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The effectiveness of the CN method in areas with saturated soil conditions

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Abstract: The Soil Conservation Service (SCS) Curve Number (CN) method has been widely used by engineers in hydrological modelling. The main advantage of this method is that only a few parameters are needed to calculate the CN. The purpose of this study was to analyse the effectiveness of the regionalized CN method for the analysis of flood vulnerability in saturated soils, commonly located in coastal floodplains.

The study area is located in the Juqueriquere River Basin, on the northern coastline of Sao Paulo, Brazil. It holds the major non-urbanised plains of the northern coastline of the state. It is constrained by the high altitude mountains of Serra do Mar, which causes intense orographic rain in the area. Added to the basin's geophysical features, the influence of tide contributes to the local high vulnerability to floods. Even though the area is not representatively gauged, and scarce runoff data is available, there is high interest to urbanise the plains, due to the recent implantation of the Gas Treatment Unit of Caraguatatuba (UTGCA) of the Brazilian Petroleum Corporation (PETROBRAS) in 2012, and the proximity to the Port of Sao Sebastiao. The City Master Plan of Caraguatatuba Municipality (CMPC) was proposed in 2011. Both the gas pipelines of UTGCA and the part of the Tamoios Highway Complex have been implemented, based on the Environmental Impact Assessment of PETROBRAS (2007), but no macro or micro drainage plans have been developed for this urbanizing area yet. The Foundation of Water Resources of Sao Paulo (Costa Norte 2017) has just approved the macro drainage plan for the downstream area, which is densely urbanised and constantly affected by floods.

In the study, the runoff in each sub-basin was derived from the CN method at the Hydrologic Modeling System (HEC-HMS). The Manning's roughness coefficients of different cross-sections were calibrated at the Hydrologic Engineering Center's River Analysis System (HEC-RAS), where the CN method was also adopted.

The rain gauge of PETROBRAS (EMQAR1), near UTGCA plant, recorded 247.20 mm in a 24h period between 17 and 18 March 2013. This event caused severe floods in the basin, especially in the upstream area. Thus, this rainfall event was used for calibration purposes, taking into consideration the water level of three different cross-sections registered by local farmers.

The CN values of the present scenario were attributed by the land use and land cover (LULC) classification of high-resolution imagery, and were regionalised per sub-basin using the LULC area weighted average approach. The future scenario was based on the collection of similar perviousness-patterned zones of the proposed CMPC. Both scenarios were simulated with the same SCS unit hydrograph, regarding the same calibration event.

The findings of the study revealed that, even though the peak discharge of the future scenario had higher values than the present scenario, they did not represent the significant increase of imperviousness of some of the CMPC zones. It occurred due to: the CN regionalization approach, potential CN losses and underestimation of the rainfall intensity, as the initial abstraction is not related to the soil infiltration.

Keywords: *CN method, soil infiltration, CN regionalisation, CN loss, flood vulnerability evaluation*

1. INTRODUCTION

The synergy between the water resources management and the urban planning provides for the sustainable development of an area (Ioris et al. 2008, Wang et al. 2008), where hydrological models are used to simulate and predict different LULC scenarios (Krysanova et al. 2005, Wang et al. 2008). These models are commonly associated with remote sensing techniques and Geographic Information Systems (GIS) because of their reliable data-processing quality, timesaving and cost-benefit advantages (Masron et al. 2015, Ramachandra et al. 2013).

Due to the variability of hydrological processes and limited data available, many conceptual models combine the properties of black box, empirical and physically-based reductionist models (Kuczera and Parent 1998, Wu et al. 2017). In physically-based reductionist models, the catchment scale is adapted to the hydrological phenomena in a laboratory scale (Grayson et al. 1992). Black box models though, only refer to external information, e.g. it is possible to quantify the catchment response to rainfall events but not to evaluate the hydrological phenomena (Kendall et al. 2001, Kuczera and Parent 1998).

In conceptual models, the scaling problems found in physically-based reductionist models are compensated by valuing dominant hydrological processes (Kuczera and Parent 1998), and assigning boundary conditions or control volumes over state variables and fluxes (Nash and Sutcliffe 1970). However, these attributes might be the result of conceptual assumptions instead of physically-based parameters, and because of that, they need to be calibrated using observed reference values that represent the catchment response to what is being predicted (Kuczera and Parent 1998, Wu et al. 2017). Additionally, the calibration process enhances the model performance, especially where there is limited data available (Cullmann et al. 2011).

It is very challenging for hydrologists to run models and make predictions in ungauged basins (Kim and Kaluarachchi 2008). Modelers have widely employed the CN method (Jeon et al. 2014) as it requires few parameters, which are normally available or easily achieved with remote sensing techniques (Boulomytis et al. 2016).

In the CN method, the estimation of surface runoff is based on the association of Hydrologic Soil Groups (HSG) with LULC classes, which define the potential maximum retention (S) after the runoff begins. Even though S is related to the soil-and-cover physical properties, it should be noticed that it is a model variable and not a physical parameter (Van Mullem et al. 2017).

In hydrological models, the CN values are regionalised per sub-basin using different approaches, among which is the LULC area weighted average. The rainfall intensity might be underestimated for small basins because the initial abstraction (Ia) of an event is not related to the soil infiltration conditions (Jeon et al. 2014).

In some applications, the CN method is erroneously referred to as an infiltration model (Van Mullem et al. 2017). However, many studies revealed that the CN losses do not often decline after a rainfall, and might even increase when the rain intensity increases (Hawkins 1993), which is a typical behaviour of a partial saturation model (Van Mullem et al. 2017). Hence, the SCS-CN method does not consider infiltration excess runoff (Jeon et al. 2014), such as the Horton or Green-Ampt, and the final steady-state infiltration rate is zero, not varying within time (Van Mullem et al. 2017).

Both the Natural Resources Conservation Service (NRCS) and the Agricultural Research Service (ARS), form the U.S. Department of Agriculture formed a group to review the CN method in 1990 (Van Mullem et al. 2017). Some of their significant updates regraded:

- The Antecedent Moisture Condition (AMC) terminology changed to Antecedent Runoff Condition (ARC), because the variation of the CN is not entirely due to prior rainfall. Thus, the CN was inferred as a random variable to the event runoff, and the ARC I and ARC III were its bound conditions.
- An automated system (fuzzy system model) was used to assign soils to HSC.
- Restatement of the spatial variability of the CN and the need of local calibration.
- Reiteration that S excludes Ia, based on the fact that the effects of rainfall interception, depression storage and infiltration are clustered into the Ia, and then subtracted from the total rainfall.

According to Van Mullem et al. (2017), there is no consensus with regard to how the infiltration rate interferes in the CN loss. The CN method integrates all the losses and provides responses in similar patterns of black box models, as it is not possible to assess the hydrological processes that caused the respective losses. The saturated hydraulic conductivity (Ks) would improve the results from the CN method applications in regions where the soil wetness is exceeded by the rainfall rates (Boulomytis et al. 2016, Sartori et al. 2009). This is characteristic of tropical countries, where infiltrometric measurements of hydraulic conductivities are mostly unavailable for calibration purposes. Sartori et al. (2009) proposed a method to achieve the HSG analysing the mineralogical properties of the Brazilian soils, and the relationship between the texture and the underground level. It makes the CN method more appropriate for the Brazilian soils, but still presents some inaccuracy when the soil is easily saturated. This paper presents the use of the CN method for the estimation of runoff in the downstream area of Juqueriquere river basin, northern coastline of the State of Sao Paulo, Brazil.

2. MATERIAL AND METHODS

2.1. Study area

The study area corresponds to the upstream sector of the Juqueriquere River Basin in the municipality of Caraguatatuba, Sao Paulo, Brazil. It comprises the area of 358.87 km², and is divided into 11 sub-basins (Boulomytis et al. 2017a) (Figure 1).

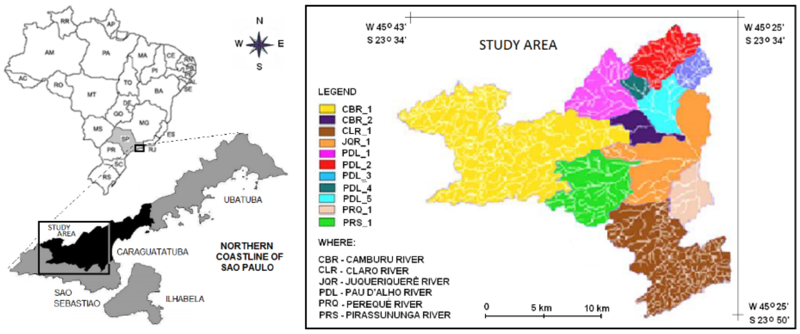


Figure 1. Study area, Caraguatatuba, SP, Brazil (Source: Adapted from Boulomytis et al. 2017a).

The weather is tropical and rainy, with intense rainfalls in the summer, but has no clearly defined dry season. The average annual temperature is 25° C and the average annual precipitation is 1652.8 (1977 - 2015). Among the 34 sub-basins of the northern coastline of the State of Sao Paulo, it is the only one with the seventh Strahler order (Souza, 2005). The catchment is highly susceptible to floods, especially due to the effects of orographic rain, tide variation, and geological features (Souza, 2005).

2.2. Proposed Methodology

2.2.1 CN attribution

The derivation of the CN parameter was based on the HSG and the LULC of the present and future scenarios). The HSG's were found by the method proposed by Sartori et al. (2009), which is based on the main hydraulic properties of the weathered soils of Brazil, such as the soil texture, the presence of iron oxide, the water table level and the restrictive layers.

The future scenario was based on the CMPC (Caraguatatuba 2011), where groups of zones were brought together according to the similarity on their CN value. The CN was first attributed to the ARC II, and then converted to ARC III (Boutomytis et al. 2016).

2.2.2 Model Parameterization

Several input data were necessary for the model implementation in the Juqueriquere river basin, which are summarised in Table 1.

The lag time is the time elapsed between the centroids of the effective rainfall hyetograph and the direct runoff hydrograph. It is short or long, depending on the time it takes for the precipitation to flow into the river. It is calculated by:

$$t_{LAG} = 0.6t_c \tag{1}$$

Where, t_{LAG} is the lag time (min) and t_c is the respective time of concentration (min).

The time of concentration is the time needed for the runoff to flow from the most remote point in the watershed to stream outlet. According to Silveira (2005), we selected three different equations for the study:

the US Corps of Engineers for the mountainous (rural) areas, Kirpich for the plains in areas with less than 26 km², and Desbordes for the plains in areas between 26 km² and 51 km². They were calculated by:

$$t_{cc} = 0.1910L^{0.76}S^{-0.19} \tag{2}$$

$$t_{ck} = 0.0663L^{0.77}S^{-0.385} \tag{3}$$

$$t_{cD} = 0.0869A^{0.3039}S^{-0.3832}A_{imp}{}^{-0.4523} \tag{4}$$

Where t_{cc} , t_{ck} , and t_{cD} are the time of concentration according to the US Corps of Engineers (h), Kirpich (h) and Desbordes (h), respectively, L is the length of the main watercourse (km), S is the slope (m/m), A is the area of the catchment (km²), and A_{imp} is the fraction of impervious areas, which was adopted as 100%, as the water table is shallow and easily saturates.

The US Corps of Engineers' equation commonly overestimates the results for larger areas (McCuen et al. 1984, Silveira 2005), which is a desirable factor for regions with high slopes covered by vegetation, making the infiltration rate higher and the time of concentration lower. The Kirpich equation is more consistent to urban basins where the surface runoff is higher, due to the higher imperviousness of the land and lower infiltration rate (Kibler 1982, McCuen et al.1984), but is limited to 26 km² (Silveira, 2005). The equation of Desbordes showed a better result for larger urban areas, limited to 51 km². The combination of the three approaches provides more reliable results, especially in areas with heterogeneous LULC features.

Table 1. Input data for the model calibration and runoff estimation.

INPUT DATA	METHODOLOGICAL BASIS	TECHNIQUES EMPLOYED
Area	Sub-basin maps	GIS (Boulomytis et al. 2017a)
CN	Regionalised with a LULC area weighted average	GIS (Boulomytis et al. 2016)
Lag time	Time of concentration	GIS
Reference discharge	Minimum discharge (dry season) Observational data of fluviometric campaigns	Empirical approach (Boulomytis et al. 2017b)
Spatial rainfall data	Kriging method for the data interpolation (vector vs. raster)	GIS and spatial analysis
Cross-sections	Elevation profile of cross-sections	Survey data and GIS (Boulomytis et al. 2017b)
Manning's roughness coefficient	Estimation and trial-and-error calibration	Empirical approach (Boulomytis et al. 2017b)
Slope	Equivalent length, according to the terrain slope.	GIS
River segment length	Between the control cross-sections	GIS

In the basin, there is a high variability of rainfall, due to the orographic effect. Between 3am of the 17th of March and 3am of the 18th of March 2013, the rain gauges of PETROBRAS (EMQAR1 and EMQAR2), which are 8 km apart from each other, registered different rainfalls (247.20 mm and 134 mm, respectively). This event caused severe floods in the basin, more intensively in the upstream rural and semi-urban areas (near EMQAR1) and in the downstream urbanised area (near EMQAR2). In order to achieve a proper spatial distribution of the rainfall, a kriging method was applied to interpolate the data from two local rain gauges (EMQAR1 and EMQAR2), a data-collecting platform (PCD 32521) and the Tropical Rainfall Measuring Mission (TRMM).

3. RESULTS AND DISCUSSION

The HSG attribution was based on the proposal of Sartori et al. (2009), and the physical and mineralogical properties of the Brazilian Soil Survey Manual (Brazilian Agricultural Research Corporation - EMBRAPA 2006) (EMBRAPA 2006) and the water table levels from the geotechnical survey sampling data of PETROBRAS (2007) and Waterloo Brazil Environmental Consulting (WBEC) (2009). This procedure was helpful in providing local features concerning the soil type, and minimizing common modelling errors due to the CN spatial variability, reported by Van Mullem et al. (2017). For the Ferralsol and Cambisol soils, the attributed HGS was type B, and for the Podzol soils, type D.

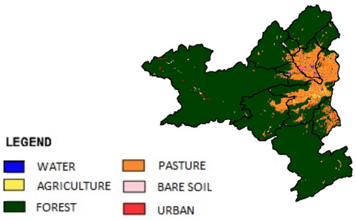
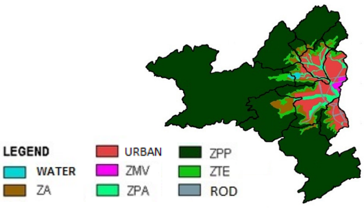
For the future scenario, the LULC classification was done according to the similar perviousness-pattern of the CMPC's zones:

- Buffer zone (ZA), located between the slopes and the plains (wetlands), with the predominant presence of straight row crops;

- Urban zone, which is the assembly of the City Master Plan Zones of Logistic and Industrial Zone (ZLI), Urban Support Zone (ZSU), Industrial Strategy for the Proper Use of Petrol and Gas (ZIEPG), Mix Vertical Zone (ZMV-9) and Urban Expansion Zone (ZEU);
- Mix vertical zone (ZMV) for the occupation of one to multi-floor housing, business centres, institutional areas, with the average impervious condition of 70%;
- Environmental protection zone (ZPA), comprising the protection areas along the watercourses, which should be protected by woods and the soil covered by litter and brush;
- Permanent Protection Zone (ZPP), located in the Serra do Mar Mountains, which is protected by the State, and according to the CMPC, no changes will affect these forests after the urban expansion of the area.
- Touristic Ecological Zone (ZTE), comprehending the residential zone (RU3) and flat condominium (RMH2), with parcels of 5,000 m² and 20% of impervious areas;
- Driveways (ROD) considering the predicted infrastructure of the CMPC.

The LULC classes for the present and future scenarios (Boulomytis et al. 2016) and the corresponding CN value attributed per class and HGS type are given in Table 2.

Table 2. CN for the LULC classes of the present and future scenarios.

LULC Classes		**CN**		
		HSG B	**HSG D**	
Present scenario	water	98	98	
	agriculture	78	89	
	forest	55	77	
	pasture	69	84	
	bare soil	82	89	
	urban	86	94	
Future scenario	water	98	98	
	ZA	81	91	
	urban	87	93	
	ZMV	78	88	
	ZPA	73	86	
	ZPP	55	77	
	ZTE	68	84	
	ROD	98	98	

The Manning's roughness coefficients of the left bank (LB), bed (B) and right bank (RB) were achieved and calibrated by the use of the stages of the three main water courses of the study area, which corresponded to: Areeiro (LB=0.085, B=0.110, RB=0.025); Camburu (LB=0.060, B=0.015, RB=0.060), and Claro (LB=0.050, B=0.056, RB=0.070) (Boulomytis et al 2017b).The remaining data was calculated, and both scenarios were simulated at HEC-HMS, as presented in Table 3.

Table 3. Input data derived for the hydrological model simulation.

Sub-basins	Area	L	S	Adopted equation	tc (min)	t_{LAG} (min)	Present		Future	
	(km²)	(km)	(m/m)				CN_{ARCIII}	Q (m^3/s)	CN_{ARCIII}	Q (m^3/s)
CBR1	120.69	28.08	0.0601	t_{cc}	246.12	147.67	74.08	127.80	74.11	127.90
CBR2	9.27	7.12	0.0072	t_{ck}	120.77	72.46	86.84	41.60	89.43	43.60
CLR_1	64.82	14.39	0.0701	t_{cc}	144.05	86.43	73.96	65.90	74.02	66.10
JQR1	44.1	9.27	0.0093	t_{cD}	99.00	59.40	87.35	145.80	91.96	162.10
PDL1	25.34	12.46	0.0734	t_{cc}	128.05	76.83	74.45	54.3	75.16	55.30
PDL2	20.69	7.44	0.0863	t_{cc}	83.94	50.36	73.89	94.50	74.28	95.10
PDL3	7.74	4.59	0.0633	t_{cc}	61.61	36.97	74.54	31.30	76.21	32.30
PDL4	3.85	2.64	0.0740	t_{cc}	39.26	23.56	78.08	17.70	80.80	18.60
PDL5	13.57	6.3	0.0062	t_{ck}	116.23	69.74	89.65	86.5	93.45	90.70
PRQ1	14.15	6.52	0.0143	t_{ck}	86.46	51.88	84.44	20.70	89.69	23.70
PRS1	34.64	12.01	0.0259	t_{cc}	151.71	91.03	76.15	45.20	77.51	47.20

Comparing the values between the present and future scenarios, it is observed that although the peak discharge increases in a rate that is higher than the CN values (Figure 2), it does not correspond to the increase of imperviousness in the CMPC zones of the urban area. In the ZLI, ZSU, and ZIEPG zones, the occupation rate of each parcel is 70%, and in the present scenario, they comprise pasture areas, where there is still a partial soil infiltration. A significant change of imperviousness is expected to occur in the sub-basins JQR1 and PRQ1, with predominant urban and ZMV classes. The deviation between the CN values for the PRQ1 and JQR1 sub-basins varied 6.22 and 5.28, and for the Q values, 14.49 and 11.18, respectively. Thus, the CN method could not represent realistically the catchment response to the expected land use and imperviousness changes.

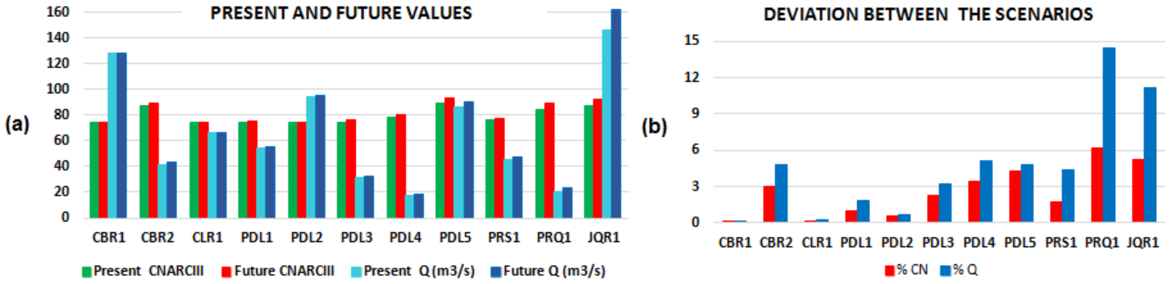


Figure 2. Comparison between the present and future scenarios: (a) CN and Q values and (b) deviation.

4. CONCLUSION

In the study, the CN method used in the HEC-HMS could not provide realistic peak discharges for the future scenario of LULC. Even though the peak discharges increased at a higher deviation than the CN, they were not compatible to the increase of imperviousness in the PRQ1 and JQR1 sub-basins, which are expected to be the most densely urbanised ones. This is due to the following: 1) As the water table is shallow, the soil becomes saturated a short time after an intense rainfall starts, but the model does not compute the infiltration rate evolution throughout an event; 2) By the use of the LULC area weighted average regionalisation approach, the average CN underestimates the effect of the highest values in the basin; 3) The rainfall intensity is underestimated because of not relating the initial abstraction with soil infiltration rates; and 4) The model does not compute the CN losses in the outcomes. Enhanced calibration and validation procedures minimise the limitation of the model, although it is a challenge for ungauged basins.

Even though the CN method has the features of conceptual models, it disregards the hydrological phenomena responsible for the catchment losses, similar to black-box models, and needs to be validated and calibrated to provide reliable outcomes. Furthermore, we conclude that the CN should not be the single method used to evaluate the flood susceptibility of ungauged basins with saturated soil conditions.

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REFERENCES

Boulomytis, V.T.G., Imteaz, M.A., Zuffo, A.C., Alves, C.D. (2016). Analysis of the urbanisation effects on the increase of flood susceptibility in coastal areas. *Theoretical and Empirical Researches in Urban Management,* 11, 30-45.

Boulomytis, V.T.G., Zuffo, A.C. and Gireli, T.Z. (2017a). Watershed spatial discretization for the analysis of land use change in coastal regions. *Boletim de Ciências Geodésicas,* 23(1), 101-114.

Boulomytis, V.T.G., Zuffo, A.C., Dalfre Filho, J.G., and Imteaz, M.A. (2017b). Estimation and calibration of Manning's roughness coefficients for ungauged watersheds on coastal floodplains. *International Journal of River Basin Management*, 15, 199-206.

Brazilian Agricultural Research Corporation - EMBRAPA (2006). *Brazilian System of Soil Classification*. Rio de Janeiro: Embrapa Solos.

Brazilian Petrol - PETROBRAS (2007). *Environmental Impact Assessment - UTGCA*, PBS1R03, v. 2, n. 2.

Caraguatatuba City Council (2011). City Master Plan of Caraguatatuba Municipality, Law n. 42, 24 November 2011.

Costa Norte (2017). *FEHIDRO aprova R$4 milhoes para combate a enchentes em Caragua.* Available at: http://www.costanorte.com.br/blog/fehidro-aprova-r-4-milhoes-para-combate-enchentes-em-caragua/ Acessed on: 10 Jul 2017.

Cullmann, J., Krausse, T. and Saile, P. (2011). Parameterising hydrological models–Comparing optimisation and robust parameter estimation. *Journal of hydrology*, 404(3), 323-331.

Grayson, R.B., Moore, I.D. and McMahon, T.A. (1992). Physically based hydrologic modelling: Is the concept realistic? *Water Resources Research*, 26 (10), 2659–2666.

Hawkins, R.H. (1993). Asymptotic determination of runoff curve numbers from data. *Journal of Irrigation and Drainage Engineering.* 119(2): 334-345.

Ioris, A. A., Hunter, C. and Walker, S. (2008). The development and application of water management sustainability indicators in Brazil and Scotland. *Journal of Environmental Management*, 88(4), 1190-1201.

Jeon, J. H., Lim, K. J. and Engel, B. A. (2014). Regional calibration of SCS-CN L-THIA model: application for ungauged basins. *Water*, 6(5), 1339-1359.

Kendall, C., McDonnell, J. J. and Gu, W. (2001). A look inside 'black box' hydrograph separation models: a study at the Hydrohill catchment. *Hydrological Processes*, 15(10), 1877-1902.

Kibler, D. F. (1982). Desk-Top Methods for Urban Stormwater Calculation. *Urban stormwater hydrology*, 87-135.

Krysanova, V., Hattermann, F. and Wechsung, F. (2005). Development of the ecohydrological model SWIM for regional impact studies and vulnerability assessment. *Hydrological Processes*, 19, 763–783.

Kuczera, G. and Parent, E. (1998). Monte Carlo assessment of parameter uncertainty in conceptual catchment models: the Metropolis algorithm. *Journal of Hydrology*, 211(1), 69-85.

Masron, T., Mohamed, B. and Marzuki, A. (2015). GIS base tourism decision support system for Langkawi Island, Kedah, Malaysia. *Theoretical and Empirical Researches in Urban Management*, 10(2), 21-35.

McCuen, R. H., Wong, S. L. and Rawls, W. J. (1984). Estimating urban time of concentration. *Journal of hydraulic Engineering*, 110(7), 887-904.

Van Mullem, J. A., Woodward, D. E., Hawkins, R. H., Hjelmfelt, A. T. and Quan, Q. D. (2002). Runoff curve number method: Beyond the handbook. *Proceedings.* 2nd Federal Interagency Hydrologic Modeling Conference, Las Vegas, Nevada, July 2002.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models, *Journal of Hydrology*, 10, 282–290.

Ramachandra, T. V., Bharath, H. A. and Sowmyashree, M. V. (2013). Analysis of spatial patterns of urbanisation using geoinformatics and spatial metrics. *Theoretical and Empirical Researches in Urban Management*, 8 (4), 5-24.

Sartori, A., Genovez, A. M. and Neto, F. L. (2009). Tentative Hydrologic Soil Classification for Tropical Soils. *Advances in Water Resources and Hydraulic Engineering*, Springer Berlin Heidelberg.

Silveira, A.L.L. (2005). Desempenho de Fórmulas de Tempo de Concentração em Bacias Urbanas e Rurais. *Revista Brasileira de Recursos Hídricos*, 10 (1), 5-23.

Souza, C. D. G. (2005). Suscetibilidade morfométrica de bacias de drenagem ao desenvolvimento de inundações em áreas costeiras. *Revista Brasileira de Geomorfologia*, 1, 45-61.

Wang, S., Kang, S., Zhang, L. and Li, F. (2008). Modelling hydrological response to different land-use and climate change scenarios in the Zamu River basin of northwest China. *Hydrological Processes* 22 (14), 2502-2510.

Waterloo Brazil Environmental Consulting (2009). *Underground Water Assessment, Caraguatatuba/SP - PETROBRAS,* Report 734.1871/09, II.

Wu, Q., Liu, S., Cai, Y., Li, X. and Jiang, Y. (2017). Improvement of hydrological model calibration by selecting multiple parameter ranges. *Hydrology and Earth System Sciences*, 21(1), 393-407.