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Water balance in Cubatão-Sul river catchment, Santa Catarina, Brazil (doi:10.4136/ambi-agua.38)

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ABSTRACT

The objective of the present study was to evaluate the water balance in the Cubatão-Sul river catchment (403.83 km²), Santa Catarina State, Brazil, which is very important for irrigated horticulture and drinking-water supply to the Great Florianópolis Region. The daily data obtained from the Poço Fundo hydrometeorological station and São José Meteorological station during the period between 1977 and 1994 were used for the analysis. A lumped and storage model HYCYMODEL was used for both water balance and evapotranspiration analyses and five additional methods were used for the evapotranspiration analysis. The results from the HYCYMODEL showed that the total discharge and the evapotranspiration in the catchment are approximately 62% and 44% of the annual rainfall (1563 mm), respectively. The total discharge consists on the direct runoff of 26% and the base flow of 74%. The actual evapotranspiration estimated with the water budget method was practically equal to that obtained with the HYCYMODEL. And the values of the ratio of the annual actual evapotranspiration to the annual potential evapotranspiration are 0.39, 0.58, 0.65 and 0.69 for Hamon method, modified Penman method, Blaney and Criddle method and Thornthwaite method, respectively. The increasing rate of the discharge over rainfall is larger than that of the evapotranspiration. When the annual rainfall is more than 930 mm, the discharge is always larger than the evapotranspiration.

Keywords: Water balance; evapotranspiration; Cubatão-Sul river.

Balanço hídrico na bacia do rio Cubatão-Sul, Santa Catarina, Brasil

RESUMO

O objetivo do presente estudo foi avaliar o balanço hídrico na bacia do rio Cubatão-Sul (403,83 km²), Santa Catarina, Brasil, que é muito importante na irrigação e suprimento de água potável para a Região da Grande Florianópolis. Os dados diários de 1977 a 1994 usados na análise foram obtidos da estação hidrometeorológica do Poço Fundo e da estação meteorológica de São José. O modelo hidrológico concentrado HYCYMODEL foi usado para fazer o balanço hídrico e a análise de evapotranspiração. Outros cinco métodos também foram usados apenas para análise de evapotranspiração. Os resultados do HYCYMODEL mostraram que a vazão total e a evapotranspiração na bacia correspondem a aproximadamente 62% e 44% da chuva total média anual (1563 mm). A vazão total é dividida em aproximadamente 26% de escoamento direto e 74% de vazão de base. A evapotranspiração real estimada com o método do balanço hídrico foi praticamente igual à estimada com o HYCYMODEL. Os valores da razão da evapotranspiração real anual com a evapotranspiração potencial anual são de 0,39, 0,58, 0,65 e 0,69 para os métodos de Hamon, Penman, Blaney e Criddle e o método de Thornthwaite, respectivamente. A taxa de aumento da vazão com a chuva é maior do que o

da evapotranspiração. Quando a chuva anual ultrapassa 930 mm, a vazão é sempre maior que a evapotranspiração.

Palavras-chave: Balanço hídrico; evapotranspiração; rio Cubatão-Sul.

1. INTRODUCTION

The hydrologic cycle consists in the hydrological processes that are mainly precipitation, runoff, evapotranspiration and soil-water storage. Each process must be evaluated by considering the interrelations among them. The estimation of evapotranspiration is relatively more difficult and complicated than those of precipitation and runoff. That is the reason why various methods have been proposed for the measurement and estimation of the evapotranspiration (Brutsaert, 1982; Pereira et al., 1997). The evapotranspiration estimation is very important in water resource management for hydroelectric power, drinking-water supply, irrigation, and fishery.

Evapotranspiration research is also connected with environmental concerns. While land cultivation extent has been increasing due to population growth, the environment has been degraded due to poor land development planning. Land use and land cover types influence the evapotranspiration mechanism that is characterized by water and heat transport, and consequently contribute to local and global climate change.

Thus, there is a social demand for catchment-level evapotranspiration research to account for water and environmental resources' impacts. This type of research can be better implemented based on water balance analysis that includes all the components of the hydrological processes.

Therefore, the objective of the present study was to evaluate the water balance in the Cubatão-Sul river catchment, Santa Catarina State, Brazil with emphasis on the evapotranspiration. This catchment is very important for irrigated horticulture and drinking-water supply to the Great Florianópolis Region (Kobiyama and Oliveira, 1999).

2. MATERIAL AND METHODS

2.1. Study area and hydrometeorological data

The Cubatão-Sul watershed covers an area of 738 km². Cubatão-Sul river catchment (CSRC) area studied covers 403.83 km² and lies approximately between latitudes 27°35'S and 27°54'S and between longitudes 48°47'W and 49°03'W, with altitudes varying from 100 to 1150 m (Figure 1). Poço Fundo hydrometeorological station (latitude 27°40'S and longitude 48°47'W) is located at the middle of the Cubatão-Sul river basin toward the upper stream area of the watershed. The regional climate type is Cfa (humid subtropical with hot summer) according to Köppen classification. The natural vegetation is Atlantic Forest, dominated by *Ocotea catharinensis* (canela-preta), *Ocotea pretiosa* (canela sassafrás) and *Aspidosperma olivaceum* (pérola vermelha) species (Santa Catarina, 1986). The bedrock in the CSRC is granite, gneiss and sedimentary rock (Silva and Bortoluzzi, 1987).

The daily discharge and rainfall data from the Poço Fundo station for the period 1977-1994 were provided by the *Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina S.A.* (EPAGRI) and used for the water balance analysis. At the São José Meteorological station, which is about 20 km northeast from the Poço Fundo station, EPAGRI collects other meteorological parameter measurements: temperature (°C), relative air humidity (%), wind velocity (km/h) and daylight hours (h) that were also used for the evapotranspiration analysis.

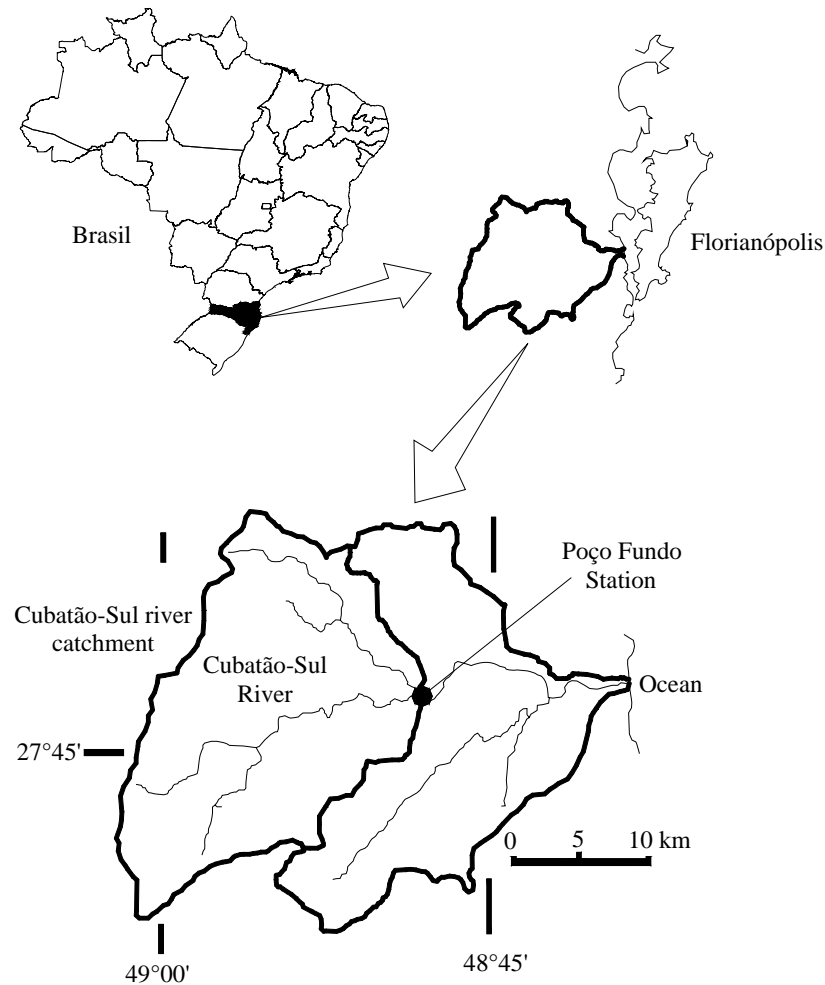


Figure 1. Location of the Cubatão-Sul river catchment area.

2.2. Application of HYCYMODEL for annual water balance

The HYCYMODEL proposed by Fukushima (1988) is a lumped and storage model. The model consists of 5 tanks related to the hillslope-channel system (Figure 2). A detailed description of the model can be seen in Fukushima (1988). A brief description follows:

With the ratio of impermeable area (C), rainfall is divided into the channel rainfall $R_c(t)$ and the gross rainfall $R_g(t)$ where t is the time. Tank I shows the interception process which is defined as:

$$R_n(t) = AG \cdot R_g(t) - AI \quad [1]$$

where $R_n(t)$ is the net rainfall and AG and AI are the interception parameters. The interception $E_i(t)$ is the difference between $R_n(t)$ and $R_g(t)$. Since D_{16} and D_{50} are defined as the effective top-soil depths in which the ratios of the contributing area are equivalent to 16% and 50%, respectively, the standard deviation is:

$$\sigma = \log\left(\frac{D_{50}}{D_{16}}\right) \quad [2]$$

The variable ξ is:

$$\xi = \frac{\log\left\{\frac{[S_u(t-1) + R_n(t)]}{D_{50}}\right\}}{\sigma} \quad [3]$$

Thus, the ratio of the contribution area is expressed by:

$$m = \int_{-\infty}^{\xi} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\xi^2}{2}\right) d\xi \quad [4]$$

Finally, the effective rainfall $R_e(t)$ can be determined with the storage $S_u(t-1)$ in Tank II and the net rainfall, i.e.:

$$R_e(t) = m \cdot R_n(t) \quad [5]$$

Tank III, IV and V represent the groundwater system, the subsurface water system and the channel system which determine the base flow $Q_b(t)$, the subsurface flow on hillslope $Q_h(t)$ and the direct runoff in channel $Q_c(t)$, respectively. In Tank II, III, IV and V, the relationship between the storage S and the discharge Q is expressed with the storage function:

$$S = K \cdot Q^P \quad [6]$$

where K and P are the storage function parameters. For Tanks II, III, IV and V, K and P are defined K_u and P_u , K_b and P_b , K_h and P_h and K_c and P_c , respectively. As Tanks IV and V form the direct runoff, the values of P_h and P_c are 0.6. As Tank II has the linear phenomenon, the value of P_u is 1.0. Following the suggestion of Fukushima (1988), the value of P_b is 0.1.

The transpiration ratio is:

$$E_t(t) = \text{Delta} \{P_{ta} + P_{tb} \cdot \sin[30^\circ - (I - IG)]\} \quad [7]$$

where Delta , P_{ta} , P_{tb} and IG are the parameters and I is the monthly number (1 to 12) corresponding to January to December. Transpiration during a drought decreases when the storage of Tank II smaller than S_{bc} . The critical discharge for transpiration Q_{bc} corresponds to S_{bc} . The evapotranspiration $E(t)$ is the sum of $E_i(t)$, $E_t(t)$ and the channel evaporation $E_c(t)$.

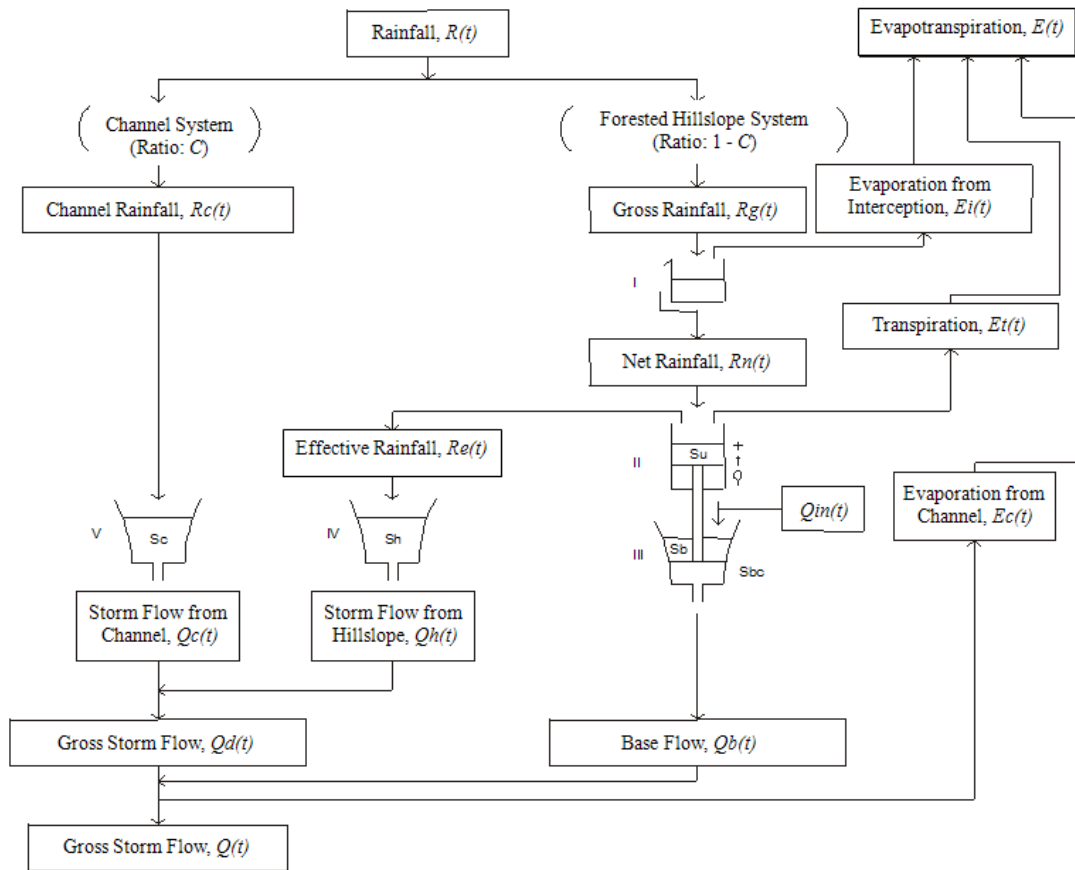


Figure 2. Flowchart of HYCYMODEL. Source: Fukushima (1988).

Kobiyama and Duarte (1997) running a simulation of 11-years hydrograph for the period 1974-1984 ascertained the applicability of this model for the rainfall-runoff processes of the Cubatão-Sul catchment and proposed the parameter values listed in Table 1. The present study used the same values for the parameters and simulated the water balance for the period 1977-1994. For the annual water balance analysis, the following equation was used:

$$P = E + Q + dS \quad [8]$$

where P is the rainfall; E is the evapotranspiration; Q is the discharge; and dS is the change of soil-water storage. By the nature of the HYCYMODEL, E consists of evaporation due to interception E_i , transpiration E_t and the evaporation from the channel E_c .

Table 1. Values of the model parameters for the Cubatão-Sul catchment.

Parameter	Value	Parameter	Value	Parameter	Value
C	0.030	K_h	28	Al	1.872
D_{10}	10	K_c	2	P_{ta}	39
D_{50}	66	P_b	0.1	P_{tb}	15
K_u	20.1	Q_{bc}	1.30	IG	10
K_b	4294	AG	0.964	$Delta$	1

Source: Kobiyama and Duarte (1997).

2.3. Estimation of evapotranspiration

To estimate the catchment evapotranspiration 6 methods were applied: water budget method, Thornthwaite (1948) method, Hamon (1961) method, modified Penman method (Doorenbos and Pruitt, 1977), Blaney and Criddle (1966) method, and the HCYMODEL.

The equation for the water budget method is:

$$E = P - Q \quad [9]$$

where EP is the actual evapotranspiration in mm/month, P is the precipitation in mm/month, and Q is the runoff in mm/month. The change of water storage in the catchment during one month was neglected.

Thornthwaite (1948) proposed the following equation:

$$EP^* = 16(10t/I)^a \quad [10]$$

where EP^* is the non-revised potential evapotranspiration in mm/month, t is the mean monthly temperature in °C, a is a constant ($= 0.000000675I^3 - 0.0000771I^2 + 0.01792I + 0.49239$), and I is the Thornthwaite's temperature efficiency index, being equal to the sum of 12 monthly values of heat index $i = (t/5)^{1.514}$. Then this author used this value to compute the correct value with the following equation:

$$EP = C_1 \times EP^* \quad [11]$$

where EP is the potential evapotranspiration in mm/month and C_1 is the correction factor which can be calculated based on UNESCO (1982) (Table 2).

Table 2. C_1 values for the Cubatão-Sul river catchment.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
C_1	1.19	1.02	1.06	0.95	0.93	0.86	0.91	0.97	1.00	1.11	1.13	1.20

Hamon (1961) pointed out that the Thornthwaite method overestimated the evapotranspiration in the summer and underestimated it in the winter and proposed the following equation:

$$EP = 1.4(n/12)^2 Pt \quad [12]$$

where n is the daylight hours; Pt is the absolute humidity in g/m^3 .

Doorenbos and Pruitt (1977) modified the Penman (1948) method and proposed a new equation:

$$EP = C_2 [W \cdot RA_n + (1 - W) \cdot f(u) \cdot (e_a - e_d)] \quad [13]$$

where C_2 is the correction factor; W is the weighing factor related to a temperature; RA_n is the net radiation in mm/day; $f(u)$ is the function of the wind; e_a is the saturation vapor pressure at the mean air temperature in mmH₂O; and e_d is the saturation vapor pressure at mean dew point in mmH₂O.

Villela and Mattos (1975) modified the equation of Blaney and Criddle (1966) with respect to the units:

$$EP = (mt - 0.5T)p \quad [14]$$

where mt is the monthly mean temperature in °C; T is the mean annual temperature in °C; p is the percentage of the monthly daylight hours on the annual daylight hours.

The hydrometeorological data observed at Poço Fundo and São José stations during the period 1977-1994 were used for the evapotranspiration analysis.

3. RESULTS AND DISCUSSION

3.1. Annual water balance

Figure 3 shows the components of the total discharge. Due to the lack of hydrological data, the year 1991 was not considered in this study. Direct runoff and base flow for the period 1977-1994, related to the total discharge and based on mean values, are 26% and 74%, respectively. This value for the base flow is in accordance with the value obtained by Hewlett (1982) who stated that about 70% of the total discharge is usually base flow in mountainous regions. Considering the direct runoff, the components from hillslope and channel are 81% and 19%, respectively.

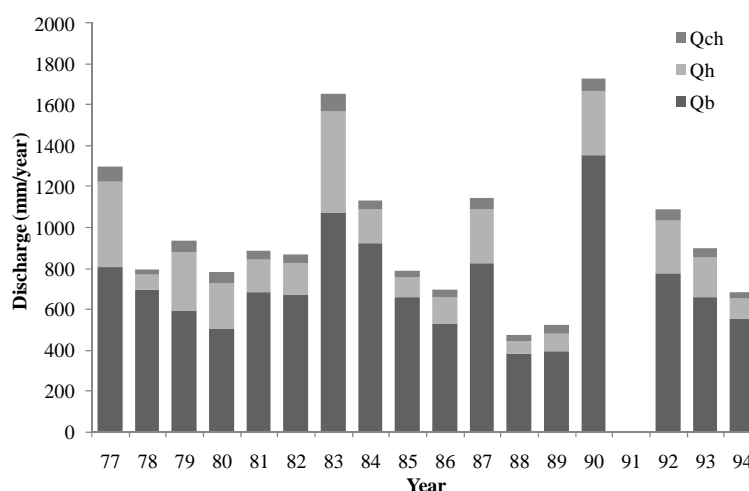


Figure 3. Components variation of total discharge for the period of 1977 to 1994. (Q_b = base flow, Q_h = direct runoff from hillslope, Q_{ch} = direct runoff from channel).

Transpiration, evaporation by interception, and evaporation from the river to the total evapotranspiration values are 65%, 33% and 2% for the period 1977 to 1994, respectively (Figure 4). According to Fujieda et al. (1997), the annual mean value of the transpiration is equal to that of the evaporation by interception in the Serra do Mar, São Paulo State. Comparing to this result, the ratio of transpiration in the CSRC is larger. It implies that, if the forest area is reduced in the CSRC the total discharge will increase significantly.

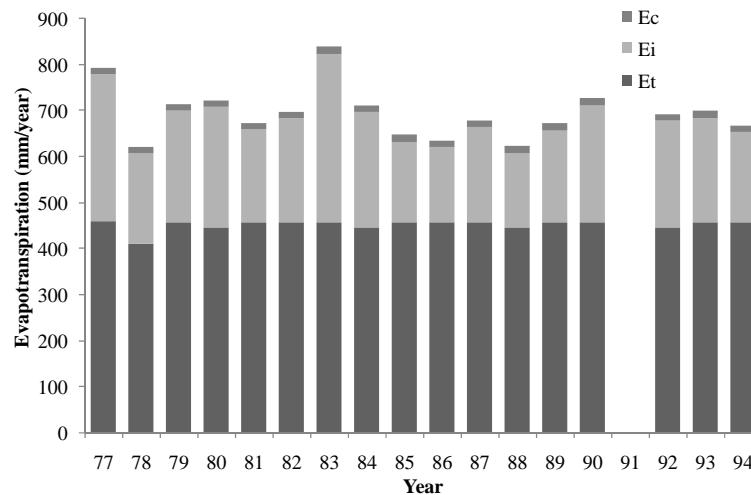


Figure 4. Components variation of evapotranspiration in the period 1977 to 1994. (E_t = transpiration, E_i = evaporation by interception, E_c = evaporation from channel).

From the data of Figures 3 and 4, the ratios of the total discharge and the total evapotranspiration on the annual rainfall are 62% and 44%, respectively (Table 3). The soil-water storage change is -6%. The mean total discharge of the CSRC is 12.3 m³/s.

Table 3. Mean annual water balance of the Cubatão-Sul river catchment in the period 1977 to 1994.

Component	(mm/year)	(%)
Rainfall (R)	1563	100.0
Total discharge (Q)	963	62
Direct runoff (Q_d)	253	16
Direct runoff from hillslope (Q_h)	206	13
Direct runoff from channel (Q_c)	47	3
Base flow (Q_b)	710	45
Evapotranspiration (E)	687	44
Evaporation through interception (E_i)	229	15
Transpiration (E_t)	445	28
Evaporation from channel (E_c)	14	1
Change of the soil-water storage (dS)	-87	-6

Figure 5 demonstrates the relationships between total discharge Q and evapotranspiration E to rainfall P . The increasing rate of Q over P is larger than that of E . In the case that P is larger than 930 mm/year, approximately, $Q > E$ and, in the opposite scenario, E could be larger than Q .

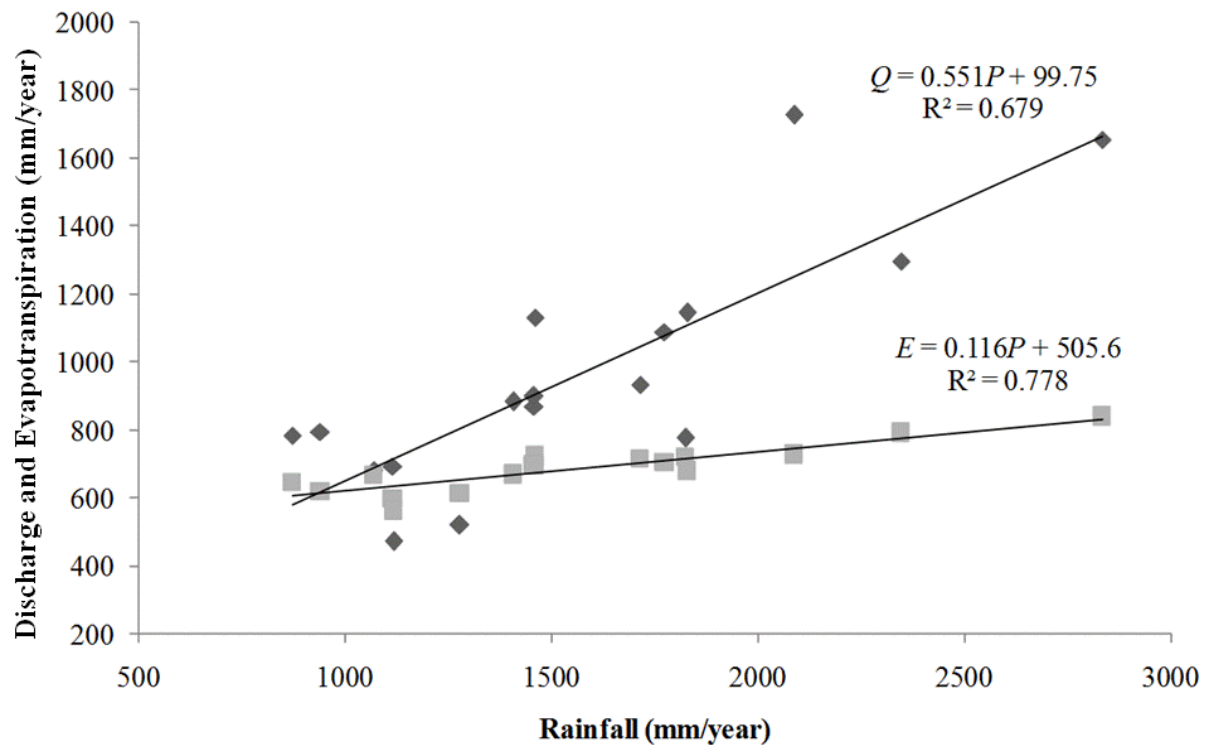


Figure 5. Relationship between discharge and evapotranspiration with rainfall.

3.2. Annual evapotranspiration

Table 4 shows the mean values of annual (actual or potential) evapotranspiration for the CSRC calculated using all six methods. According to the data obtained by EPAGRI, the mean annual precipitation in the catchment was 1563 mm for the study period. This value is smaller than that of the potential evapotranspiration calculated with the Hamon method. In practice, the values of the actual evapotranspiration, estimated with the water budget method and the HCYMODEL, were the same.

Table 4. Mean annual evapotranspiration of the Cubatão-Sul river catchment for the study period.

Method	<i>E</i> (mm/year)	<i>E/P</i> (%)
Hamon	1752*	112
Modified Penman	1197*	77
Blaney and Criddle	1058*	68
Thornthwaite	994*	64
Water budget	690 [†]	44
HCYMODEL	690 [†]	44

* is potential evapotranspiration; [†] is actual evapotranspiration.

Fujieda et al. (1997) showed that the actual evapotranspiration is 30% of the annual precipitation in the Serra do Mar, São Paulo State. Compared with this value, the annual evapotranspiration in the CSRC can be considered high. With the values of the evapotranspiration calculated with the water budget method and the HCYMODEL, the runoff ratio (*F*), which is defined as the ratio of the annual runoff on the annual rainfall, was calculated as 62% in the CSRC approximately.

The annual ratio of the actual evapotranspiration to the potential evapotranspiration calculated with the Hamon method, the modified Penman method, the Blaney and Criddle method, and the Thornthwaite method are 0.39, 0.58, 0.65 and 0.69, respectively.

3.3. Monthly evapotranspiration

Figure 6 shows the change of monthly evapotranspiration calculated by all six methods. The graph patterns obtained with the modified Penman method, the Blaney and Criddle method and the Thornthwaite method are comparatively similar in the period analyzed (Figure 6(b), (c) and (d)). On the other hand, results of Hamon method and water budget method demonstrate high variation patterns (Figure 6 (a) and (e)).

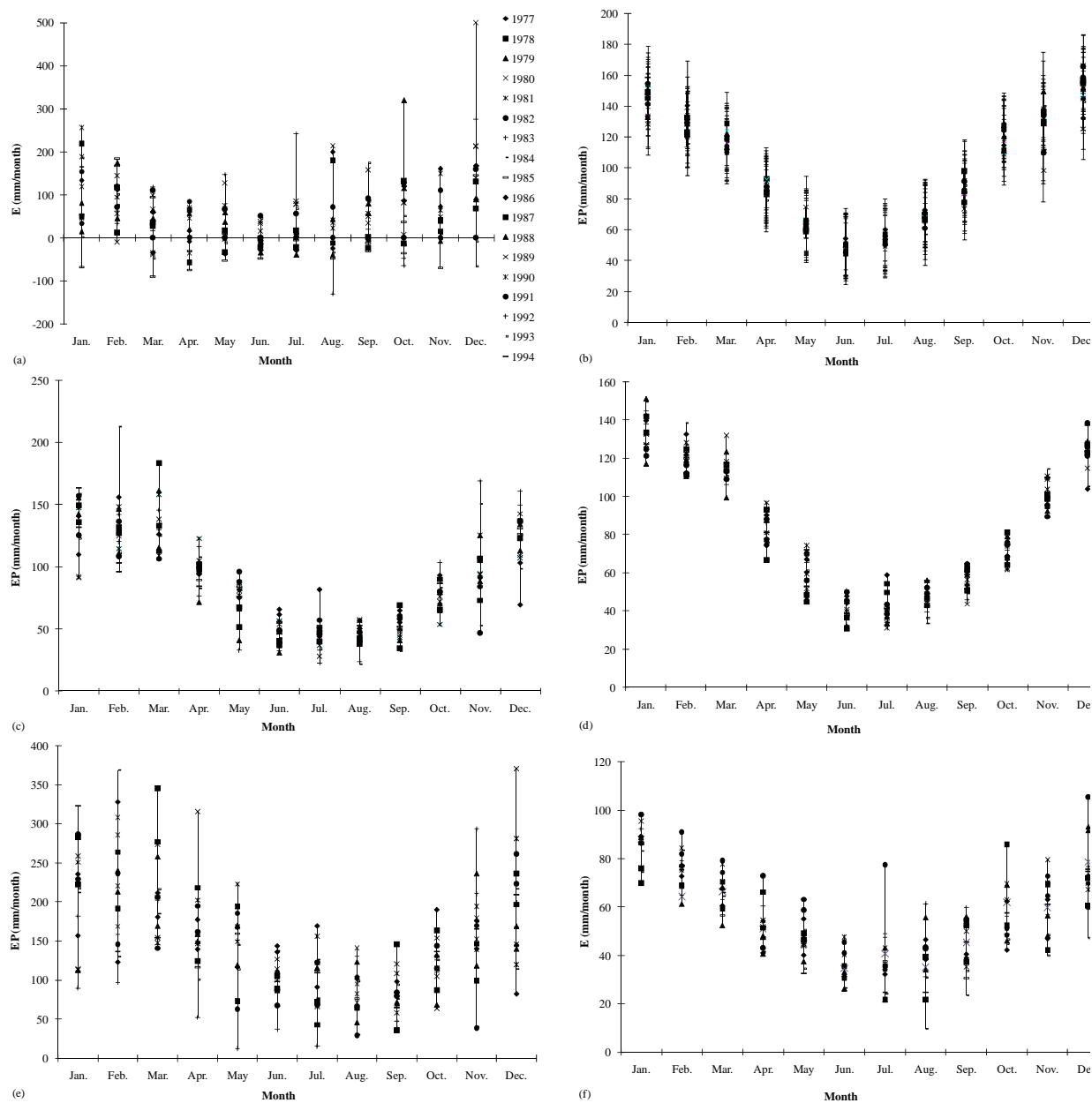


Figure 6. Monthly evapotranspiration of the Cubatão-Sul river catchment during the study period: (a) water budget method; (b) modified Penman method; (c) Blaney and Criddle method; (d) Thornthwaite method; (e) Hamon method; e (f) HCYMODEL.

In Figure 6(a) some monthly evapotranspiration values are negative. The occurrence of negative E values indicates that the monthly water budget method is not adequate for this catchment. That is why mean values were used instead.

The mean monthly evapotranspiration during the study period was calculated with each method. The changes of the mean monthly evapotranspiration obtained with the six methods are graphically shown in Figure 7. The graphs obtained with the Penman modified method, the Blaney and Criddle method and Thornthwaite method have similar patterns. The result with Hamon method is very different from the others. Observing the results of Table 4, it can be stated that Hamon method overestimates the potential evapotranspiration and that it is unrealistic for the CSRC situation.

Figure 7 shows clearly that evapotranspiration rate is highest in the summer. Winter was the season with the lowest monthly evapotranspiration shown by Blaney and Criddle method, Thornthwaite method, Hamon method and HYCYMODEL. Fall shows lower values with the water budget method and modified Penman method.

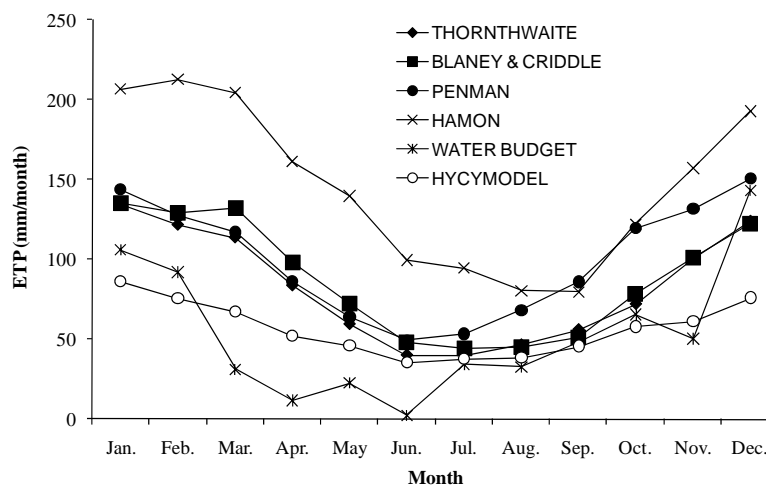


Figure 7. Comparison of mean monthly evapotranspiration change of the Cubatão-Sul river catchment during the study period using six methods.

4. CONCLUSIONS

In order to study the annual water balance of the Cubatão-Sul river catchment (403.83 km²), Santa Catarina State, Brazil, the data observed at the hydro-meteorological stations during the period 1977-1994 was analyzed with HYCYMODEL proposed by Fukushima (1988). The total discharge and the evapotranspiration are approximately 62% and 44% of the total rainfall, respectively. The base flow is about 74% of the total discharge, which agrees with the data of Hewlett (1982). The high ratio of transpiration to the evapotranspiration implies that, if deforestation occurs in the catchment, the total discharge will strongly increase.

The increasing rate of discharge over rainfall is larger than that of the evapotranspiration. When the annual rainfall is more than 930 mm, the discharge is always larger than the evapotranspiration.

Using six methods (water budget method, Thornthwaite method, Hamon method, modified Penman method, Blaney and Criddle method and the HYCYMODEL), the monthly and annual evapotranspiration in the CSRC during the period 1977-1994 was evaluated.

Although the annual values of the actual evapotranspiration estimated with the water budget method and the HYCYMODEL were similar, the monthly patterns obtained were different. The values of the ratio of the annual actual evapotranspiration to the annual potential evapotranspiration are 0.39, 0.58, 0.65 and 0.69 for Hamon method, Penman modified method, Blaney and Criddle method and Thornthwaite method, respectively.

The annual potential evapotranspiration value obtained with Hamon method is larger than that of the annual discharge. Therefore, this method is not suitable for this region.

These results will be useful for establishing water resources management strategies and land use guidelines for the Cubatão-Sul watershed.

5. ACKNOWLEDGEMENTS

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