PROPOSAL OF TANK MOISTURE INDEX TO PREDICT FLOODS AND DROUGHTS
IN PEIXE RIVER WATERSHED, BRAZIL

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Abstract

Rio do Peixe watershed, southern Brazil, has suffered natural disasters caused by excess and shortage of rainfall. Four incremental basins were studied (Pe_1, 803 km^2; Pe_2, 2,018 km^2; Pe_4, 3,708 km^2 and Pe_4, 5,238 km^2. Historical series (28 years) of daily hydro meteorological data were used. The mean values [mm.d^{-1}] of precipitation (*P*), potential evapotranspiration (*ETP*), real evapotranspiration (*ETR*) were 4.70; 2.83; 2.32 (Pe_1); 4.83; 2.85; 2.63 (Pe_2); 4.93; 2.90; 2.53 (Pe_3); 4.95; 2.95; 2.73 (Pe_4), respectively. The Tank Model, with four vertical reservoirs and twelve parameters, was calibrated and validated. The mean daily observed and calculated discharges [mm.d-1] were: 2.38 and 2.43 (Pe_1); 2.20 and 2.19 (Pe_2); 2.40 and 2.35 (Pe_3); 2.22 and 2.18 (Pe_4), respectively. The Tank Moisture Index (*TMI*) was created, considering the daily water storage in reservoirs 1 to 4, and use of central tendency (average and median). *TMI* (0-10) was applied to analyze public calamity states due natural hazards, period of 1977 to 2004. Median compared with average produced higher adjustment (floods, 84%; droughts, 90%). The present study showed that Tank Moisture Index, on daily basis, applied to extreme hydrological events, is useful for floods' warnings, and also for droughts duration and severity analyses.
Key words: Tank Model; floods; droughts; Tank Moisture Index

INTRODUCTION

The Rio do Peixe watershed, southern Brazil, has frequently suffered from hydrological extreme events, registered since the valley colonization, at the beginning of the 20th century. To obtain an adequate watershed management for its sustainable development, the Rio do Peixe Committee, created in 2001 to promote the watershed management, based in Joaçaba city, requires hydrological models. The Tank Model (Sugawara, 1995) was applied, with daily monitoring data from 1977 to 2004. A survey of public calamity states associated with the extreme hydrological events was accomplished for the corresponding period. The objective of the present work was to propose the Tank Moisture Index (*TMI*), on a daily basis, derived from the Tank Model and validated for the studied watershed, which can predict the occurrence of extreme hydrological events (flood and drought).

STUDIED AREA RIO DO PEIXE WATERSHED

The Rio do Peixe watershed is the right margin tributary of the Uruguay River (ANA, 2006), and is located between the parallels S 26°36′24″ and 27°29′19″ and meridians W 50°48′04″ and 51°53′57″ (Fig. 1). The maximum altitude is 1350 m (watershed) and 1250 (main river). The population is 336,660 inhabitants (IBGE, 2010). The river is the main source for drinking and industrial water supply after conventional treatment.

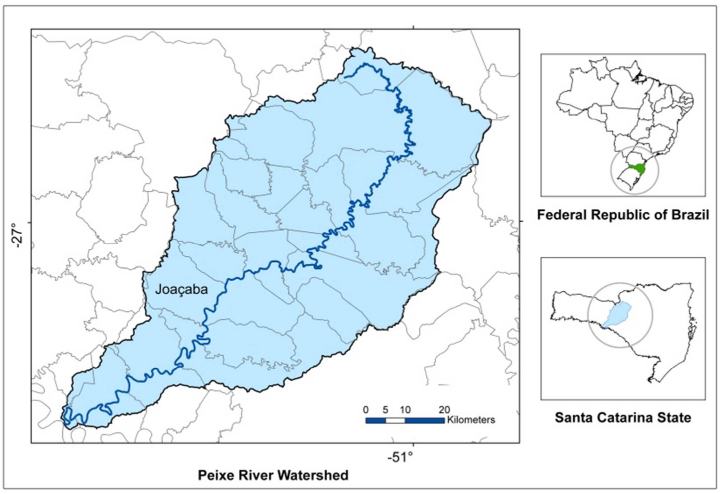
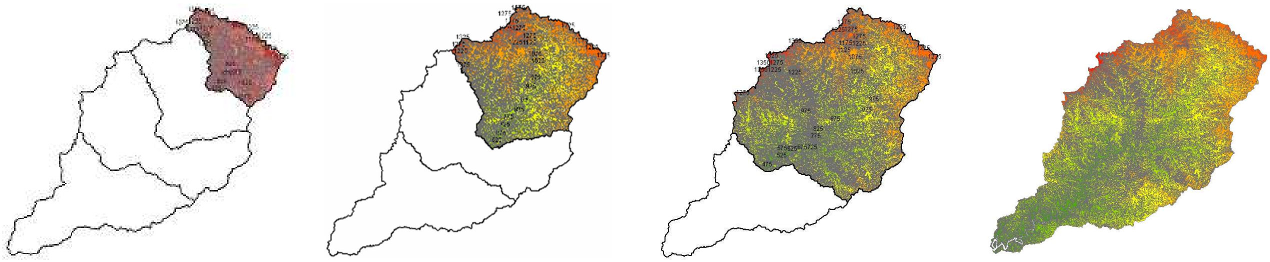


Fig. 1 Location of the Rio do Peixe watershed, Santa Catarina State, Brazil

The watershed delimitation was detailed considering four gauging stations, named with the municipality location, resulting in incremental basins 1 to 4, henceforth designed by Pe_1, Pe_2, Pe_3 and Pe_4 (Fig. 2). The Table 1 presents the morphologic data.



Rio das Antas Pe_1 Tangará Pe_2 Joaçaba Pe_3 Piratuba Pe_4 (Peixe)

Fig. 2 Incremental basins of the Rio do Peixe watershed, Santa Catarina State, Brazil

Table 1 Data and morphologic characterization of incremental basins in Rio do Peixe watershed

Parameters/data	Pe_1	Pe_2	Pe_3	Pe_4
ANA National gauging station code	72715000	72810000	72849000	72980000
Area (*A*, km²)	803	2018	3708	5238
Total perimeter (*P*, km)	154	233	319	425
Main river extension (*L*, km)	81	148	189	299
Minimum altitude (m)	781	602	493	387
Average altitude (m)	1042	995	945	876
Median altitude (m)	1035	1005	950	880
Time of concentration (hours)	16	25	31	53

Hydrometeorological Data

The hydrological data were processed for the period of 1977-2004. The discharge (*Q*) was obtained from the four gauging station (ANA, 2007). The precipitation (*P*) comes from 19 stations and the meteorological parameters (temperature, insulation, relative humidity and wind speed) from 4 meteorological stations. In order to calculate the mean rainfall value for each incremental basin and for the whole watershed, the Thiessen polygons method was utilized. Fig. 3 shows the Thiessen polygons, whose boundaries define the area that is closest to each point relative to all other points, expressed in percentage, for each precipitation station, identified by its municipality location name (ANA, 2007, EPAGRI, 2007, INMET, 2007).

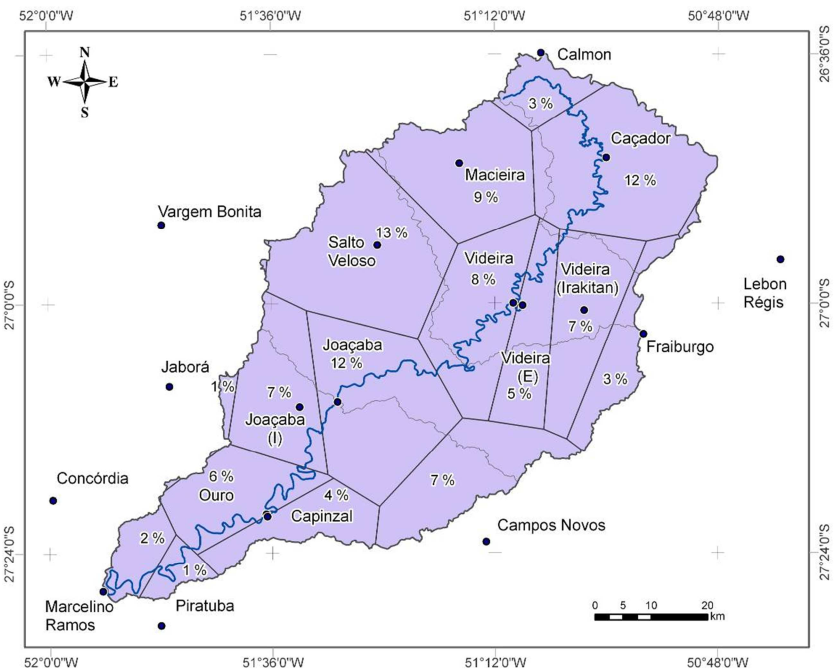


Fig. 3 Thiessen polygons applied to 19 precipitation stations for Rio do Peixe watershed

For Rio do Peixe watershed (1977-2004), regarding to precipitation, the humid years, in decreasing order, were 1983, 1998, 1990 and 1997. Years with shortage of rain were 1985, 1978, 1981, 1991, 2003 and 2004.

The precipitation is similar in the incremental basins. The average values for Pe_1, Pe_2, Pe_3 and Pe_4 of 28 years show October as the month receiving more precipitation (196, 197, 203 and 205 mm) and August receiving less rain (107, 109, 111 and 113 mm).

Precipitation, potential evapotranspiration and observed flow in Rio do Peixe watershed

Lindner *et al*. (2006) estimated the daily potential evapotranspiration (*ETP*) with the Penman modified method (Doorenbos & Pruit, 1977), using the parameters: temperature, wind velocity, air relative humidity and sunshine hours. The main variable which affects the *ETP* is the sunshine hours. For this reason in winter the *ETP* is lower and it is higher in summer. The average *ETP* for each incremental basin was calculated weighting coefficients related to the altitude. The average monthly *ETP* for Pe_1, Pe_2, Pe_3 and Pe_4 were 41, 41, 42 and 43 mm (June) and 130, 131, 133 and 136 mm (December).

Table 2 shows annual values (mm) for precipitation (*P*), observed flow (Q_{obs}) and potential evapotranspiration (*ETP*) for the incremental basins of Rio do Peixe watershed.

Table 2 Annual values of precipitation, potential evapotranspiration and observed flow in Rio do Peixe watershed

Period 1977-2004	Pe_1, 803 km^2			Pe_2, 2018 km^2			Pe_3, 3708 km^2			Pe_4, 5238 km^2		
	$mm.year^{-1}$			$mm.year^{-1}$			$mm.year^{-1}$			$mm.year^{-1}$		
	P	*ETP*	Q_{obs}	*P*	*ETP*	Q_{obs}	*P*	*ETP*	Q_{obs}	*P*	*ETP*	Q_{obs}
Minimum	1084	931	377	1177	939	318	1456	1012	484	1195	972	307
Average	1716	1032	856	1766	1041	803	1836	1076	871	1824	1074	799
Maximum	2494	1130	1621	2572	1140	1544	2424	1158	1627	2698	1181	1439

Minimum annual average flows were verified in the years 1978 and 1981. The potential evapotranspiration increases from upstream to downstream, related to temperature and altitude. The maximum annual value of *ETP* occurred in 1991 and the minimum in 1979.

In Rio do Peixe the months of flooding were October (1970, 1997) and July (1983). Drought months occurred in December and April. The flooding trimester is September-October-November. The drought trimester is February-March-April. Level and flow statistical studies were developed by Zilio (2007) for the incremental basins Pe_1, Pe_2, Pe_3 and Pe_4 (1977-2004). The analyses were amplified (1941-2000) for the entire basin (Peixe, Pe_4).

Considering the coincident period, incremental basins Pe_1 and Pe_3 have distinct behavior. In Table 3 Pe_3 presents higher specific flow, explained by lower number of data and high slope upstream, 38% (strongly undulating terrain: 20- 45%) and 8% (mountainous terrain: 45-75%), increasing the runoff. The subbasin Pe_1 has different soil and less evapotranspiration due higher altitude (lower temperature).

Table 3 Statistical data of daily river level, depth *h* (cm) and observed flow, *Q* ($m^3.s^{-1}$)

Parameter / Subbasin	Pe_1		Pe_2		Pe_3		Pe_4		Pe_4 (1941-2000)	
	h	Q_{obs}	*h*	Q_{obs}	*h*	Q_{obs}	*h*	Q_{obs}	*h*	*Q* Q_{obs}
Average	149	22.1	100	51.2	154	100.5	127	132.6	123	119.2
Median	145	12.3	90	27.1	129	49.0	104	72.2	100	57.4
Minimum	71	1.3	60	1.3	44	3.5	23	5.3	10	0.9
Maximum	460	596.0	505	1481.2	905	2375.0	1300	4097.0	1300	4097.0

Source: Zilio (2007)

Average long period evapotranspiration

The real average long period evapotranspiration ($\overline{ETR}$), for each incremental basin and Rio do Peixe watershed, was calculated in accordance to Porto and Zahed Filho (2002), considering the sums obtained for the entire historical database (Lindner, 2007).

Table 4 shows the average long period calculated parameters of real evapotranspiration (*ETR*), potential evapotranspiration (*ETP*) and the relative evapotranspiration (ET_{rel}) for the incremental basins of Rio do Peixe. The number of years (*T*) is different due to lack of observed discharge data.

Table 4 Long period average values of *ETR*, *ETP* and ET_{rel} for Rio do Peixe watershed

Parameter/subbasin	Pe_1	Pe_2	Pe_3	Pe_4 (Peixe)
$\sum P - \sum Q$ (mm)	48,055 - 23,959	49,443 - 22,476	34,875 - 16,543	43,782 - 19,166
R^2	0.9992	0.9985	0.9985	0.9979
T (years)	28	28	19	24
$\overline{ETR}$ (mm)	861	963	965	1.026
$\overline{ETP}$ (mm)	1032	1041	1076	1074
ET_{rel}	0.83	0.92	0.90	0.96

Average daily values of precipitation (*P*), potential evapotranspiration (*ETP*), real evapotranspiration (*ETR*) and observed flow (Q_{obs}) for each incremental basin and Rio do Peixe watershed (January 1st 1977 to December 31st 2004) are shown in Table 5, considering the full range of data, with average values. The data of precipitation, potential evapotranspiration and real evapotranspiration are available for the entire period (10,227 daily registers), exception to the lack of discharge data. The value of ET_{rel} is coincident only for subbasin Pe_2, the only one that has the complete series of parameters.

Table 5 Average daily values of precipitation (*P*), potential evapotranspiration (*ETP*), real evapotranspiration (*ETR*) and observed flow (Q_{obs}) for each incremental basin and Rio do Peixe watershed (1977-2004)

Parameter/incremental basin	Pe_1	Pe_2	Pe_3	Pe_4
P ($mm.d^{-1}$)	4.70	4.83	4.93	4.95
ETP ($mm.d^{-1}$)	2.83	2,85	2.90	2.95
ETR ($mm.d^{-1}$)	2.32	2.63	2.53	2.73
Q_{obs} ($mm.d^{-1}$)	2.38	2.20	2.40	2.22
Number of flow data (days)	9236	10148	6459	8080
ET_{rel} resulting	0.82	0.92	0.87	0.93

Applying the simplified water balance to find the real annual evapotranspiration (*ETR*), considering that $ETR = P - Q$. The daily *ETR* values were calculated as $ETP \times kc$. For the whole period (1977–2004) the coefficient (*kc*) between *ETR* and *ETP*, was 0.93. On daily basis Lindner (2007) showed that the mean values of *P*, *ETP* and *ETR* for the Rio do Peixe watershed are 4.95 mm day^{-1}, 2.95 mm day^{-1} and 2.73 mm day^{-1}, respectively.

Soil, slope and land use and occupation in Rio do Peixe watershed

Rio do Peixe watershed is located in a basalt effusion region. The predominant soils presented are Nitosol (51.5%), Neosol (22.4%), Cambisols (22.3%) and, in minor degree, Latosol (2.8%). Litholic Neosol has the higher percentage (30%) in subbasin Pe_3 (Lindner, 2007). Planialtimetric maps in digital shape (EPAGRI, 2007) were used to obtain the slope in each incremental basin in Rio do Peixe watershed. The areas (*A*, km^2) for each class of slope are shown in Table 6. Pe_3The main soil classes were defined and mapped according to the Brazilian System of Soil Classification (EMBRAPA, 1999).

Table 6 Classes of slope in Rio do Peixe watershed

Slope (%)	Relief	Pe_1 (*A*, km^2)	Pe_2 (*A*, km^2)	Pe_3 (*A*, km^2)	Pe_4 (*A*, km^2)
0 - 3	Plain	423	945	1.575	2.201
3 - 8	Gently undulated	62	87	106	123
8 - 20	Undulated	221	489	748	994
20 - 45	Strongly undulated	93	444	1.086	1.612
45 - 75	Mountainous	5	48	176	277
> 75	Escarpment	0	4	18	31
Total		803	2018	3708	5238

The use and real land occupation in Rio do Peixe watershed was obtained through CBERS satellite image, year 2003, as shown in Table 7. The subbasin Pe_1 has the highest percentage of reforestation (48.3%), annual culture (12.8%) and urban conglomeration (2.5%), city of Caçador. In Pe_3, proportionality it is found the best values of native and transition forest preservation (9.9%). Field for grazing area is prevailing in Rio do Peixe watershed (35.5%), corresponding to 1859 km^2, together with exotic essences reforested area (40.4%), equivalent to 2116 km^2.

Table 7 Areas in percentile for different class of land use and occupation in Rio do Peixe watershed

Class/Area (%)	Pe_1	Pe_2	Pe_3	Pe_4 (Peixe)
Native forest	1.7	5.7	6.5	6.3
Transition forest	1.8	3.7	3.4	3.2
Reforestation	48.3	45,2	41.8	40.4
Field grazing	31.1	30.3	33.2	35.5
Annual culture	12.8	11.8	12.1	11.7
Water bodies	1.8	1.7	1.8	1.8
Urban area	2.5	1.6	1.2	1.1

NATURAL DISASTERS IN RIO DO PEIXE WATERSHED

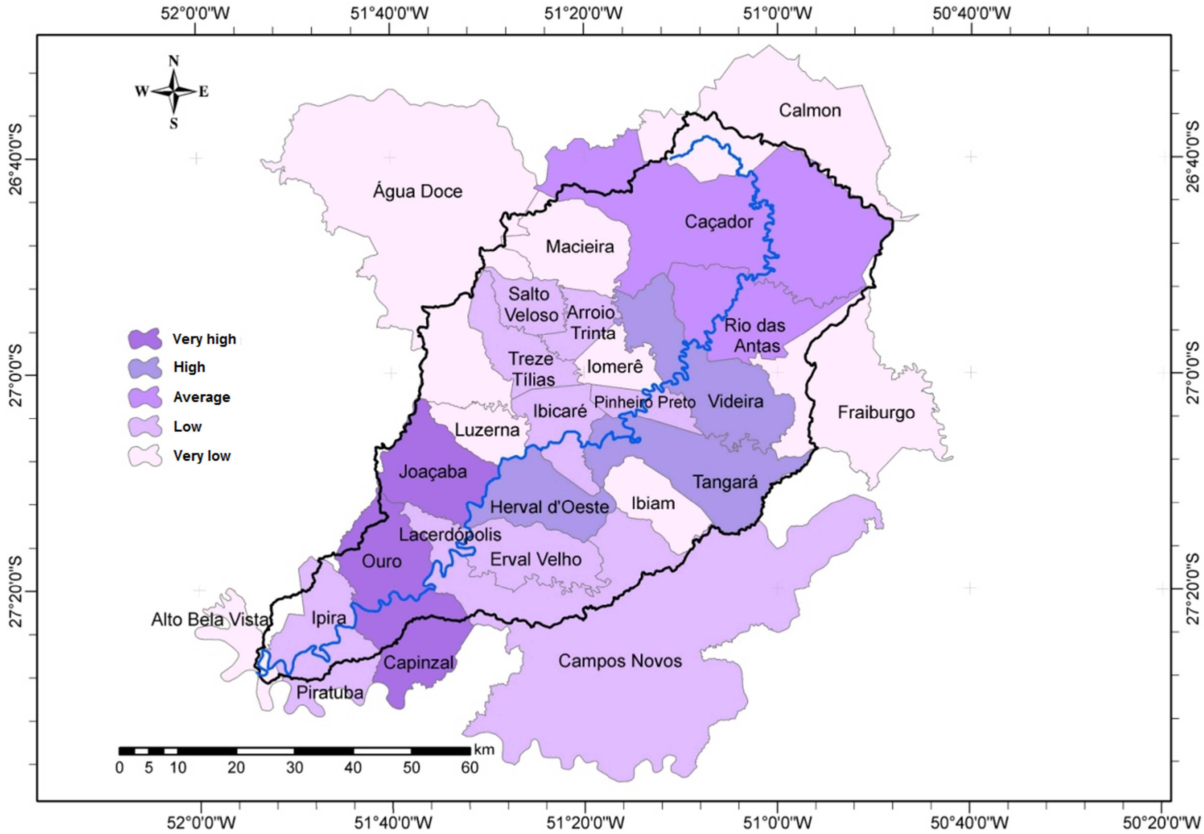
The occurrences of natural disasters have been published in decrees of public calamity state (CP) and emergency situation (SE) signed by mayors and submitted to the National Civil Defense Secretary for recognition (Brazil, 2006). Research was made visiting 26 municipalities belonging to Rio do Peixe watershed. The natural disasters registered by 25 city halls (one did not suffer any natural disaster) and nationally accepted, for the period 1972 to 2006, totalize 452 decrees, being 442 valid decrees.

Table 8 shows the occurrences of emergency situation and public calamity classified in three main groups of water-related natural disasters. In case of “too much water” it was called “water excess” and for “not enough water”, it was grouped as “water deficiency”. The “others” classification include events of strong winds and hail and are not considered in the present study.

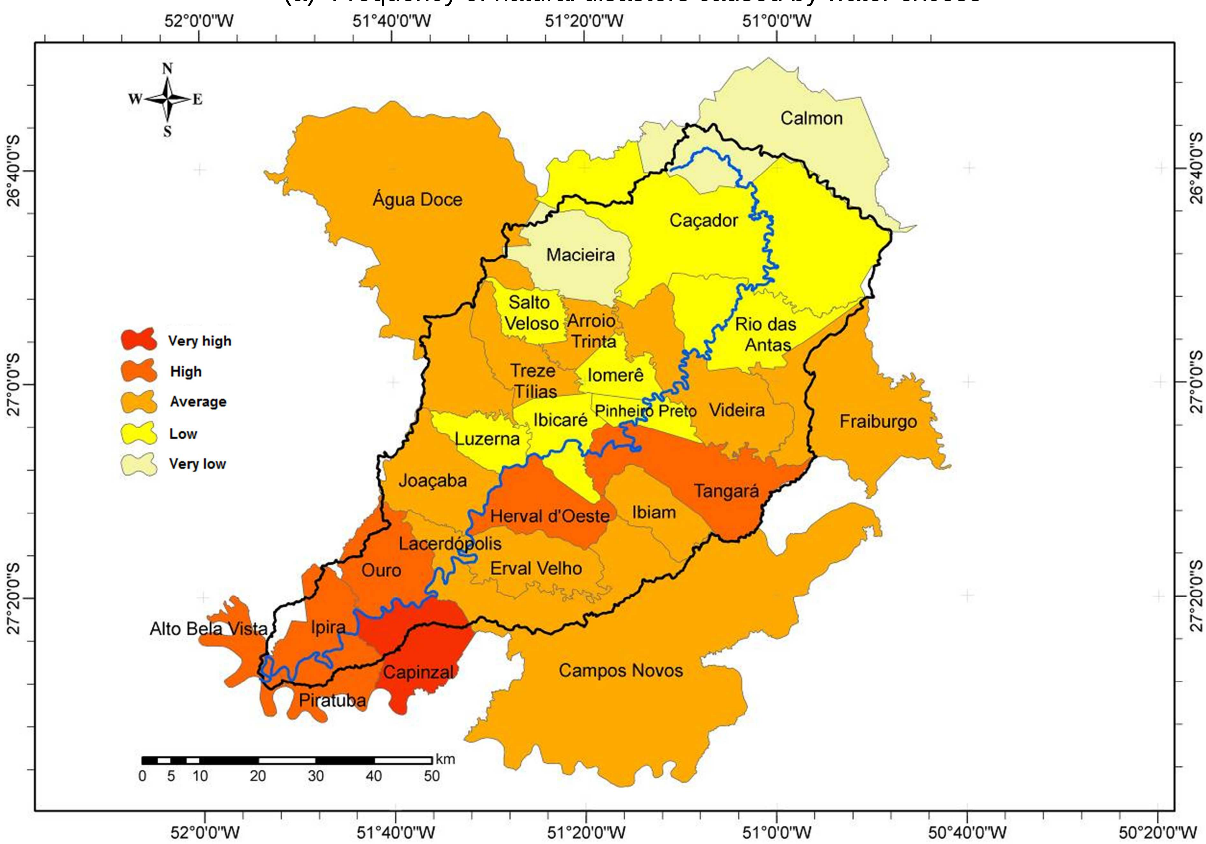
Table 8 Water-related natural disaster (1972-2006) in municipalities of Rio do Peixe watershed

Types of natural disaster occurrences	Number of Decrees		
	Water excess	Water deficiency	Others
Over flooding	58		
Flooding	36		
Flooding and landslide	28		
Landslide	14		
Flash floods	6		
Flash floods and strong wind	6		
Flooding and strong wind	8		
Over flooding and landslide	3		
Strong wind and landslide	3		
Flash floods and hail	2		
Flash floods and landslide	1		
Over flooding and strong wind	1		
Flooding/amplifying of area	1		
Flash flood/prorogation	1		
Dry spell		192	
Drought		8	
Dry spell/prorogation		22	
Dry spell/economic reflection		4	
Dry spell/retification		3	
Strong wind and hail			17
Strong wind			16
Hail			12
Total	168	229	45

For the common period of the hydrometeorology study, 1977–2004, 330 decrees were established, divided in: water excess (161 decrees); water deficiency (129); hail and strong winds (40). It was observed that the major floods occurred in 1983 (39 decrees), 1990 (28), 1997 (19), and 1992 (18), and that the more severe droughts occurred in 2002 (30), 1991 (27) and 2004 (24).The incidence of water-related natural disasters, considering the political division of 26 municipalities is shown in Fig. 4. Letter *F* stands for Frequency.



(a) Frequency of natural disasters caused by water excess



(b) Frequency of natural disasters caused by water deficiency

Too high 20> F ≥16	High16 > F ≥12	Average 12 > F ≥8	Low 8 > F ≥4	Too low 4 > *F* ≥0

Fig. 4 Frequency of water-related natural disasters in 26 municipalities of Rio do Peixe watershed, period 1977-2006: (a) water excess; (b) water deficiency

For the period 1977-2006, the municipalities which higher number of decrees due the event “water excess” were Joaçaba (17), Ouro (16), Capinzal (16), Videira (14) and Herval d’Oeste (13). It is noted that these municipalities have their urban site along the riverside of the main channel of Rio do Peixe due to water excess.
The municipalities with the major number of natural disasters due to the lack of precipitation, “water deficiency” were: Capinzal (16), Ipira (15), Alto Bela Vista (15), Ouro, Piratuba e Tangará (13, each) and Herval d’Oeste (12). Exceptionally the last two, there is a high tendency to lack of water in downstream areas of Rio do Peixe watershed. The municipalities located downstream concentrate 31% of the water deficit decrees. In accordance to Lindner et al. (2007), lower altitudes, higher temperature promote higher evapotranspiration, even for the same rainfall, causes water deficit.

Drought Annual Indexes and Natural Disasters

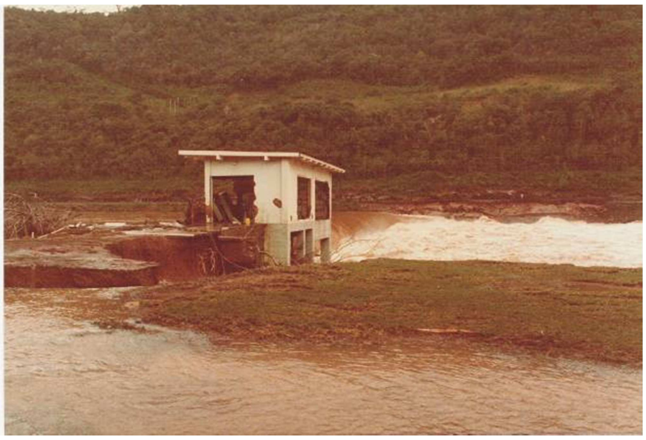
It was applied the precipitation classification in Decile (Hayes, 2002) for the rainfall recorded in the watershed. Table 9 presents the number of decrees, including emergency situation and public calamity for events of “water excess” and “water deficiency”, the precipitation classification in Decile and the occurrences of El Niño e La Niña, registered by Guetter (2003), period of 1977 to 2004.
Regarding to the annual rainfall, the precipitation classification in Decile presented 56% of data coincidence for episodes of excess discharge in comparison with the numbers of emergency situation and public calamity decrees. For the four years most significant anomalous events of water deficiency it was not found relationship between the Deciles of precipitation classification and the natural disasters decrees.

Table 9 Number of decrees referent to water excess and deficiency in Rio do Peixe watershed, annual precipitation classification in Deciles and *El Niño e La Niña* events

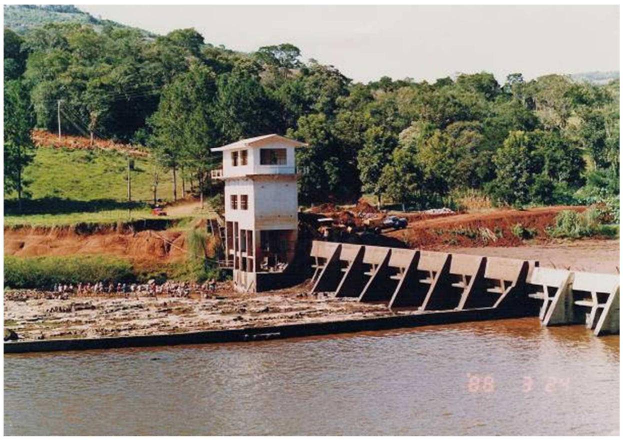
Year	Number of decrees			Annual Precipitation Decile classifications (Hayes, 2002)	Events (Guetter, 2003)	
	Excess hydric	Hydric deficiency	Others		*El Niño*	*La Niña*
1977	0	0	0	Near normal	Jul. 76 to Feb. 77 (8 months)	
1978	0	0	0	Much above normal		
1979	0	3	0	Above normal		
1980	0	0	0	Near normal		
1981	0	0	1	Much above normal		
1982	2	0	1	Much above normal	Apr. 82 to Ago. 83 (17 months)	
1983	38	0	1	Much above normal		
1984	11	0	2	Above normal		Jul. 84 to Feb. 86 (18 months)
1985	0	4	0	Much above normal		
1986	0	4	0	Near normal	Sep. 86 to Jan. 88 (17 months)	
1987	1	0	0	Near normal		
1988	0	9	1	Below normal		Apr. 88 to May 89 (14 months)
1989	5	0	2	Near normal		
1990	28	0	3	Much above normal		
1991	0	26	6	Below normal	May 91 to Jun. 92 (14 months)	
1992	18	0	6	Much above normal		
1993	2	0	1	Above normal		
1994	1	0	0	Much above normal		
1995	2	5	1	Below normal		Ago. 95 to Mar. 96 (8 months)
1996	4	2	3	Much above normal		
1997	19	8	0	Much above normal	Apr. 97 a jun. 98 (15 months)	
1998	13	1	0	Much above normal		Sep. 98 to Dec. 99 (16 months)
1999	0	8	0	Below normal		
2000	5	3	1	Much above normal		
2001	3	0	4	Above normal		
2002	6	31	1	Above normal		
2003	3	1	1	Below normal		
2004	2	24	0	Below normal		

The years with the major number of decrees of excess discharge were: 1983 (38); 1990 (28); 1997 (19); 1992 (18 decrees). The water deficiency was evident in the years: 1991 (26); 2002 (31); 2004 (24) (Table 6). It was found that not all the events of excess discharge were related to the occurrence of El Niño. In the studied area, not all the events of water deficiency were related to La Niña,

Fig. 5 illustrates Rio do Peixe in episodes of floods (a) and dry well (b), municipality of Luzerna, place of a small hydroelectric power plant. Effects of erosion are shown in (a1) and the high discharge in (a2) and (a3). In (b1) is registered the dam maintenance, possible due the low flow. In (b2) e (b3) can be seen the rocky bed of the river.



(a1) Overflow in 07/07/1983



(b1) Dry well in 24/03/1988

(a2) Flooding in 11/10/1997

(b2) Dry well in 20/02/2002

(a3) Flooding in 14/12/2003

(b3) Drought in 13/02/2005

Fig. 5 Floods and droughts in Rio do Peixe, municipality of Luzerna

The precipitation classification in Deciles, the humidity index, aridity index, effective humidity index, in annual periods, were not suitable to characterize the events of dry well and excess of water in the Rio do Peixe watershed, showing there is a need for humidity index on daily basins (Lindner et al., 2007).
The aridity index of the watershed by the Thornthwaite and Mather method indicates “little or no water deficiency” and the annual moisture index is 75.90, corresponding to a “humid climate III (B3)”.

The annual index, humidity index (I_u) and the effective humidity (I_m) (Ometto, 1981), were compared with the decrees of " excess discharge" and "water deficiency", published by the 26 municipalities which belong to Rio do Peixe watershed, period of 1977 to 2004. The climate index I_u and I_m are more related to the water deficiency decrees. The similarity was not found for the excess discharge decrees.

TANK MODEL APPLICATION

The present study adopted the four tanks in series, based on Sugawara (1995). The Tank Model structure used for the Rio do Peixe Watershed is shown in Fig. 6. The initial values of parameters suggested by Sugawara (1995) were used for each year of calibration (1977–1990). The automatic calibration proposed by Sugawara (1995) and visual checking were used to optimize the procedure.

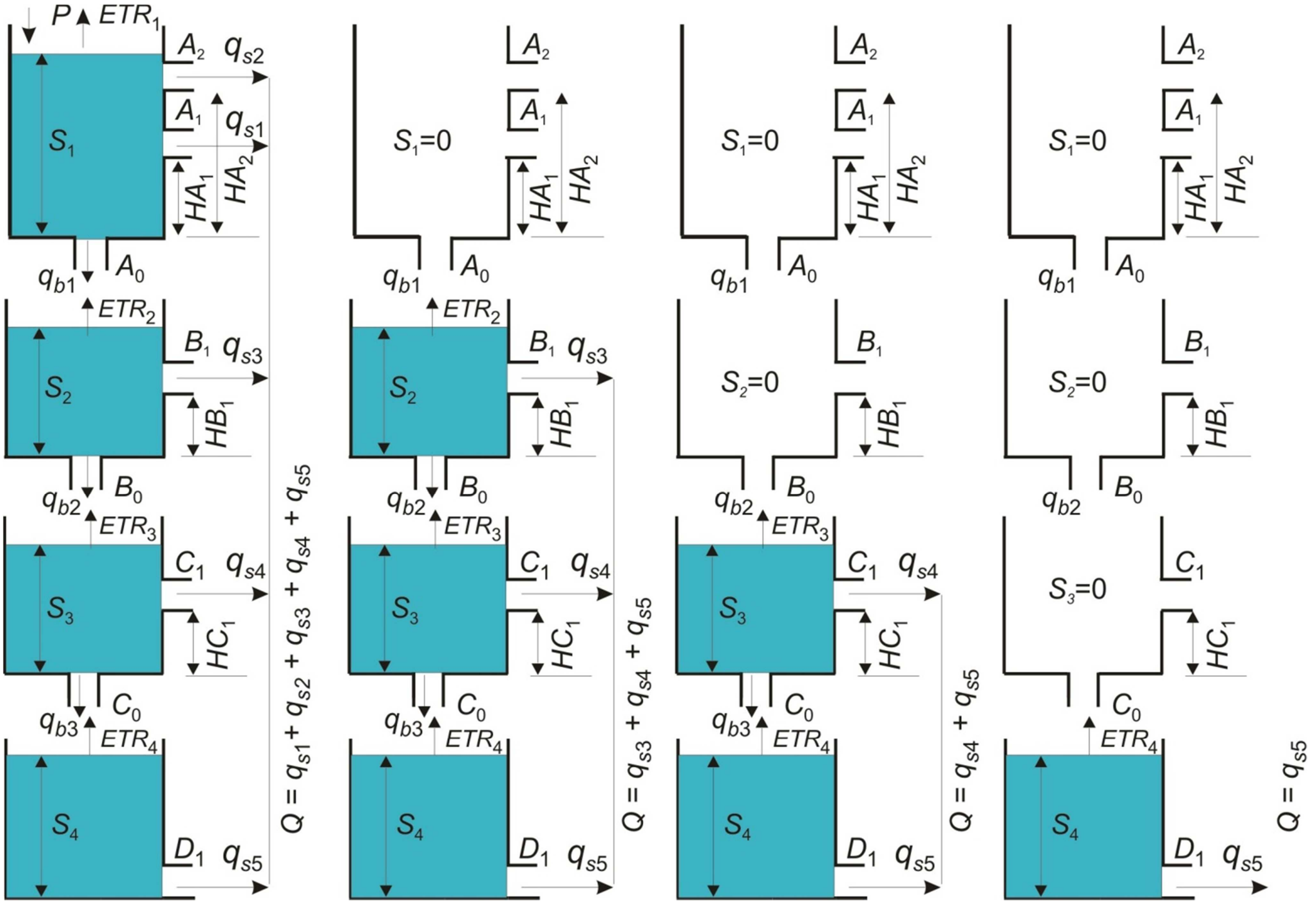
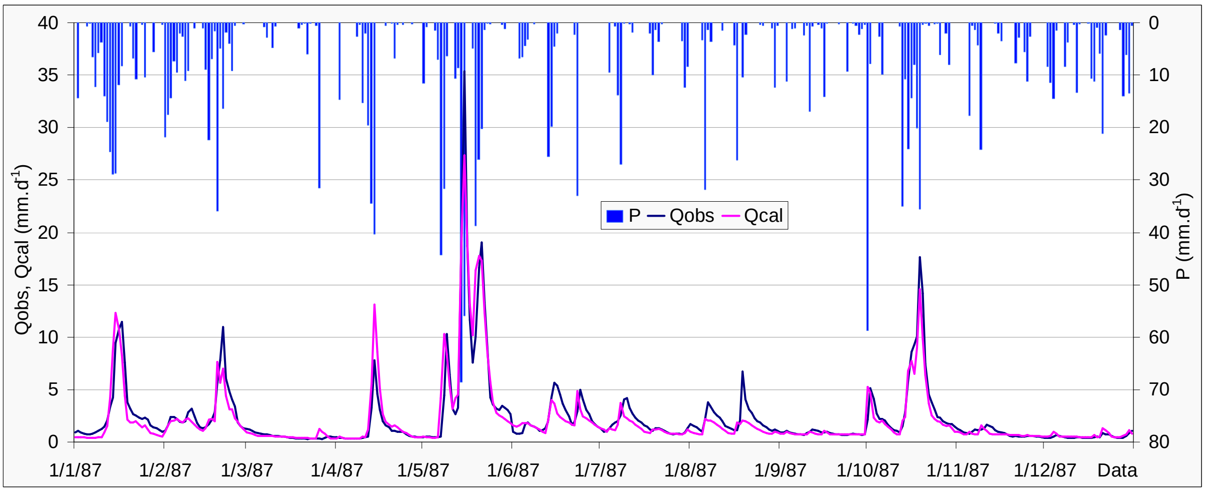


Fig. 6 Change of the storage level in reservoirs 1 to 4 due the precipitation and evapotranspiration, with flow generation: (a) storage in S_1 to S_4; (b) storage in S_2 to S_4; (c) storage in S_3 and S_4; storage in S_4.

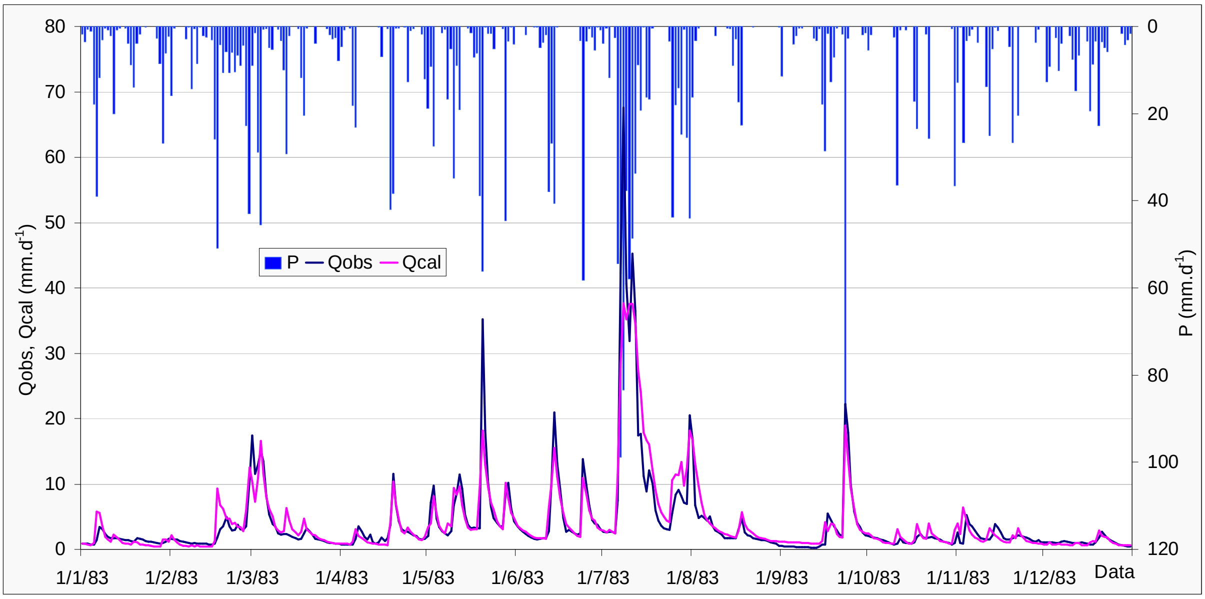
For the model performance evaluation multi-objective criteria were applied: coefficient of correlation, coefficient of determination (R^2), and errors indicators such as Relative Error (RE), Volume Standard Error (ΔV), Nash coefficient (NS), Nash Logarithmic coefficient (NSlog), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Logarithmic RMSE (RMSElog) (Setiawan *et al*., 2003; Fujihara *et al*., 2004). After calibration, the model validation was carried out for each year from 1991 to 2004. It is noted that the initial storage heights were 0 mm in Tank 1 (S_1), 0 mm in Tank 2 (S_2), 60 mm in Tank 3 (S_3), and 200 mm in Tank 4 (S_4).

Tank Model calibration and validation

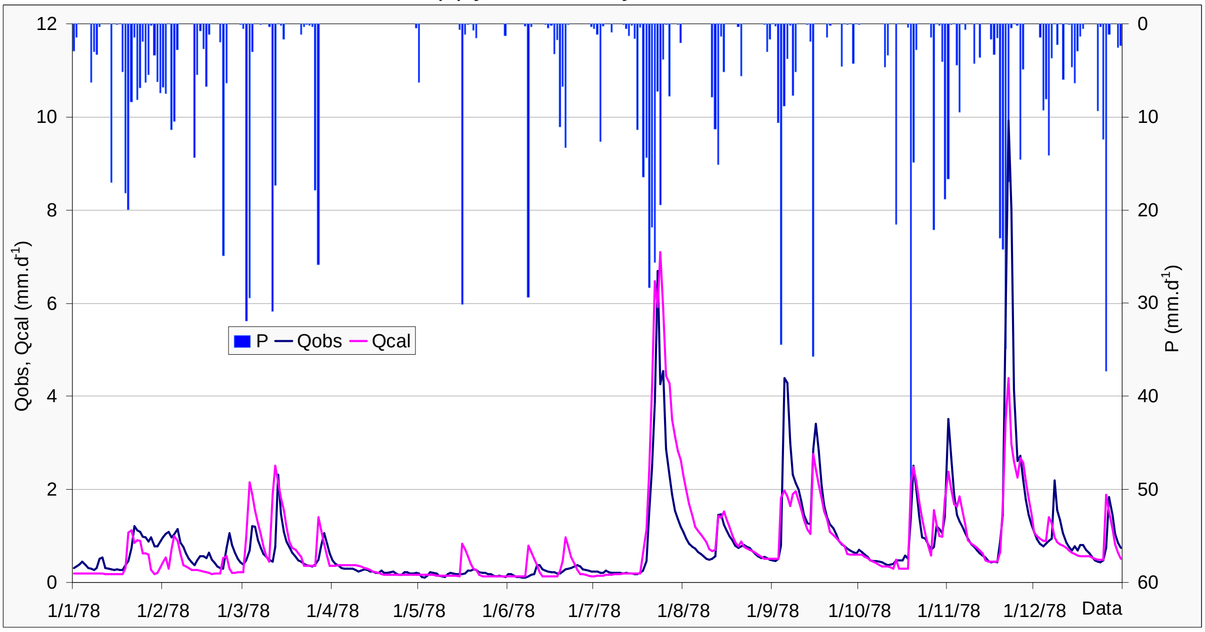
In ExcelTM, the Tank Model was programmed to generate graphical representations of the hyetograph and hydrographs simultaneously with the change of parameters. The hyetograph (secondary axis) and hydrographs (main axis) for observed and calculated discharges for Rio do Peixe watershed are illustrated for three distinct years, in accordance do Hayes Decile classification (Table 9). The years are illustrated in Fig. 7: 1987, near normal (a), 1983, much above normal (b) and 1978, much below normal (c). The years 1983 and 1978 represent the extremes during the period 1977-2004, being 1983 the year with the major water excess and the year 1978, the more significant lack of water or water deficiency.



(a) year 1987, near normal,



(b) year 1983, hydric excess



(c) year 1978, hydric deficiency

Fig. 7 Hyetograph and hydrographs for Pe_4 (Rio do Peixe): (a) year 1987, near normal, (b) year 1983, water excess, (c) year 1978, water deficiency

The model performance evaluation is presented in Table 10. The errors to be minimized (Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Logarithmic RMSE (RMSElog) reached level below 1 (one), exception for RMSE (1987), RMSE and MAE (1983).

Table 10 Tank Model performance evaluation for Rio do Peixe (Pe_4)

Year	Relative error (*RE*, %)	Volume Standard Error (ΔV, %)	Nash coefficient (NS, %)	Nash log coefficient (NS_{log}, %)	Coefficient of correlation (R, %)
1987	27.3	8.4	88.3	88.2	94.1
1983	40.4	2.4	84.5	83.6	92.3
1978	37.1	0.6	62.0	75.1	79.7

The best performance of the Tank Model simulation for the whole period (1977-2004) showed the following adjustment: R^2 = 0.847, RE = 0.385, ΔV = 0.033, NS = 0.846, Nslog = 0.849, RMSE = 1.363, MAE = 0.656, and RMSElog = 0.197. The mean discharge obtained in the simulation was 2.14 mm day^{-1}. The parameters values of the four tanks are shown in Table 11.

Table 11 Tank Model calibrated parameters for Rio do Peixe watershed.

Parameter	Unit	Tank $_1$	Tank $_2$	Tank $_3$	Tank $_4$
Runoff coefficient	d^{-1}	A_2 = 0.2800	B_1 = 0.0345	C_1 = 0.0100	D_1 = 0.0010
	d^{-1}	A_1 = 0.0579			
Infiltration coefficient	d^{-1}	A_0 = 0.0841	B_0 = 0.0553	C_0 = 0.0081	
Height of the side outlets	mm	HA_1 = 13.0	HB_1 = 15.0	HC_1 = 15.0	
	mm	HA_2 = 50.0			

TANK MOISTURE INDEX

Observation focused on the hydrograph peaks is needed for the flood studies. The information on the minimum values or base-flow is useful for the water uses planning during the dry periods. As the Tank Model shows, the discharge results from the water quantity stored in the watershed. In other words, the excess and lack in discharge quantity can be associated with the water storage (watershed moisture) condition. Hayes (1999) mentioned that a drought index value is typically a single number, far more useful than raw data for decision making. In this sense, the present study proposes a kind of moisture index derived from the Tank Model which is called Tank Moisture Index (TMI) that can be used for floods and droughts predictions. The TMI considers the daily change in storage values (*S*) of the Tank Model for runoff generation applied to the Rio do Peixe watershed. TMI aims to represent the hydrological extremes considering the maximum values of storage corresponding to floods and the minimum values to droughts.

Tank Moisture Index (TMI) development

Tank Model with vertical reservoirs represents, schematically, the soil layers from surface to the bottom. Deduced the *ETR*, the exceeded precipitation infiltrates and percolate to reservoirs 1–4.

TMI reaches its maximum when precipitation is occurring, corresponding to water saturation in the superior reservoir (Tank 1), and simultaneously the reservoirs below are filled with water to its maximum capacity (saturation).

The higher the water height, *S* (mm) stored simultaneously in reservoirs: Tank 1(S_1); Tank 2 (S_2); Tank 3 (S_3) and Tank 4 (S_4), the higher the index will become. When the reservoirs are losing water through flow or evapotranspiration, without rainfall the index becomes lower. Figure 2 illustrates the TMI concept, considering the multiples combinations of S_1, S_2, S_3 and S_4.

The maximum extreme value of TMI express the situation of maximum S_1 (storage in Tank 1) with the maximum S_4 (storage in Tank 4), combined with the maximum values in reservoir 2 (S_2) and 3 (S_3).

The central tendency indicates the flow situation normality pattern. The mean ($\overline{S_j}$) and the median values (Smd_j) were obtained for the studied period, where the digit *j* represents the reservoir number, from 1 to 4.

The storage S_1, S_2, S_3 and S_4 (mm) are correlated one to another. The mathematical expression of multiplication was chosen for the present work to relate S_1 and S_4. To moisture indication, from normality to the maximum or to the minimum level, the moisture of day *i* in Tank 1 is related to the mean (or the median) moisture stored in Tank 4 ($\overline{S_4}$ for the mean or S_{md4} for the median). For Rio do Peixe watershed, during the period 1977–2001, the maximum value corresponds to the day of maximum discharge, which occurred on 8 July 1983.

The multiplication result $S_1 \times S_4$ is the most representative in discharge generation. To express the transference between the four reservoirs different combinations are used for them. For the daily water balance reservoirs 2 and 3 are considered. The expression $S_1 \times S_4$ corresponds to 78% (mean) and 80% (median) of the total flow, important for high flow (floods). The combination between the storage levels in the others reservoir are important to represent low discharge (droughts). The equations (1) and (2) show TMI_1 (step g) by the mean and median based approach, respectively.

$$\mathrm{TMI}_1\ (\mathrm{mean}) = S_{\max 4} \cdot \overline{S_1} + S_{\max 3} \cdot \overline{S_2} + S_{\max 2} \cdot \overline{S_3} + S_{\max 1} \cdot \overline{S_4} \tag{1}$$

where TMI_1 (mean) is the Tank moisture index (step g), by mean approach; S_{max4}, S_{max3}, S_{max2}, S_{max1} are the maximum storages in reservoirs 4 to 1, respectively; $\overline{S_1}$, $\overline{S_2}$, $\overline{S_3}$ and $\overline{S_4}$ are the mean values of storage in the reservoirs 1 to 4.

$$\mathrm{TMI}_1(\mathrm{median}) = S_{\max 4} \cdot S_{\mathrm{md}1} + S_{\max 3} \cdot S_{\mathrm{md}2} + S_{\max 2} \cdot S_{\mathrm{md}3} + S_{\max 1} \cdot S_{\mathrm{md}4} \tag{2}$$

where TMI_1 (median) is the Tank Moisture Index (step g), by median approach; S_{md4}, S_{md2}, S_{md3} and S_{md4} are median values of storage in the reservoirs 1 to 4.

The results of equations (1) and (2) are expressed in mm^2. To be a friendly number, the TMI is expressed from zero to 10 and becomes dimensionless with the use of a scale factor. The scale factor initially proposed as F_1 is made equal to the TMI_1 value for the maximum event:

$$\mathrm{TMI}_1 = F_1 = (S_{\max 4} \cdot \overline{S_1} + S_{\max 3} \cdot \overline{S_2} + S_{\max 2} \cdot \overline{S_3} + S_{\max 1} \cdot \overline{S_4})\ \mathrm{mm}^2 \tag{3}$$

where F_1 is the scale factor (step h).

Dividing TMI_1 by F_1 to get TMI_2, with the value of one unit (TMI, step i):

$$\mathrm{TMI}_2 = \frac{\mathrm{TMI}_1}{F_1} = 1 \tag{4}$$

where TMI_2 is the Tank moisture index (step i).

Aiming that the result of TMI for the event of maximum is not equal to one unit but equal to ten. The value of TMI_2 is multiplied by 10, getting TMI_3 (TMI, step j). This transformation is transferred to the scale factor, by multiplying 0.1 shown below:

$$\mathrm{TMI}_3 = \frac{10 \cdot \mathrm{TMI}_1}{F_1} \text{ then } \mathrm{TMI}_3 = \frac{\mathrm{TMI}_1}{F_1 \cdot 0.1} \text{ then } \mathrm{TMI}_3 = 10 \tag{5}$$

where TMI_3 is the Tank moisture index (step j).

For the purpose of using TMI in events greater than that registered in 08th July 1983, it is used 90% of the maximum value (TMI, step xiv). Aiming to a good memorization and simplicity, 0.01 is added to the value of 0.1, resulting in 0.11. For the Rio do Peixe watershed data the maximum value of TMI is 9.09, shown in equation (6). Higher level can be expressed in case of a future catastrophic event.

$$\mathrm{TMI}_4 = \frac{\mathrm{TMI}_1}{F_1 \cdot (0.1 + 0.01)} \text{ then } \mathrm{TMI}_4 = \frac{\mathrm{TMI}_1}{0.11 \cdot F_1} \tag{6}$$

where TMI_4 is the Tank moisture index (step k).

The scale factor (F), that is automatically changed by spread sheet-application used for TMI calculation, is represented by mean and median based approach:

$$F = 0.11\ F_1 \tag{7}$$

where F is the scale factor (mm^2).

The scale factor (F), by mean and median based approach is shown in equations (8) and (9), respectively:

$$F(\mathrm{mean}) = \max(S_{1_i} \cdot \overline{S_4} + S_{2_i} \cdot \overline{S_3} + S_{3_i} \cdot \overline{S_2} + S_{4_i} \cdot \overline{S_1}) \cdot 0.11\ ,\ \left| 1 \le i \le n \right. \tag{8}$$

$$F(\mathrm{median}) = \max(S_{1_i} \cdot S\mathrm{md}_4 + S_{2_i} \cdot S\mathrm{md}_3 + S_{3_i} \cdot S\mathrm{md}_2 + S_{4_i} \cdot S\mathrm{md}_1) \cdot 0.11 \left| 1 \le i \le n \right. \tag{9}$$

where i is the number of the considered day; and n is the number of days of the historical series, such that i is greater or equal to 1 and lower or equal to n.

With the use of mean, for the analysed day, the Tank Moisture Index – $TMI(mean)_i$ is obtained:

$$\text{TMI(mean)}_i = \frac{S_{1i} \cdot \overline{S_4} + S_{2i} \cdot \overline{S_3} + S_{3i} \cdot \overline{S_2} + S_{4i} \cdot \overline{S_1}}{F(\text{mean})} \tag{10}$$

where TMI(mean)_i is the Tank Moisture Index for the central tendency "mean"; S_{1i}, S_{2i}, S_{3i}, S_{4i} is the water stored in the reservoirs, respectively, Tank 1 to 4; $\overline{S_4}$, $\overline{S_3}$, $\overline{S_2}$, $\overline{S_1}$ are the mean values of storage in the reservoirs, Tanks 4 to 1; *F* (mean) is the scale factor (mm^2) by mean approach; and *i* is the variable representing the day of the temporal series.

In the same way, considering the central tendency of median, Tank Moisture Index − TMI(median)$_i$ is obtained:

$$\text{TMI(median)}_i = \frac{S_{1i} \cdot S\text{md}_4 + S_{2i} \cdot S\text{md}_3 + S_{3i} \cdot S\text{md}_2 + S_{4i} \cdot S\text{md}_1}{F(\text{median})} \tag{11}$$

where TMI(median)$_i$ is the Tank Moisture Index by median approach; $S_{\text{md}4}$, $S_{\text{md}3}$, $S_{\text{md}2}$, $S_{\text{md}1}$ are the median values of storage in reservoirs, Tanks 4 to 1; F(median) is a scale factor (mm^2) using the median consideration.

To give flexibility for the equations appliance is considered *j* as the number of the reservoir and *m* as the number of reservoirs chosen for the Tank Model. Equation (8) for the maximized scale factor (mm^2) becomes:

$$F = \max \left[\sum_{j=1}^{m} S_{j_i} \cdot \overline{S_{(m-j+1)}} \right]_{i=0}^{i=today} \cdot 0.11 \tag{12}$$

where *F* is the maximized value of the heights product of storage in the temporal series: $\sum_{j=1}^{m} S_{j_i} \cdot S_{(m-j+1)}$ (mm^2); *i* is the tested day for maximization; *j* corresponds to the number of the considered reservoir (in the present example, m = 4); S_{j_i} is the storage in reservoir *j* in the day *i*; $S_{(m-j+1)}$ is the storage in the reservoir at the opposite position, that is $(m-j+1)$; $\overline{S_{(m-j+1)}}$ is the mean value of storage in reservoir at the opposite position.

The Tank Moisture Index (TMI), for any number of reservoirs, by mean based approach, is represented by equation (13) for each day *i* of the analysed temporal series *n*.

$$\text{TMI(mean)}_i = \frac{1}{F} \sum_{j=1}^{m} S_{j_i} \cdot \overline{S_{(m-j+1)}} \tag{13}$$

Equation (9), by median approach for any number of reservoirs, is transformed into equation (14):

$$F = \max \left[\sum_{i=1}^{m} S_{j_i} \cdot S_{\text{md}(m-j+1)} \right]_{i=0}^{i=today} \cdot 0.11 \tag{14}$$

where $S_{\text{md}(m-j+1)}$ is the median value of storage in the reservoir at the opposite position, that is, $(m-j+1)$.

Finally, the Tank Moisture Index (TMI), for any number of reservoirs, by median approach, is represented by equation (15) for each day *i* of the analysed temporal series *n*.

$$\text{TMI(median)}_i = \frac{1}{F} \sum_{j=1}^{m} S_{j_i} \cdot S_{\text{md}(m-j+1)} \tag{15}$$

Tank Moisture Index (TMI) validation procedures

TMI on-site application TMI was applied to the four incremental basins of Rio do Peixe watershed (Lindner, 2007). In the present work the results are presented for the watershed (Pe$_4$). Using the entire series of daily data, the mean (average), median, maximum and minimum values of the water storage were calculated (Table 12).

Table 12 Mean, median, maximum and minimum values of water storage (S_1, S_2, S_3, S_4) in the Tanks 1, 2, 3, and 4 in mm.

Value/Tank	S_1 (mm)	S_2 (mm)	S_3 (mm)	S_4 (mm)
Mean, $\overline{S_i}$	16.64	16.24	51.14	329.77
Median, Smd_i	12.80	15.77	50.11	322.86
Maximum, S_{max} (8 July 1983)	122.88	54.51	122.70	407.06
Minimum, S_{min} (11 February 1979)	0.00	0.00	0.00	106.25

Exemplifying for the highest flow (day *i* = 8 July 1983), TMI is equal to 9.09, both, by mean and median based approach. Table 9 data are used in equation (11) corresponding to the median approach resulting in equation (16):

$$\mathrm{TMI} = \frac{122.88 \cdot 322.86 + 54.71 \cdot 50.11 + 122.70 \cdot 15.77 + 407.06 \cdot 12.80}{49549.88 \cdot 0.11} \text{ therefore TMI = 9.09} \quad (16)$$

In the same way, exemplifying for low flow (day *i* = 11 February 1979), TMI becomes 0.31 by the use of mean approach (equation 10). Table 2 data are used in equation (11) corresponding to the median approach resulting in equation (17):

$$\mathrm{TMI} = \frac{0 \cdot 322.86 + 0 \cdot 50.11 + 0 \cdot 15.77 + 106.25 \cdot 12.80}{49549.88 \cdot 0.11} \text{ Therefore, TMI = 0.25} \quad (17)$$

TMI classification

Through the data observation as river level (cm), observed discharge (mm day^{-1}), natural disaster decrees of floods and droughts (no.) the TMI is classified in five classes. Table 13 presents the TMI classification, intervals, and on-site application on the Rio do Peixe watershed regarding the observed river water level, h (cm) and discharge (mm day^{-1}), period from 1977 to 2004.

Table 13 Tank Moisture Index (TMI) classification, TMI intervals, and on-site application on Rio do Peixe watershed regarding to observed river water level and discharge.

TMI classification	TMI interval	Water level, *h* (cm)	Discharge, *Q* (mm day^{-1})
Very wet	TMI > 6	$h > 700$	$Q > 20$
Wet	4 < TMI ≤ 6	$300 < h \leq 700$	$4 < Q \leq 20$
Normal	2 < TMI ≤ 4	$100 < h \leq 300$	$1 < Q \leq 4$
Dry	1 < TMI ≤ 2	$40 < h \leq 100$	$0.4 < Q \leq 1$
Very dry	TMI ≤ 1	$h \leq 40$	$Q \leq 0.4$

TMI on-site validation

The TMI values were checked, day by day, with extremes events registered through the natural disasters decrees published in the Rio do Peixe Watershed (1977–2004). Table 14 exemplifies TMI intervals, and on-site application regarding to decrees number of public calamity state and emergency situation due floods and droughts, for both cases, median-based and mean-based approaches.

Table 14 Tank Moisture Index (TMI) intervals and on-site application on Rio do Peixe watershed regarding to decrees number of public calamity state and emergency situation due floods and droughts.

TMI interval	No. decrees (flood)		No. decrees (drought)	
	Median	Mean	Median	Mean
TMI > 6	72	71	0	0
4 < TMI ≤ 6	63	66	1	2
2 < TMI ≤ 4	22	23	12	21
1 < TMI ≤ 2	4	1	41	54
TMI ≤ 1	0	0	75	52

The adjustment for floods (very wet and wet) of the TMI reached 84% and 85% of adjustment for floods and 90% and 82% for drought (dry and very dry), considering the median and mean approaches, respectively. The mean and median efficiency values are similar for floods, while for droughts the adjustment obtained by median based approach was more favorable. On the whole, the median based approach, compared with the mean based approach, gave better adjustment and was adopted for natural disasters analysis.

The variations of TMI obtained with the use of *Smd* (Equation (15)), the observed and calculated discharges are presented for flood (Fig. 8) and drought (Fig. 9) events.

In July, 1983, at the beginning of the month TMI was near 3 (normal), illustrated in Fig. 8 (a). TMI increased to 5.1 (wet, day 6); 7.9 (very wet, day 7) and 9.1 in day 8, with the discharges of 67.6 mm day^{-1} (observed) and 51.9 mm day^{-1} (calculated). From 6 to 8 July 1983, 11 municipalities declared “Public Calamity State” (PC) and six municipalities, “Emergency Situation” (ES).

In May 1992, an episode of gradual flood reached its peak at day 29, TMI increase going above 6, with the discharges of 43.9 mm day^{-1} (observed) and 43.2 mm day^{-1} (calculated) and TMI increasing, as clarified in Fig. 8 (b). In May 1992 two PC decrees and seven ES were recognized.

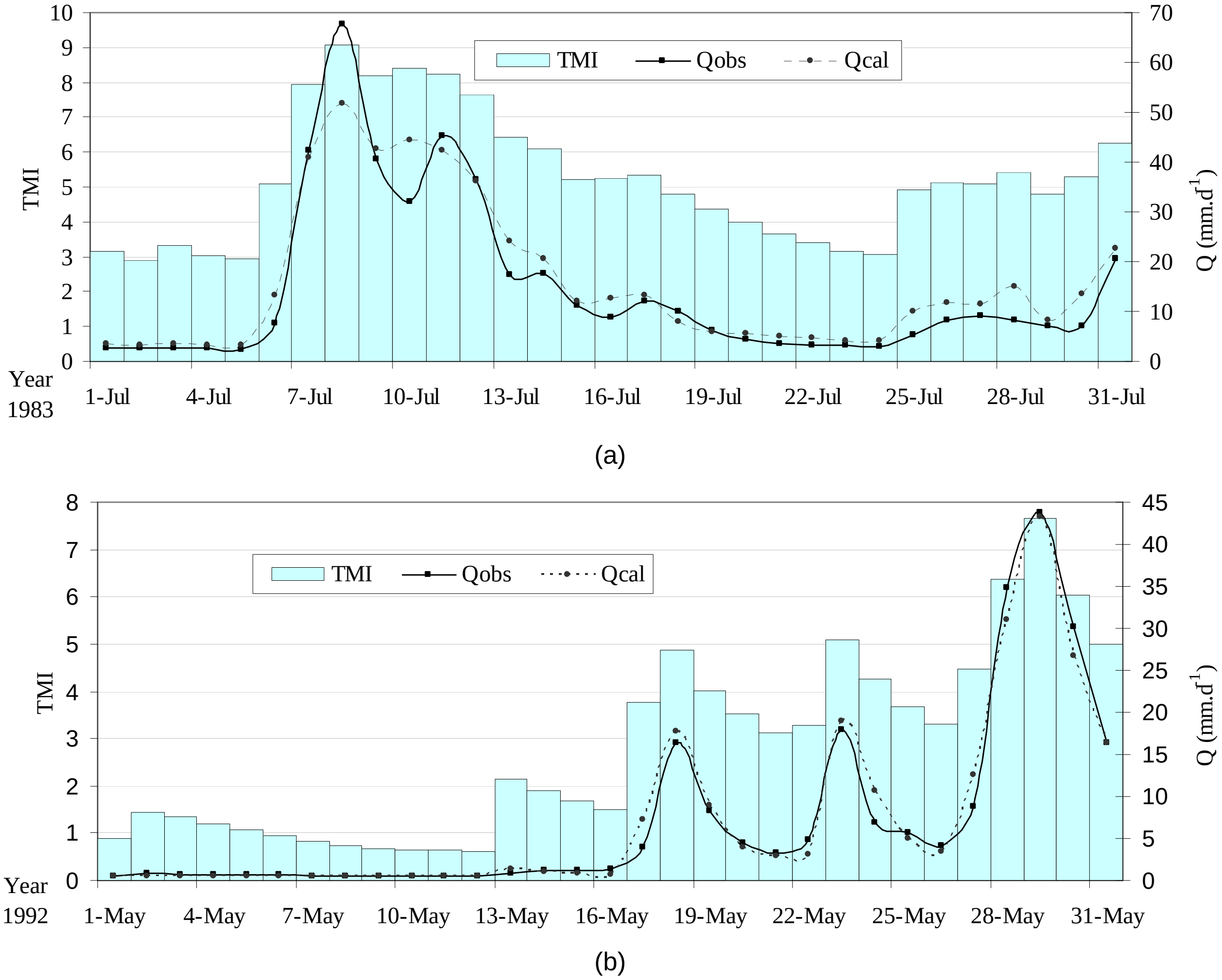


Fig. 8 Variations of TMI, observed (*Qobs*) and calculated (*Qcal*) discharge in Rio do Peixe watershed during flood events: (a) July 1983 (b) May 1992.

Drought events are shown in Fig. 9, when TMI decreased going below 1 during the drought of January–February 1979.

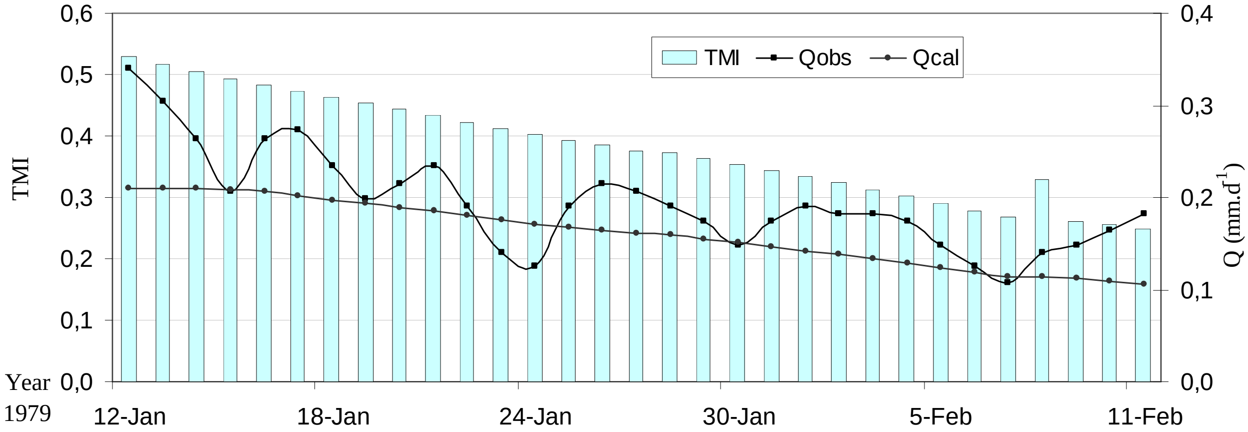
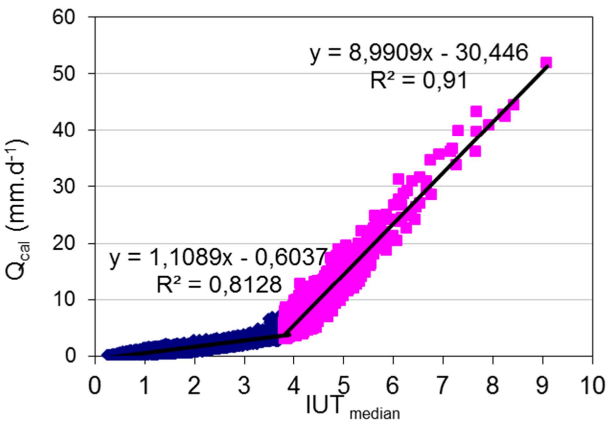


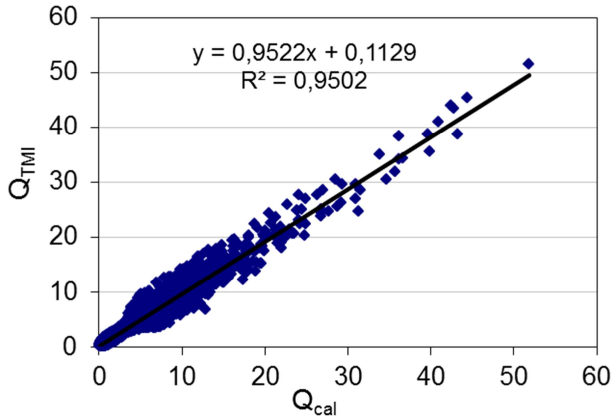
Fig. 9 Variations of TMI, observed (*Qobs*) and calculated (*Qcal*) discharge in Rio do Peixe watershed, drought event of January–February 1979.

TMI and Tank discharge relationship

In general, water level is very stable during the normality and drought periods, while it varies quickly during the flood events. Two broken linear regressions can represent the relationship between daily calculated discharge and the daily TMI_{md} shown in Fig. 10(a).



(a) TMI_{md} and Q_{cal}



(b) Q_{cal} and Q_{TMI}

Fig. 10 (a) Segmented linear regression of TMI_{md} and calculated discharge (Q_{cal}); (b) linear regression of calculated discharge and discharged regenerated by TMI for Rio do Peixe watershed.

The first and the second segments are strongly characterized with the low and high discharges, respectively. A threshold point between two segments is determined to be around TMI_{md} = 3.8. The situation near the threshold point, which contains a lot of scattered points, is considered as the normality. This scattered zone is at the range of 2 to 4. It is noted that in the case of the use of the TMI_{mean}, the adjustment was lower and that the threshold point was also TMI_{mean} = 3.8.
By application of the first and second segmented linear equations in Fig. 10(b), the discharge (Q_{TMI}) can be regenerated. The linear regression analysis between Q_{cal} and Q_{TMI} shows a very good fitting (R^2 = 0.9338 and 0.9502 with TMI_{mean} and TMI_{md}, respectively).

CONCLUSIONS

The Tank Model was applied to the Peixe River watershed, southern Brazil, and had a good adjustment. The present study proposed the moisture index derived by Tank Model water storage parameters, and called it Tank Moisture Index (TMI). This index presents daily values with the range 0 to 10. The TMI was validated for both extremes meteorological events (droughts and floods) in the Rio do Peixe watershed for the period of January 1977 to December 2004.
It is concluded that the TMI can be a good tool for making decision on watershed and natural disasters management. The TMI application can be recommended to other watersheds.

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