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

STUDY AREA:
Peixe River watershed (5238 km²), tributary of Uruguay River, southern Brazil (ANA, 2006) (Fig. 1), has suffered from natural disasters caused by excess and shortage of rainfall. Characteristic: main river extension 307 km; watershed altitude 1350 m (max.), 387 m (min.), 900 m (median). Soil: basalt rocks; Nitosoil (51.5%); Cambisoil (22.3%) and Neosoil (22.4%) (Lindner *et al*., 2007).

Hydrological data (1977 – 2004)
Discharge (*Q*) from one gauging station; rainfall (*P*) from 19 rainfall stations (Thiessen mean rainfall); parameters temperature, insulation, relative humidity and wind speed from 4 meteorological stations. Daily potential evapotranspiration (*ETP*) using the Penman modified method (Doorenbos & Pruit, 1977). Real annual evapotranspiration (*ETR*) obtained by simplified water balance ($ETR = P - Q$). The daily *ETR* values were calculated as $ETP \times kc$. The coefficient (*kc*) between *ETR* and *ETP*, was 0.93 (1977–2004). The mean values of *P*, *ETP* and *ETR* for the Peixe River watershed are 4.95 mm day^{-1}, 2.95 mm day^{-1} and 2.73 mm day^{-1}, respectively (Lindner, 2007).

Natural disasters data
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). During the period 1977–2004, 330 decrees were established by 25 city halls in Peixe River watershed. Lindner *et al*. (2007) classified them in three categories: excess discharge (161 decrees); drought (129); hail and strong winds (40). The last category would not be considered in the present study. It is 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).

TANK MODEL APPLICATION
The Tank Model (Sugawara, 1995) with four vertical tanks was applied for the Peixe River Watershed (Fig. 2). Annually calibration (1977–1990) and model validation (1991 – 2004) with hydrographs checking. For the model performance evaluation were applied: coefficient of correlation, coefficient of determination (R²), 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 initial storage heights used: 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). The best performance of the Tank Model simulation for the whole period 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, RMSElog = 0.197. The mean discharge obtained in the simulation was 2.14 mm day^{-1}. The parameters values are shown in Table 1.

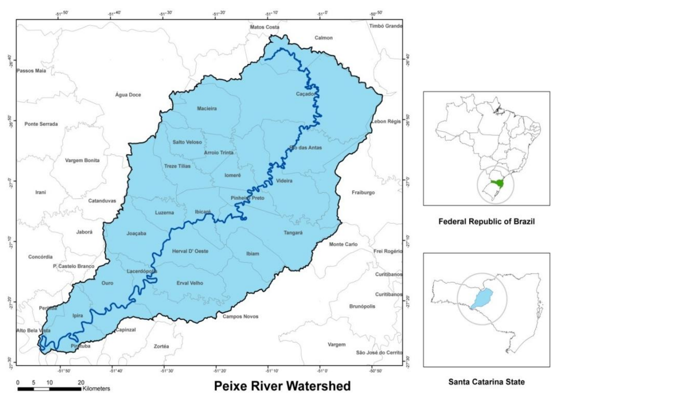

Fig. 1 Location of Peixe River watershed, Santa Catarina State, Brazil

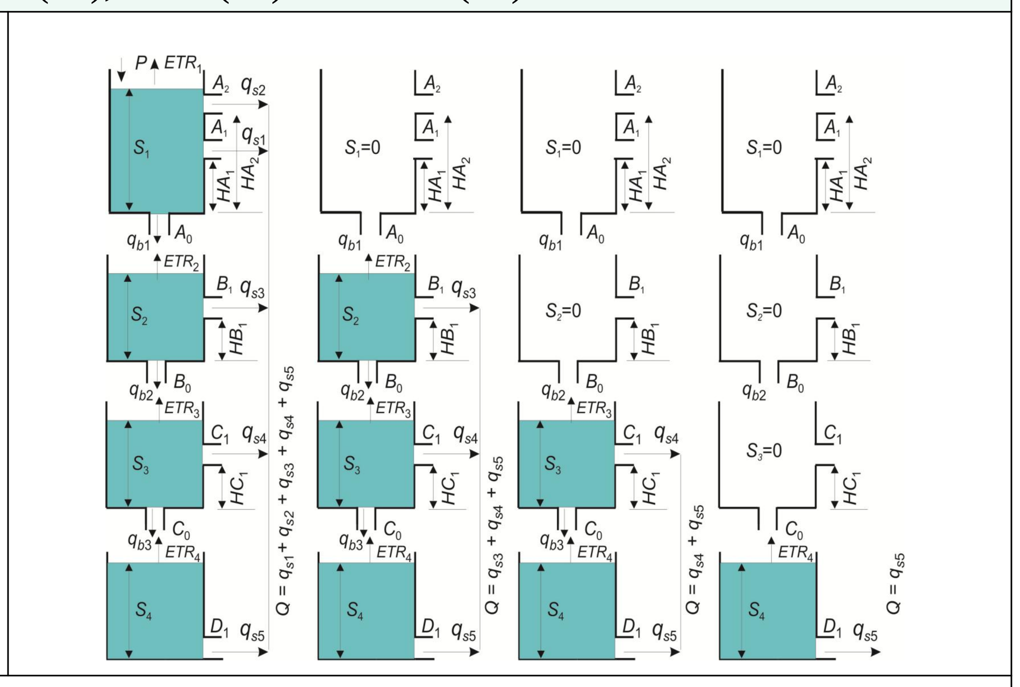

Fig. 2 Change of the storage level in reservoirs 1 to 4 due the precipitation and evapotranspiration, with flow generation: (a) storage in S_1 to S_4; b) storage in S_2 to S_4; (c) storage in S_3 and S_4; (d)storage in

Table 1 Tank Model calibrated parameters for Peixe River watershed

Parameter	Unit	Tank 1		Tank 2	Tank 3	Tank 4
Runoff coefficient	d^{-1}	$A_2 = 0.2800$	$A_1 = 0.0579$	$B_1 = 0.0345$	$C_1 = 0.0100$	$D_1 = 0.0010$
Infiltration coefficient	d^{-1}	$A_0 = 0.0841$		$B_0 = 0.0553$	$C_0 = 0.0081$	
Height of the side outlets	mm	$HA_1 = 13.0$	$HA_2 = 50.0$	$HB_1 = 15.0$	$HC_1 = 15.0$	

TANK MOISTURE INDEX

The Tank Moisture Index (TMI) considers the daily change in storage values (*S*) of the Tank Model for runoff generation applied to Peixe River watershed. TMI can represent the hydrological extremes, with the storage values: maximum → floods; minimum → droughts.
• Higher water height, *S* (mm) in reservoirs: Tank 1(S_1); Tank 2 (S_2); Tank 3 (S_3) and Tank 4 (S_4) → higher TMI;
• Maximum extreme value of TMI → 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).
• To moisture indication, from normality to the maximum or to the minimum level, the moisture of day *i* in Tank 1 is related, by multiplication, to the mean (or the median) moisture stored in Tank 4.
• The expression $S_1 \times S_4$ corresponds to 78% (mean); 80% (median) of the total flow → high flow (floods)
• Combination between the storage levels in the others reservoir → low flow (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). TMI equations are presented for mean (1), (2) and media approach (3), (4).

Maximized scale factor (mm²), considering *j* as the number of the reservoir and *m* as the number of reservoirs chosen for the Tank Model

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

where *F* (mm²) is the maximized value of the heights product of storage in the temporal series:

$$\sum_{j=1}^{m} S_{j_i} \cdot S_{(m-j+1)}$$

i is the tested day for maximization; *j* corresponds to the number of the considered reservoir (in the present example, m = 4); is the storage in reservoir *j* in the day *i*; $S_{(m-j+1)}$ is the storage in the reservoir at the opposite position (*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 (Eq. 2) for each day *i* of the analyzed temporal series *n*.

$$TMI(mean)_i = \frac{1}{F} \sum_{j=1}^{m} S_{j_i} \cdot \overline{S_{(m-j+1)}} \quad (2)$$

Median approach for any number of reservoirs:
Were: $S_{md\,(m-j+1)}$ is the median value of storage in the reservoir at the opposite position (*m*-*j*+1);

$$F = \max \left[\sum_{i=1}^{m} S_{j_i} \cdot S_{md(m-j+1)} \right]_{i=0}^{i=today} \cdot 0.11 \quad (3)$$

The Tank Moisture Index (TMI), for any number of reservoirs, by median approach (Eq. 4) for each day *i* of the analyzed temporal series *n*.

$$TMI(median)_i = \frac{1}{F} \sum_{j=1}^{m} S_{j_i} \cdot S_{md(m-j+1)} \quad (4)$$

Tank Moisture Index (TMI) validation procedures: TMI on-site application

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

Value/Tank	S_1 (mm)	S_2 (mm)	S_3 (mm)	S_4 (mm)
Mean,	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

Replacing the data of Table 2, for the highest flow (day *i* = 8 July 1983), TMI is equal to 9.09, both, by mean and median based approach; low flow (day *i* = 11 February 1979), TMI becomes 0.31 (mean, Eq. 2) and 0.25 (median, Eq. 3).

TMI classification Through the data observation (1977 to 2004) as river level (cm), observed discharge (mm day^{-1}), natural disaster decrees of floods and droughts (nr.) the TMI is classified in five classes (Table 3).

Table 3 Tank Moisture Index (TMI) classification, TMI intervals, and on-site application on Peixe River 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	$4 < TMI \leq 6$	$300 < h \leq 700$	$4 < Q \leq 20$
Normal	$2 < TMI \leq 4$	$100 < h \leq 300$	$1 < Q \leq 4$
Dry	$1 < TMI \leq 2$	$40 < h \leq 100$	$0.4 < Q \leq 1$
Very dry	$TMI \leq 1$	$h \leq 40$	$Q \leq 0.4$

TMI on-site validation

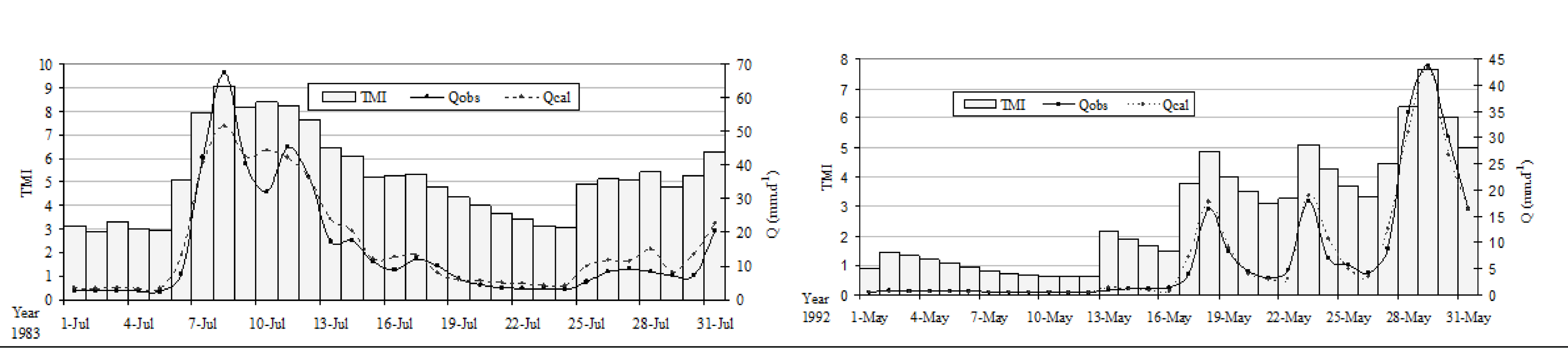

Fig. 3 Variations of TMI, observed (*Qobs*) and calculated (*Qcal*) discharge in Peixe River watershed during flood events: (a) July 1983 (b) May 1992.
In July, 1983 (a) TMI was near 3 (normal). TMI increased to 5.1 (wet, day 6); 7.9 (very wet, day 7) and 9.1 in day 8; discharges of 67.6 mm day^{-1} (*Qobs*) and 51.9 mm day^{-1} (*Qcal*). From 6 to 8 July 1983, 11 municipalities declared “CP” and six, “ES”. In May 1992 (b) an episode of gradual flood reached its peak at day 29, TMI increase going above 6, discharges of 43.9 mm day^{-1} (*Qobs*) and 43.2 mm day^{-1} (*Qcal*) and TMI increasing.

Drought events are shown in Fig. 4, when TMI decreased going below 1 during the drought of January–February 1979.

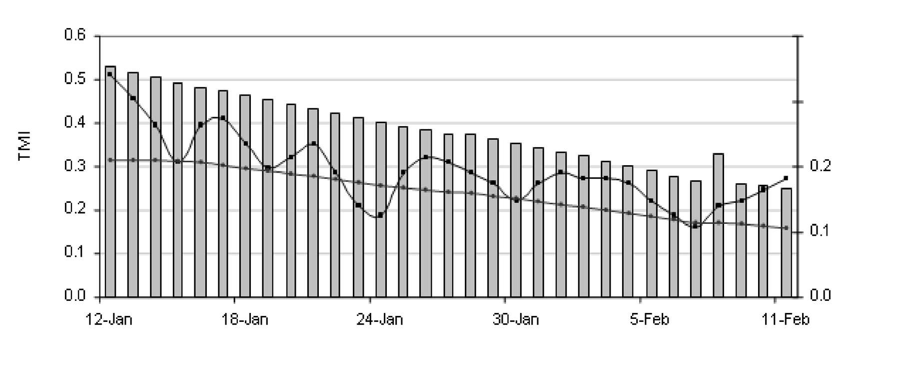

Fig. 4 Variations of TMI, observed (*Qobs*) and calculated (*Qcal*) discharge in Peixe River watershed, drought event of January–February 1979.

CONCLUSION
The Tank Model with 4 vertical tanks and 12 parameters was validated for the whole period (Nash, 85% and Nash log, 85%) for Peixe River watershed, southern Brazil. 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 Peixe River watershed for the period of 1977–2004. With the median and mean approaches the TMI adjustment reached 84% and 85% for floods (very wet and wet) and 90% and 82% for drought (dry and very dry). 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. TMI_{md} and Tank discharge had 97% of correlation by the segmented regression. It is concluded that the TMI can be a good tool for making decision on watershed management and for natural hazards prevention.

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