THE MORPHO-CLIMATIC BASIN DESCRIPTORS USED IN THE CUBIST PROJECT

Alberto VIGLIONE

Meaningful morphoclimatic descriptors of river basins should have direct connection to the hydrological processes taking place in drainage basins. These indices give synthetic information on the shape of basin surfaces, the nature of soil and vegetation and its climatic features. Ideally, these indices should play a role in the average water balance within the basin, with the morphologic ones related to the hydrologic response, and the climatic ones related to the water losses.

1.1 SELECTION OF MORPHOLOGIC PARAMETERS

In this subsection, some morphometric parameters of drainage basins and river networks are described. All of them can be computed automatically using GIS tools, using a procedure that has been developed within the "Linux" operating system, using the "bash" language of scripting, to exploit together the "GRASS" GIS and the "Fluidturtle" libraries (`http://www.ing.unitn.it/~rigon/indexo.html`). The "R" statistical computing software has been also used for the computation of statistical indices. The choice of open source software, under the GNU General Public License, has been determined by the fact that all these packages are constantly updated and improved by experts of the international scientific community. Following this philosophy our script is open, easily customizable, and available at the address `www.idrologia.polito.it/~alviglio/software/GRASSindex.htm`.

Two different types of morphologic parameters are considered: drainage basin and river network parameters.

1.1.1 Drainage basin parameters

For each drainage basin, morphological parameters were calculated operating on a Digital Elevation Model (DEM) with the "Fluidturtle" libraries. These libraries provide tools for DEM analysis like the pit removal (to ensure hydraulic connectivity within the watershed), the computation of flow directions, the delineation of channel networks and much more (see Figure 1).

The parameters selected with regard to drainage basins are as follows:

- Area S [km^2]: area of the plane projection of the drainage basin (see Figure 2).
- Centroid X_{bar}, Y_{bar} [m]/[deg]: position of the centroid of the plane projection of the drainage basin (see Figure 2).
- Perimeter P [km]: length of the contour of the plane projection of the drainage basin (see Figure 2).
- Reference elevations H_{max}, H_{min}, H_m [m a.s.l.]: maximum, minimum and mean elevation of the drainage basin (Figure 1.a) above sea level.

- Area above 2000 m a.s.l. S_{2000} [%]: ratio between the area lying above 2000 m a.s.l. and the total basin area.

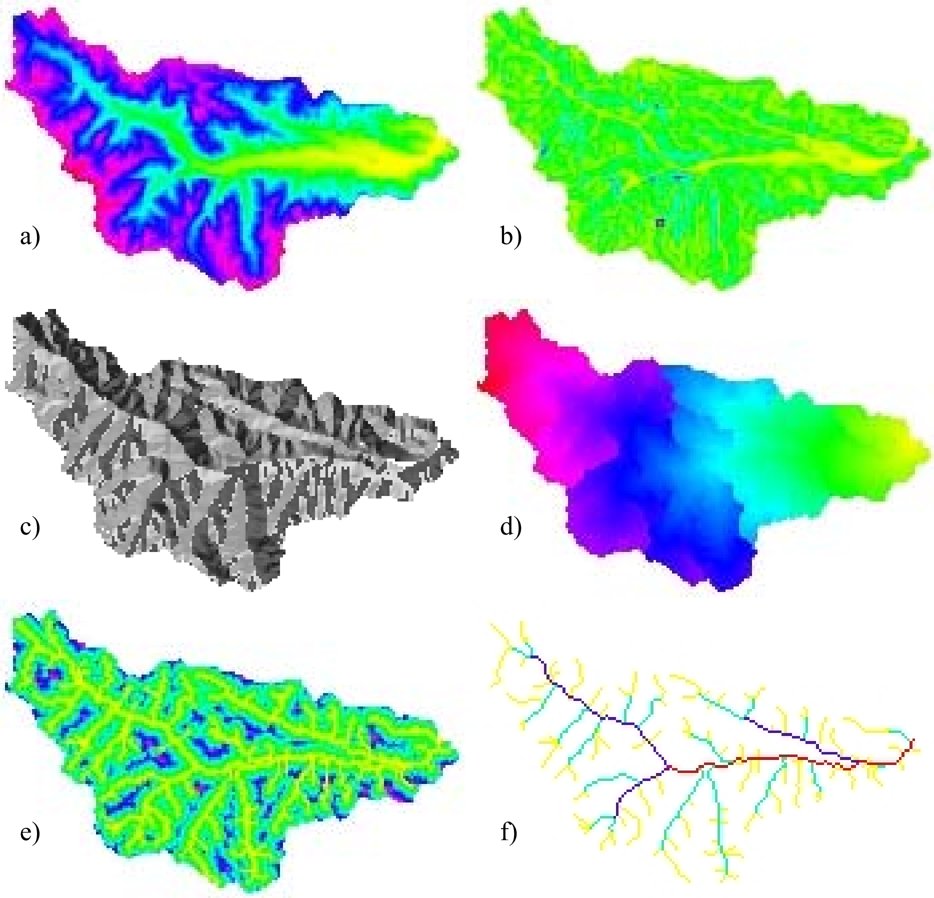

Figure 1 - Examples of parameter maps of a drainage basin obtained from the DEM: matrix of elevations (a), matrix of slopes (b), matrix of aspects (c), matrix of distances to the outlet (d), matrix of pixel distances to the network (e), Horton-Stralher ordering of the river network (f).

- Bounding box corners X_{max}, X_{min}, Y_{max}, Y_{min} [m]: coordinates of the rectangle containing the drainage basin. It refers to the smallest rectangle which entirely encloses the drainage basin (see Figure 2).

- Length of the orientation vector L_{OV} [km]: length of the segment joining the basin centre of mass to the basin outlet (see Figure 2).

- Main orientation angle O_{OV} [deg]: angle between the orientation vector and the north (see Figure 2).

Figure 2 - Geographic parameters of the catchment.

- Northing NORD and Easting EST: cosine and sine of O_{OV} . NORD is 1 if the basin is oriented northward, -1 if it is oriented southward. EST is 1 if the basin is oriented eastward, -1 if it is oriented westward.

- Mean small-scale slope p_m [%]: average of the slope values associated to each pixel in the DEM of the drainage basin (Figure 1.b).

- Mean large-scale slope P_m [%]:

$$P_m = arctg\left(\frac{2(H_{med} - H_{\min})}{\sqrt{S}}\right) \tag{1}$$

  where S is the basin area, H_{med} the median elevation and H_{min} the elevation of the closing section. The P_m is a slope measure of a square equivalent basin, and does not account for basin shape; its definition is objective, i.e. not affected by the DEM resolution.

- Mean aspect *MA* [deg]: geometric (vector) average of the aspect of each cell (Figure 1.c). The aspect is the direction towards which a slope faces and is important in hilly or mountainous terrain. Here it is defined as the angle of exposure of the cell (computed from the north).

- Area-elevation curve (hypsometric curve) $h_{\%}$ [m a.s.l.]: the curve represents the portion of the basin area located above a given elevation (Figure 3). The curve is represented recording elevations corresponding to the 2.5%, 5%, 10%, 25%, 50%, 75%, 90%, 95% and 97.5% of the area.

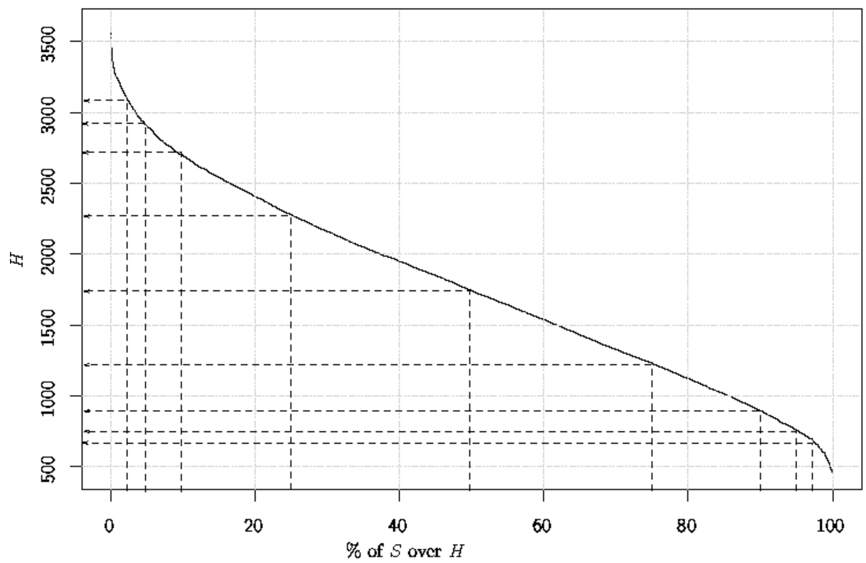

Figure 3 - Area-elevation curve.

- Circularity ratio R_c: ratio between the basin area and the area of a circle having the same perimeter:

$$R_c = \frac{4\pi S}{P^2} \tag{2}$$

where P is the watershed perimeter.

- Compactness (Gravelius) coefficient C_c: ratio between the perimeter of the basin and the diameter of the equivalent circle:

$$C_c = \frac{P}{2\sqrt{S/\pi}} \tag{3}$$

1.1.2 River network parameters

Selected analyses can be performed on the river network, that is automatically extracted from the DEM, using the above-described drainage directions and the following constraints:

- a pixel belongs to the network if its contributing area exceeds 1 km^2;
- a stream belongs to the network if it is composed of more than one pixel.

Parameters computed on the river networks are as follows:

- Length of the main stream L_{MS} [km]: length of the longest series of streams that connects the basin outlet to the foremost source point (i.e. the upper stream end).

- Main stream mean slope MS_{MS} [%]: the mean slope of the main stream is defined as the ratio between its total elevation drop ΔH and its length:

$$MS_{MS} = \frac{\Delta H}{L_{MS}} \tag{4}$$

- Length of the longest drainage path L_{LDP} [km]: the longest drainage path is the longest path between the basin outlet and the most distant point on the basin border, following drainage directions. Actually the longest drainage path corresponds to the main stream plus the path on the hillslope that connects the stream source to the basin border.

- Slope of the longest drainage path P_{LDP} [%]: average of the slope values associated to each pixel in the longest drainage path.

- Elongation ratio R_{al}: ratio between the diameter of a circle with area equivalent to the basin area and the length of the longest drainage path:

$$R_{al} = \frac{2\sqrt{S/\pi}}{L_{LDP}} \tag{5}$$

- Shape factor F_f: ratio between the basin area and the square of the longest drainage path length:

$$F_f = \frac{S}{L_{LDP}^2} \tag{6}$$

- Width function *FA* [m]: moments (mean, variance, skewness and kurtosis) and percentiles (5%, 15%, 30%, 40%, 50%, 60%, 70%, 85%, 95%) of the width function, which is defined as the cumulated frequency of the pixel metric distance from the basin outlet (Figure 1.d).

- Mean hillslope length *MHL* [m]: average distance (throughout all the basin) between pixels and channel (Figure 1.e).

- Magnitude *M*: number of source points of the network.

- Topological diameter d_T: number of links that constitute the main stream, or number of confluences to the main stream.

- Horton-Strahler ordering: number of links, average length, average contributing area and mean slope corresponding to every Horton class. These classes form an ordering classification system in which channel segments are ordered numerically from a stream's headwaters to the basin outlet (Figure 1.f). Numerical ordering begins with the tributaries at the stream's headwaters being assigned the value 1. A stream segment that results from the joining of two 1st order segments is given an order 2. Two 2nd order streams form a 3rd order stream, and so on.

- Horton ratios Rh_b, Rh_l, Rh_a, Rh_s: slope of the interpolation straight line (computed with the Ordinary Least Squares method) between the points given by the order and the variable (number of links, average length, average contributing area and mean slope) on a semi-logarithmic diagram. R.E. Horton applied morphometric analysis to a variety of stream attributes and from these studies he proposed a number of laws of drainage composition. For instance, Horton's law of stream lengths suggests that a geometric progression exists between the number of stream segments in successive stream orders (Rh_b).

- Total network length TNL [km]: sum of the lengths of all stream within the basin.

- Drainage density D_d [km/km^2]: measure of the length of stream channel per unit area of drainage basin. Mathematically it is expressed as the total network length divided by the area of the drainage basin. The measurement of drainage density provides a hydrologist or geomorphologist with a useful numerical measure of landscape dissection and runoff potential. On a highly permeable landscape, with small potential for runoff, drainage densities are sometimes less than 1 kilometer per square kilometer. On highly dissected surfaces densities of over 500 kilometers per square kilometer are often reported. Closer investigations of the processes responsible for drainage density variation have discovered that a number of factors collectively influence stream density. These factors include climate, topography, soil infiltration capacity, vegetation, and geology.

1.2 Estimation of climatic parameters

For a river basin, average climatic features can be considered attributes or “descriptors”, similarly to its morphologic parameters. Some scalar indices were considered, that account for climatic features related to the average water balance:

- Mean annual rainfall A_m [mm] areally averaged over the catchment;

- Thornthwaite index I_T: a global moisture index that can be estimated, in its simplest form, as the ratio

$$I_T = \frac{A_m - ET_0}{ET_0} \tag{7}$$

where ET_0 the mean annual potential evapotranspiration on the basin;

- Budyko index I_B: a radiational aridity index expressed as

$$I_B = \frac{R_n}{\lambda A_m}, \tag{8}$$

where R_n is the mean annual net radiation and λ is the latent vaporization heat. Values assumed by I_B are lower than 1 for humid regions and greater than 1 in arid regions.

The computation of the climatic indices proposed by Thornthwaite and Budyko requires the estimate of average annual precipitation, temperature, evapotranspiration and net radiation in the study area.

Evapotranspiration and solar radiation are estimated here using the procedures suggested by FAO (Allen et al., 1998). In place of the potential evapotranspiration, the reference crop evapotranspiration ET_0 is computed as a climatic parameter expressing the evaporation potential of the atmosphere from a unit surface, under well-watered conditions, cultivated with a reference crop with specific characteristics. The only factors affecting ET_0 are of climatic nature.
ET_0 has been estimated through the Hargreaves formulation (Hargreaves-Samani, 1982):

$$ET_{0H} = 0.0023 \cdot (T_{mean} + 17.8) \cdot (T_{max} - T_{min})^{0.5} \cdot R_a \tag{9}$$

where R_a is the extraterrestrial radiation, expressed in mm and computed on a daily basis. The Hargreaves formula is applied on a monthly basis, using the mean monthly temperature T_{mean} and the monthly averages of daily maximum and minimum temperatures T_{max} and T_{min} [°C]. R_a [MJ m^{-2} day^{-1}] can be easily calculated as a function of latitude and Julian day as:

$$R_a = \frac{24 \times 60}{\pi} \cdot R_o \cdot d_r \cdot (\omega_s \cdot sen\varphi \cdot sen\delta + \cos\varphi \cdot \cos\delta \cdot sen\omega_s) \tag{10}$$

with:

$$d_r = 1 + 0,033 \cdot cos\left(\frac{2\pi}{365} \cdot J\right) \tag{11}$$

$$\delta = 0,409 \cdot sen\left(\frac{2\pi}{365} \cdot J - 1,39\right) \tag{12}$$

$$\omega_s = ar\cos(-\tan\varphi \cdot \tan\delta) \tag{13}$$

where R_0 is the solar constant, that is the radiation reaching a surface perpendicular to the sun's rays at the top of the earth's atmosphere (0.082 MJ m^{-2} min^{-1}), d_r is the relative distance between the Earth and the Sun, δ [rad] is the solar declination, φ [rad] is the latitude, ω_s [rad] is the hour angle at sunset and J is the Julian day. To give a monthly balance, J can be determined by the relation:

$$J = int(30.42M - 15.23) \tag{14}$$

where M is the sequential number of the month.

As regards net radiation R_n, a much more complex procedure is requested for its estimation. As the radiation enters the atmosphere, it is partly scattered, reflected or absorbed by the atmospheric gases, clouds, aerosols and dust. The amount of radiation reaching a horizontal plane is named the solar radiation, R_s. For a cloudless day, R_s is roughly 75% of extraterrestrial radiation. A well-known method of estimation of R_s [MJ m^{-2} day^{-1}] is the Angstrom relation (1924):

$$R_S = \left(a + b \cdot \frac{n}{N}\right) \cdot R_a \tag{15}$$

where n is the actual duration of sunshine [hour], N is the maximum possible duration of sunshine for any given day [hour] and a and b are regression constants. The daylight hours, N, are given by:

$$N = \frac{24}{\pi}\omega_S \tag{16}$$

where ω_s is the sunset hour angle in radians given by Equation (13). Depending on atmospheric conditions (humidity and dust) and solar declination (latitude and month), the Angstrom parameters a and b vary. Where observed solar radiation data are not available and no specific calibration has been carried out, the values a=0.25 and b=0.50 are recommended. In Italy we suggest the coefficients a=0.33 and b=40, determined by Canova (2003) using a database published by ENEA (Petrarca et al., 1999).

When n is unknown, the ratio n/N can be estimated using the cloudiness fraction m_c with:

$$\frac{n}{N} = 1 - m_c \tag{17}$$

A considerable amount of solar radiation reaching the earth's surface is reflected. The fraction, α_s, of the solar radiation reflected by the surface is known as the albedo. For the green grass reference crop, α_s is assumed to have a value of 0.23. The net shortwave radiation R_{ns} [MJ m^{-2} day^{-1}] is the fraction of the solar radiation R_s that is not reflected from the surface:

$$R_{ns} = R_s(1 - \alpha_s) \tag{18}$$

The solar radiation absorbed by the earth is converted to heat energy. The earth's surface both emits and receives longwave radiation. The difference between outgoing and incoming longwave radiation is called the net longwave radiation, R_{nl} [MJ m^{-2} day^{-1}] that can be estimated as (see e.g. Allen et al., 1998):

$$R_{nl} = k \cdot \left[\frac{T_{maxK}^4 + T_{minK}^4}{2} \right] \cdot \left(0.34 - 0.14\sqrt{e_a} \right) \cdot \left(1.35 \frac{R_s}{R_{s0}} - 0.35 \right) \qquad (19)$$

where k is the Stefan-Boltzmann constant [4.903 10-9 MJ K^{-4} m^{-2} day^{-1}], T_{maxK} and T_{minK} are the maximum and minimum absolute temperatures during the 24-hour period [K = °C + 273.16], e_a is the actual vapour pressure [kPa] and R_s/R_{s0} is the relative shortwave radiation [MJ m^{-2} day^{-1}] (R_s is the measured or calculated (Equation (15)) solar radiation and R_{s0} is the computed clear-sky radiation). The actual vapour pressure e_a has been estimated assuming the minimum daily temperature as a good estimation of the dew-point temperature (see e.g. Allen et al., 1998) using the expression $e_a = 0.611 \exp[17.27\, T_{min}/(T_{min}+237.3)]$.

The net radiation R_n [MJ m^{-2} day^{-1}] is the difference between incoming and outgoing radiation of both short and long wavelengths:

$$R_n = R_{ns} - R_{nl} \qquad (20)$$

R_n represents the balance between the energy absorbed, reflected and emitted by the earth's surface. It is normally positive during the daytime and negative during night time. The total daily value for R_n is almost always positive over a period of 24 hours, except in extreme conditions at high latitudes.

REFERENCES

Allen R.G., Pereira L.S., Raes D., Smith M. *Crop evapotranspiration. Guidelines for computing crop water requirements*. FAO Irrigation And Drainage Paper 56, Roma, 1998.

Angstrom A. Solar and terrestrial radiation. *Q.J.Meteorol. Soc.*, Vol.50, pp. 121-125, 1924.

Bellardone G., Biancotti A., Bovo S., Cagnazzi B., Giacomelli L., Marchisio C. *Precipitazioni e temperature. Collana studi climatologici in Piemonte* (CD-ROM). Regione Piemonte, Università degli Studi di Torino, 1998.

Canova M.E., *Valutazione a scala nazionale dell'evapo-traspirazione e della radiazione solare*. Tesi di laurea, Politecnico di Torino, 2003.

Claps P., Mancino L., *Impiego di classificazioni climatiche quantitative nell'analisi regionale del deflusso annuo.* In XXVIII Convegno di Idraulica e Costruzioni Idrauliche, pp. 169–178, Potenza, 2002.

Hargreaves G.H., Samani Z.A. *Estimating potential evapotranspiration*. Tech. Note, J.Irrig. and. Drain Eng. ASCE 18: pp. 980-984, 1982.

Neteler M., Mitasova H. *OPEN SOURCE GIS. A GRASS GIS Approach*. 464 pp., Kluwer Academic Publishers, Boston, Dordrecht, 2004.

New M., Hulme M., Jones P.D. *Global 30-Year Mean Monthly Climatology, 1961-1990 Data set*. Available on-line [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A, 2000.

Petrarca S., Spinelli F., Cogliani E., Mancini M. *Profilo climatico dell'Italia*. ENEA (6 volumes), 1999.

USGS GTOPO30. U.S. Geological Survey's EROS Data Center, Available on-line [http://edcdaac.usgs.gov], 1996.

WEB REFERENCES

Fluidturtles, tools for geomorphology, http://www.ing.unitn.it/~rigon/indexo.html

Geographic Resources Analysis Support System (GRASS), http://www.grass.itc.it/

The R Project for Statistical Computing, http://www.r-project.org/

The GRASS script r.parametri_bacino.pg.sh
www.idrologia.polito.it/~alviglio/software/GRASSindex.htm