Annual Journal of Hydraulic Engineering, JSCE, Vol.53, 2009, February

REGIONAL GEOMORPHOLOGICAL CHARACTERITICS OF SMALL HILLSIDE RIVER BASINS IN SEMIARID REGION OF TUNISIA

Achraf HENTATI[1], Akira KAWAMURA[2] and Hideo AMAGUCHI[3]

[1]Student Member of JSCE, Graduate student, Dept. of Civil & Environmental Eng., Tokyo Metropolitan University
(1-1 Minami-Ohsawa, Hachioji, Tokyo 192-0397, Japan)
[2]Member of JSCE, Dr. Eng., Professor
[3]Member of JSCE, B. Eng., Research Associate

The small hillside reservoirs are very crucial for the sustainability of the water resources in the semiarid area of Tunisia. The Tunisian government has initiated a policy of small dam construction since 1990. However, flash floods and severe soil loss are jeopardizing the lifetime of those small hydraulic structures. The geomorphology has fundamental effects on the flood hydrologic response. In this paper, we studied the geomorphological characteristics of small hillside catchments in the semiarid region of Tunisia. The hypsometric curve and topographic index were used as geomorphological indicators. The results showed that the concavity of the hypsometric curve affects the peakedness of the topographic index distribution in the studied catchments.

Key Words: *geomorphological characterization, hypsometric curve, topographic index, small hillside catchments, semiarid region of Tunisia, flash floods.*

1. INTRODUCTION

Water shortage is a major concern in Tunisia as well as in most of the Mediterranean countries which are situated in the arid and semiarid climatic zone where the mean annual rainfall does not exceed 550 mm. Furthermore, this climate is characterized by irregular rainfall, drought, poor vegetation cover, severe soil loss and violent erosion during the flood season[1)].

In the beginnings of the 1990s, the Tunisian government launched an ambitious program for constructing small hillside reservoirs in the northern and central region of the country. The idea is to stimulate the local agriculture[2)]. However, with both the intensive irregular rainfall and severe soil erosion, the lifetime of these hydraulic structures is in jeopardy. Flash floods with high sediment load are threatening many of these reservoirs and some of them have already been filled up with sediment in less than 10 years (after construction). For example, the Sadine reservoir (volume of 34380 m^3) in central Tunisia was entirely silted up with sediments from two floods in August 1995 and in September 1995.

Consequently there is an urgent need to predict flood volume and maximum runoff as well as the hydrograph shape. This is especially important in semiarid regions where flash floods are very frequent. These floods happen very suddenly and are usually difficult to forecast because the time to hydrograph peak is very short, less than six hours[1)]. Damages caused by such floods are often serious.

In 1993, a network for studying and observing over thirty small hillside catchments in the semiarid region of Tunisia was set up to form a hydrological database. In 1996, HYDROMED research project, led by IRD (Institut de Recherche pour le développement, ex-ORSTOM) and financed by the European Union, selected several sites for pilot schemes in countries of the Mediterranean periphery: Lebanon, Morocco, Syria and Tunisia. The main objective of this project was to build a hydrological model suitable for semiarid Mediterranean catchments with hill reservoirs[3),4)]. Several researches were carried out within the frame of HYDROMED[5)]. However, they were hydrological-aspect oriented. There were no detailed studies on the geomorphological characterization of semiarid catchments in Tunisia. That's why our study is aimed at characterizing the geomorphological aspect of those small hillside catchments in the semiarid region of Tunisia.

Investigations have shown that the geomorphology of a catchment has fundamental effects on its hydrologic response[6),7)]. On the local scale, flow paths and flow velocities are directly influenced by the slope angle and upslope drainage area. The topographic index of Beven[8),9)] is a suitable parameter for indicating the geomorphic control on the flood response. On the basin scale, the watershed area and often some measure of the relief were found to correlate at a significant level to the flood response[10)]. In fact, Harlin showed that time to-hydrograph-peak correlates with various statistical attributes (skewness and kurtosis) of the hypsometric curve of Strahler[11)].

In this study, both hypsometric curve and topographic index are used as geomorphological indicators. As a first stage of basic information before analyzing hydro-meteorological variables themselves, we focused more on the geomorphological aspect to i) understand the semiarid watershed characteristics; ii) classify them into similar groups and iii) explore whether it is better to group the watersheds using the topographic index or the hypsometric curve and if any relationship exists between them.

We prepared the digital elevation models of the thirty hillside catchments in semiarid region of Tunisia. We used a GIS software and self-developed tools to obtain the hypsometric curves and topographic index distributions for all the catchments. Furthermore, some hypsometric attributes and topographic index statistics were calculated to study the watersheds morphology.

2. STUDY AREA

(1) SELECTED CATCHMENTS

Tunisia is a country situated on the Mediterranean coast of North Africa. Despite its small size, Tunisia has relatively great climatic diversity. The Tunisian climate is influenced by the Mediterranean climatic perturbation from the North and the arid desertic climate from the South. This situation gives the central region of Tunisia a semiarid climate. It is characterized by generally hot and dry summers, mild to cool and rainy winters, and warm-temperate coasts. Tunisia receives relatively low rainfall in winter. It also has low humidity in summer, which creates high solar radiation intensity and high evapotranspiration rates[12),13)]. The vegetation cover is sparse and unevenly distributed. Intense rainstorms over sparsely vegetated surfaces create a pronounced erosion process.

Since 1996, the Direction of Soil and Water Conservation, Tunisia (DCES) and the Institute of Research for Development, France (IRD) have collaborated in a research program on small hillside reservoirs[14)]. In central Tunisia, in the semiarid mountainous region that extends from the northeast of the country to the Algerian border in the West, 30 hill reservoirs were chosen to make up a network of hydrological observations within the HYDROMED project[15)] (see **Fig.1**). The catchment areas vary from a few hectares to 100 km^2 and have reliefs ranging from a minimum altitude of 70 m to a maximum altitude of 1432 m (see **Table 1**). They are representative of rainfall gradient of the semiarid region of Tunisia, which is 250 to 550 mm of annual rainfall.

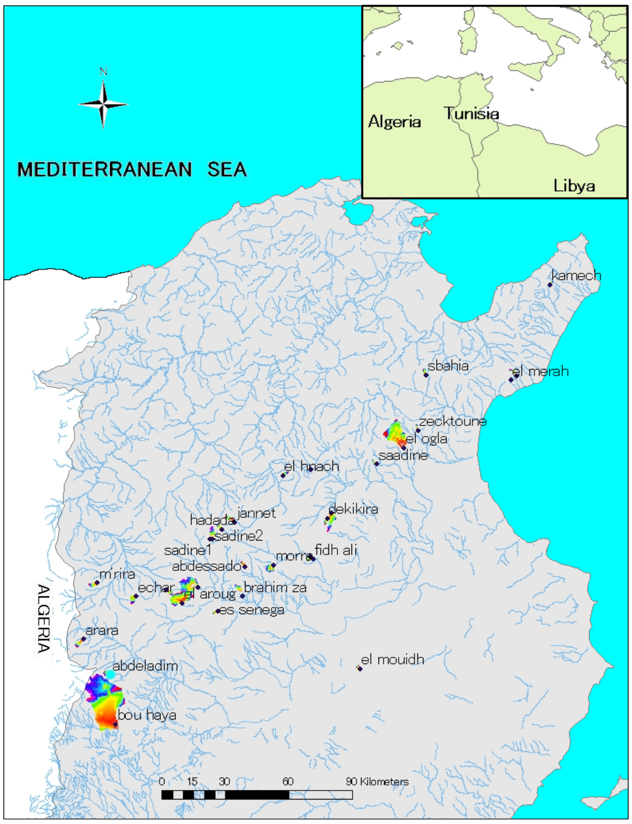

Fig.1 Location of Tunisia and the studied catchments.

(2) DIGITAL ELEVATION MODELS (DEMs)

Our 30 watershed DEMs came from the Shuttle Radar Topographic Mission (SRTM) data that is available as 3-Arc Second resolution DEMs (http://srtm.csi.cgiar.org/). This mission was a collaborative effort by the National Aeronautics and Space Administration (NASA), the National Imagery and Mapping Agency (NIMA) and Italian space agency. The mission was launched February 11, 2000. It is an example of such a data set, providing an almost complete global coverage of the earth's land surface at a resolution of 90 m horizontal grid scale[16)]. The DEMs were converted to the GRID format of Arc/info GIS software. Once in grid format, adjacent DEMs were mosaicked together into a DEM mosaic to cover Tunisia. This mosaic DEM is projected into the coordinate system Carthage-UTM-Zone 32N and then resampled to 100 m resolution. The DEMs of the studied watersheds were clipped out from the mosaic DEM.

3. METHODOLOGY

(1) HYPSOMETRIC ANALYSIS

The hypsometric curve represents the relative proportion of basin area that lies below a given height. For a selected basin, the range of elevations is divided into equal elevation intervals. For each interval the proportion of basin area is calculated. Elevations and areas are normalized by the relief (elevation difference between summit and outlet) and the total area of the catchment, respectively.

Quantitative description of the curve becomes important in hypsometric analysis. Hypsometric integral (the area under the curve) is the most often used quantitative measure. While this is a useful parameter, it has its limitation as different hypsometric curves may have the same integral. Harlin developed a technique that is able to quantitatively describe subtle differences of the shape of the curve with statistical skewness and kurtosis by treating the hypsometric curve as a cumulative probability distribution function[17),18),19)] as shown in the following equation:

$$F(Z) = \int_Z^1 f(Z)dZ \qquad (1)$$
$$0 \le F(Z) \le 1; \quad 0 \le Z \le 1$$

where F is the cumulative probability distribution of finding a normalized catchment area at or above a normalized altitude Z and f is the probability density function or the relative frequency of area change with altitude.

The hypsometric curves of the studied watersheds are obtained by using DEMs to determine the point-pairs (area, height). Finally, a self-developed program was used to compute the hypsometric integral, the skewness and kurtosis.

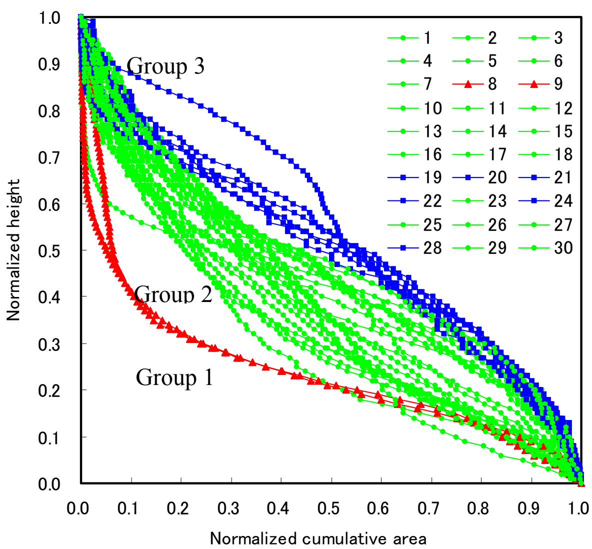

Fig.2 Hypsometric curves of the 30 studied catchments.

(2) TOPOGRAPHIC INDEX (TI)

The topographic index represents the propensity of a point within a watershed to generate saturation excess overland flow. This kind of hydrological process is due to a topographic control of surface and subsurface flow. In 1979, Beven and Kirkby defined the topographic index[8),9)] as follows:

$$TI = \ln\left(\frac{a}{\tan\beta}\right) \qquad (2)$$

where TI is the topographic index of a point/pixel within a watershed, a is the specific upslope area per unit contour length L draining through the point and β is the local topographic slope angle acting at the point (see **Fig.2**).

Many authors used the topographic index as an index of saturation. Rodhe and Seibert[20)] showed that the topographic index allows estimating the position and extension of saturated areas that are not connected to the hydrographic network. Rousseau, Hentati *et al.*[21)] used the topographic index as indicator of risk of water contamination by phosphorus, which is generated by the agriculture activities in some watersheds in Quebec.

The computation of the topographic index distribution on our catchments is performed by ArcGIS software. It follows five steps: Preparation of the DEM; DEM pre-processing by sink removal algorithm; implementation of a single flow direction algorithm on the reconditioned DEM; determination of the flow accumulation; computation of the slope by applying a slope algorithm on the original DEM; and calculation of the topographic index values.

4. RESULTS AND DISCUSSION

(1) HYPSOMETRIC RESULTS AND DISCUSSION

According to the definition of the hypsometry and after determining the proportion of areas at different elevations within all watersheds, thirty hypsometric curves were obtained (**Fig.2**). The hypsometric integral, skewness and kurtosis were also calculated (see **Table 1**).

From a simple visual comparison we divided those curves into three groups (see **Table 1**). The first group includes the concave hypsometric curves (red line) whose hypsometric integrals are the smallest, El Aroug and El Ogla with HI values of 0.237 and 0.242 (see **Table 1**). Due to their heterogeneous geology, those two watersheds display very irregular curves, with a rapid drop in the upper reaches of the catchments and then relatively flat as the area increases. This rapid drop in the upper reaches represents the more erosion resistant geology, whereas in the lower reaches the geology is less erosion resistant[22]. The second group corresponds to the S-shaped hypsometric curves (green line). Their hypsometric integrals range from 0.306 to 0.471.

The remaining watersheds belong to the third group. The hypsometric curves are convex (blue line). Their hypsometric integrals are the largest. They vary from 0.497 to 0.525 (see **Table 1**). In those catchments, the streams are less developed therefore the total amount of mass removed by the river process is less than the other watersheds[17].

Fig.3 reveals a linear relationship between the hypsometric integral and skewness for those studied watersheds. This finding also confirms our visual classification for the hypsometric curves. It shows clearly the three groups of watersheds. This relationship between the hypsometric skewness and integral was found to be perfectly linear with R^2=0.97 for Tunisian semiarid watersheds. However, Harlin showed that this correlation is not perfectly linear for five small watersheds in Iowa and Nebraska (USA)[17]. We thought this difference is due to the fact that Tunisian and American watersheds belong to different climate contexts. But, Evans stated that HI and skewness are linearly correlated just when the range of HI is small[23],

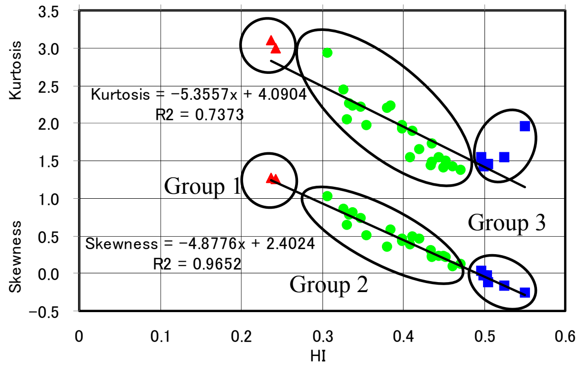

Fig.3 Relation between Hypsometric Integral (HI) and Skewness and Kurtosis of the hypsometric curves

which is the case for the Tunisian watersheds. In this study, thirty watersheds were studied and the range of their hypsometric integrals is wider than the watersheds in USA. Principally, the Tunisian watersheds clearly confirm the relationship postulated by Evans.

Concerning the kurtosis values, they range from 1.38 to 3.10 (see **Fig.3**). Kurtosis increases when an advanced erosion process has occurred in both the upper and lower reaches of a basin[17]. For El Ogla and El Aroug kurtosis are 2.99 and 3.10, respectively. Consequently, they are likely the most eroded in their upper and lower reaches among all studied watersheds.

Table 1 Hypsometric attributes and topographic index statistics for the 30 catchments.

		Main charcteristics of the studied watersheds				Hypsometric attributes			TI statistics			Group
No	Catchments	Area (km²)	Annual Rain (mm)	Alt. Min (m)	Alt. Max (m)	HI	Skewness	Kurtosis	Mod TI	Peak Freq	Mean TI	
1	Abdeladim	6.42	268	1030	1224	0.333	0.78	2.27	8.00	17.53	8.53	2
2	Abdessadok	3.07	336	815	1189	0.306	1.03	2.93	7.00	21.38	7.75	2
3	Arara	7.08	247	910	1352	0.399	0.43	1.98	7.00	17.23	8.21	2
4	baouejer	4.86	346	987	1118	0.337	0.81	2.23	7.50	22.15	8.36	2
5	brahim	4.64	204	570	1015	0.399	0.46	1.93	7.00	17.62	8.19	2
6	bou haya	359.00	NA	810	1432	0.330	0.64	2.05	8.50	14.30	8.99	2
7	Dekikira	3.07	366	380	479	0.435	0.21	1.48	8.00	21.38	8.62	2
8	El Aroug	40.25	NA	872	1309	0.237	1.27	3.10	8.00	18.45	8.70	1
9	El Ogla	80.10	333	145	880	0.242	1.26	2.99	7.50	17.02	8.19	1
10	Echar	9.17	338	970	1190	0.450	0.23	1.41	8.00	21.61	8.75	2
11	Es Segir	4.31	524	70	232	0.444	0.23	1.54	7.00	24.31	8.28	2
12	Es Senaga	3.63	287	618	883	0.326	0.86	2.44	7.50	20.30	8.45	2
13	Fidh Ali	4.12	264	335	444	0.409	0.38	1.54	7.50	27.24	8.57	2
14	Fidh Ben naceur	1.69	239	350	462	0.434	0.31	1.44	8.00	21.00	8.81	2
15	Gouazine	18.10	338	376	575	0.461	0.10	1.43	7.50	20.90	8.60	2
16	Hadada	4.69	344	900	1246	0.453	0.21	1.50	7.50	21.53	8.79	2
17	Hanach	3.95	351	447	834	0.412	0.50	1.90	7.00	26.30	8.16	2
18	Jannet	5.21	412	820	1191	0.384	0.58	2.24	7.50	24.64	7.94	2
19	Jedeliane	47.00	NA	740	1206	0.505	-0.12	1.46	7.00	21.05	8.03	3
20	Kamech	2.45	603	95	203	0.525	-0.16	1.54	7.50	23.79	8.35	3
21	Maleh	0.85	472	90	144	0.497	0.04	1.54	7.50	30.00	8.11	3
22	Morra	12.50	NA	590	746	0.499	-0.02	1.43	7.50	24.06	8.47	3
23	Mouidhi	2.66	252	235	363	0.420	0.46	1.66	7.00	18.46	7.94	2
24	Mrichet	1.58	329	590	730	0.504	-0.02	1.46	7.50	26.46	8.53	3
25	Mrira	6.13	313	770	940	0.348	0.73	2.22	8.00	20.47	9.19	2
26	Saadine	2.72	390	245	552	0.354	0.51	1.97	7.50	21.64	8.46	2
27	Sadine1	3.84	NA	842	1250	0.436	0.24	1.73	6.50	19.87	7.67	2
28	Sadine2	6.53	459	825	1267	0.550	-0.26	1.96	7.00	22.54	7.91	3
29	Sbaihia	3.24	436	300	473	0.471	0.13	1.38	7.00	28.07	7.94	2
30	Zectoune	2.05	199	195	569	0.380	0.36	2.20	6.50	18.75	7.75	2

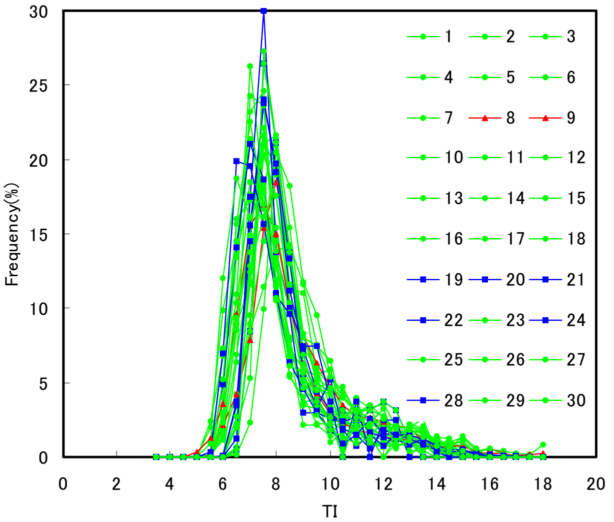

Fig.4 The topographic index distributions for the 30 studied watersheds.

(2) TOPOGRAPHIC INDEX RESULTS AND DISCUSSION

Thirty topographic index maps were generated from the application of a simple flow direction algorithm to the digital elevation models of the studied catchments. **Fig.4** shows that in all cases the topographic index distributions are unimodal and positively skewed. We could not visually discriminate the curves as we made for the hypsometric curves. However, by averaging each group of hypsometric curves and corresponding topographic index distributions group we found a general tendency: In fact, the hypsometric curve concavity has an effect on the topographic index distribution peakedness (see **Fig.5**). In the case of the Tunisian semiarid watersheds, we found that the more concave the average hypsometric curves, the lower the peak of the average topographic index distributions is. The watersheds of the first group have concave hypsometric curve. They are more eroded in their upper reaches than in their lower reaches (see **Fig.5**). Strahler stated that the slope of the hypsometric curve and the mean ground slope are linearly correlated[11]. Consequently, the mean ground slopes are steeper in upper reaches than in the lower reaches. Values of $\tan\beta$ tend to decrease and the upslope areas a continue to cumulate along the lower reaches (The bottom of the valleys). Therefore higher topographic index values are more frequent than group 2 and group 3. Above a value of 10 on the topographic index, pixels on or near the river represent an increasing tail[24] of the averaged distribution of the first group and hence the peak decreases.

On the contrary, the watersheds of the third group are generally less eroded. The mean ground slopes are gentler and are globally the same within

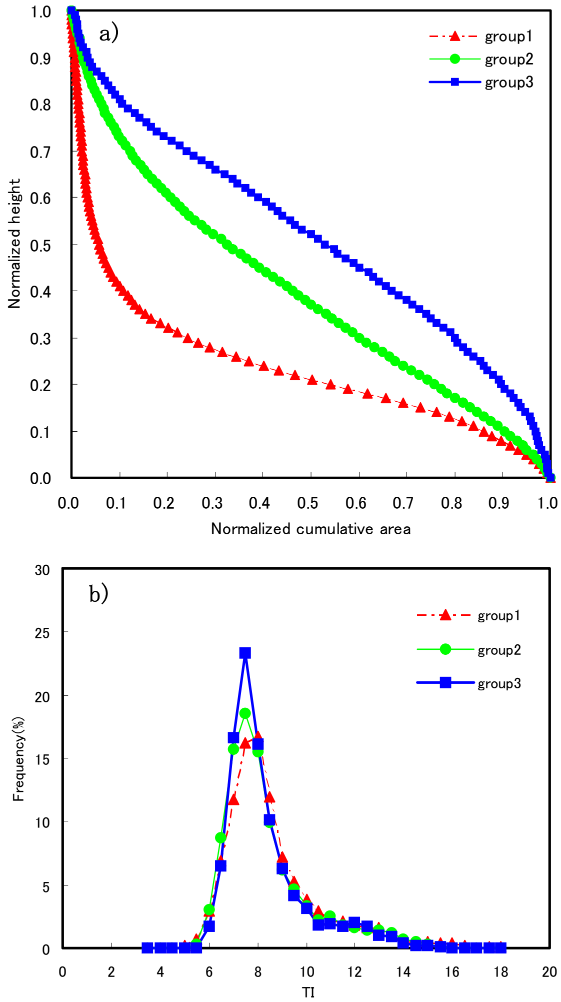

Fig.5 Relation between **a)** averaged hypsometric curves and **b)** averaged topographic index distributions.

those watersheds. Consequently, The high values of the topographic index are expected to be less frequent. Therefore in case of the third group, the tail of the topographic index distribution decreases and the peak increases. The second group of watersheds is intermediate.

5. CONCLUSION

In this paper, we have characterized the geomorphology of small hillside reservoir catchments in the semiarid region of Tunisia by the use of the hypsometric curve and the topographic index as geomorphic indicators. The results have shown that the hypsometric curves of those watersheds can be visually classified in three groups: Concave, S-shaped and convex hypsometric curves. Findings have also revealed a linear relationship between the hypsometric integral and skewness. This result confirmed the grouping of the studied watersheds.

Finally our study suggests that there is a general tendency between the hypsometric curves shape and the topographic index distributions for the studied watersheds. The more concave the average hypsometric curves, the lower the peak of the average topographic index distributions is. This finding will be the subject of further investigations. This geomorphological characterization is important since it can be useful for extrapolating information and knowledge from gauged basins to poorly gauged or ungauged basins on the basis of hydrological similarity, thus answering recent calls for interdisciplinary effort within predictions in ungauged basins (PUB) project.

ACKNOWLEDGMENT: The authors would like to thank Jonas Olsson from the Swedish Meteorological and Hydrological Institute (SMHI) for his valuable comments and his insightful reviews. The authors are grateful to Philipp Markup for his proofreading which helped to improve an earlier version of this paper.

REFERENCES

1) Xiao, L.: Flash floods in arid and semiarid zones. UNESCO International Hydrological Programme, IHP-V, *Technical Documents in Hydrology,* No.23, UNESCO, Paris, France 1991.
2) Nasri, S., Cudennec C., Albergel, J. and Berndtsson, R.: Use of a geomorphoplogical transfer function to model design floods in small hillside catchments in semiarid Tunisia, *Journal of Hydrology*, Vol.287, 197-213, 2004.
3) Ragab, R., Austin B. and Moidinis D.: a) The HYDROMED model and its application to semi-arid Mediterranean catchments with hill reservoirs: The rainfall-runoff model using a genetic algorithm for optomisation, *Hydrology and Earth System Sciences.* Vol.5, 543-553, 2001.
4) Ragab, R., Austin B. and Moidinis D.: c) The HYDROMED model and its application to semi-arid Mediterranean catchments with hill reservoirs: Reservoirs storage capacity and probability of failure model, *Hydrology and Earth System Sciences,* Vol.5, 563-568, 2001.
5) Albergel, J. and Nasri, S.: HYDROMED: Rapport final du programme de recherche sur les lacs collinaires dans les zones semi-arides du pourtour mediterraneen. Contrat europeen INCO DC ERBIC 18 CT 960091-STD4. IRD/INRGREF Tunis, 120p, 2001.
6) Harlin, J.M.: Watershed morphometry and time to hydrograph peak, *Journal of Hydrology,* Vol.67, 141-154, 1984.
7) Luo, W. and Harlin, J.M.: A theoretical travel time based on watershed hypsometry, *Journal of the American Water Resources Association,* Vol.39, No.4, 785-792, 2003.
8) Beven, K. J. and Kirkby, M .J: A physically-based,variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin*, Vol.24, 43-69, 1979.
9) Quinn, P.F., Beven, K. J. and Lamb, R.: The ln (a/tanβ) index: How to use it within the TOPMODEL framework. Hydrological Processes, Vol.9, 161-182, 1995.
10) Howard, A. D.: Role of hypsometry and planform in basin hydrologic response, *Hydrological Processes,* Vol.4, 373-385, 1990.
11) Strahler, A. N.: Hypsometric (Area-Altitude) analysis of erosional topography, *Bulletin of the Geological Society of America,* Vol.63, 1117-1142, 1952.
12) Berndtsson, R.: Spatial and temporal variability of rainfall and potential evaporation in Tunisia. The influence of climate change and climatic variability on the hydrologic regime and water resources, proceedings of the Vancouver Symposium, August 1987. *IAHS Publ*. No. 168, 1987.
13) Fiorentino, M., Carriero, D., Iacobellis, V., Manfreda, S. and Portoghese, I.: Medclub-starting line and first activities. Predictions in Ungauged Bassins (PUB): Promises and Progress. *IAHS Publ,* 1-14, 2005.
14) Albergel, J. and Rejeb, N.: Les lacs collinaires en Tunisie: Enjeux, contraintes et perspectives, *CR. Acad. Agric.* Fr., 77-88. Session of March 9, 1997.
15) Albergel, J., Nasri S., Boufaroua, M., Droubi, A., Merzouk, A. A. 2004: Rain water harvesting and management of small dams in Mediterranean areas (North Africa and Middle East), *Conference in Ohrid*, FY Republic of Macedonia, 25-29, 1-12, May 2004.
16) Martinez C., Hancock G. R., Evans K. G. and Moliere D. R.: A catchment based assessment of the 3-Arc Second SRTM Digital Elevation Data set. MODSIM 2005 International Congress, Australia and New Zealand, December 2005, 1409-1415.
17) Harlin, J.: Statistical moments of the hypsometric curve and its density function, *Mathematical Geology*, Vol.10, No.1, 59-72, 1978.
18) Evans, I.S.: Hypsometry, Statistics, and simplicity: A comment, *Mathematical geology,* Vol.11, No.1, 1979.
19) Luo, W.: Hypsometric analysis with a geographic information system, *Computers and Geosciences*, Vol. 24, No.8, 815-821, 1998.
20) Rhode A. and Seibert J.: Wetland occurrence in relation to topography: a test of topography indices as moisture indicators, *Agric For Meteorol*, Vol.98/99, 325-340, 1999.
21) Rousseau, A. N., Hentati A., Tremblay S., Quilbé R., Villeneuve, J. P.: Computation of the topographic index on 16 watersheds in Quebec. Report No.R800-f, INRS-ETE, La Couronne, Quebec , Canada, 2005.
22) Hancock, G. R.: The use of digital elevation models in the identification and characterization of catchments over different grid scales. *Hydrological Processes,* Vol.19, No.9, 1727-1749, 2005.
23) Evans, I.S.: General gomorphometry, derivatives of altitude, and descriptive statistics. Mimeo Paper read at *British Geomorphological Research Group, Symposium on Spatial Analysis in geomorphology,* Cambridge, England, 1972.
24) Saulnier G.M., Beven K. and Obled C.: Digital elevation analysis for distributed hydrological modeling: Reducing scale dependence in effective hydraulic conductivity values. *Water Resources Research*, Vol.33, No.9, 2097-2101, 1997.

(Received September 30, 2008)