Vol.50, n. 5 : pp. 905-912 September 2007
ISSN 1516-8913 Printed in Brazil

BRAZILIAN ARCHIVES OF
BIOLOGY AND TECHNOLOGY
AN INTERNATIONAL JOURNAL

Water Balance in Karst: Case Study of the Ribeirão da Onça Catchment in Colombo City, Paraná State - Brazil

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ABSTRACT

With the objective to analyze the hydrological processes and the water balance, a simplified water balance method and the modified Penman formula were applied to the Ribeirão da Onça river catchment in Colombo city, Paraná State. For the analysis, the data obtained during the monitoring period from 1997 to 2000 were utilized. The results showed that the values of the real evapotranspiration estimated by the method of the simplified water balance were negative for the certain periods and for other period sometimes more than those of the potential evapotranspiration estimated by the modified Penman formula. It implied the existence of significant groundwater recharge from other catchments to the study area, and indicates that the simplified water balance method was not suitable for the hydrological study of this karst catchment. The value of the groundwater recharge received by this catchment was estimated as 554 mm/year for the analysis period.

Keys word: Water balance; evapotranspiration; karst

INTRODUCTION

The population of the Curitiba Metropolitan Region (CMR) is approximately over 2.7 millions presently. COMEC (1997) pointed out a deficit of water supply to the CMR between 10 and 25%. This region has been suffering from the continuous water-rationings performed by the SANEPAR (Paraná Sanitary Company) and consequently from the lack of water. The water supply to the CMR is the most important challenge. According to Andreoli et al. (1999), the water resources would be exhausted in 2030. The water demand in the CMR has been increasing due to the population and industry explosion, and the increase of water consumption per capita. Because of a high water quality, the low exploration cost and the difficulty of settlement of a conventional sanitation infrastructure on steep areas, the SANEPAR started to explore the groundwater in the karst without detailed hydrogeological and environmental impacts studies.

In the Ribeirão da Onça catchment, Colombo City, Paraná State (PR), which is one of water resources areas for the CMR, the water resources management has been the conflict focus between the local population and the SANEPAR. The knowledge on the water balance and the hydrological processes offer information that can be the base for decision making and that subsidizes the environmental management in karst areas. The water resources management adapts the socioeconomic factors to the environmental ones in the complex geology and morphology of karst.

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The better understanding of the water dynamics of the Ribeirão da Onça catchment makes it possible to encounter solutions for the existent divergences of water multipurpose-uses.

The objective of the present study was to analyze the hydrological processes, to model and to evaluate the water balance of the catchment. A simple water balance method and the modified Penman method were used to estimate the real evapotranspiration (*ETR*) and the potential evapotranspiration (*ETP*), respectively.

MATERIAL AND METHODS

The delimitation of the study catchment was done and the exit of the catchment is defined as the locality of the Montante da Ponte discharge monitoring station (Code: 81290500) which is 4 km upper stream to the mouth of the Ribeirão da Onça River. This station has been operated by the SUDERHSA (Superintendence of Water Resources Development and Environmental Sanitation) since the end of 1997. The catchment is located in the northeast of the Colombo City, between the S25º15'00" and S25º17'30" and between W49º09'00" and W49º13'00". Its area is of 16.118 km^2 (Fig. 1). According to IAPAR (1994), the climate of the area is the Cfb (subtropical humid mesothermic) type in the Köppen classification. It means temperate climate with fresh summers where the mean temperature of the hottest month is below 22ºC, without defined dry winter, with the occurrence of severe and frequent frosts, and with the mean temperature of the coldest month below 18ºC.

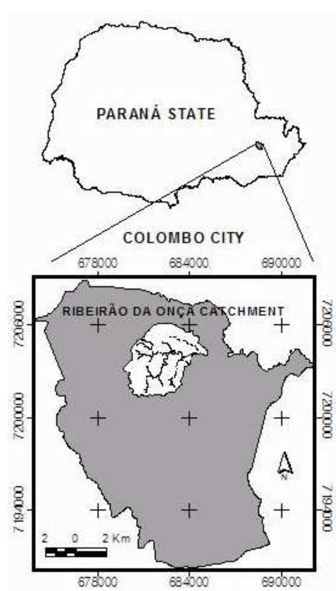

Figure 1 - Location of the study area

The land-use in this catchment is characterized with small-size agriculture like vegetable garden (41%). The presence of vegetation cover is expressive (the forest covers 31% of the total land and the bush 21%), meanwhile the residential and commercial areas represent only 7% (Vestena, 2002). The study area has a complex geology where permeable rocks (limestones) are surrounded by impermeable rocks (fillite, quartzites and diabase dikes) (Fig. 2). The intercross of two crests composed of diabase dikes with two crests of quartzite-filite composition forms individual unitary compartments (Figure 3), which causes flow conditions to be differentiated and independent (Lisboa, 1997).

The diabase dikes with 20 to 30 meters thickness, which are more resistant to the weathering than limestones, stand out in the topography, originating small crests aligned with the NW-SE direction. The filites and quartzites layers also constitute high topography and insert the dolomites (Marini et al., 1967). In the limestones the topography is lowered and shows very characteristic karst forms like dolines, drains, uvalas and caves. The dissolution processes act more intensively in the limestones, generating the differential erosion.

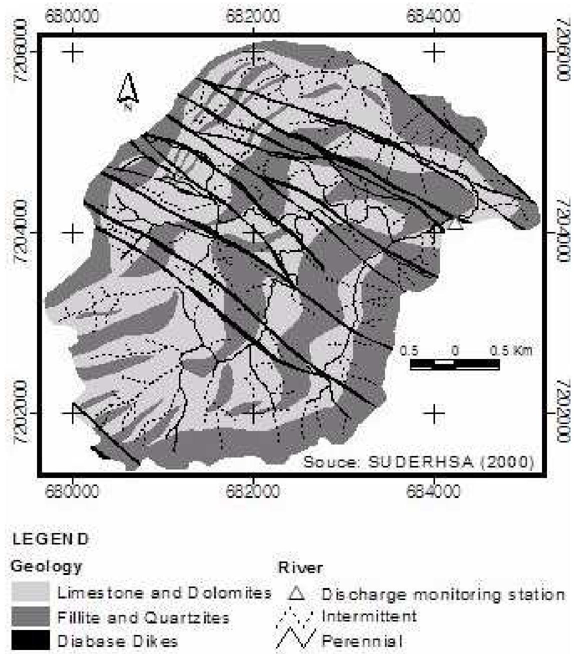

Figure 2 - Geology of the study area

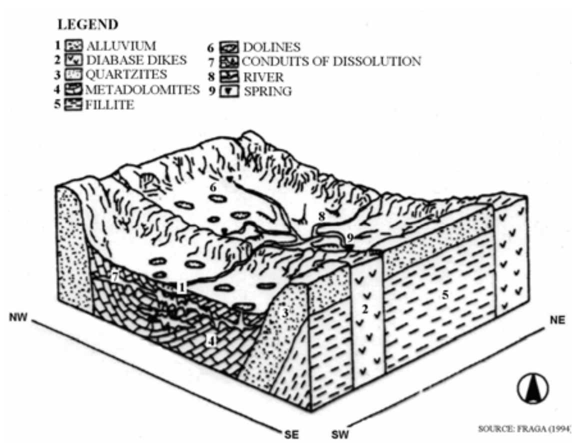

Figure 3 - Three-dimensional model representing the unitary compartments

In order to estimate the values of *ETP* and *ETR*, to evaluate the hydrological processes and to establish the water balance of the Ribeirão da Onça River catchment, the following data were used: daily precipitation obtained at the Colombo rainfall station (Code: 02549090) and the Capivari station (Code: 02549108), daily temperature, relative humidity, day light hour, solar radiation and wind speed at the Piraquara meteorological station (Code: 2549041) and daily discharge at Montante da Ponte discharge station (Code: 81290500). All of the data were obtained during the period from 1997 to 2000.

The Penman method modified by Doorenbos and Pruit (1977) was used to calculate the daily values of *ETP*. According to Müller (1995) and Oliveira (1999), the modified Penman method was the best one to estimate *ETP*, in the Paraná State. The simple water balance method was used to estimate *ETR* and the groundwater flow.

In the modified Penman method, the *ETP* can be estimated with the following equation:

$$ETP = C[\underbrace{W \cdot R_n}_{\text{Radiation component}} + \underbrace{(1\text{-}W) \cdot f(u) \cdot (e_a - e_d)}_{\text{Aerodynamic component}}] \qquad (1)$$

where *ETP* is the potential evapotranspiration (mm/day); *C* is the correction factor to compensate the day and night effect under climatic conditions, and relates the solar radiation, the maximum relative humidity and the day and night wind speed (dimensionless); *W* is the weighing factor related with the temperature and the altitude (dimensionless); R_n is the liquid radiation (mm/day); $f(u)$ is the function related with the wind (dimensionless); e_a is the water vapor saturation pressure (mbar); e_d is the real saturation pressure of the vapor in the air (mbar). In the simple water balance method, the value of *ETR* was equal to the precipitation (input) minus the runoff at the mouth (output) minus the water quantity captured at the wells inside the catchment (output).

Monthly *ETR* was also calculated multiplying monthly *ETP* with the monthly coefficient of correlation of reference (*K*). Müller (1995) calculated the historical monthly averages of the potential evapotranspiration (*HETP*) and the real evapotranspiration (*HETR*) by the modified Penman method and the CRAE (*Complementary Relationship Areal*) method proposed by Morton (1983), respectively. In the present study, these values of *HETP* and *HETR* were used to calculate the monthly values of *K* (Table 1).

Considering the water balance concept and using the value of *ETR* for each month, the equation (2) was established to quantify the groundwater flow.

$$Q_S = P - ETR - Q - Q_P$$

or $$Q_S = P - ETP \cdot K - Q - Q_P$$

or $$Q_S = P - ETP \cdot \frac{HETP}{HETR} - Q - Q_P \qquad (2)$$

where Q_S is the groundwater flow that enters into (+) or that leaves (-) the catchment (mm/month); *P* is the precipitation (mm/month); *ETR* is the real evapotranspiration (mm/month); *Q* is the runoff (mm/month); and Q_P is the captured water at the wells (mm/month).

Table 1 – Coefficients of correlation between historical monthly averages of *HETR* (CRAE) and *HETP* (Penman) of the meteorological station of Piraquara (code: 2549041), for the period of February of 1970 to October of 1992

Month	*HETP* (*Penman*)* (*mm*)	*HETR* (*CRAE*)* (*mm*)	*K* (*HETR/HETP*)
January	124	131	1.056
February	97	112	1.155
March	90	103	1.144
April	66	73	1.106
May	48	52	1.083
June	39	38	0.974
July	45	38	0.844
August	58	54	0.931
September	70	71	1.014
October	94	101	1.074
November	107	117	1.093
December	115	126	1.096
Annual	953	1016	1.066

SOURCE: * Müller (1995).

RESULTS AND DISCUSSION

In the hydrographs obtained during the period for the analysis, small variations of the water quantity captured by SANEPAR were found, especially in 1998 (Fig. 4).

In the case that only precipitation, runoff and captured water quantity were used as the variables in the simple water balance method, the *ETR* values were negative, which allowed to infer that other variables influenced the water balance in the Ribeirão da Onça catchment. Thus, it was thought that this catchment received water from outside of the catchment divisons. The catchment might have groundwater recharge areas that extrapolated the topographic divisons. It meant that the topographic divisors did not coincide with the phreatic ones. This fact strongly influenced the hydrological cycle in this catchment.

The mean annual value of *ETP* for the period from 1997 to 2000, obtained with the modified Penman method, was 1141 mm (= 3.12 mm/day). The minimum and maximum of the daily *ETP* were 1.11 mm and 5.86 mm, respectively. The standard deviation of the daily *ETP* for each year was between 1.07 mm and 1.20 mm, and the coefficient of variation between 34.5 and 38.4% (Table 2).

The *ETP* was larger in the summer (November, December and January) than in the winter (June, July and August). It confirmed that the temperature exercises significant influence on the *ETP*. The maximum and minimum extremes were observed in the summer and in the winter, respectively (Fig. 5).

The values of the monthly *ETR* obtained from the multiplication of *ETP* (Penman) estimated for each month with *K* were larger in November, December, January and February and smaller in July and June. The annual *ETR* was 1221 mm and its behavior was similar to that of the *ETP* during the year (Table 3). The mean annual precipitation for the period from 1997 to 2000 was 1594 mm. There was more rain in January and September and less in May. The runoff was larger in September and October and the smallest in May.

The Fig. 6 shows the correlations (a) between the runoff and precipitation and (b) between the runoff and captured water quantity. The former was very small and positive, and the latter was negative. When the runoff was larger than 25 mm/month, the water quantity captured at the wells decreased abruptly and kept constant.

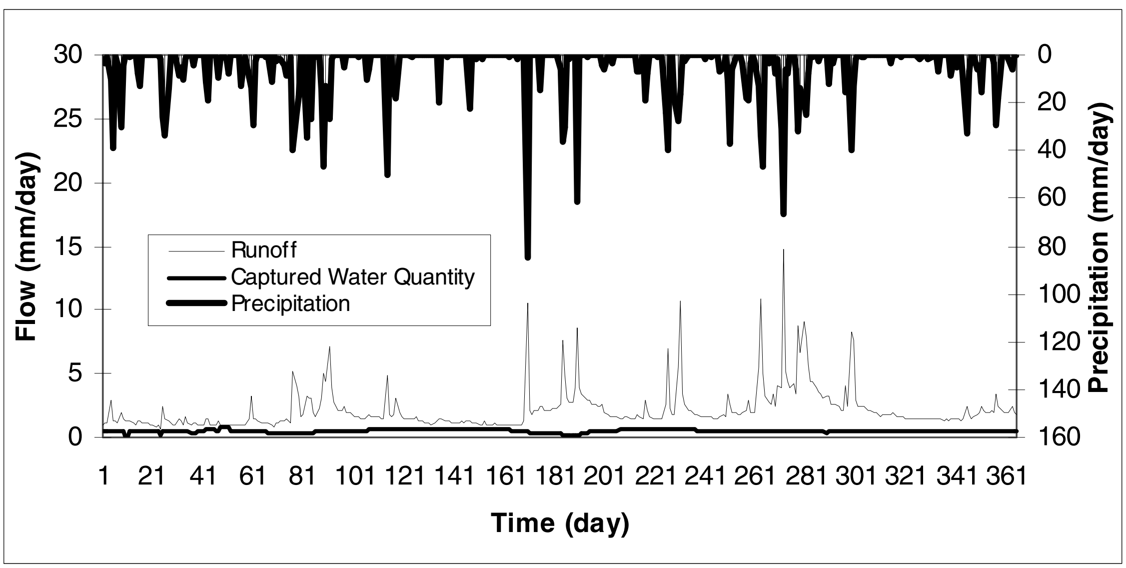

Figure 4 - Precipitation, runoff and water quantity captured at the wells in 1998

Table 2 – *ETP* characteristics of the Ribeirão da Onça river catchment for the period from 1997 to 2000

	1997	1998	1999	2000	AVERAGE
Annual *ETP* (mm)	1131.75	1124.34	1148.81	1159.39	1141.07
Mean daily *ETP* (mm)	3.10	3.08	3.15	3.17	3.12
Minimum daily *ETP* (mm)	1.11	1.27	1.18	1.18	1.18
Maximum daily *ETP* (mm)	5.45	5.78	5.86	5.70	5.70
Standard deviation (mm)	1.07	1.18	1.20	1.17	1.16
Coefficient of variation (%)	34.53	38.40	38.19	37.02	37.03

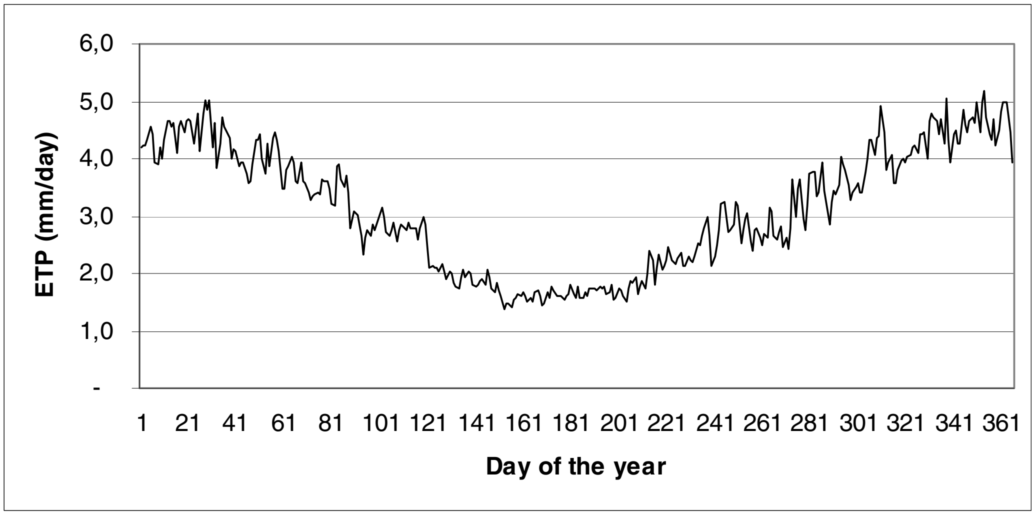

Figure 5 - Mean daily *ETP* (mm) estimated with the modified Penman method for the period from 1997 to 2000

Table 3 – Mean monthly *ETR* (mm), precipitation (mm), runoff and water quantity captured at the wells by SANEPAR in the Ribeirão da Onça river catchment during the period of 1997 - 2000

Month	*ETR* (mm)	Precipitation (mm)	Water Quantity Captured (mm)*	Runoff (mm)**
January	147	217	41	38
February	135	171	52	41
March	126	133	33	48
April	93	64	26	42
May	65	50	25	32
June	46	123	25	38
July	45	115	36	48
August	68	92	26	40
September	85	203	26	65
October	117	170	29	71
November	138	103	25	43
December	156	149	25	47
Annual	1221	1590	369	553

NOTE: * averages obtained for the period from Dec/1997 to Dec/2000 and ** for the period from Aug/1997 to Dec/2000.

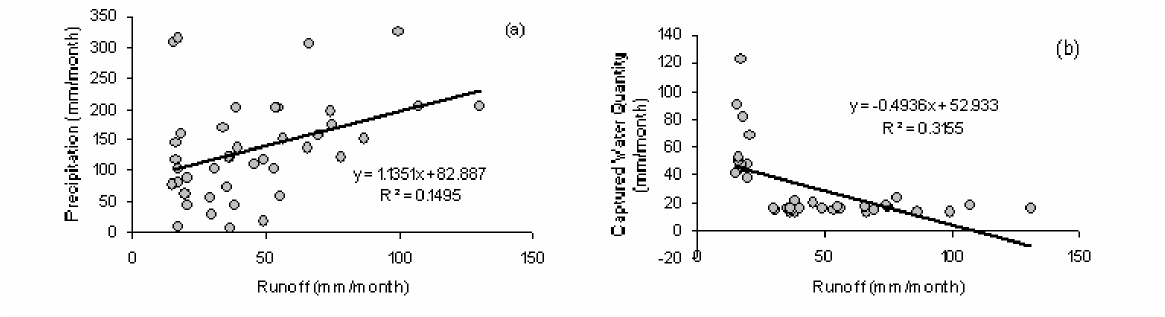

Figure 6 – Characteristics of runoff: (a) with precipitation; (b) with captured water quantity

By using the values of *ETR* and the equation (2), the amount of the groundwater flow was evaluated. The mean annual groundwater flow received by this catchment during the period from 1998 to 2000 was 554 mm. This value was 34.84% of the mean annual precipitation (1590 mm) of the catchment. Fig. 7 shows the components of the annual water balance of the Ribeirão da Onça catchment. The dynamics of the groundwater flow in this catchment resulted from the geological structure characterized with the karst. The impermeable rocks (filites, quartzites and diabase dikes) in the area determined the direction of the groundwater flow. The Ribeirão da Onça catchment presented areas of groundwater recharge that extrapolate the topographic divisors. The dynamics of the water was influenced by the phreatic divisons which were very different from the topographic ones in this area.

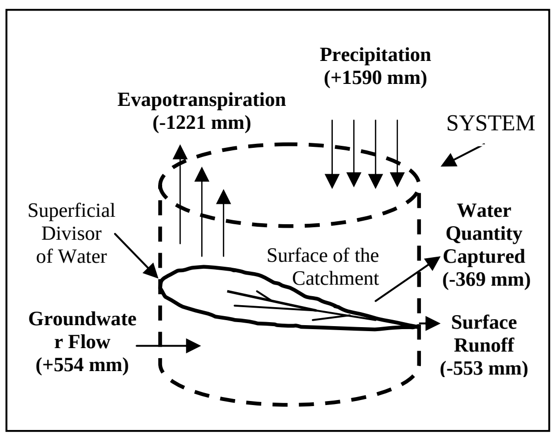

Figure 7 - Annual water balance of the Ribeirão da Onça riber catchment for the Period from 1998 to 2000

CONCLUSIONS

In order to understand the hydrological processes in the Ribeirão da Onça river catchment which offered water resources to the Curitiba Metropolitan Region, the present study applied a simplified water balance method and the modified Penman formula to the data obtained during the monitoring period from 1997 to 2000. The results showed the existence of significant groundwater recharge from other catchments to the study area and indicated that the simplified water balance method was not suitable for the hydrological study of this karst catchment. Analyzing the water balance, it was found that the catchment annually received the groundwater flow of 554 mm for the period from 1998 to 2000. A more precise analysis of the hydrological processes in karst areas requires long monitoring, longer than 10 years.

ACKNOWLEDGEMENTS

The authors are grateful to the SUDERHSA (Superintendence of Water Resources Development and Environmental Sanitation), especially Mr. Edson Sakae Nagashima and Mr. Nilson Antonio de Morais for supplying the discharge and precipitation data.

RESUMO

O presente trabalho teve como objetivo analisar os processos hidrológicos e avaliar o balanço hídrico da bacia hidrográfica do Ribeirão da Onça, no município de Colombo/PR, área de manancial da Região Metropolitana de Curitiba, para o período de monitoramento existente, de 1997 a 2000. Os métodos utilizados foram o do balanço hídrico simplificado e de Penman modificado. O método do balanço hídrico mostrou-se inválido para estimar a evapotranspiração real da área de estudo, por produzir valores negativos e superiores a evapotranspiração potencial, permitindo inferir que em determinados períodos, o volume de recursos hídricos extraídos é superior ao índice de precipitação, o que leva a deduzir que existem áreas de recarga do aqüífero externa aos divisores superficiais da bacia. O balanço hídrico da bacia do Ribeirão da Onça permitiu identificar a contribuição da água subterrânea, onde a média anual recebida pela bacia para o período de 1998 a 2000, foi de 554 mm/ano.

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Received: October 21, 2005;
Revised: July 27, 2006;
Accepted: May 14, 2007