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ESTIMATION OF CLIMATOLOGICAL WATER DEFICIT IN AN EXPERIMENTAL WATERSHED IN THE BRAZILIAN CERRADO

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ABSTRACT: This study aimed to estimate the probability of climatological water deficit in an experimental watershed in the Cerrado biome, located in the central plateau of Brazil. For that, it was used a time series of 31 years (1982–2012). The probable climatological water deficit was calculated by the difference between rainfall and probable reference evapotranspiration, on a decennial scale. The reference evapotranspiration (ET_0) was estimated by the standard FAO-56 Penman-Monteith method. To estimate water deficit, it was used gamma distribution, time series of rainfall and reference evapotranspiration. The adherence of the estimated probabilities to the observed data was verified by the Kolmogorov-Smirnov nonparametric test, with significance level (α-0.05), which presented a good adjustment to the distribution models. It was observed a climatological water deficit, in greater or lesser intensity, between the annual decennials 2 and 32.

KEY WORDS: gamma distribution, Penman-Monteith, rainfall.

INTRODUCTION

Currently, the Cerrado is the main Brazilian agricultural region. It has a climate with two well-defined seasons and the occurrence of water deficit is a major cause of crop losses and low water availability, which puts at risk the agricultural production sustainability in the region. There are several studies in the literature dealing with climatological water deficit (DE LA CASA & OVANDO, 2016; AUTOVINO et al., 2016); however, few of them take into account its occurrence in terms of probability.

Reference evapotranspiration (ET_0) and rainfall (R) are the two variables used to calculate water deficit. In the literature, there are several studies on the application of different probability distributions to these variables (YAN & CHEN, 2013; LA CASA & OVANDO, 2016).

For irrigation expansion in agriculture in the Brazilian Cerrado, it is interesting to characterize how the climatological water demand behaves. Its knowledge allows intensify land use by using rationally the available water resources (MANETA et al., 2009). The climatological water deficit receives knowledge of the water availability in a given area. R and ET_0 are climatological components with spatiotemporal variability as highlighted by several studies at global level (BOSCHI et al., 2011; LI, 2014).

DAMÉ et al. (2013) reported that climate change and anthropogenic action impacts could cause errors in hydro-agricultural projects, which led them to study the presence or absence of tendency in the total annual rainfall series in a watershed in southern Brazil, seeking greater projects reliability. The main probability distributions involved in event studies of rainfall and probable reference evapotranspiration are: gamma, incomplete gamma, lognormal, Weibull, GEV–generalized extreme value, exponential, three-parameter lognormal and normal (SOCCOL et al., 2010).

SOCCOL et al. (2010) estimated probable monthly rainfall for the township of Lages, SC, in Brazil; the results showed that gamma distribution was well adjusted to the data series and in periods without null values in the rainfall decennial time series, it was properly adjusted to the observed data.

The gamma distribution is used to model probability density function and is well adjusted to rainfall and evapotranspiration time series, according to researches carried out in Brazil. BLAIN et al.

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(2009) studied the sample variability of monthly rainfall series in Pelotas (RS) and Campinas (SP), in Brazil, using the incomplete gamma function for null sample values; they noted that the distribution had a good fit to the database. In addition, BLAIN et al. (2010) found a good adjustment for this distribution when studying a standardized rainfall index applied to drought conditions in the state of Espírito Santo.

An adequate knowledge of the water deficit is essential to set which crop to be grown, planting season, irrigation strategies and management of water resources. Interestingly, however, it is that water deficit is estimated in terms of its probability of occurrence, as it allows the decision maker to adopt the most appropriate strategy for each situation.

In this context, this study aimed to estimate the probability of occurrence of climatological water deficit, on a decennial scale, in an experimental watershed of the Cerrado biome, located in the central plateau of Brazil.

MATERIAL AND METHODS

Study area and dataset

The study was carried out in an experimental watershed of the *Buriti Vermelho* River. Its drainage area has approximately 10 km^2 (Figure 1) and is located in the southeastern region of the Distrito Federal, Brazil, between the georeferenced geographical coordinates of 15° 53' 30" and 15° 55' 56" S and 47°23'53" W (UTM/ ZONE 23/ DATUM SAD 69). According to the Köppen's classification, climate within Distrito Federal region is tropical (*Aw*).

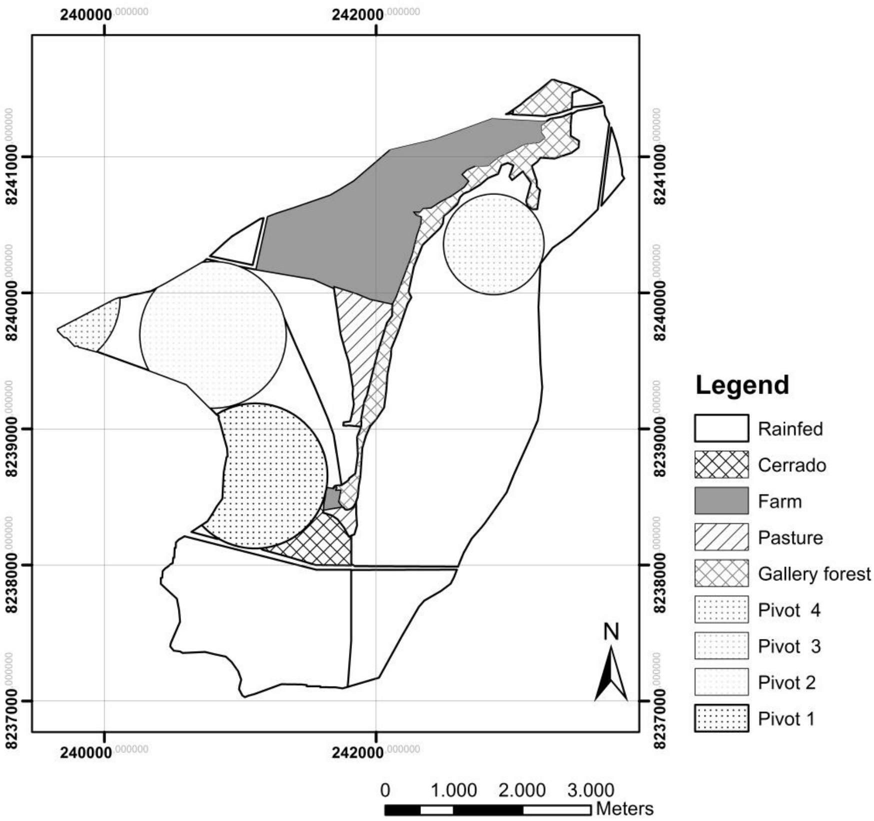


FIGURE 1. Land use map of the Buriti Vermelho River watershed.
Source: Adapted from RODRIGUES et al. (2009).

Climatic data from 1982 to 2012 were provided by the *Centro de Pesquisas Agropecuária do Cerrado* (CPAC). Water deficit analysis was carried out on a decennial scale, totaling 36 periods of ten days, starting the hydrological year on January 1st and ending on December 31st.

Reference evapotranspiration was predicted by the FAO-56 Penman-Monteith method (ALLEN et al., 1998) with the support of the computational tool Reference Evapotranspiration Calculator REF–ET.

The decennial series were adjusted to the probability distribution models of gamma and incomplete gamma to obtain likely rainfall and reference evapotranspiration associated with a probability level.

Figure 2 shows a flowchart of the climatological water deficit calculation steps, which consists of: (i) database assembly, (ii) reference evapotranspiration estimation, (iii) probability distributions adjustment to the data, and (iv) probable water deficit calculation R (X ≥ x) for different probability levels.

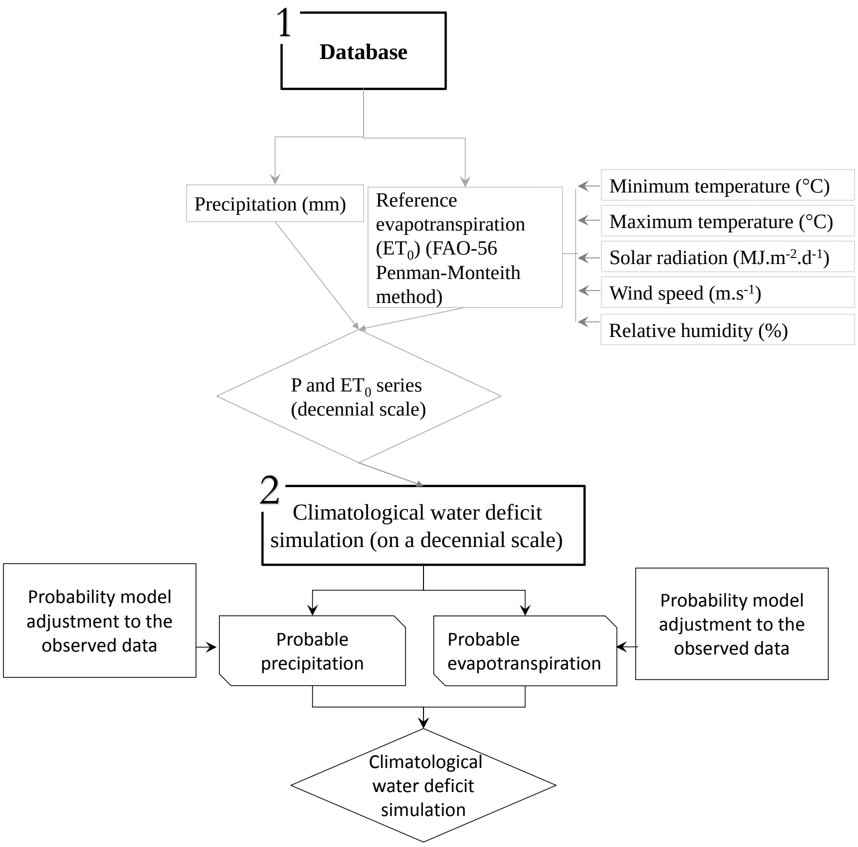


FIGURE 2. Flowchart showing the climatological water deficit simulation.

Probabilistic distribution and parameter estimation methods

As described by NAGHETTINI & PINTO (2007), frequency analysis can be performed empirically, i.e., the ordered observations are marked against a probability scale, as in Equation (1) by Kimball, and it is used a best judgment to choose between the magnitudes of a past event, or hypothetical events, and their respective return periods. In the analytic frequency analysis of hydrological variables, in addition to the problems related to statistical inference, it is necessary to consider the distributive model to be used. Thus, different probabilistic models can be tested, but there is no a consensual specific distribution that can describe, under any conditions, the behavior of the considered variable.

In the empirical distribution or frequency observed, data were preliminarily arranged in an ascending order and assigned to each value a number of order *m* to set a frequency with which an event of order *m* is equaled or exceeded using the Kimball equation, as described in [eq. (1)].

$$F = \frac{m}{n+1} \tag{1}$$

where,

F is the frequency with which an event of order *m* is equaled or inferior;

m is the number of order of the total monthly rainfall, arranged in ascending order (m = 1, 2, …, n), and

n is the number of years of study series.

The probabilistic model used for the study of probable rainfall and reference evapotranspiration, on a decennial scale, was a gamma probability distribution; on the other hand, when the time series presented null records, it was used an incomplete gamma distribution for adjustment of the observed data to the probability distribution (BLAIN et al., 2009; BLAIN et al., 2010).

Estimators of shape and scale parameters were determined in two distinct ways: a) through L-moment method (LMM), being the parameters of the gamma density function to the data of decennial series estimated using the software R (R Development Core Team) and the lmom package (HOSKING, 2014); and b) by maximum likelihood estimation method (MLE).

Estimation of probability distribution parameters through L moment theory is made with a finite-size sample (n), starting by ordering the elements in an ascending order, i.e., $x_1 \leq x_2 \leq \ldots \leq x_n$. The non-biased estimators of the probability-weighted moments are given by eqs. (2) and (3).

$$a_r = \frac{1}{N}\sum_{i}^{N}\frac{\binom{N-i}{r}}{\binom{N-1}{r}}x_i \tag{2}$$

$$b_r = \sum_{i}^{r}\binom{r}{i}(-1)^i a_i \tag{3}$$

The non-biased estimators of the sample L-moments are defined by eqs. (4) to (7).

$$l_1 = b_0 \tag{4}$$

$$l_2 = 2b_1 - b_0 \tag{5}$$

$$l_3 = 6b_2 - 6b_1 + b_0 \tag{6}$$

$$l_4 = 20b_3 - 30b_2 + 12b_1 - b_0 \tag{7}$$

Similarly, the quotients of the sample L-moments are given by eqs. (8) to (10).

$$t = \frac{l_2}{l_1} \tag{8}$$

$$t_3 = \frac{l_3}{l_2} \tag{9}$$

$$t_4 = \frac{l_4}{l_2} \tag{10}$$

where

t is coefficient of variation L-CV;

t_3 is the L- asymmetry, and

t_4 is the L-kurtosis.

Estimated the quotients of the L-moments, it is possible to perform the parameters estimation of the probability distributions. The gamma distribution parameters can be estimated by eqs. (11) and (12).

$$\frac{l_1}{l_2} = \frac{\Gamma(\alpha + 0.5)}{\sqrt{\pi}\Gamma(\alpha + 1)} \tag{11}$$

$$\beta = \frac{l_1}{\alpha} \tag{12}$$

The shape and scale parameters estimation of the probability distribution by using the maximum likelihood estimation method are described in eqs. (13), (14) and (15).

$$\alpha = \frac{1 + \sqrt{1 + \frac{4A}{3}}}{4A} \tag{13}$$

$$A = \ln(x) - \frac{1}{n}\sum_{i=1}^{n}(x_i) \tag{14}$$

$$\beta = \frac{x}{\alpha} \tag{15}$$

where

x is the average rainfall for the n years of the series (mm);

x_i is the rainfall occurred in the i-th decennial (mm),

α is the shape parameter and β is the scale parameter.

According to Thom (1958), the two-parameter gamma distribution is a special case of the Pearson type II distribution wherein the local parameter is zero and its probability density function is given by eqs. (16) and (17).

$$f(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha - 1} e^{-x/\beta} \tag{16}$$

$$\Gamma(\alpha) = \int_0^{\infty} x^{\alpha-1} e^{-x} dx \tag{17}$$

where

$f(x)$ is the probability density function;

β is the scale parameter;

α is the shape parameter, and

$\Gamma(\ )$ is the gamma function represented in Equation (3).

Two different situations may occur when using the gamma distribution: i) the data series does not contain null values: in this case, the frequency estimation typically occurs for the distribution adjustment; and ii) the series contains null values: it is used the incomplete or mixed gamma, which is determined in two parts, as eqs. (18) and (19).

$$F(x) = P_0 + (1 - P_0).G(x) \tag{18}$$

$$P_0 = \frac{N_0}{(N+1)} \tag{19}$$

where

P_0 is the probability of occurrence of null values;

$G(x)$ is the gamma distribution, and

N_0 is the number of null values in the series.

The theoretical model adjustment to the time series was performed using the Kolmogorov-Smirnov test, which is based on the maximum difference between the cumulative probability functions (empirical and theoretical), according to [eq. (20)].

$$D_N = \sup_{-\infty<x<\infty} \left| F_N(x) - F_X(x) \right| \tag{20}$$

where

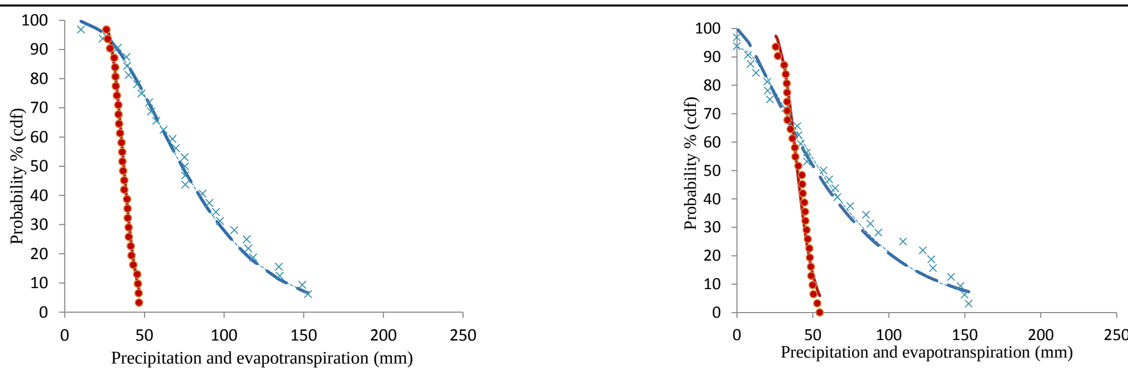
F_N is the empirical frequency, and

F_N is the theoretical frequency estimated by the gamma distribution, considered the top value in module.

Water demand temporal simulation is based on models of probability distributions as gamma and incomplete gamma, adjusted by MLE and LMM methods. These simulations use data series of rainfall and reference evapotranspiration (FAO-56 Penman-Monteith method), time series (1980–2010), on a decennial scale evaluating at first the climatological water deficit or surplus, and, in a second time, different probabilities of occurrence or non-exceedance of occur a particular event.

RESULTS AND DISCUSSION

The results presented in this study indicate, for different probability levels, the climatological water demand, arbitrating a probability level for R and other for ET_0, wherewith, by the difference between the occurrence of the probable decennial rainfall R ($X \geq x$) and the occurrence of the probable reference evapotranspiration R ($X \geq x$), it is estimated values of probable climatological water demand. In the results presented in Figures 3, 4, 5, 6 and 7, it is possible to observe the probability distributions adjustment associated with different probability of occurrence levels, which represent the occurrence of the minimum probable rainfall R ($X \geq x$) and the minimum probable evapotranspiration R ($X \geq x$). In its turn, Table 1 presents their absolute values, in which it is possible to observe the water deficit. Depending on the difference, if the presented value is positive, there is no climatological water deficit; on the other hand, if it is negative, there is climatological water deficit.



(a) (b)

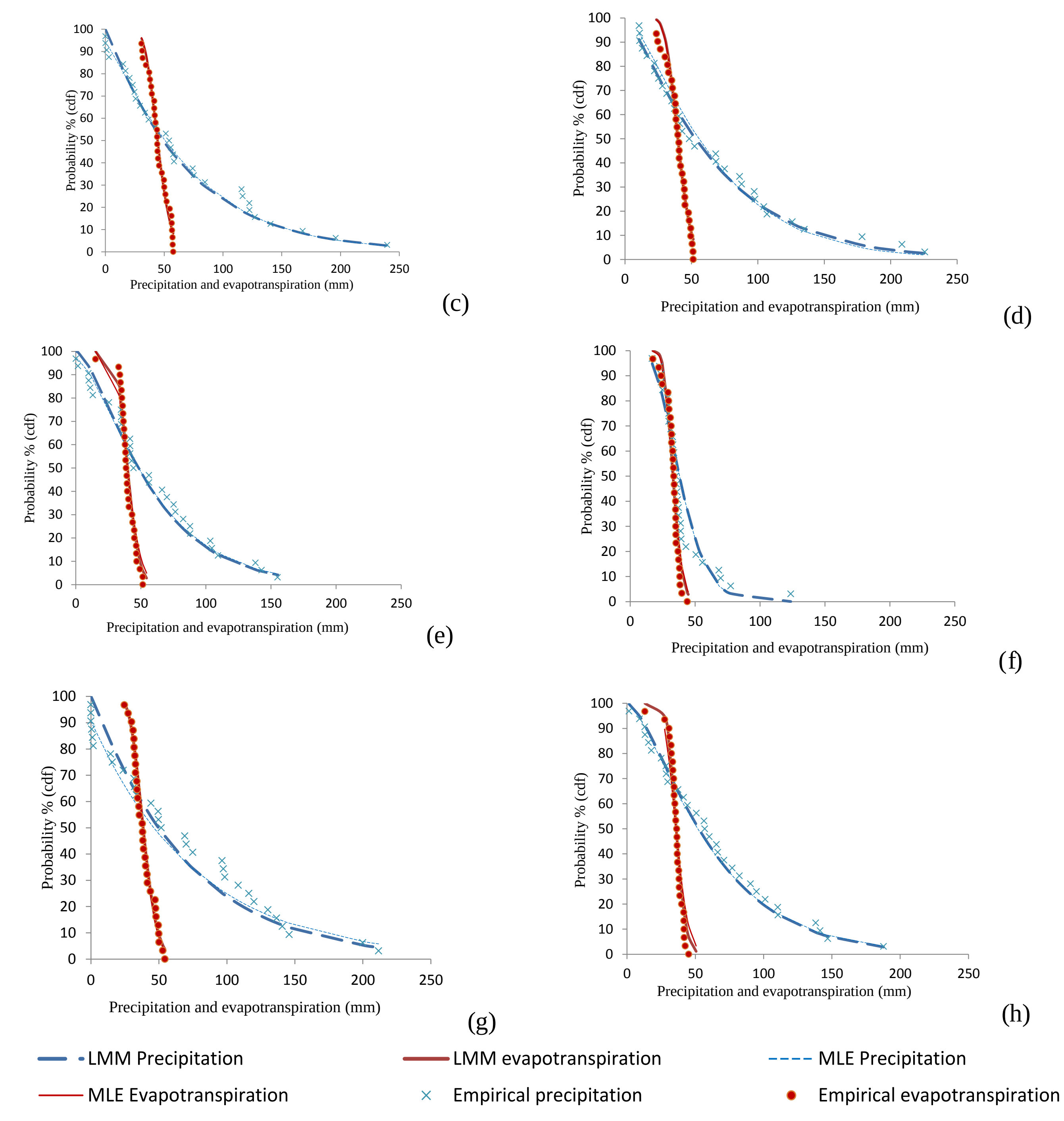


FIGURE 3. Gamma distribution adjustment (decennials 1 to 8, respectively a to h) for rainfall (R) and reference evapotranspiration (ET_0).

TABLE 1. Climatological water deficit and surplus for different probability levels, in absolute values.

Period	Probability level (%)									
(decennial	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%
1	-2	4	8	13	17	20	24	28	32	37
2	-20	-17	-14	-11	-8	-4	-1	3	7	12
3	-27	-26	-23	-21	-17	-14	-10	-6	-1	5
4	-22	-19	-16	-13	-9	-5	-1	3	8	13
5	-21	-18	-15	-12	-9	-6	-3	1	4	8
6	-8	-6	-4	-3	-2	0	1	2	4	5
7	-22	-21	-18	-15	-12	-8	-4	1	6	11
8	-18	-15	-11	-8	-4	0	3	8	12	17
9	-29	-28	-27	-25	-22	-20	-17	-13	-9	-5
10	-24	-22	-20	-17	-15	-13	-10	-8	-5	-2
11	-29	-30	-31	-31	-30	-29	-28	-27	-25	-23
12	-31	-32	-33	-33	-34	-34	-34	-33	-32	-31
13	-31	-32	-33	-34	-34	-35	-35	-36	-36	-36
14	-29	-30	-31	-32	-32	-32	-33	-33	-33	-33
15	-33	-34	-35	-36	-36	-36	-37	-37	-37	-37
16	-31	-32	-32	-33	-33	-34	-34	-34	-35	-35
17	-30	-31	-32	-33	-33	-34	-34	-35	-35	-36
18	-30	-31	-32	-32	-33	-34	-34	-34	-35	-35
19	-33	-34	-35	-35	-36	-36	-36	-37	-37	-37
20	-33	-34	-35	-36	-36	-37	-37	-38	-38	-38
21	-40	-41	-42	-42	-43	-43	-44	-44	-45	-45
22	-39	-40	-41	-42	-42	-43	-43	-44	-44	-45
23	-40	-42	-43	-43	-44	-45	-45	-46	-46	-47
24	-40	-42	-44	-45	-47	-48	-48	-49	-50	-50
25	-39	-42	-43	-44	-46	-47	-48	-48	-49	-50
26	-38	-41	-42	-43	-44	-45	-45	-46	-46	-45
27	-34	-35	-36	-36	-36	-36	-35	-35	-34	-33
28	-34	-36	-36	-36	-36	-35	-35	-34	-33	-31
29	-31	-33	-33	-33	-32	-31	-29	-27	-25	-22
30	-27	-26	-25	-23	-21	-20	-18	-16	-13	-11
31	-22	-21	-19	-17	-14	-11	-8	-4	-1	4
32	-20	-18	-15	-12	-10	-7	-4	-1	2	6
33	-14	-10	-7	-3	0	4	7	11	15	19
34	-14	-10	-6	-2	2	5	9	13	17	21
35	-18	-14	-10	-6	-2	2	6	11	15	21
36	-10	-4	1	6	11	15	20	25	30	36

Negative values indicate climatological water deficit

For all decennial periods, in both models gamma and incomplete gamma, shape and scale parameters of the distribution by MLE and LMM were well adjusted and showed distribution fit to the data by the Kolmogorov-Smirnov test at a significance level of 5%. It indicates that there has been no statistical difference between the theoretical distribution and the observed values, when testing both methods.

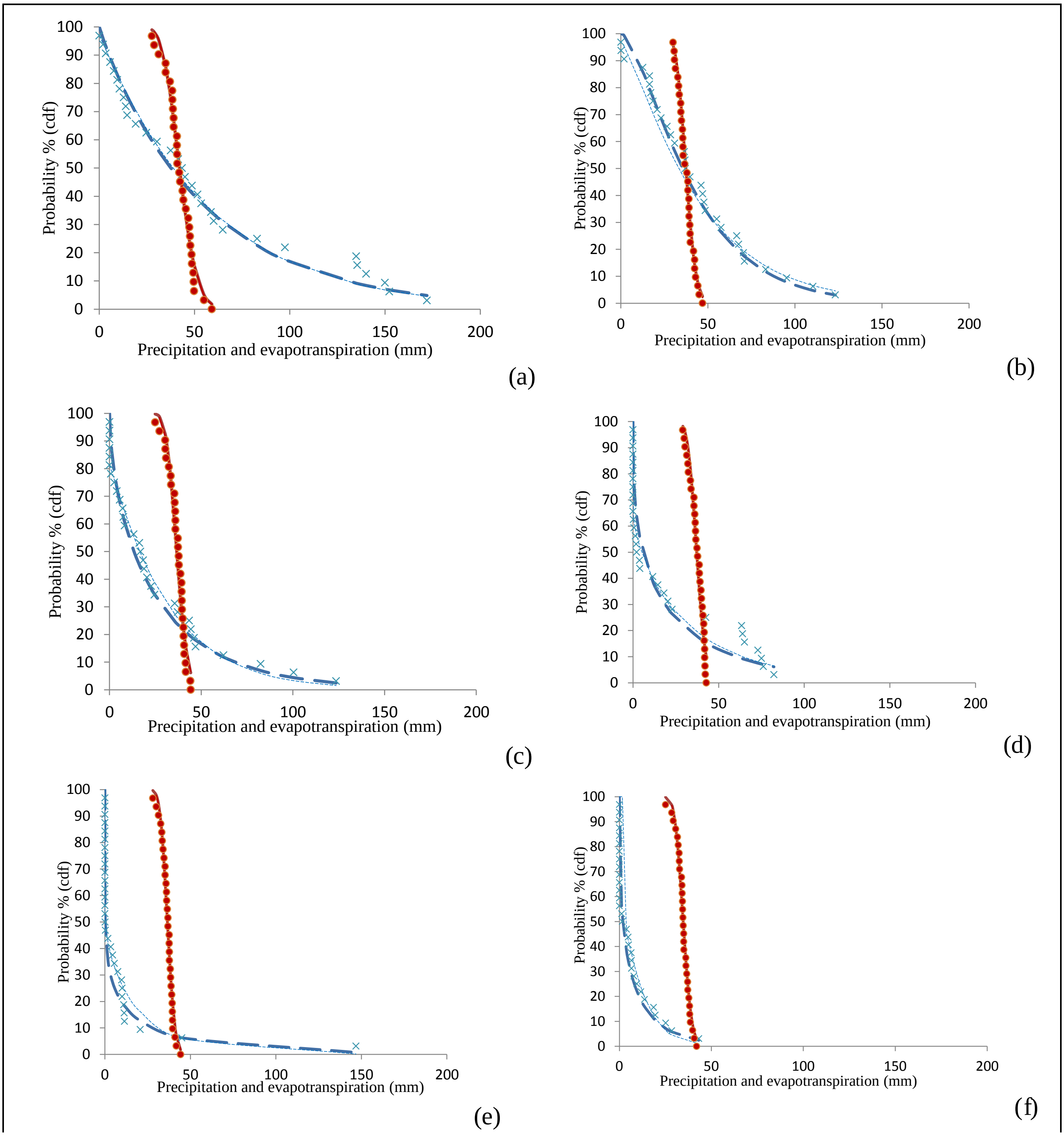
The adjustment of gamma and incomplete gamma distributions through MLE and LMM corresponding to the rainy period from January to March (decennials 1 to 8) is respectively shown in Figures 3a to 3h. For this adjustment, reference evapotranspiration and rainfall were set as parameters at a probability of occurrence of 75%, being observed no climatological water deficit in the decennial 1, which corresponds to Figure 3a. On the contrary, the decennials 2 to 8, identified in Figures 3b to 3h, respectively, showed a climatological water deficit ranging from 2 to 17 mm (Table 1).

At the end of February, specifically in the decennial 6, there was a typical dry spell period in the region within a probability range between 95% to 50%, which represents respectively a water deficit of 8 mm and a surplus of 5 mm, demonstrating a period of greater water availability.

The adjustment of gamma and incomplete gamma distributions through MLE and LMM corresponding to the months from April to June, which corresponds to the decennials 9 to 16, is shown respectively in Figures 4a to 4h. In March and April, which represents the decennials 9 and 10 and at the end of the rainy season and beginning of the dry period, considering a probability of occurrence level of 75%, there was a turning point that indicates the beginning of a greater water deficit period, corresponding respectively to Figures 4a and 4b.

Regarding the decennials from 11 to 20, it is observed the beginning of the dry period, at a probability level of 75% of occurrence, with a more pronounced climatological water deficit, which corresponds to Figures 4c, 4d, 4e, 4f, 4g, 4h, 5a and 5b, with deficit values between 30 and 36 mm. In its turn, from the decennials 21 to 26, it was observed the beginning of a period with zero rainfall, at a probability level of 75%, i.e. with severe climatological water deficit. Such shortage corresponds to values above 40 mm, observing rainfalls of 43, 42, 44, 47, 46 and 44 mm for the decennials 21 22, 23, 24, 25 and 26, respectively, as can be seen in Figures 5e, 5f, 5g, 5h, 6a and 6b.

The adjustment of gamma and incomplete gamma distributions through MLE and LMM corresponding to the months from June to August, which corresponds to the decennials from 17 to 24, is shown respectively in Figures 5a–5h.



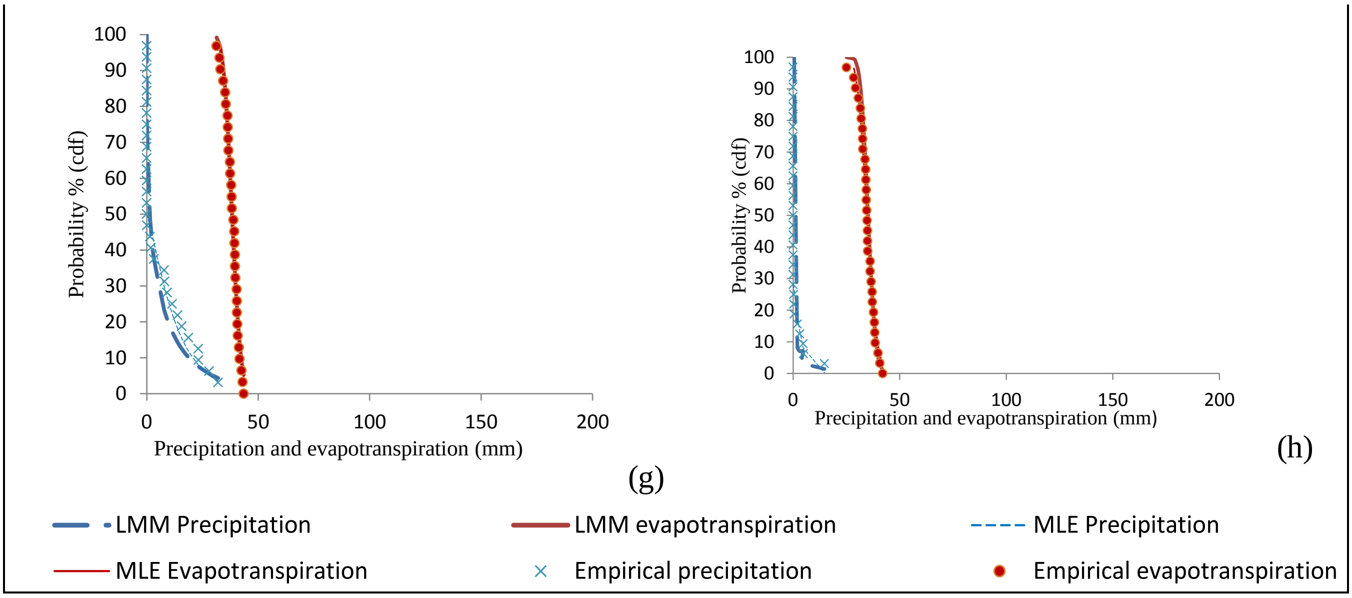
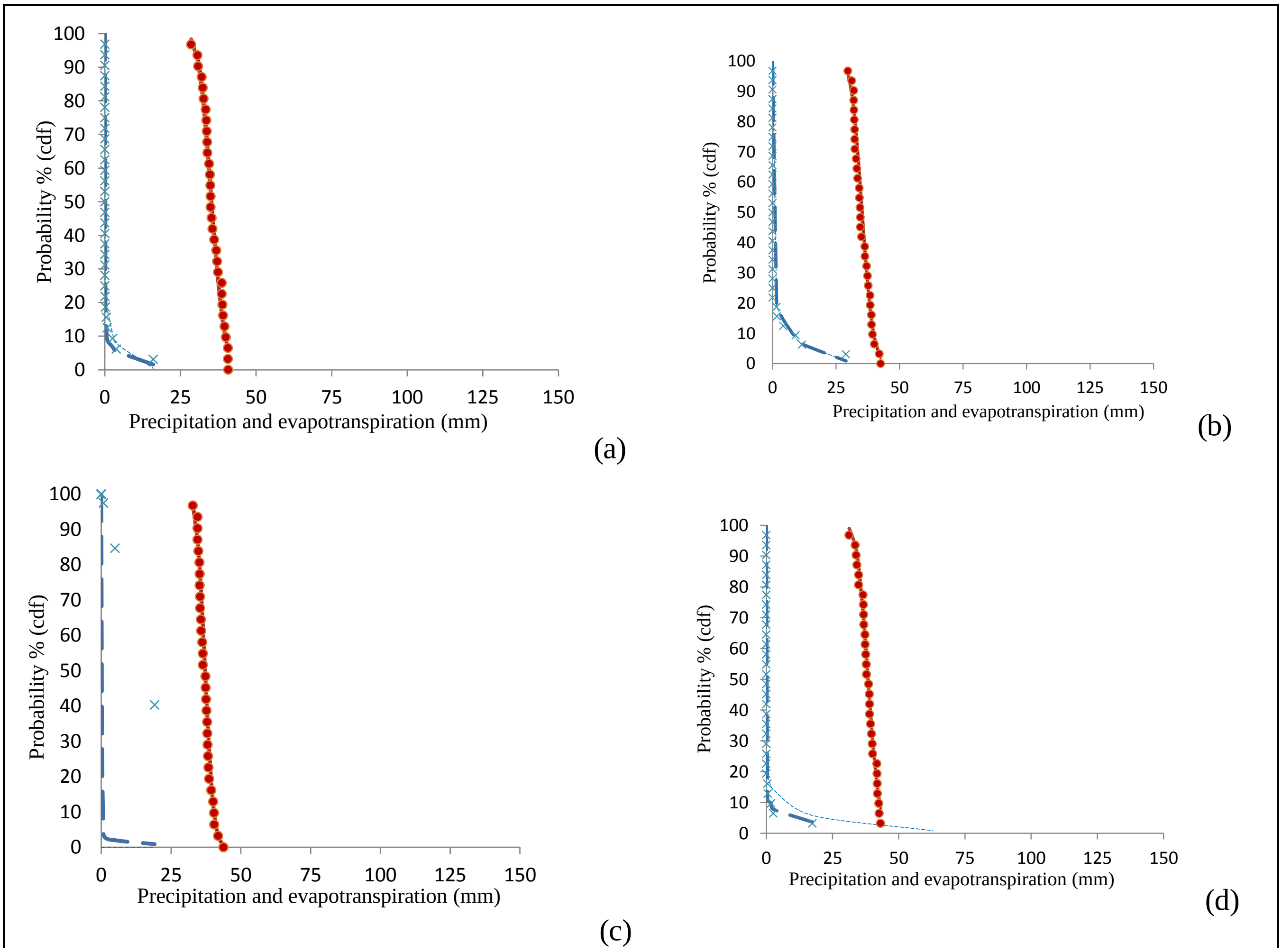


FIGURE 4. Gamma distribution adjustment (decennials 9 to 16, respectively a to h) for rainfall (R) and reference evapotranspiration (ET_0).



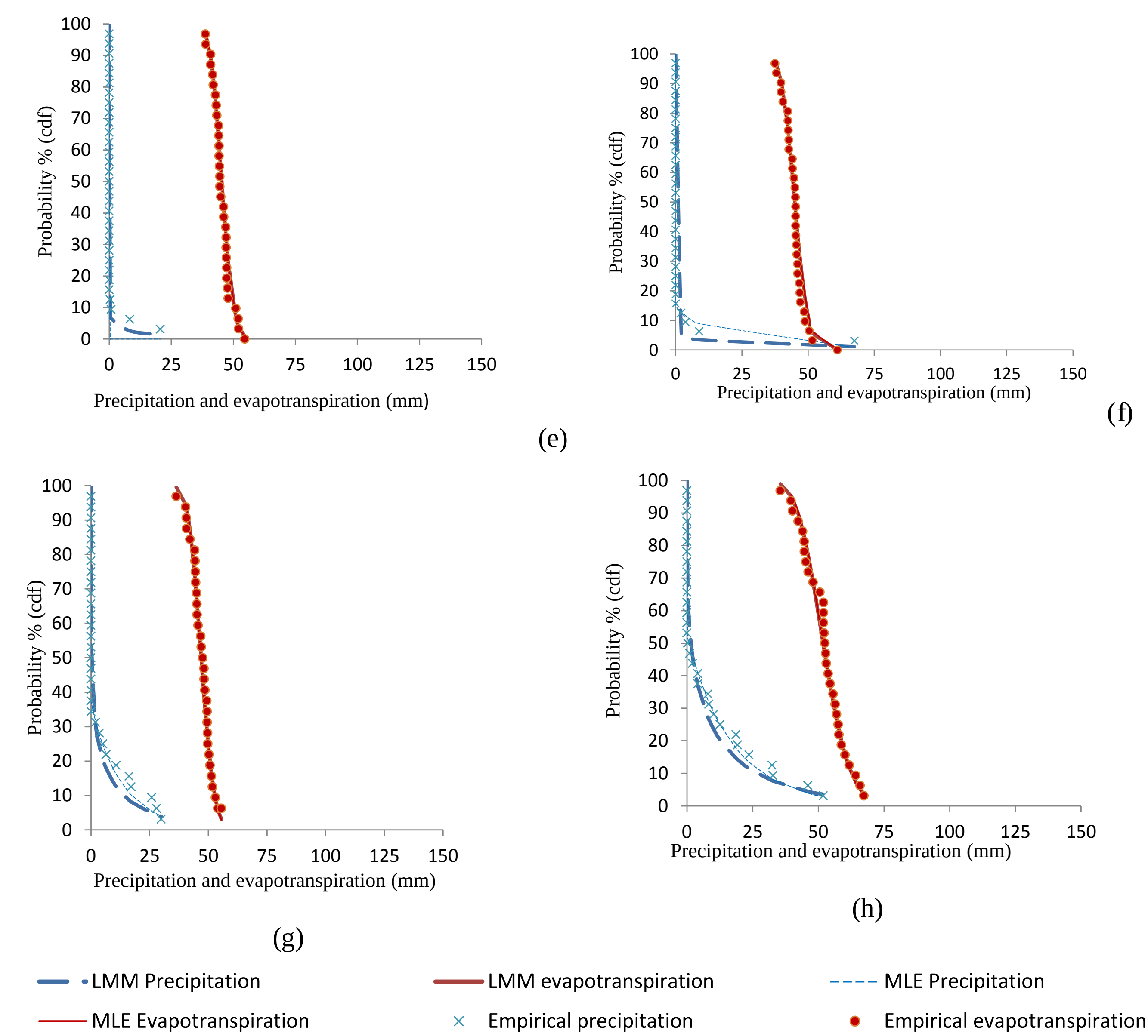
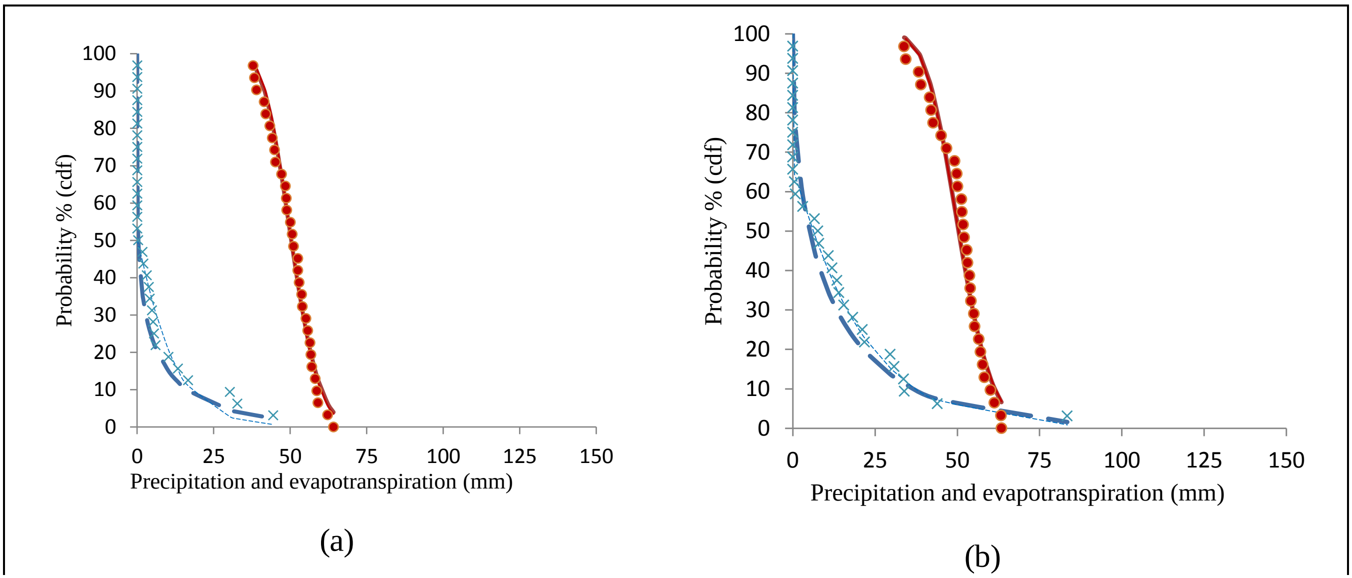


FIGURE 5. Gamma distribution adjustment (decennials 17 to 24, respectively a to h) for rainfall (R) and reference evapotranspiration (ET_0).



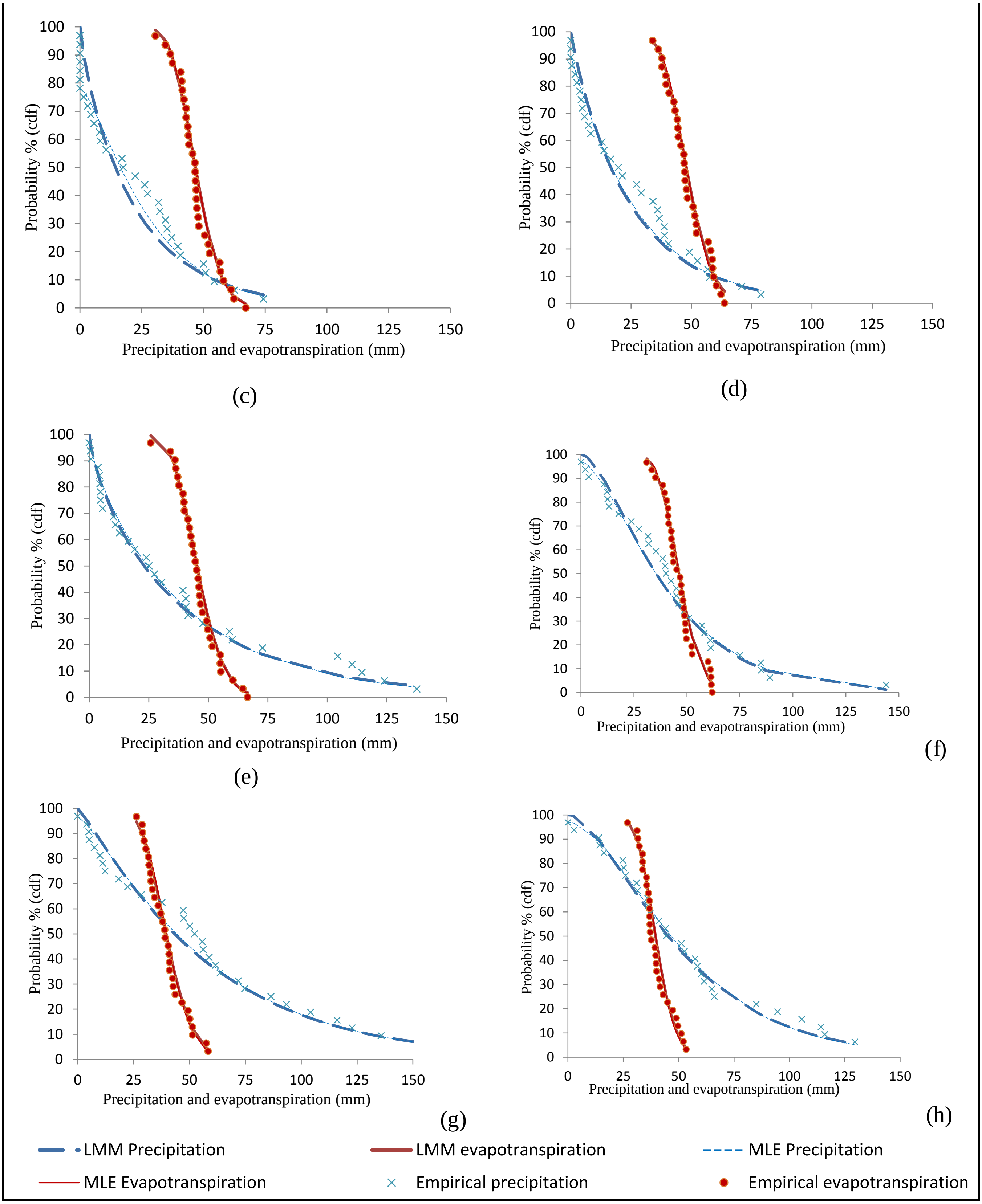


FIGURE 6. Gamma distribution adjustment (decennials 25 to 32, respectively a to h) for rainfall (R) and reference evapotranspiration (ET_0).

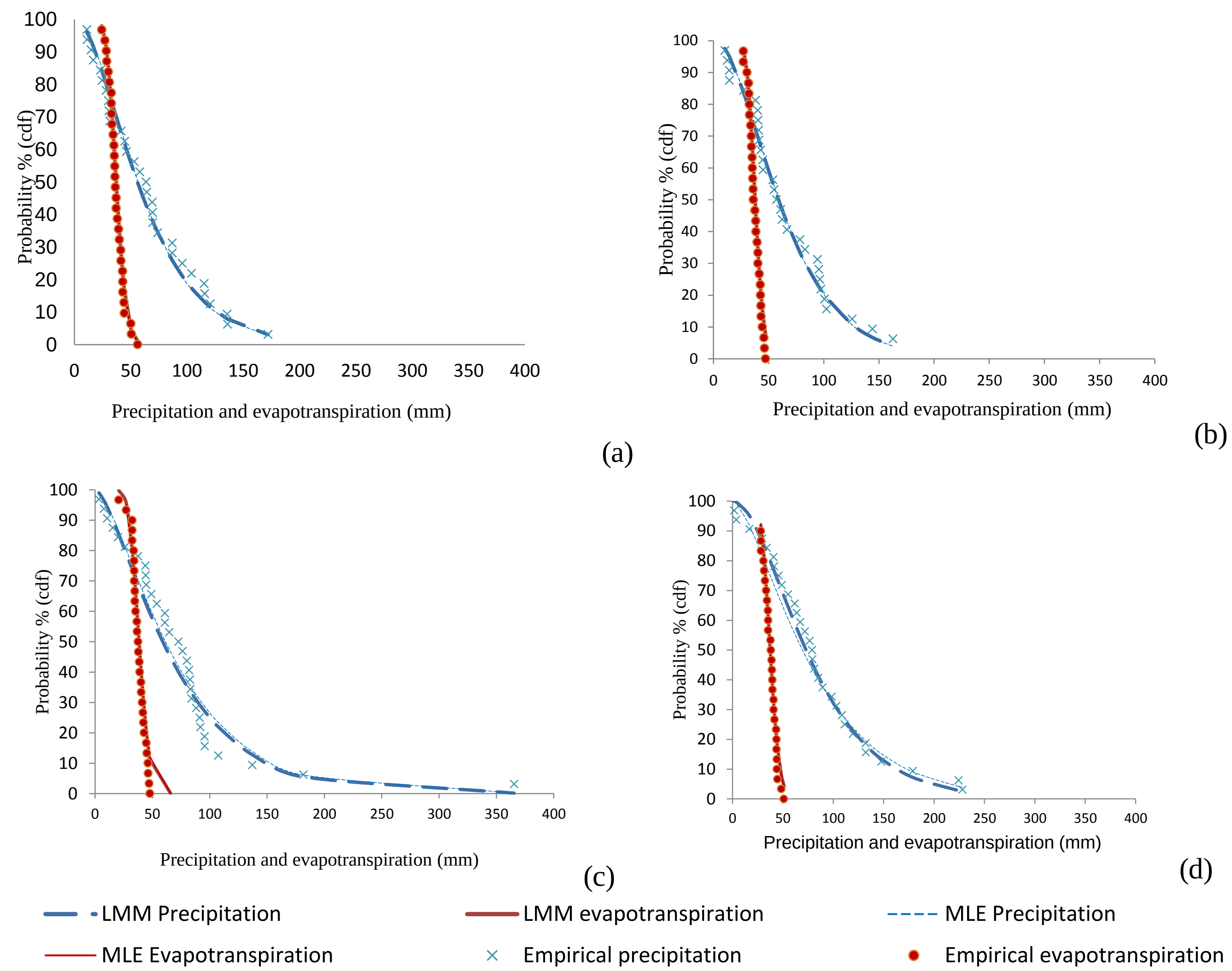


FIGURE 7. Gamma distribution adjustment (decennials 33 to 36, respectively a to d) for rainfall (R) and reference evapotranspiration (ET_0).

Figures 6 and 7 are corresponding to the decennial series from 25 to 36 that were estimated at different probability levels. At a 75% probability level, it is possible to see that deficit extends from 27 up to 29, with absolute values of 36, 36 and 32 mm respectively for the 27, 28 and 29 decennial series (Figures 6c, 6d and 6e). Moreover, it is identified a regression of climatological water demand due to the beginning of rainy season and the end of dry season, between September and October.

In November and December, which refers to decennials 30 to 36 (rainy period), it is observed that the regression of climatological water demand persists, being the decennials 30, 31 and 32 those that presented deficits of 21, 14 and 10 mm, respectively (Figures 6f, 6g and 6h). During the period corresponding to Figures 7a, 7b, 7c and 7d, considering the probability level of 75%, it was observed a surplus in the decennials 33, 34 and 36. However, the decennial 35 presented a deficit of 2 mm.

The adjustment of the distributions gamma and incomplete gamma, by using the MLE and LMM methods and related to the months from September to November, which corresponds to the decennials from 25 to 32, is shown respectively in Figures 6a to 6h. In its turn, the adjustment of the distributions gamma and incomplete gamma, by using the MLE and LMM methods and related to the months from September to November, which corresponds to the decennials from 33 to 36, is shown respectively in Figures 7a to 7d.

Figure 8 presents the climatological water deficit, estimated for the probability levels of occurrence of a minimum probable rainfall R ($X \geq x$) of 75, 80, 85, 90 and 95% and minimum probable reference evapotranspiration R ($X \geq x$) at a probability level of 75 to 80%. The evaluations were carried out by the difference of the studied climatological variables combined as follows:

minimum probable rainfall at probability levels of 80, 85, 90 and 95% and minimum probable reference evapotranspiration of 80%, in addition to a second simulation, as follows: minimum probable rainfall at probability levels of 75% and minimum reference evapotranspiration at level of 75%.

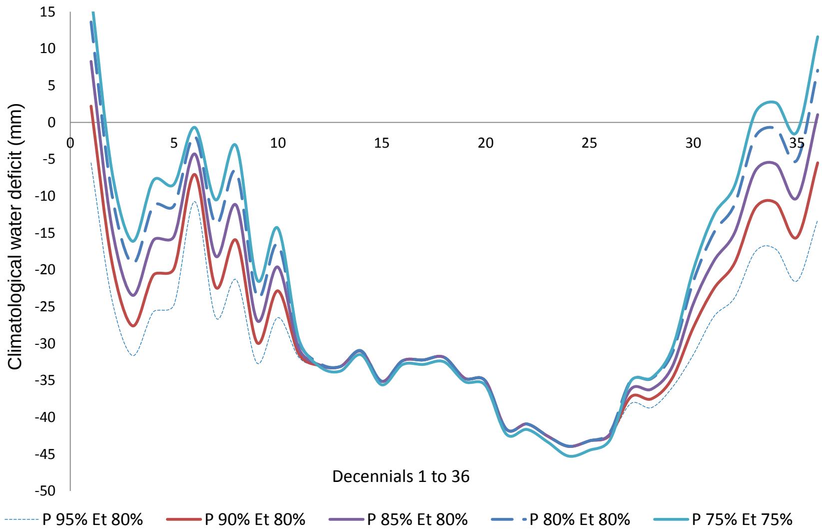


FIGURE 8. Climatological water deficit and surplus for different probability levels.

It is observed in Figure 8, in the dry periods and decennials from 9 to 30, that there is virtually no difference between the water deficits for the different probability levels. This fact occurs because the rainfall in this period is practically zero, which makes the probabilities of occurrence of rainfall be pretty much the same. As it approximates the rainy season, the differences tend to be larger.

CONCLUSIONS

In general, the climatological water deficit occurred between the decennials 2 and 32, estimated by the difference between the reference evapotranspiration and the minimum probable rainfall, at a probability level of 75%. It is noteworthy that for this probability level of occurrence, it results in a maximum water deficit of 47 mm in August. In this study, it is evident the need for supplemental irrigation in the studied area in almost the entire period of the year.

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