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Rainfall estimation in SWAT: An alternative method to simulate orographic precipitation

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SUMMARY

The input of water from precipitation is one of the most important aspects of a hydrologic model because it controls the basin's water budget. The model should reproduce the amount and distribution of rainfall in the basin, spatially and temporally. SWAT (Soil and Water Assessment Tool) is one of the most widely used hydrologic models. In this paper the rainfall estimation in SWAT is revised, focusing on the treatment of orographic precipitation. SWAT was applied to the Odiel river basin (SW Spain), with a surface of 2300 km^2. Results show that SWAT does not reflect reallisticaly the spatial distribution of rainfall in the basin. In relation to orographic precipitation, SWAT estimates the daily precipitation in elevation bands by adding a constant amount to the recorded precipitation in the rain gauge, which depends on the increase in precipitation with altitude and the difference between the mean elevation of each band and the elevation of the recording gauge. This does not reflect rainfall in the subbasin because the increase in precipitation with altitude actually it is not constant, but depends on the amount of rainfall. An alternative methodology to represent the temporal distribution of orographic precipitation is proposed. After simulation, the deviation of runoff volume using the SWAT elevation bands was appreciably higher than that obtained with the proposed methodology.

1. Introduction

An accurate representation of rainfall distribution is essential in hydrologic and water quality modeling because rainfall is the major driving force of runoff and contamination transport (Cho et al., 2009). Hence, a model will not be able to generate accurate predictions of hydrograph if rainfall is not adequately characterized (DeBarry, 2004; Faures et al., 1995; Schilling and Fuchs, 1986). The spatial variation in precipitation is generally more important than the temporal variation (Beven, 2005; Andreassian et al., 2001; Chaplot et al., 2005; Chaubey et al., 1999; Gassman et al., 2007: Cho et al., 2009), and even though spatially uniform rainfall is generally assumed in modeling of the hydrolgical behaviour of small watersheds, the assumption of spatially uniform rainfall may not be valid for larger watersheds (Cho et al., 2009; Faures et al., 1995; Goodrich et al., 1995). Even at small scale, spatial variability of precipitation can translate in large variations in modeled runoff (Faures et al., 1995).

Rainfall volumes and intensities can vary rapidly in space and time, particularly in convective events. A number of techniques are available for rainfall spatial integration. One of the simplest approaches is the Thiessen method, which assigns the record from the closest rain gauge to the unsampled location (Thiessen, 1911). The inverse square distance technique is an improvement over Thiessen, but neither allows factors such as topography, which can affect the rainfall in a gauge to be considered (Goovaerts, 2000). The isohyetal method requires an extensive rain network to obtain accurate results (Goovaerts, 2000). In small mountainaous watersheds with sparse gauging stations the precipitation variability is of particular concern (Hrachowitz and Weiler, 2011). In recent years, geostatistical treatment has outperformed these interpolation methods (e.g. Goovaerts, 2000; Lloyd, 2005; Moral, 2010). The use of Geographic Information System techniques (GIS) allows take into account the effect on rainfall of topographics variables as elevation, slope, orientation, distance in wind direction from orographic barriers, etc. (Bindlish and Barros, 2000; Marquínez et al., 2003; Guan et al., 2005; Wagner et al., 2012). Weather forecasts (Tobin et al., 2011) and remotely sensed precipitation from ground-based radar and satellites also can be used to improve rainfall estimates over complex terrains (Clark and Slater, 2006; Crochet, 2009).

SWAT (Soil Water Assessment Tool) is a hydrological model developed by the USDA Agricultural Research Service (Arnold et al., 1998; Arnold and Fohrer, 2005). SWAT is a semi-distributed model coupled with a GIS interface (Winchell et al., 2009), which

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delimits watersheds and river networks using the Digital Elevation Model (DEM) and calculates the daily water balance based on soil type, slope, land use and weather data. It was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds. Because its simplicity, SWAT is a widely used tool by the scientific community for: the impact on land management decisions on streamflow and water quality (e.g. Jayakrishnan et al., 2005; Arabi et al., 2008), hydrologic analysis (e.g. Cao et al., 2006; Abbaspour et al., 2007; Gitau and Chaubey, 2010), studies of the impact of climate change (e.g. Ficklin et al., 2009), pollutant load assessment (e.g. Galván et al., 2009), etc. At present, over 1230 peer-review articles have been published (Scopus, accessed 12 February 2013). The model is used by many U.S. federal agencies, such as the Environmental Protection Agency (USEPA), U.S. state agencies and also in other countries (Gassman et al., 2007).

SWAT uses elevations bands to calculate the orographic precipitation. The daily precipitation in elevation bands is estimated by adding a constant amount to the recorded precipitation in the rain gauge, which depends on the increase in precipitation with altitude and the difference between the mean elevation of each band and the elevation of the recording gauge. The main objective of this work is to analyze the capacity of SWAT model to represent the distribution of orographic precipitation in a basin and its influence in the modeled runoff.

2. Methodology

2.1. Site description

The Odiel river (SW Spain, Fig. 1) starts in the “Sierra de Aracena” (maximum elevation of 926 m) and, together with the Tinto river, flows into a coastal wetland known as the Ría of Huelva estuary in the Gulf of Cadiz. The Odiel river is 140 km long and its basin has an approximate area of 2300 km^2. Its mean annual flow has been estimated at about 500 hm^3/yr, however marked variations occurs due to the Mediterranean climate, which includes long periods of drought and intense rain events. The mean annual rainfall in the basin is close to 700 mm, 60% of which occurs from October to January. The Odiel river drainage network is intensively contaminated by acid mine drainage from the mining facilities spread throughout the Iberian Pyrite Belt (Sarmiento et al., 2009).

2.2. Modeling framework

The ArcSWAT 2.1.6 user interface was used for the simulation. The simulation process starts with the Digital Elevation Model (DEM) with a spatial resolution of 10 × 10 m. The information provided for the Environmental Council of Regional Government of Andalusia has been used for the land use map (scale 1:50.000). The existing land-uses in the watershed have been related to the land-uses database of the model through a reclassification tool.

Soil data have been obtained from a prior thorough reconnaissance of the area. Firstly, 45 edaphological units were identified. Later soil units with an area lesser than 3% of the basin surface were clustered in 11 soil types. Depth, available water capacity, texture, organic material, hydraulic conductivity to 50 and 100 cm of depth, bulk density and hydrologic group according the curve number method are available for each soil unit.

There are 40 rain gauges belonging to the Spanish meteorological service in the area but those with incomplete data (lacking more than 20%) were not considered. Thus, 21 rain gauges were selected in the Odiel river basin and the surrounding area (Fig. 1). This is a ratio of one rain gauge per 98 km^2 although they are not homogeneously distributed in the basin (Fig. 1). Daily data from 1980 to 2010 were checked and completed using statistical methods according the recommendations of WMO (1983). Temperature data are available from 11 stations. Potential evapotranspiration

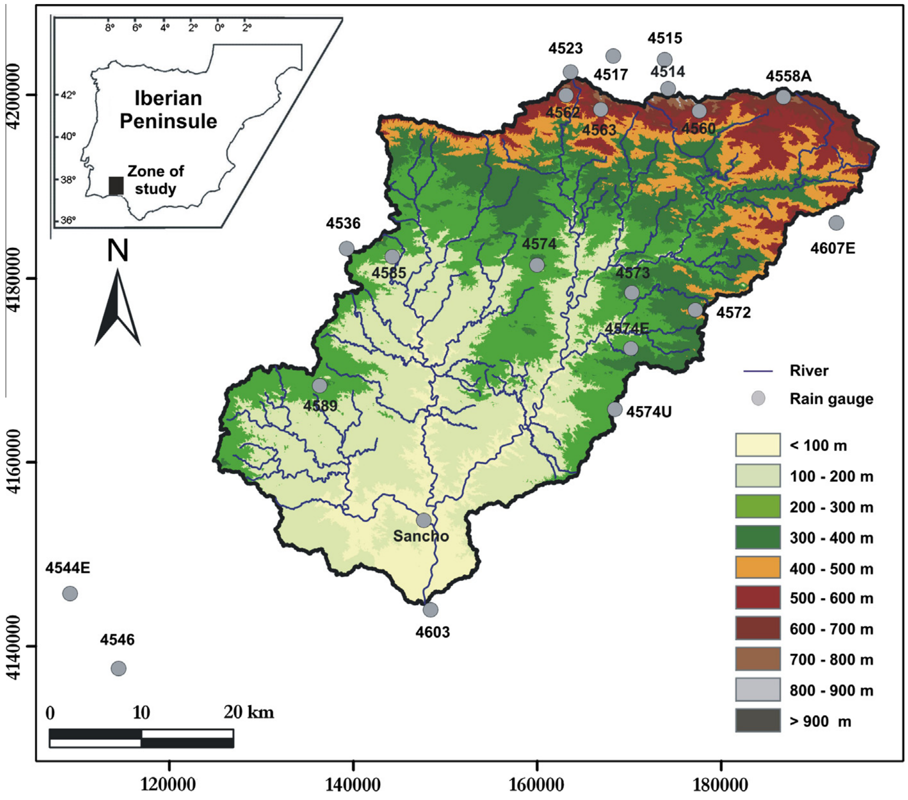

Fig. 1. Location map showing the digital elevation model of the Odiel basin and position of the rain gauges.

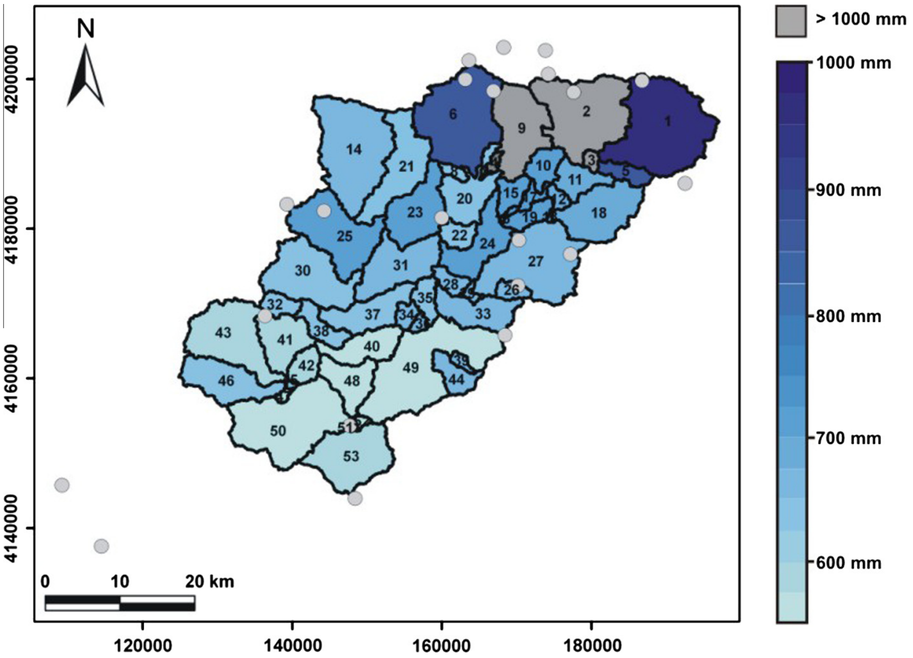

Fig. 2. Average annual rainfall in the Odiel river basin from SWAT.

(PET) was calculated according the Hargreaves method (Hargreaves, 1975).

2.3. Model evaluation statistics

To evaluate the efficiency of the different simulations for the calibration, the following statistical parameters, which are usually employed in hydrology, are calculated: Pearson Correlation Coefficient (r), Efficiency Parameter of Nash and Sutcliffe (NSE; Nash and Sutcliffe, 1970), root mean square error ($RMSE$; Hogue et al., 2006) and deviation of the runoff volumes (DV; Martinec and Rango, 1989; Boyle et al., 2000):

$$r = \frac{\sum_{t=1}^{n}(Q_{obs} - \overline{Q_{obs}})(Q_{sim} - \overline{Q_{sim}})}{\sqrt{\sum_{t=1}^{n}(Q_{obs} - \overline{Q_{obs}})^2 \sum_{t=1}^{n}(Q_{sim} - \overline{Q_{sim}})^2}} \tag{1}$$

where Q_{obs} is the observed flow, $\overline{Q_{obs}}$ is the average observed flow, Q_{sim} is the simulated flow, $\overline{Q_{sim}}$ is the average simulated flow and n is the number of data.

$$NSE = 1 - \left(\frac{\sum_{t=1}^{n}(Q_{obs} - Q_{sim})^2}{\sum_{t=1}^{n}(Q_{obs} - \overline{Q_{obs}})^2}\right) \tag{2}$$

where Q_{obs} is the observed flow, $\overline{Q_{obs}}$ is the average observed flow, Q_{sim} is the simulated flow and n is the number of data.

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(Q_{obs} - Q_{sim})^2} \tag{3}$$

where Q_{obs} is the observed flow, Q_{sim} is the simulated flow and n is the number of data.

$$DV = \frac{\sum_{t=1}^{n} Q_{sim}}{\sum_{t=1}^{n} Q_{obs}} \tag{4}$$

where Q_{obs} is the observed flow, Q_{sim} is the simulated flow and n is the number of data.

2.4. Elevation bands in SWAT

SWAT represents spatial variability in the watershed by discretizing it into smaller units in two steps. First, division into subbasins is carried out and the water network is delineated. Second, each subbasin is divided into several Hydrologic Response Units (HRUs) with homogeneous characteristics of land use, soil type and slope. HRUs represent percentages of the subbasin area and are not

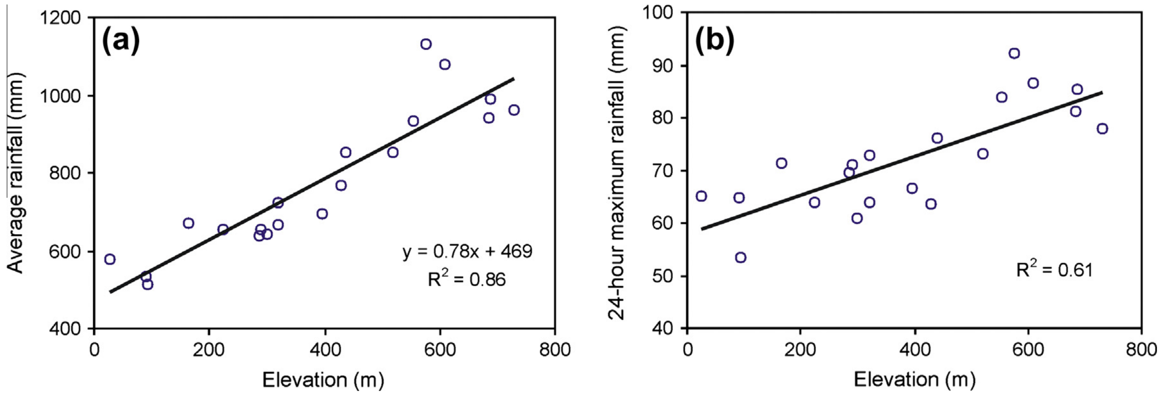

Fig. 3. Rain gauge elevation versus (a) annual average rainfall in the Odiel River basin and (b) annual average values of 24-h maximum rainfall.

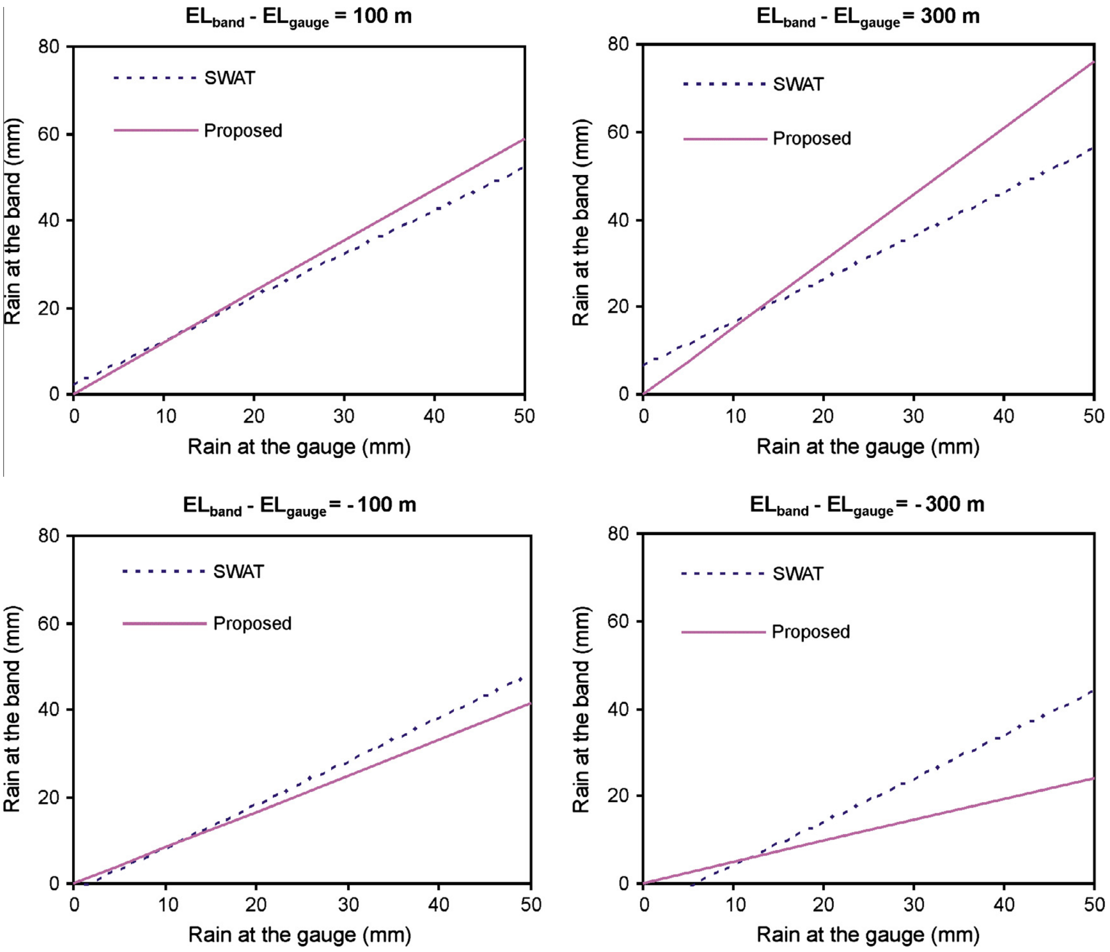

Fig. 4. Comparison of results obtained by SWAT and by the proposed methodology for different values of $EL_{band}–EL_{gauge}$. The graphs were obtained with pcp_{year} = 850 mm, *plaps* = 780 mm/km and $days_{pcp,year}$ = 60.

identified spatially in the simulation. Precipitation for each subbasin is calculated from: (1) weather generator or (2) recorded data from rain gauges. The use of measured precipitation is strongly recommended (Neitsch et al., 2005). In this work we only refer to this option. For each subbasin SWAT uses the rain gauge nearest to its centroid, this method will accurately represent the spatially variable rainfall if the subwatershed delineation sufficiently incorporates the density of observed rainfall stations (Cho et al., 2009).

To account for the orographic effects on precipitation and temperatures in mountainous areas, SWAT allows up to 10 elevation bands in each subbasin (Fontaine et al., 2002). In this work only precipitation is studied. SWAT2005 and SWAT2009 calculate the precipitation in each band as (Neitsch et al., 2005, 2010):

$$R_{band} = R_{day} + (EL_{band} - EL_{gauge}) \cdot \left(\frac{plaps}{days_{pcp,yr} \cdot 1000} \right), \text{ when } R_{day} > 0.01 \tag{5}$$

where R_{band} is the precipitation in the elevation band (mm), R_{day} is the precipitation recorded at the rain gauge (mm), EL_{band} is the mean elevation at the elevation band (m), EL_{gauge} is the elevation at the recording gauge (m), *plaps* is the precipitation lapse rate (mm/km) and $days_{pcp,year}$ is the average number of days of precipitation in the subbasin in a year. Once the precipitation values have been calculated for each band, a new average subbasin precipitation is calculated:

$$R_{day} = \sum_{bnd=1}^{b} R_{band} \cdot fr_{bnd} \tag{6}$$

where R_{day} is the daily average precipitation adjusted for orographic effects (mm), R_{band} is the precipitation falling in each elevation band, fr_{bnd} is the fraction of the subbasin area within the elevation band and b is the total number of elevation bands in the subbasin.

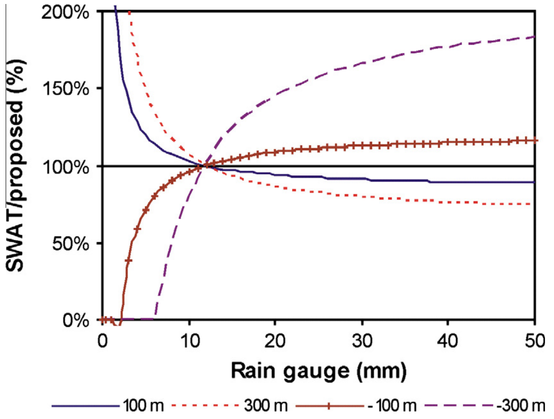

Fig. 5. Differences between the values obtained by SWAT and the proposed methodology versus the amount of rain for different values of $EL_{band}–EL_{gauge}$ (100, 250, 500 and 1000 m). Data are those from Fig. 4: pcp_{year} = 850 mm, plaps = 780 mm/km and $days_{pcp,year}$ = 60.

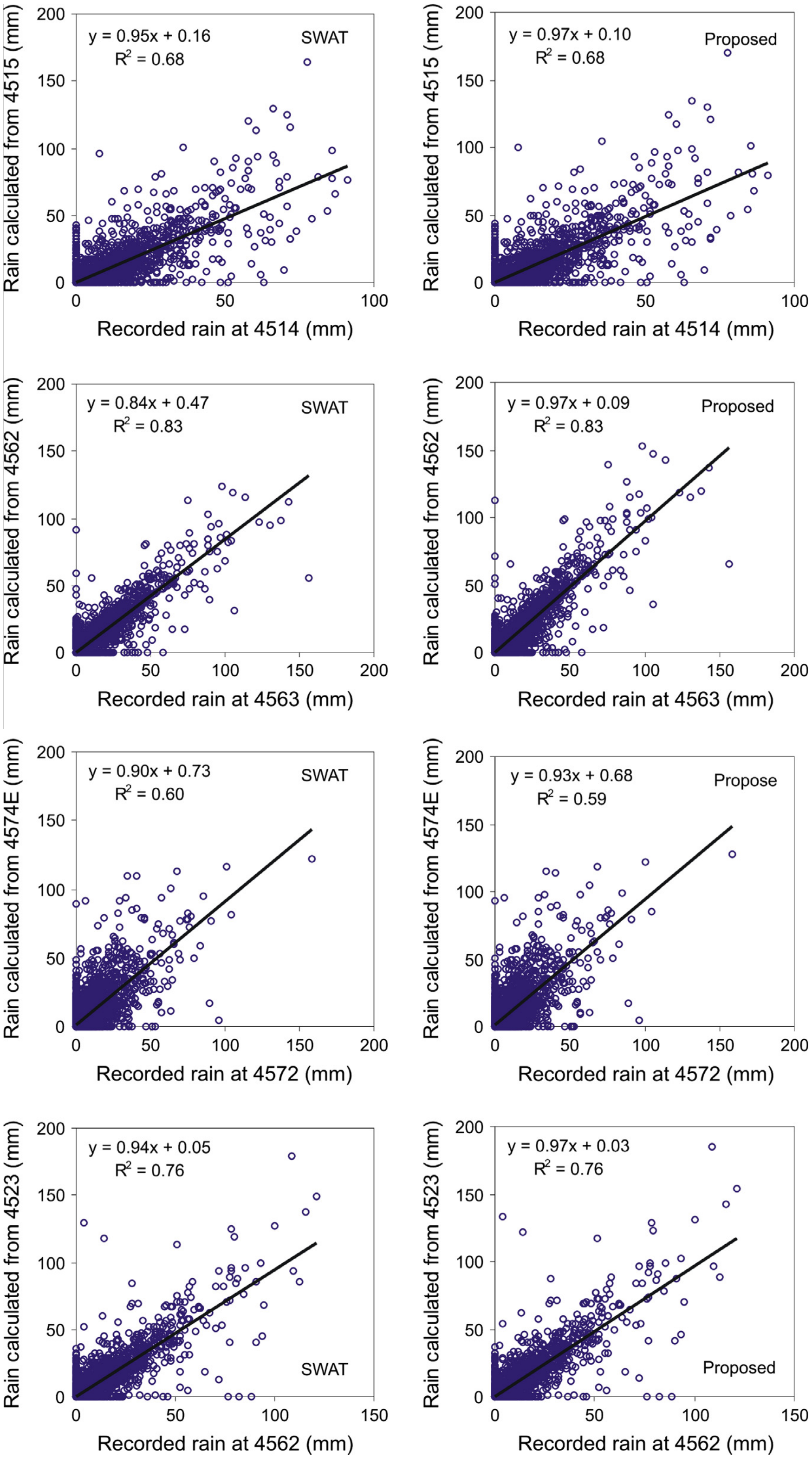

Fig. 6. Comparison of daily rainfall recorded in some rain gauges with the calculated values by the methodology used in SWAT and that proposed in this work.

3. Results and discussion

3.1. Spatial distribution of annual average rainfall

A total of 53 subbasins were defined in the Odiel river basin. As mentioned in Section 2.4, for the precipitation in each subbasin, SWAT uses only one rain gauge for each subbasin, the nearest to its centroid. This gives an artificial precipitation distribution, with large differences between neighboring subbasins (Fig. 2). In addition, data from 7 gauges are not used by SWAT and therefore information is lost, becasue there are some subbasins with more than one rain gauges. The method used by SWAT does not represent precipitation adequately as pointed out by Masih et al. (2011).

Table 1
Values of precipitation obtained from the regression lines of Fig. 6.

Ppcion	SWAT		Proposed		Ppcion	SWAT		Proposed	
mm	mm	Dif (%)	mm	Dif (%)	mm	mm	Dif (%)	mm	Dif (%)
4572 from 4574E (Altitude dif. 67 m)					*4563 from 4562 (Altitude dif. 90 m)*				
0.1	0.8	724	0.8	670	0.1	0.6	451	0.2	87
1	1.6	64	1.6	61	1	1.3	31	1.1	6
2	2.5	27	2.5	27	2	2.2	8	2.0	1
5	5.3	5	5.3	7	5	4.7	−6	4.9	−1
10	9.8	−2	10.0	0	10	8.9	−11	9.8	−2
50	45.9	−8	47.2	−6	50	42.6	−15	48.6	−3
100	91.1	−9	93.7	−6	100	84.6	−15	97.0	−3
4514 from 4515 (Altitude dif. −124 m)					*4562 from 4523 (Altitude dif. −177 m)*				
0.1	0.3	155	0.2	97	0.1	0.14	44	0.13	27
1	1.1	11	1.1	7	1	1.0	−1	1.0	0
2	2.1	3	2.0	2	2	1.9	−4	2.0	−2
5	4.9	−2	5.0	−1	5	4.8	−5	4.9	−2
10	9.7	−3	9.8	−2	10	9.5	−6	9.7	−3
50	47.7	−5	48.6	−3	50	47.1	−6	48.5	−3
100	95.2	−5	97.1	−3	100	94.1	−6	97.0	−3

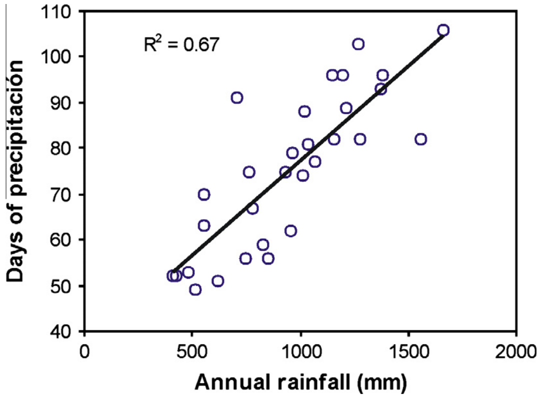

Fig. 7. Relationship between annual precipitation and days of precipitation in rain gauge 4514.

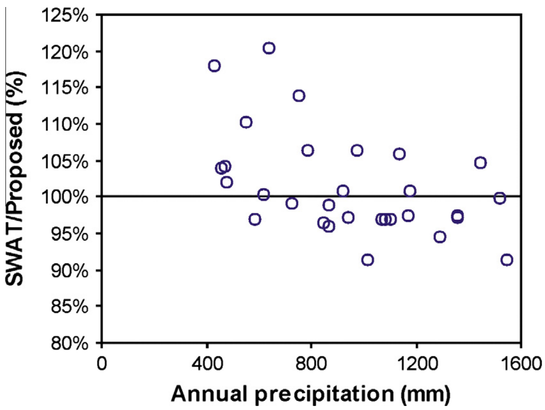

Fig. 8. Example of the difference in the annual values of precipitation obtained by SWAT and the proposed methodolgy in a subbasin of the Odiel river (pcp_{year} = 768 -mm, $plaps$ = 780 mm/km, $days_{pcp,year}$ = 65, $EL_{band}–El_{guage}$ = 225).

Table 2
Statistics index for the model of the Odiel river basin using the proposed methodology and the elevation bands from SWAT.

	Calibration		Validation	
	Daily	Monthly	Daily	Monthly
Proposed methodology				
Pearon correlation coefficient (r)	0.86	0.93	0.76	0.87
Nash-Sutclife efficiency index (NSE)	0.73	0.83	0.57	0.70
Root Mean square error (RMSE, m^3/s)	46.7	20.55	42.37	24.28
Deviation of runoff volume (DV)	1.10	1.10	1.10	1.10
SWAT elevation bands				
Pearon correlation coefficient (r)	0.85	0.92	0.76	0.86
Nash-Sutclife efficiency index (NSE)	0.73	0.83	0.58	0.69
Root mean square error (RMSE, m^3/s)	46.68	20.22	41.99	24.07
Deviation of runoff volume (DV)	1.15	1.15	1.15	1.15

The annual average precipitation for the basin (taking into account the surface area of each subasin) in the period 1980–2010 is 710 mm. There is an increase in precipitation to the NW, where the altitudes are higher. The high correlation between elevation and average annual precipitation (Fig. 3a) shows the existence of an orographic effect in the Odiel river basin: for each kilometer rainfall increases 780 mm.

SWAT elevation bands were used to take into account this orographic effect. If melting snow is not considered (in the Odiel river basin snow precipitation is negligible), a unique elevation band in the subbasin can be considered (results with more than one band are the same). First, there was an error in the ArcSWAT interface and the parameter plaps had to be introduced in mm/m, not in mm/km as indicated. Also, in SWAT simulations the $days_{pcp,year}$ variable (Eq. (5)) takes a constant default value of 12 and it was necessary to correct this parameters for each rain gauge. With elevation bands, an average precipitation in the basin of 685 mm is obtained, slightly lower than the previous result. Obviously, the same problems exist as before in terms of information lost.

3.2. New method to simulate orographic precipitations

In relation to the spatial distribution of rainfall, when using elevation bands to take into account orographic precipitation, applying Eq. (5) gives a constant value of precipitation for each elevation band. This value is added to the daily precipitation, regardless of the amount of precipitation. However, usually in a mountainous basin the increase (in mm) in precipitation must be greater when the daily precipitation increases, and smaller when it rains less

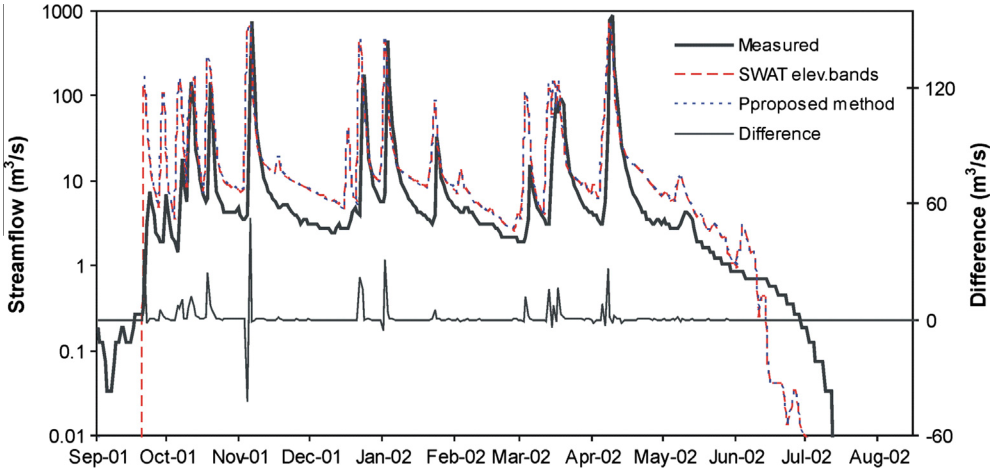

Fig. 9. Observed streamflow at the exit of the Odiel river basin in 1995/96 and estimated values with the proposed methodology and the elevations bands included in SWAT. Difference is obtained as values from SWAT elevation bands minus values from the proposed methodology.

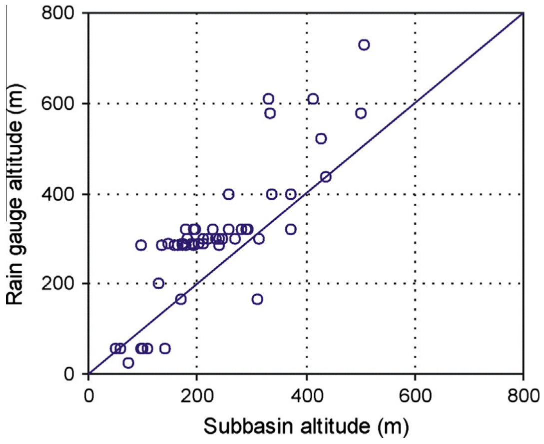

Fig. 10. Altitude of the rain gauges versus average altitude of the subbasins.

(Fig. 3b). Thus, SWAT tends to overestimate lower daily precipitation and to underestimate more intense rainfall.

3.2.1. Proposed methodology

A simple modification is proposed that can be easily included in the source code of SWAT. It is based on calculating a ratio (*iplaps*) to multiply the daily precipitation, instead of an amount to add to the daily precipitation. The ratio for the precipitation in each elevation band (*iplaps*) is calculated as:

$$ipalps = \left[(EL_{band} - EL_{gauge})\left(\frac{plaps}{1000}\right) + pcp_{year}\right] \Big/ pcp_{year} \qquad (7)$$

where pcp_{year} is the annual average precipitation. The rest of the variables are the same as in Eq. (5). The daily precipitation for each band is obtained as:

$$R_{band} = R_{day} \cdot iplaps \qquad (8)$$

3.2.2. Comparison of the proposed methodology with that used by SWAT

When the rain gauge height is lower than the average altitude of the band, the results obtained by SWAT are higher for values less than the average daily precipitation and lower for more intense precipitations (Figs. 4 and 5). The differences are greater as the values move away from the average daily precipitation. Also, the deviations are greater when the precipitation lapse rate (*plaps*) and the difference between the elevation of the band and the gauge increase. When the rain gauge altitude is higher than that of the elevation band the differences are inverted (Figs. 4 and 5).

In order to check the proposed methodology a cross validation method was used. We considered pairs of close rain gauges (distance less than 10 km) and with and altitude difference higher than 50 m (7 rain gauge pairs). From the rain gauge located at lower elevation the precipitation at the higher gauge was calculated, taking into account the difference in altitude and in average annual precipitation between them. This was carried out with the methodology used with SWAT (Eq. (5)) and that proposed in this work (Eqs. (7) and (8)) and calculated and recorded rainfall at the higher gauge are compared. We used a period of thirty years (1980–2010), which means more than 11,000 data pairs in each case. Some examples of the results obtained are shown in Fig. 6. The determination coefficients between recorded and calculated values are the same in both procedures. In both cases low precipitation values (2–5 mm) are overestimated, while high values are underestimated (Table 1). Nevertheless, the differences are smaller in the proposed methodology, which proves a better fit with the recorded data.

The annual average rainfall obtained from both methodologies are equal, since underestimated values are compensated for with overestimated ones, but the interannual precipitation distribution is different. When the average altitude of the basin is higher than that of the rain gauge, SWAT overestimates lower values of precipitation and underestimates higher values. This favors a decrease in runoff and an increase in evapotranspiration. The contrary occurs when the average altitude of the basin is lower than the rain gauge altitude.

However, depending on the precipitation in each year the annual results can be different as SWAT considers a constant numbers of days of precipitation in a year. This is not real: in drier years the number of days of precipitation is lower and in wetter years there are more days of precipitation (Fig. 7). This means that the more the number of days of precipitation differs from the average value the larger the differences. Fig. 8 shows how in dry years the annual precipitation calculated with SWAT is higher than that of the proposed method and in wet years tends to be lower (depending on the days of precipitation in each year). In a Mediterranean climate, with a high variability, these differences can be important.

3.2.3. Application to the Odiel river basin

SWAT was applied to the Odiel river basin with the proposed methodology (Galván, 2011). The only streamflow gauge station

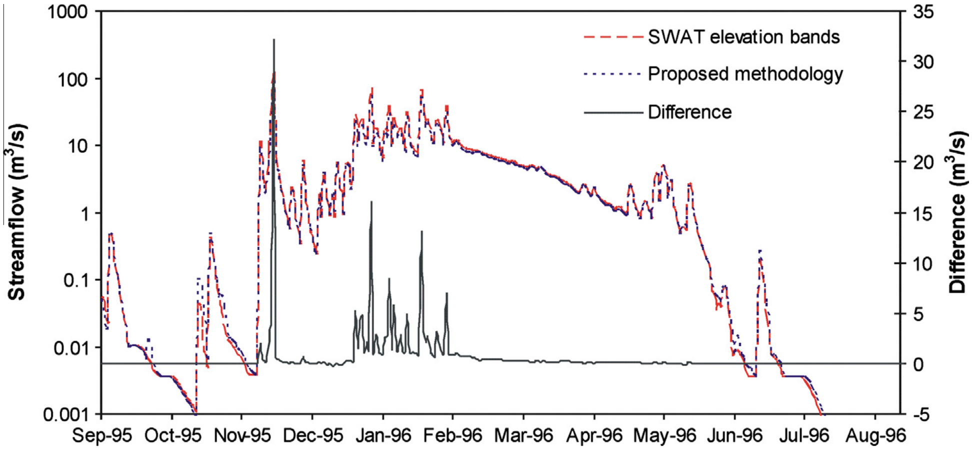

Fig. 11. Streamflow for subbasin 3 in 1996/96 from the proposed methodology and from SWAT elevation bands.

is located at the exit of the basin (Fig. 1). At this point, the model was calibrated for the period 1982–2000 and validated for the period 2001–2010, using the proposed methodology and the elevation bands from SWAT (Table 2). According of Moriasi et al. (2007) models are considered very good if the monthly Nash-Sutcliffe efficiency index (NSE) is >0.75.

At a basin scale the results with both methods were similar (Fig. 9; Table 2) because differences between subbasin are counteracted. The only important variation was the deviation of runoff volume (DV) using the elevation bands from SWAT was appreciably higher (1.15 instead 1.10). Nevertheless, at a daily scale, it can be seen that elevation bands from SWAT generates higher values during streamflow peaks (Fig. 9). This difference is due to the average altitude of most of the subbasins is lower than that of the rain gauge considered by SWAT for each subbasin (Fig. 10). Thus, the daily rainfall values calculated by SWAT are overestimated (Figs. 4 and 5).

Differences are greater a subbasin scale. Fig. 11 shows discharges calculated by both methodologies in a wet year for a subbasin with an average altitude of 335 m and the rain gauge at 577 m. Apparently the flows are similar, but high differences are produced during the peaks. The mean streamflow in this year was 3.48 m^3/s using our methodology and 3.98 m^3/s with the elevation bands of SWAT (15% higher).

4. Conclusions

SWAT is a widely used tool by the international scientific community and numerous organizations, however, the methodology used by this program to represent the spatial distribution of precipitation has limitations. First, the assignment to each subbasin of the rain gauge nearest to its centroid, does not guarantee that the gauge selected is the most representative of the precipitation in the subbasin. If more than one rain gauge is available in the subbasin, precipitation data are lost.

In addition, the methodology used to estimate orographic precipitations, when the subbasin average altitude is higher than that of the elevation band, contributes more elevated values for daily precipitation below the average and underestimates precipitations higher than the average. The contrary occurs when the average altitude of the basin is lower than the rain gauge altitude. The greater the difference between the average elevation at the band and the actual elevation at the rain gauge, the greater the errors.

Another problem stems from the introduction of a constant number of days of precipitation in a year, independently of the annual precipitation. This means the annual precipitation in dry years is overestimated and in wet years underestimated. In a climate with a high interannual or intraannual variability, such as the Mediterranean, these differences can be large. When using SWAT elevation bands in this climate conditions, the introduction of a site specific and year-varying number of rainfall days is recommended.

This paper proposes a simple alternative methodology to take into account the effect of orographic precipitation, which can be included in the source code of SWAT and improves the estimation of precipitation. The daily precipitation is calculated by multiplying the recorded precipitation by a factor depending on the difference between the center of the elevation band and the elevation of the rain gauge, instead of adding a constant amount as used in SWAT. Nevertheless, these results have been obtained in a simple basin from the point of view of orographic effects, its applicability to more complex basins should be checked. In addition, neither SWAT nor our method are able to take into account the rain shadow effect in the leeward slopes. The use of techniques more suitable for representing the spatial distribution of rainfalls is strongly recommended.

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