GEOMORPHOLOGICAL CHARACTERIZATION OF SMALL HILLSIDE RIVER BASINS IN SEMIARID REGION OF TUNISIA FOR REDUCING UNCERTAINTIES IN WATER RESOURCES MANAGEMENT

Akira Kawamura[1], Achraf Hentati[1] and Hideo Amaguchi[1]

[1] Department of Civil and Environmental Engineering, Graduate School of Urban Environmental Sciences, Tokyo Metropolitan University, Minami-Ohsawa, Hachioji, Tokyo 192-0397, Japan

ABSTRACT: The small hillside river basins in the semiarid region of Tunisia are very crucial for the sustainability of the water resources, especially for agricultural irrigation water. Tunisian government has introduced a political water resources plan constructing small hillside reservoirs since 1990. Since then, quite a few small hillside reservoirs have constructed. However, flash floods and severe soil loss which jeopardized the function of those small hillside reservoirs are reported. In order to reduce the uncertainties in water resources management of the small hillside river basins in semiarid region, studying the basic information of the river basins which prescribes the fundamental behavior of the basins has a very important role. In this paper, as the first stage of such basic information before analyzing hydro-metrological variables, we focused on the geomorphological characteristics of fifteen small hillside river basins in the semiarid region of Tunisia. The hypsometric curve and topographic index were used as geomorphological indicators. Hypsometric attributes and topographic index statistics were calculated to compare watersheds morphology and to interpret the effect of hypsometric curve shape on the topographic index distribution. The results show that he hypsometric curves of those watersheds can be classified in three groups and the concavity of the hypsometric curve affects the peakedness of the topographic index distribution.

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 450 mm. Furthermore, this climate is characterized by irregular rainfall, drought, poor vegetation cover, severe soil loss and violent erosion during the flood season (Xiao, 1991).

In the beginnings of the 1990s, the Tunisian government launched an ambitious program for constructing small hillside reservoirs in the northern and central semiarid region of the country. The basic idea is to stimulate the local agriculture producing agricultural irrigation water (Nasri *et al.*, 2004). However, with both the intensive irregular rainfall and severe soil erosion, the lifetime of these reservoirs is in jeopardy. The accumulation of sediment in reservoirs reduces their storage capacity and causes the degradation of water quality. 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 34,380 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 (Xiao, 1991). Damages caused by such floods are often serious.

In order to reduce the uncertainties in water resources management of the small hillside river basins in semiarid region, studying the basic information of the river basins which prescribes the fundamental behavior of the basins has a very important role. Investigations have shown that the geomorphology of a river basin has fundamental effects on its hydrologic response (Luo *et al.*, 2003). Consequently, in this work, as the first stage of basic information before analyzing hydro-metrological variables themselves, we focused more on the geomorphological aspect to understand the semiarid watershed characteristics and to bypass the lack of hydrological data on those countries. Both hypsometric curve and topographic index are valuable geomorphological indicators. The river basin area and landform are accurately represented by the hypsometric curve. At the same time it includes a lot of topographical features and provides a visual representation of the watershed's profile (Luo, 1998; Hancock, 2005). The topographic index is a suitable parameter for indicating the geomorphic control on the generation of the excess-saturation runoff and on the creation of flash floods.

There are no detailed studies on the geomorphological characterization of semiarid river basins in Tunisia. Therefore, the aim of this paper is to represent the geomorphological characteristics of small hillside river basins in semiarid region of Tunisia. Fifteen small hillside river basins were chosen for this study because other data were not available. Their digital elevation models and stream networks were prepared. The hypsometric curves and topographic index distributions were obtained for all basins. Hypsometric attributes and topographic index statistics were calculated to compare watersheds morphology and to interpret the effect of hypsometric curve shape on the topographic index distribution.

2. STUDY AREA

2.1 SELECTED RIVER BASINS

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 (Berndtsson R., 1987; Fiorentino *et al.*, 2005). The vegetation cover is sparse and unevenly distributed. Intense rainstorms over sparsely vegetated surfaces create a pronounced erosion process.

Since 1993, 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 (Albergel *et al.*, 2004). 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 (Albergel *et al.*,

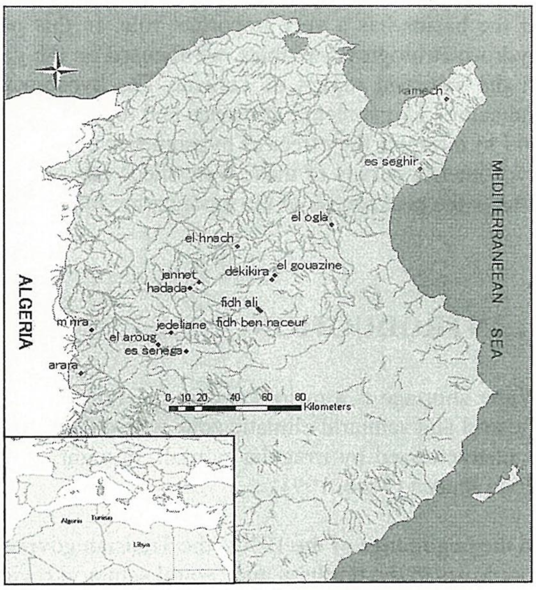

Figure 1. Location of the studied river basins.

Table 1. Characteristics of the studied river basins and their reservoirs.

No	River Basins	Area (Km^2)	Average annual Rainfall (mm)	Altitude Min (m)	Altitude Max (m)	Storage Capacity (m^3)	Construction Year
1	Arara	7.08	247	910	1352	91150	1993
2	Dekikira	3.07	366	380	479	219100	1991
3	El Aroug	40.25	NA	872	1309	2334920	1994
4	El Ogla	80.10	333	145	880	5887080	1989
5	Es Segir	4.31	524	70	232	192450	1992
6	Es Senaga	3.63	287	618	883	86420	1991
7	Fidh Ali	4.12	264	335	444	134710	1991
8	Fidh Ben naceur	1.69	239	350	462	47110	1990
9	Gouazine	18.10	338	376	575	237030	1990
10	Hadada	4.69	344	900	1246	84970	1992
11	Hanach	3.95	351	447	834	77220	1992
12	Jannet	5.21	412	820	1191	94280	1992
13	Jedeliane	47.00	NA	740	1206	1550660	1992
14	Kamech	2.45	603	95	203	142560	1993
15	Mrira	6.13	313	770	940	126350	1991

2004). Just Fifteen river basins among them are selected for this study (see Figure1). The river basin 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 1309 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. As mentioned before, those sites represent hillside river basin reservoirs. The dams are constructed between 1989 and 1994 and the capacity of their reservoirs range from some ten thousand to some millions m^3. The dikes of those dams are between 5 and 13 m high (lower limit for large dams established by the international commission on Large Dams) (Albergel *et al.*, 2001).

2.2 DIGITAL ELEVATION MODELS (DEMS)

Our 13 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 (Martinez *et al.*, 2005). 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

3.1 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 *a(z)* is calculated. Elevations and areas are respectively normalized by the relief (elevation difference between summit and outlet) and the total area of the river basin as shown in the following equations:

$$f(z) = \frac{a(z)}{A} \qquad (1)$$

$$Z = \frac{z - z_{\min}}{z_{\max} - z_{\min}} \qquad (2)$$

where $f(z)$ is the normalized relative frequency of area change with the elevation Z, A is the total area of the watershed and Z is the normalized elevation.

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 (1978) 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 (Harlin, 1978; Luo, 1998) as shown in the following equation:

$$F(Z) = \int_0^Z f(Z)dZ \qquad (3)$$

$$0 \le F(Z) \le 1; \quad 0 \le Z \le 1$$

where F is the cumulative probability distribution of finding a normalized river basin 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 DEM to determine the point-pairs (area, height) and the hypsometric integral, and finally the skewness and kurtosis are calculated.

3.2 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 (1979) defined the topographic index as follows:

$$TI = \ln\left(\frac{a}{\tan\beta}\right) \qquad (4)$$

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.

Many authors used the topographic index as an index of saturation. Rodhe and Seibert (1999) showed that the topographic index allows estimating the position and extension of saturated areas that are not connected to the hydrographic network. Rousseau *et al.* (2005) 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 river basins 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

4.1 HYPSOMETRIC RESULTS AND DISCUSSION

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

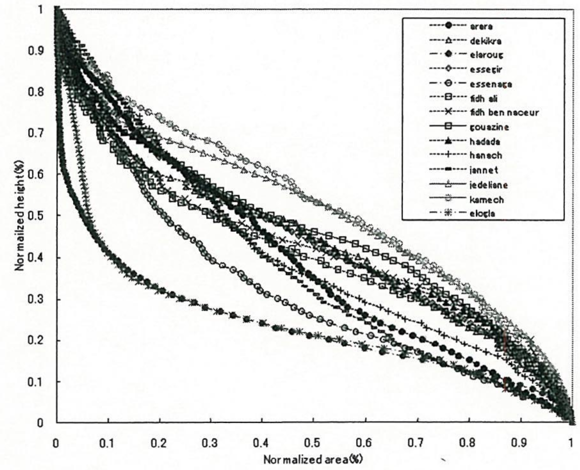

Figure 2. Hypsometric curves for 15 catchments.

From a simple visual comparison we divided those curves into three groups. The first group includes the concave hypsometric curves whose hypsometric integrals are the smallest, El Aroug and El Ogla with HI values of 0.234 and 0.242 (see Table 2). Due to their heterogeneous geology, those two watersheds display very irregular curves, with a rapid drop in the upper reaches of the river basins 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 (Hancock, 2005). The second group corresponds to the convex hypsometric curves of Jedeliane and Kamech watersheds. Their hypsometric integrals are the largest, 0.505 and 0.525, respectively (see Table 2). In those river basins, the streams are less developed therefore the total amount of mass removed by the river process is less than the other watersheds (Harlin, 1978). The remaining watersheds belongs to the third group where the hypsometric curves are S-shaped. Their hypsometric integrals range from 0.347 to 0.461.

Table 2. Hypsometric attributes and topographic index statistics for the 15 catchments.

		Hypsometric attributes			TI statistics					
No	**Catchments**	**HI**	**Skewness**	**Kurtosis**	**Min TI**	**Max TI**	**Mod TI**	**Peak Freq**	**Mean TI**	**SD TI**
1	Arara	0.398	0.43	1.98	5.76	15.64	7.00	17.23	8.21	1.86
2	Dekikira	0.434	0.21	1.48	6.67	13.97	8.00	21.38	8.62	1.55
3	El Aroug	0.234	1.27	3.10	5.31	17.40	8.00	18.45	8.70	1.91
4	El Ogla	0.242	1.26	2.99	4.87	19.27	7.50	17.02	8.19	2.08
5	Es Segir	0.444	0.23	1.54	6.30	14.72	7.00	24.31	8.28	1.80
6	Es Senaga	0.324	0.86	2.44	5.98	14.90	7.50	20.30	8.45	1.74
7	Fidh Ali	0.408	0.38	1.54	6.59	13.98	7.50	27.24	8.57	1.58
8	Fidh Ben naceur	0.434	0.31	1.44	6.46	14.03	8.00	21.00	8.81	1.57
9	Gouazine	0.461	0.10	1.43	6.31	17.23	7.50	20.90	8.60	1.93
10	Hadada	0.453	0.21	1.50	6.37	14.41	7.50	21.53	8.79	1.77
11	Hanach	0.411	0.50	1.90	6.01	13.92	7.00	26.30	8.16	1.72
12	Jannet	0.383	0.58	2.24	6.05	14.76	7.50	24.64	7.94	1.73
13	Jedeliane	0.505	-0.12	1.46	5.60	17.24	7.00	21.05	8.03	1.91
14	Kamech	0.525	-0.16	1.54	6.40	13.78	7.50	23.79	8.35	1.51
15	Mrira	0.347	0.73	2.22	6.67	15.49	8.00	20.47	9.19	1.80

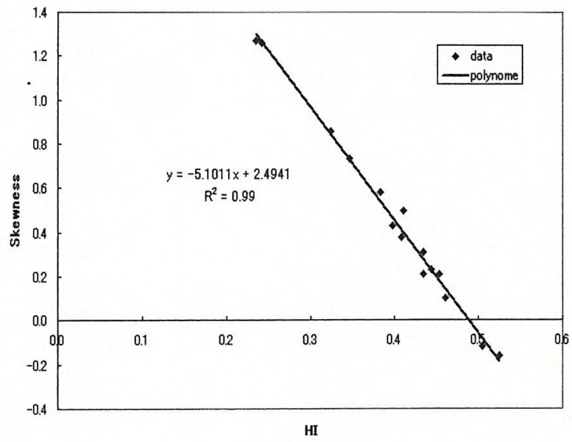

Figure 3. Relationship between HI and skewness.

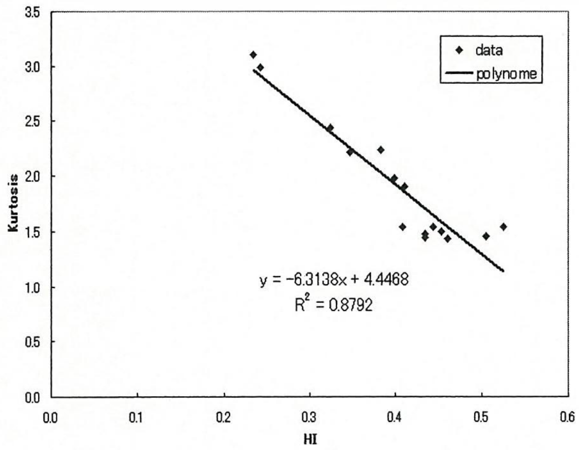

Figure 4. Relationship between HI and Kurtosis.

Figure 3 shows a linear regression between the hypsometric integral and skewness of the hypsometric curves of the studied watersheds. In Kamech river basin, the fluvial process demonstrates only a little development and the hypsometric curve is slightly skewed, -0.16 and has a high hypsometric integral 0.505. On the contrary, the hypsometric curve becomes more and more positively skewed with the development of the stream network (Harlin, 1978). For example, the hypsometric skewness of El Ogla is 1.27 and his hypsometric integral is 0.242. The relationship between the hypsometric skewness and integral was found to be perfectly linear with R^2=0.99. However, Evans (1972) and Harlin (1978) showed that this correlation is nonlinear. Concerning the kurtosis values, they range from 1.48 to 3.10 (see Figure 4). Kurtosis increases when an advanced erosion process has occurred in both the upper and lower reaches of a basin (Harlin, 1978). 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.

4.2 TOPOGRAPHIC INDEX (TI) AND DISCUSSION

Fifteen TI maps were generated from the application of a simple flow direction algorithm to the digital elevation models of the studied river basins. High TI values indicate areas characterized by large areas contributing to excess saturation runoff and relatively flat slopes, typically at the base of hill slopes, in valleys and riparian zones. Low TI values are found at the top of hill slopes, where there is relatively little upslope contributing areas and steep slopes. Figure 5 shows that in all cases the TI distributions are unimodal and positively skewed. All statistical values are homogeneous for all the 15 watersheds (see Table 2).

We studied whether there is a relation between the hypsometric curves and TI distributions relatively in the region of study. As a result, we found that both the shape of the hypsometric curve and its relative position on the plot x-y affect the TI distribution. First, the more elevated the hypsometric curve is, the more shifted to the right is the TI distribution. The highest curve corresponds to the least eroded watershed. The slope of Jedeliane watershed is the steepest. Consequently, the TI values are lower than in the other watersheds. On the contrary, the TI values will be the highest for Mrira watershed, which has the lowest hypsometric curve, and thus is the most eroded. The slopes are gentler in Mrira watershed and therefore the TI values low. Second, findings also showed that the concavity of the hypsometric curve affects the peakedness of the TI distribution. The hypsometric curve of El Ogla watershed is more concave and we can clearly distinguish the rapid decrease of the elevations. This shape leads to a lowering effect of the TI values near the peak.

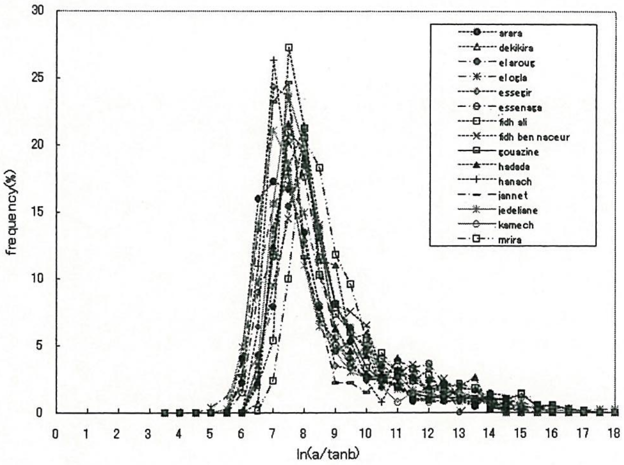

Figure 5. TI distributions for 15 catchments.

5. CONCLUSIONS

In this paper, we have characterized the geomorphology of small hillside river basins 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 classified in three groups. The most eroded watersheds have concave hypsometric curves with the smallest hypsometric integral and as expected, a higher frequency of topographic index values showing more contributing areas to excess-saturation runoff. On the contrary, the second group of river basins has convex hypsometric curves and higher hypsometric integrals. They have steeper slopes and smaller contributing upslope areas. In this case, lower topographic index values are more frequent. The third group is intermediate. Further, this study suggests that the hypsometric curve shape affects the topographic index distribution. This finding will be the subject of further investigation. The obtained morphological characteristics of small hillside river basins in semiarid region of Tunisia will provide effective and useful information for the next stage of reducing uncertainties in water resources management by analyzing hydro-metrological variables of the river basins.

6. REFERENCES

Albergel, J. and Nasri, S. (2001). "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, p. 120.

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)." *Proc. of Conference in Ohrid, FY Republic of Macedonia*, pp.1-12.

Berndtsson, R. (1987), "Spatial and temporal variability of rainfall and potential evaporation in Tunisia." *IAHS Publ.* No. 168, pp.91-100.

Beven, K. J. and Kirkby, M .J. (1979). "A physically-based,variable contributing area model of basin hydrology." *Hydrological Sciences Bulletin,* No. 24, pp.43-69.

Evans, I.S. (1972), "General gomorphometry, derivatives of altitude, and descriptive statistics." *Proc. of Symp. on Spatial Analysis in geomorphology,* Cambridge, England.

Fiorentino, M., Carriero, D., Iacobellis, V., Manfreda, S. and Portoghese, I. (2005). "Medclub-starting line and first activities." *IAHS Publ,* pp.1-14.

Hancock, G. R. (2005). "The use of digital elevation models in the identification and characterization of catchments over different grid scales." *Hydrological Processes* Vol.19, No.9, pp.1727-174.

Harlin, J. (1978). "Statistical moments of the hypsometric curve and its density function." *Mathematical Geology* Vol.10, No.1, pp.59-72.

Luo, W. (1998). “Hypsometric analysis with a geographic information system.” *Computers and Geosciences* Vol.24, No.8, pp.815-821.

Luo, W. and Harlin, J.M. (2003). “A theoretical travel time based on watershed hypsometry.” *Journal of the American Water Resources Association,* Vol.39, No.4, pp.785-792.

Nasri, S., Cudennec C., Albergel, J. and Berndtsson, R. (2004), “Use of a geomorphoplogical transfer function to model design floods in small hillside catchments in semiarid Tunisia.” *Journal of Hydrology*, No.287, pp.197-213.

Martinez C., Hancock G. R., Evans K. G. and Moliere D. R. (2005). “A catchment based assessment of the 3-Arc Second SRTM Digital Elevation Data set.” *Proc. of MODSIM 2005*, pp. 409-1415.

Rhode A. and Seibert J. (1999). “Wetland occurrence in relation to topography: a test of topography indices as moisture indicators.” *Agric. For Meteorol.* No.98/99, pp.325-340.

Rousseau, A. N., Hentati A., Tremblay S., Quilbй R. and Villeneuve, J. P. (2005). “Computation of the topographic index on 16 watersheds in Quebec.” *Report No.R800-f, INRS-ETE,* La Couronne, Quebec , Canada.

Xiao, L. (1991). “Flash floods in arid and semiarid zones.” *IHP-V Technical Documents in Hydrology,* No.23, UNESCO, France.