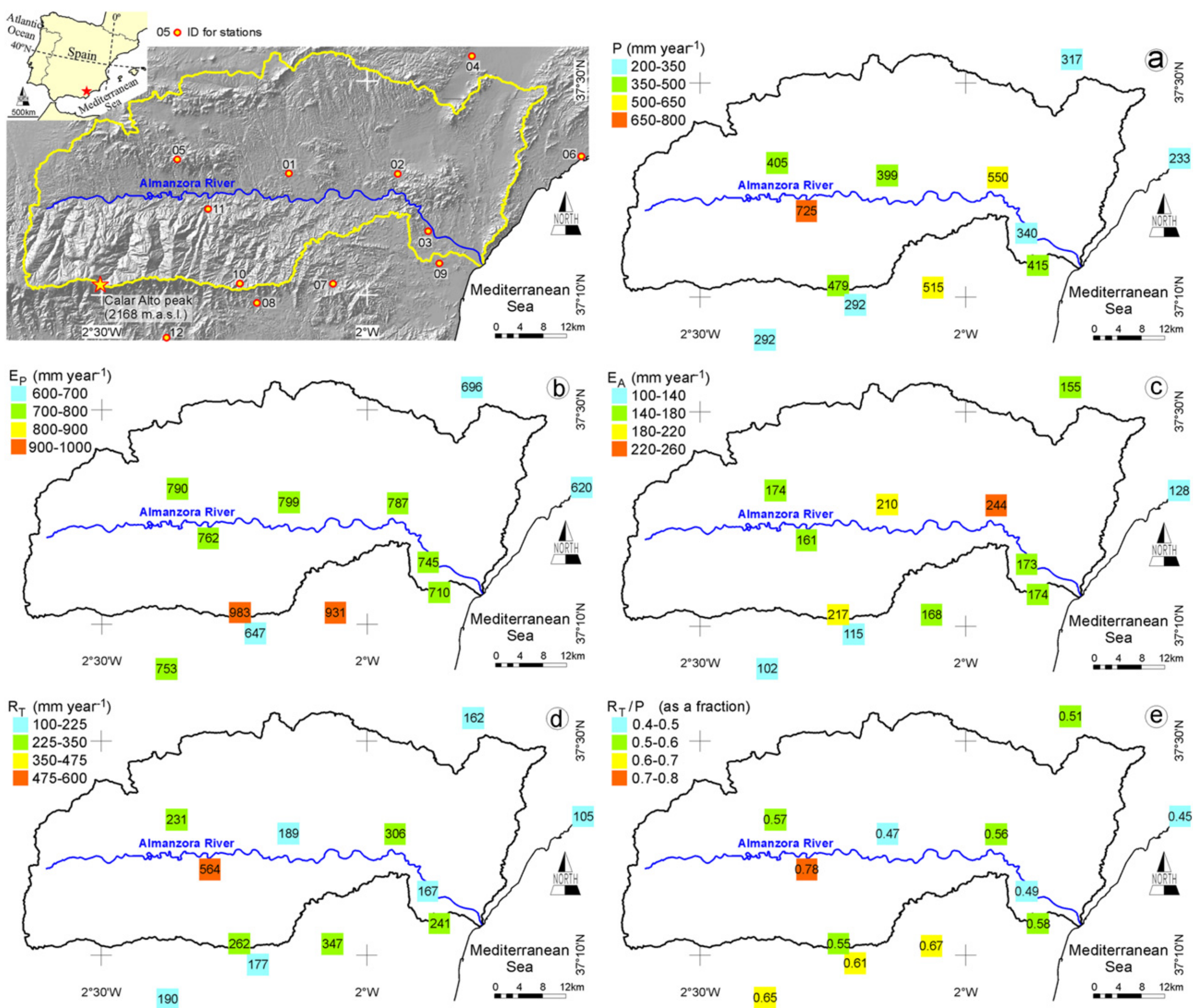

Fig. 4. ArcE application. Yearly results for the average hydrological year 1992–93 in the Almanzora River basin (SE Spain). (a) P; (b) E_P; (c) E_A; (d) R_T (mm year^{-1}); (e) R_T relative to P dimensionless ratio.

Please cite this article as: España, S., et al., ArcE: A GIS tool for modelling actual evapotranspiration. Computers & Geosciences (2011), doi:10.1016/j.cageo.2011.03.008

ranges from 15 °C in the highlands to 19 °C on the coastal fringe, with the minimum in January and maximum in August. Insolation is high, with more than 3300 h per year in low-lying places. Annual potential evapotranspiration is 800–1200 mm. The average climate index is 0.36 (Arora, 2002).

Referring to land-use, rain-fed crops occupy 34% of the basin, 1% are irrigated crops, 49% is sparsely vegetated areas (steppes and badlands), 5% is covered by woodland and shrublands, 10% is forest, and less than 0.1% is occupied by wetlands and groundwater-fed ecosystems (EEA, 2002; Salinas and Casas, 2007).

The varied geology and land-use of the Almanzora River basin was classified by España et al. (2008) into four groups according to their different hydrological behaviour: (1) Triassic carbonate formations over impervious metapelitic rocks form moderately to highly permeable aquifers, with large bare and fissured bedrock areas, regosols, and lithosols. (2) Metapelitic formations represent low permeability areas with lithosols, regosols, and cambisols. (3) Tortonian to Upper Miocene sedimentary basins include large impervious areas (badlands) and local aquifers of moderate productivity with regosols and xerosols. (4) Plio-quaternary and Quaternary alluvial and colluvials form water-table aquifers over impervious bedrocks with fluvisols and xerosols.

3. Data management and results

Meteorological data from the Spanish Agency for Meteorology [http://www.aemet.es] were used to develop ArcE. Twelve meteorological stations (Fig. 4), each having 20 years of daily records of P and T from 1975 to 1995, were selected to compute monthly E_P, E_A, and R_T. Monthly values are summed to get annual values (Table 3). The average hydrological year 1992–1993 (October through to September) was selected to show E_P, E_A, and R_T results. Additional information is also shown for the wet 1988–1989 and the unusually dry 1978–1979 hydrological years, in order to evaluate the influence of climatic aridity on estimates.

For the average hydrological year 1992–93, annual E_P ranges from 620 mm on the coast to 980 mm in the highlands (Table 3; Fig. 4b). The E_P/P ratio ranges from 2.7 on the coastline to 1.1 in the mid-slope; these figures highlight the semiarid condition of the basin (Arora, 2002). Annual E_A ranges from 102 to 244 mm (Table 3; Fig. 4c). The E_A/P ratio ranges from 0.22 in the highlands to 0.55 in coastal areas. E_P and E_A data for wet and dry hydrological years, respectively, are also included in Table 3. The R_T/P ratio varies from less than 0.5 at lowlands sparsely vegetated areas with thin soils over low permeability geological formations to about 0.8 in fissured carbonated landscapes with bare and fissured bedrock areas, thin soils, and shrublands. Rain-fed crops areas are characterised by R_T/P ratios from 0.55 to 0.65 (Table 3; Fig. 4e).

4. Applications and limitations

Management of a large meteorological database of hundreds to thousands data is a tedious preliminary task for water budget evaluation, and one that is not error-free as a result of gaps in the series, data simplifications, etc.; this makes it difficult to distinguish errors due to inaccuracy of data management from those derived from spatial interpolation once mapping variables from simple data points. Since most of non-coupled GIS models performed to estimate E_A are Grid-Based Spatial Surface Water Balance Models, they generate a spatially distributed estimation of the variable as a raster file from single data points (Ludwig and Mauser, 2000; Portoghese et al., 2005). Interpolation uses commonly geostatistical tools as co-kriging, block kriging, etc. with

Table 3
Results from the application of ArcE at 12 meteorological stations in the Almanzora River basin (SE Spain).

ID	Station	Longitude	Latitude	Elevation (m asl)	Geology	Land-use	Period		P^M	T^M	E_P^D	E_P^M	E_P^W	E_A^D	E_A^M	E_A^W	R_T^M	(1)	(2)	(3)
							From	To												
1	Albox	2°08′52″W	37°23′20″N	420	Quaternary alluvial	Urbanized areas	1975	1995	399	17.7	842	799	818	151	210	223	189	2.0	0.53	0.47
2	Huercal Overa	1°56′17″W	37°23′00″N	230	Tertiary marls	Sparsely vegetated areas	1975	1995	550	17.3	828	787	821	153	244	261	306	1.4	0.44	0.56
3	Cuevas del Almanzora	1°52′47″W	37°17′50″N	90	Quaternary alluvial	Urbanized areas	1975	1995	340	17.9	1096	745		167	173		167	2.2	0.51	0.49
4	Puerto Lumbreras	1°48′36″W	37°33′42″N	465	Quaternary alluvial	Rain-fed crops	1975	1995	317	16	762	696	770	115	155	198	162	2.2	0.49	0.51
5	Purchena	2°21′45″W	37°20′50″N	560	Triassic limestone, dolomites	Coniferous forest	1975	1992	405	16	795	790	731	150	174	187	231	2.0	0.43	0.57
6	Águilas	1°35′00″W	37°24′40″N	20	Quaternary colluvial	Urbanized areas	1975	1995	233	19.1	761	620	786	136	128	183	105	2.7	0.55	0.45
7	Lubrín	2°03′57″W	37°12′50″N	500	Palaeozoic schist, quartzites	Rain-fed crops	1975	1995	515	16.2	702	931	702	134	168	165	347	1.8	0.33	0.67
8	Uleila del Campo	2°12′17″W	37°12′00″N	820	Tertiary conglomerates, marls	Rain-fed crops	1975	1995	292	17.3	793	647	643	128	115	177	177	2.2	0.39	0.61
9	Vera	1°51′47″W	37°14′40″N	100	Quaternary alluvial	Irrigated crops	1975	1995	415	17.2	736	710	758	147	174	219	241	1.7	0.42	0.58
10	Benizalón	2°14′27″W	37°12′45″N	935	Palaeozoic schist, quartzites	Rain-fed crops	1987	1995	479	16.3		983			217		262	2.1	0.45	0.55
11	Macael	2°18′17″W	37°19′50″N	536	Permian-Triassic marbles	Urbanized areas	1975	1995	725	17.1	820	762	784	107	161	165	564	1.1	0.22	0.78
12	Rambla Honda	2°22′47″W	37°07′47″N	630	Palaeozoic schist, phyllites	Badlands and steppes	1989	2009	292	15.1		753			102		190	2.6	0.35	0.65

ID code is singled out in Fig. 4.
D—dry (1978–1979); M—average (1992–1993); W—wet (1988–1989) hydrological years.
P^M—precipitation (mm year^{-1}); T^M—temperature (°C).
E_P, E_A, and R_T estimates in mm year^{-1}, and (1) E_P^M/P^M, (2) E_A^M/P^M, and (3) R_T^M/P^M dimensionless ratios.
E_P and E_A estimates for series with gaps exceeding 30% of daily records of P and T are omitted.

external covariates based on geographical items, which introduce a new source of uncertainty.

The role of models has always been to extrapolate data in both time and space. This role becomes more explicit when extrapolating from sites where data are available, compared to the frequent case of sites lacking data and whose characteristics are poorly known. Learning about places and taking account of the inherent uncertainty in doing so will become more important than when using particular model structures (Beven, 2007). Data trends should be considered by themselves to delimit the area for non-global models application. ArcE can be used to resolve the task of assessing the spatial limits to use non-global models for E_P and E_A in heterogeneous territories with contrasting climate and limited data. The use of ArcObjects allows advanced users in this programming language to modify the most sensitive terms in equations as new experiments are performed, or to introduce new, complex formulations for more accurate results.

The quality of the E_A estimates depends on the accuracy of the method used to calculate E_P and E_A. This means that E_A cannot be directly used as an estimator until it has been calibrated using accurate estimates from global models developed in well-equipped stations (López-Urrea et al., 2006; Weiß and Menzel, 2008). To provide some guide about the degree of correction that might be required, accurate daily E_A estimates by Domingo et al. (2001) using Penman–Monteith equation were compiled for Rambla Honda (37°07′47″ N; 2°22′17″ W; 630 m asl), a well-equipped station (Table 3; Fig. 4) providing daily records of P, T, and other meteorological variables and aerodynamics components, soil moisture field data, vegetation cover, etc., from 1989 to 2004. Estimates of E_A were cross-validated from Budyko (B) through Hargreaves, and Domingo et al. (D), for the average hydrological year 1992–1993. The B/D ratio is 1.15. This means that non-global models overestimate E_A by 15% in those most restrictive areas with E_P/P ratio above 2.5. Similar conditions are found in other meteorological stations in the Almanzora River basin (Table 3), as well as in other semiarid areas of southern Spain (Gavilán et al., 2006), southern Italy (Detto et al., 2006), Greece (Dalezios et al., 2002), and Israel (Weiß and Menzel, 2008).

5. Conclusions

ArcE calculates E_P and E_A sequentially from monthly P, T, and t data using an undefined number of meteorological stations submitted to variable hydrological boundary conditions. The programming of non-global models for calculating E_A requires that these results are calibrated before using them. In the semiarid Almanzora River basin, E_A is overestimated by 15% in lowlands with E_P/P ratio above 2.5. This error gives a rough idea of the correction needed before E_A, which can be mapped using geostatistical or deterministic methods. ArcE allows for the segregation of low-divergent areas suitable to map E_A, as a step to evaluate the non-evaporative fraction of precipitation as the difference in P and E_A in regions with significant changes in climate, lithology, relief, and land-use.

Acknowledgements

This research was funded by UE Integrated Project Contract no. 003950 (DeSurvey). The authors thank the specialists of the local Water Authorities and the EEZA. The second author thanks the "Ciência 2008" Programme Contract C2008-IST/CVRM.1, the "Juan de la Cierva" Programme Contract JCI-2007–334, and the Andalusian Research Projects P06-RNM-01732 and P08-RNM-3721. The authors also wish to express their gratitude to two anonymous reviewers for their valuable advice and constructive comments.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cageo.2011.03.008.

References

Alcalá, F.J., Cantón, Y., Contreras, S., Were, A., Serrano-Ortiz, P., Puigdefábregas, J., Solé-Benet, A., Custodio, E., Domingo, F., 2011. Diffuse and concentrated recharge evaluation using physical and tracer techniques: results from a semiarid carbonate massif aquifer in southeastern Spain. Environmental Earth Sciences 62 (3), 541–557.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and Drainage. Paper 56 UN-FAO, Rome, Italy, 465pp.

Arora, V.K., 2002. The use of the aridity index to assess climate change effect on annual runoff. Journal of Hydrology 265 (1–4), 164–177.

Batelaan, O., De Smedt, F., 2007. GIS based recharge estimation by coupling surface-subsurface water balances. Journal of Hydrology 337 (3–4), 337–355.

Beven, K., 2007. Towards integrated environmental models of everywhere: uncertainty, data and modelling as a learning process. Hydrology and Earth System Science 11 (1), 460–467.

Budyko, M.I., 1974. Climate and Life. Academic Press, New York 508pp.

Chang, K.T., 2008. Programming Arcobjects with VBA. A Task-Oriented Approach 2nd ed. CRC Press 342pp.

Chen, Y., Li, X., Li, J., 2006. A TSAR model for daily evapotranspiration at broad spatial scales: a case study in Northern China. Computers and Geosciences 32 (4), 476–484.

Chenini, I., Ben Mammou, A., 2010. Groundwater recharge study in arid region: an approach using GIS techniques and numerical modeling. Computers and Geosciences 36 (6), 801–817.

Cherkauer, D.S., 2004. Quantifying ground water recharge at multiple scales using PRMS and GIS. Ground Water 42 (1), 97–110.

Contreras, S., Boer, M.M., Alcalá, F.J., Domingo, F., García, M., Pulido-Bosch, A., Puigdefábregas, J., 2008. An ecohydrological modelling approach for assessing long-term recharge rates in semiarid karstic landscapes. Journal of Hydrology 351, 42–57.

Dalezios, N.R., Loukas, A., Bampzelis, D., 2002. Spatial variability of reference evapotranspiration in Greece. Physics and Chemistry of the Earth 27 (23–24), 1031–1038.

Detto, M., Montaldo, N., Albertson, J.D., Mancini, M., Katul, G., 2006. Soil moisture and vegetation controls on evapotranspiration in a heterogeneous Mediterranean ecosystem on Sardinia, Italy. Water Resources Research 42, W08419. doi:10.1029/2005WR004693.

Domingo, F., Villagarcía, L., Boer, M.M., Alados-Arboledas, L., Puigdefábregas, J., 2001. Evaluating the long-term water balance of arid zone stream bed vegetation using evapotranspiration modelling and hillslope runoff measurements. Journal of Hydrology 243 (1–2), 17–30.

Droogers, P., Allen, R.G., 2002. Estimating reference evapotranspiration under inaccurate conditions. Irrigation and Drainage Systems 16 (1), 33–45.

Duffie, J.A., Beckman, W.A., 1981. Solar Engineering of Thermal Processes, 3rd ed. John Wiley & Sons, Inc., New York, N.Y 928pp.

EEA, European Environmental Agency, 2002. CORINE Land Cover 2000 (CLC2000) Seamless Vector Database. 〈http://www.eea.europa.eu〉.

España, S., Pulido-Bosch, A., Vallejos, A., Alcalá, F.J., Daniele, L., 2008. GIS application for hydrogeological mapping in the Almanzora River basin (SE Spain). GeoTemas 10, 789–792 in Spanish.

ESRI, 2000. Developing applications with ArcInfo: an overview of Arcobjects, An ESRI White Paper. ESRI Press, Redlands, California. 〈http://downloads2.esri.com/support/whitepapers/ao_/ArcObjects_w_AI.pdf〉.

ESRI, 2004. Geoprocessing in ArcGIS, Guide ArcGIS 9. ESRI Press, Redlands, California 368pp.

Evett, S.R., Lascano, R.J., 1993. ENWATBAL.BAS: a mechanistic evapotranspiration model written in compiled BASIC. Agronomy Journal 85 (3), 763–772.

Gavilán, P., Lorite, I.J., Tronero, S., Berengena, J., 2006. Regional calibration of Hargreaves equation for estimating reference ET in a semiarid environment. Agricultural Water Management 81, 257–281.

Gerrits, A.M.J., Savenije, H.H.G., Veling, E.J.M., Pfister, L., 2009. Analytical derivation of the Budyko curve based on rainfall characteristics and a simple evaporation model. Water Resources Research 45, W04403. doi:10.1029/2008WR007308.

Hargreaves, G.H., 1994. Defining and using reference evapotranspiration. Journal of Irrigation and Drainage Engineering 120 (6), 1132–1139.

Hess, T.M., 1996. Potential Evapotranspiration [DAILYET]. Silsoe College, UK. 〈http://www.cranfield.ac.uk/sas/naturalresources/research/projects/dailyet.html〉.

López-Urrea, R., Martín de Santa Olalla, F., Fabeiro, C., Moratalla, A., 2006. Testing evaporation equations using lysimeters observations in a semiarid climate. Agricultural Water Management 85, 15–26.
Ludwig, R., Mauser, W., 2000. Modelling catchment hydrology within a GIS based SVAT-model framework. Hydrology and Earth System Sciences 4–2, 239–249.
Milly, P.C.D., Eagleson, P.S., 1987. Effects of spatial variability on annual average water balance. Water Resources Research 23, 2135–2143.
Portoghese, I., Uricchio, V., Vurro, M., 2005. A GIS tool for hydrogeological water balance evaluation on a regional scale in semi-arid environments. Computers and Geosciences 31, 15–27.
Salinas, M.J., Casas, J.J., 2007. Riparian vegetation of two semi-arid Mediterranean rivers: basin-scale responses of woody and herbaceous plants to environmental gradients. Wetlands 27 (4), 831–845.
Sobrino, J.A., Gómez, M., Jiménez-Muñoz, J.C., Olioso, A., 2007. Application of a simple algorithm to estimate daily evapotranspiration from NOAA-AVHRR images for the Iberian Peninsula. Remote Sensing of Environment 110, 139–148.
Stevens, D., Dragicevic, S., Rothley, K., 2007. iCity: a GIS-CA modelling tool for urban planning and decision making. Environmental Modelling and Software 22 (6), 761–773.
Summer, G., Homar, V., Ramis, C., 2000. Precipitation seasonality in eastern and southern coastal Spain. International Journal of Climatology 21, 219–247.
Turc, L., 1961. Estimation of irrigation water requirements, potential evapotranspiration: a simple climatic formula evolved up to date. Annales Agronomiques 12 (1), 13–49 in French.
Weiß, M., Menzel, L., 2008. A global comparison of four potential evapotranspiration equations and their relevance to stream flow modelling in semi-arid environments. Advances in Geosciences 18, 15–23.

Please cite this article as: España, S., et al., ArcE: A GIS tool for modelling actual evapotranspiration. Computers & Geosciences (2011), doi:10.1016/j.cageo.2011.03.008