

# A

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## Appendix

### A.1 Selected equations used in GRASS modules

This appendix section includes equations for selected GRASS modules to provide theoretical background of the methods used in these modules and give users opportunity to assess advantages and limitations of their functionality. The equations are also helpful for those who would like to improve or extend the modules.

#### Basic Statistics

Several GRASS modules, such as `r.univar`, `v.univar`, `r.stats`, `r.series`, `r.neighbors` compute basic statistical measures. We list the relevant equations here for reference, but check the source code to see the exact implementation. In the following equations, we are using  $\bar{x}$  for mean estimated from sample of the population; replace it by  $\mu$  when you are working with the entire population.

*Arithmetic mean:*

$$\bar{x} = \frac{1}{n}(x_1 + x_2 + \dots + x_n) = \frac{1}{n} \sum_{i=1}^n x_i \quad (\text{A.1})$$

Arithmetic mean  $\bar{x}$  has the same units as  $x_i$ .

*Median:*

The median is the value below which 50% of the sample lie. To find the median, the data have to be ordered from the smallest to the highest. In case of an odd number of samples, it is the middle value; in case of an even number of samples, it is as half way between the two middle samples. Median has the same units as as the samples.

*Mode:*

The mode is defined as the most frequently occurring measurement in a data set. Continuous data need to be discretized into intervals to compute the mode. For data with normal distribution the mean, median and mode lead to the same value (in the limit of a large data sample).

*Mean absolute deviation:*

$$MD = \frac{1}{n} \sum_{i=1}^n |x_i - \bar{x}| \quad (\text{A.2})$$

The mean absolute deviation is an expression of dispersion about the mean. If the given values are deviations (e.g., provided by `v.surf.rst`), then we need arithmetic mean of absolute values:

$$\bar{x}_D = \frac{1}{n} (|x_1| + |x_2| + \dots + |x_n|) = \frac{1}{n} \sum_{i=1}^n |x_i| \quad (\text{A.3})$$

Arithmetic mean of absolute values has the same units as  $x_i$ .

*Variance for a population and for a sample:*

$$\sigma^2 = \frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2 \quad \sigma^2 = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2 \quad (\text{A.4})$$

The variance is another measure of dispersion, it is mean squared deviation and has the squared units of  $x_i$ .

*Standard deviation for a population and for a sample:*

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2} \quad \sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (\text{A.5})$$

The standard deviation is the positive square root of the variance and has the same units as  $x_p$ .

*Coefficient of variation:*

$$v = \frac{\sigma}{|\bar{x}|} * 100 \quad (\text{A.6})$$

The coefficient of variation is the ratio of the standard deviation to the mean and is dimensionless. It is expressed as a percentage when multiplied by 100 as in the above equation.

*Skewness:*

$$skewness = \frac{1}{n} \sum_{i=1}^n \left( \frac{x_i - \bar{x}}{\sigma} \right)^3 \tag{A.7}$$

Skewness is zero for any symmetric distribution. A distribution with a long tail towards larger values has a positive skewness (left skewed, typical for remote sensing images, Schowengerdt, 1997:118). Skewness is dimensionless and sensitive to outliers.

*Kurtosis:*

$$kurtosis = \left[ \frac{1}{n} \sum_{i=1}^n \left( \frac{x_i - \bar{x}}{\sigma} \right)^4 \right] - 3 \tag{A.8}$$

Kurtosis is zero for a normal distribution. If a distribution has a positive kurtosis, then the peak is sharper than of a Gaussian distribution. Kurtosis is dimensionless and sensitive to outliers.

*Covariance:*

$$covariance = \frac{1}{n-1} \sum_{i=1}^n (x_{im} - \bar{x}_m)(x_{in} - \bar{x}_n) \tag{A.9}$$

## Interpolation

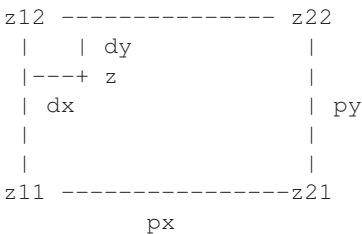
***Bilinear and bicubic interpolation*** Bilinear interpolation uses 4 neighboring cells to compute the unknown value  $z$  by performing linear interpolation in east-west and then north-east direction, leading to the following function:

$$z = a_0 + a_1 * x + a_2 * y + a_3 * x * y \tag{A.10}$$

Note that the above function is not linear, in spite of its name. Using the notation from the figure below the function can be written as follows:

$$z = z12*(1-u)*(1-v) + z22*u*(1-v) + z11*(1-u)*v + z21*u*v \tag{A.11}$$

where  $u = dx/px, v = dy/py$ .



Bicubic interpolation uses 16 cells leading to the following function:

$$z = a_0 + a_1x + a_2y + a_3x^2 + a_4xy + a_5y^2 + a_6x^2y + a_7xy^2 + a_8x^2y^2 + a_9x^3 + a_{10}y^3 + a_{11}x^3y + a_{12}xy^3 + a_{13}x^3y^2 + a_{14}x^2y^3 + a_{15}3x^3y^3 \quad (\text{A.12})$$

The coefficients are derived from the height at the four vertices, together with three partial derivatives at each vertex estimated using the neighboring vertices.

**Inverse distance weighted interpolation (IDW)** The method is based on an assumption that the value at an unsampled point can be approximated as a weighted average of values at points within a certain cut-off distance, or from a given number  $m$  of the closest points (typically 10 to 30). Weights are usually inversely proportional to a power of distance (Watson, 1992; Burrough, 1986) which, at an unsampled location  $\mathbf{r} = (x, y)$ , leads to an estimator:

$$F(\mathbf{r}) = \sum_{i=1}^m w_i z(\mathbf{r}_i) = \frac{\sum_{i=1}^m z(\mathbf{r}_i) / |\mathbf{r} - \mathbf{r}_i|^p}{\sum_{j=1}^m 1 / |\mathbf{r} - \mathbf{r}_j|^p} \quad (\text{A.13})$$

where  $p$  is a parameter (typically  $p = 2$ , for more details on the influence of this parameter, see Watson, 1992). GRASS modules use  $p = 2$  and  $m = 12$  as default values.

**Regularized Spline with Tension** The function is a sum of a *trend function* and a *radial basis function* with an explicit form which depends on the choice of the measure of smoothness, for more details see Mitsova and Mitsova (1993) and Mitsova et al. (1995):

$$z(\mathbf{r}) = T(\mathbf{r}) + \sum_{j=1}^N \lambda_j R(\mathbf{r}, \mathbf{r}^{[j]}). \quad (\text{A.14})$$

The trend function  $T(\mathbf{r})$  is given by

$$T(\mathbf{r}) = \sum_{l=1}^M a_l f_l(\mathbf{r}) \quad (\text{A.15})$$

where  $\{f_l(\mathbf{r})\}$  is a set of linearly independent functions (monomials) which have zero smooth seminorm.  $R(\mathbf{r}, \mathbf{r}^{[j]})$  is a radial basis function with an explicit form which depends on the choice of weights for partial derivatives in the smooth seminorm. See Mitsova and Mitsova (1993); Mitsova et al. (1995) for the RST smoothness seminorm, which includes derivatives of all orders with their weights decreasing with the increasing derivative order.

RST can be generalized to an arbitrary dimension and the corresponding  $d$ -variate formula for the radial basis function is given by

$$R_d(\mathbf{r}, \mathbf{r}_j) = R_d(|\mathbf{r} - \mathbf{r}_j|) = R_d(r) = \varrho^{-\delta} \gamma(\delta, \varrho) - \frac{1}{\delta} \quad (\text{A.16})$$

where  $r = |\mathbf{r} - \mathbf{r}_j|$ ,  $\delta = (d - 2)/2$ , and  $\varrho = (\varphi r/2)^2$ . Further,  $\varphi$  is a generalized tension parameter, and  $\gamma(\delta, \varrho)$  is the incomplete gamma function, not to be confused with semivariogram (Abramowitz and Stegun, 1964). For the special cases  $d = 2, 3, 4$  (`s.surf.rst`, `s.vol.rst`, `s.volt.rst`, respectively), the equation A.16 can be rewritten as:

$$R_2(r) = -[E_1(\varrho) + \ln \varrho + C_E] \quad (\text{A.17})$$

$$R_3(r) = \sqrt{\frac{\pi}{\varrho}} \operatorname{erf}(\sqrt{\varrho}) - 2 \quad (\text{A.18})$$

$$R_4(r) = \frac{1 - e^{-\varrho}}{\varrho} - 1 \quad (\text{A.19})$$

where  $C_E = 0.577215\dots$  is the Euler constant,  $E_1(\varrho)$  is the exponential integral function and  $\operatorname{erf}(\sqrt{\varrho})$  is the error function (Abramowitz and Stegun, 1964), while the trend function is a constant ( $M = 1$ ):

$$T(\mathbf{x}) = a_1, \quad d = 2, 3, 4 \quad (\text{A.20})$$

The coefficients  $a_1, \{\lambda_j\}$  are obtained by solving the following system of linear equations:

$$a_1 + \sum_{j=1}^N \lambda_j [R(\mathbf{r}^{[i]}, \mathbf{r}^{[j]}) + \delta_{ji} w_0/w_j] = z^{[i]}, \quad i = 1, \dots, N \quad (\text{A.21})$$

$$\sum_{j=1}^N \lambda_j = 0. \quad (\text{A.22})$$

where  $w_0/w_j$  are positive smoothing weights.

### Topographic analysis

Topographic parameters slope, aspect and curvatures are computed using the principles of differential geometry and derived, for example, by Krcho (1973, 1991), and Mitasova and Hofierka (1993). First we introduce the following simplifying notations:

$$f_x = \frac{\partial z}{\partial x}, \quad f_y = \frac{\partial z}{\partial y}, \quad f_{xx} = \frac{\partial^2 z}{\partial x^2}, \quad f_{yy} = \frac{\partial^2 z}{\partial y^2}, \quad f_{xy} = \frac{\partial^2 z}{\partial x \partial y} \quad (\text{A.23})$$

and

$$p = f_x^2 + f_y^2, \quad q = p + 1 \quad . \quad (\text{A.24})$$

The steepest slope angle  $\gamma$  in degrees or percent, and aspect angle  $\alpha$  in degrees are computed from gradient  $\nabla f = (f_x, f_y)$  (its direction is upslope) as follows

$$\gamma = \arctan \sqrt{p} \quad \gamma[\%] = 100 \cdot \sqrt{p} \quad (\text{A.25})$$

$$\alpha = \arctan \frac{f_y}{f_x} \quad (\alpha = 0 \text{ in west direction}) \quad . \quad (\text{A.26})$$

Sometimes we need to compute change of the surface in a direction given by an angle  $\alpha$ . The directional derivative of the surface  $z = g(x, y)$  can be computed as

$$E = \frac{\partial g}{\partial s} = \frac{\partial g}{\partial x} \cos \alpha + \frac{\partial g}{\partial y} \sin \alpha \quad (\text{A.27})$$

where  $(x, y)$  are the georeferenced coordinates, and  $\alpha$  is aspect (given direction).

**Curvatures** In general, a surface has different curvatures in different directions. For applications in geosciences, the curvature in gradient direction (profile curvature) is important because it reflects the change in slope angle and thus controls the change of velocity of mass flowing downwards along the slope curve. The curvature in a direction perpendicular to the gradient (tangential curvature) reflects the change in aspect angle and influences the divergence/convergence of water flow. Both curvatures are measured in the normal plane. Equations for these curvatures can be derived using the general equation for curvature  $\kappa$  of a plane section through a point on a surface (Rektorys, 1969; Mitasova and Mitas, 1993).

The equation for the profile curvature  $\kappa_s [m^{-1}]$  is

$$\kappa_s = \frac{f_{xx}f_x^2 + 2f_{xy}f_xf_y + f_{yy}f_y^2}{p\sqrt{q^3}} \quad . \quad (\text{A.28})$$

The equation for tangential curvature  $\kappa_t [m^{-1}]$  at a given point is derived as the curvature of normal plane section in a direction perpendicular to gradient (direction of tangent to the contour line)

$$\kappa_t = \frac{f_{xx}f_y^2 - 2f_{xy}f_xf_y + f_{yy}f_x^2}{p\sqrt{q}} \quad . \quad (\text{A.29})$$

The positive and negative values of profile and tangential curvature can be combined to define the basic geometric relief forms (Krcho, 1973, 1991; Dikau, 1989). Each form has a different type of flow. Convex and concave forms in gradient direction have accelerated and decelerated flow, respectively, and

convex and concave forms in tangential direction exhibit converging and diverging flow, respectively.

Other types of curvatures, such as the principle, mean, or Gauss curvatures as well as curvatures in an arbitrary direction can be computed directly from the interpolation function.

**Gradient and curvatures for volumes** Volumes can be modeled by a trivariate interpolation function in the general form of  $w = f(x, y, z)$ . When this function is differentiable at least up to the 2nd order, the topographic parameters for volumes (3D) can be computed directly from its partial derivatives (Mitasova et al., 1995). First, we introduce simplifying notations for partial derivatives of this function:

$$\begin{aligned}
 f_x &= \frac{\partial f}{\partial x}, & f_y &= \frac{\partial f}{\partial y}, & f_z &= \frac{\partial f}{\partial z}, \\
 f_{xx} &= \frac{\partial^2 f}{\partial x^2}, & f_{xy} &= \frac{\partial^2 f}{\partial x \partial y}, & f_{xz} &= \frac{\partial^2 f}{\partial x \partial z}, \\
 f_{yy} &= \frac{\partial^2 f}{\partial y^2}, & f_{yz} &= \frac{\partial^2 f}{\partial y \partial z}, & f_{zz} &= \frac{\partial^2 f}{\partial z^2}.
 \end{aligned}
 \tag{A.30}$$

Volume geometry parameters are also derived from differential geometry, using additional independent spatial coordinate (z). Theoretically, such topographic parameters can be derived up to N-dimensional space (see Hofierka, 1997b). For a three-dimensional cartesian space these parameters have the following form:

Size of gradient:

$$|\nabla f| = \sqrt{f_x^2 + f_y^2 + f_z^2} \tag{A.31}$$

Direction of gradient can be defined by two angles.

Horizontal angle  $A_n$ :

$$A_n = \arctan \left( \frac{f_y}{f_x} \right) \tag{A.32}$$

and vertical angle  $B_n$ :

$$B_n = \arctan \left( \frac{\sqrt{f_x^2 + f_y^2}}{f_z} \right) \tag{A.33}$$

The change of gradient size in its direction has the following form:

$$\frac{\partial |\nabla f|}{\partial n} = \frac{f_x^2 f_{xx} + 2f_{xz} f_x f_z + 2f_{xy} f_x f_y + f_y^2 f_{yy} + 2f_{yz} f_y f_z + f_z^2 f_{zz}}{f_x^2 + f_y^2 + f_z^2} \tag{A.34}$$

When we note principal curvatures in 3D cartesian space as  $k_1, k_2, k_3$ , then the Gauss-Kronecker curvature  $K$  can be expressed as:

$$K = k_1 * k_2 * k_3 \quad (\text{A.35})$$

The mean curvature  $M$  is:

$$M = \frac{k_1 + k_2 + k_3}{3} \quad (\text{A.36})$$

In cartesian system these equations can be expressed as follows:

$$K = \frac{f_{xz}^2 f_{yy} + f_{yz}^2 f_{xx} + f_{xy}^2 f_{zz} - f_{xx} f_{yy} f_{zz} - 2 f_{xy} f_{yz} f_{xz}}{\left(\sqrt{1 + f_x^2 + f_y^2 + f_z^2}\right)^5} \quad (\text{A.37})$$

$$H = \frac{\begin{vmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{vmatrix}}{3(1 + f_x^2 + f_y^2 + f_z^2)} \quad (\text{A.38})$$

where:

$$h_{11} = \frac{-f_{xx}}{\sqrt{1 + f_x^2 + f_y^2 + f_z^2}} + 2(1 + f_x^2) \quad (\text{A.39})$$

$$h_{12} = h_{21} = \frac{-f_{xy}}{\sqrt{1 + f_x^2 + f_y^2 + f_z^2}} + 2f_x f_y \quad (\text{A.40})$$

$$h_{22} = \frac{-f_{yy}}{\sqrt{1 + f_x^2 + f_y^2 + f_z^2}} + 2(1 + f_y^2) \quad (\text{A.41})$$

$$h_{13} = h_{31} = \frac{-f_{xz}}{\sqrt{1 + f_x^2 + f_y^2 + f_z^2}} + 2f_x f_z \quad (\text{A.42})$$

$$h_{23} = h_{32} = \frac{-f_{yz}}{\sqrt{1 + f_x^2 + f_y^2 + f_z^2}} + 2f_y f_z \quad (\text{A.43})$$

$$h_{33} = \frac{-f_{zz}}{\sqrt{1 + f_x^2 + f_y^2 + f_z^2}} + 2(1 + f_z^2) \quad (\text{A.44})$$

**Estimation of partial derivatives** To compute the above described equations for gradients and curvatures, we need to estimate first and second order partial derivatives.

In the RST-based modules, partial derivatives of RST functions are used. First, several definitions are introduced:

$$\eta = \frac{\varphi}{2} \quad (\text{A.45})$$



$$R'(r_j) = 2 \frac{1 - e^{-(\eta r_j)^2}}{r_j} \quad (\text{A.46})$$

$$R''(r_j) = 2 \frac{(2(\eta r_j)^2 + 1) e^{-(\eta r_j)^2} - 1}{r_j^2} \quad (\text{A.47})$$

Partial derivatives for the bivariate RST basis function can then be expressed as follows:

$$\frac{\partial R(r_j)}{\partial x} = R'(r_j) \frac{(x - x^{[j]})}{r_j}, \quad l = 1, 2 \quad (\text{A.48})$$

$$\frac{\partial^2 R(r_j)}{\partial x_1^2} = R''(r_j) \frac{(x - x^{[j]})^2}{r_j^2} + R'(r_j) \frac{(y - y^{[j]})^2}{r_j^3} \quad (\text{A.49})$$

whereas the derivatives, according to  $y$ , are found easily from Equation A.49 by exchange of  $x$  to  $y$ . The mixed derivative is given by

$$\frac{\partial^2 R(r_j)}{\partial x \partial y} = \left[ R''(r_j) - \frac{R'(r_j)}{r_j} \right] \frac{(x - x^{[j]})(y - y^{[j]})}{r_j^2} \quad (\text{A.50})$$

These expressions for first and second order derivatives are used for the computation of slope, aspect and curvatures in the modules `s.surf.rst`, `v.surf.rst` and `r.resamp.rst`. Optionally, the values of these partial derivatives are output by the module `s.surf.rst` when using the flag `-d`.

Partial derivatives for trivariate RST :

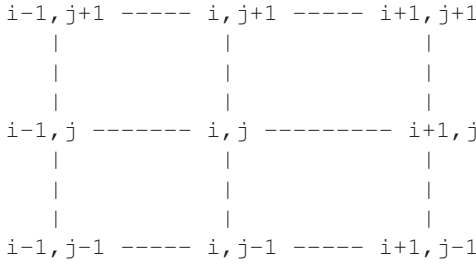
$$R'(r_j) = \frac{1}{r_j \sqrt{\pi}} \exp \left[ - \left( \frac{\varphi r_j}{2} \right)^2 \right] - \frac{1}{\varphi r_j^2} \operatorname{erf} \left( \frac{\varphi r_j}{2} \right) \quad (\text{A.51})$$

$$R''(r_j) = \frac{2}{\varphi r_j^3} \operatorname{erf} \left( \frac{\varphi r_j}{2} \right) - \sqrt{\pi} \left( \frac{2}{r_j^2} + \frac{\varphi^2}{2} \right) \exp \left[ - \left( \frac{\varphi r_j}{2} \right)^2 \right] \quad (\text{A.52})$$

In `r.slope.aspect`, second order polynomial approximation of a surface defined by given point and its  $3 \times 3$  neighborhood is used leading to the following equations for the partial derivatives (as used in Horn's formula, see Horn, 1981):

$$z(x, y) = a_0 + a_1 x + a_2 y + a_3 xy + a_4 x^2 + a_5 y^2 \quad (\text{A.53})$$

By fitting this polynomial to the 9 grid points (the given point  $z_{i,j}$  and its  $3 \times 3$  neighborhood, as shown below), using weighted least squares, we can derive the coefficients of this polynomial as well as its partial derivatives ( $f_x = a_1$ ,  $f_y = a_2$ ,  $f_{xx} = 2a_4$ ,  $f_{yy} = 2a_5$ ,  $f_{xy} = a_3$ ):



$$f_x = \frac{(z_{i-1,j-1} - z_{i+1,j-1}) + (2z_{i-1,j} - 2z_{i+1,j}) + (z_{i-1,j+1} - z_{i+1,j+1})}{8\Delta x} \tag{A.54}$$

$$f_y = \frac{(z_{i-1,j-1} - z_{i-1,j+1}) + (2z_{i,j-1} - 2z_{i,j+1}) + (z_{i+1,j-1} - z_{i+1,j+1})}{8\Delta y} \tag{A.55}$$

where  $\Delta x$  and  $\Delta y$  is the resolution (grid spacing) in the east-west and north-south direction respectively.

Let us denote  $D(i, \delta) = z_{i,j+1} + z_{i,j-1} - 2z_{i,j}$  and  $D(\delta, j) = z_{i+1,j} + z_{i-1,j} - 2z_{i,j}$ . Then we can write

$$f_{xx} = \frac{D(\delta, j + 1) + (4z_{i-1,j} + 4z_{i+1,j} - 8z_{i,j}) + D(\delta, j - 1)}{6(\Delta x)^2} \tag{A.56}$$

$$f_{yy} = \frac{D(i - 1, \delta) + (4z_{i,j+1} + 4z_{i,j-1} - 8z_{i,j}) + D(i + 1, \delta)}{6(\Delta y)^2} \tag{A.57}$$

$$f_{xy} = \frac{(z_{j-1,i-1} - z_{j-1,i+1}) - (z_{j+1,i-1} - z_{j+1,i+1})}{4\Delta x\Delta y} \tag{A.58}$$

where  $z_{i,j}$  is the elevation value at row  $j$  column  $i$ ,  $\Delta x$  is the east-west grid spacing and  $\Delta y$  is the north-south grid spacing (resolution).

### Insolation

Equations for computation of solar energy related parameters used in `r.sun` (Hofierka, 1997a; Hofierka and Sári, 2002, further citations in the manual page of `r.sun`). The clear-sky solar radiation model applied in this module is based on the work undertaken for development of European Solar Radiation Atlas (Scharmer and Greif, 2000; Page et al., 2001; Rigollier et al., 2000).

### *Solar geometry*

Declination  $d$  [rad]:

$$\delta = \arcsin(0.3978 \sin(j - 1.4 + 0.0355 \sin(j - 0.0489))) \quad (\text{A.59})$$

where:

$$j = 2\pi \text{day} / 365.25 \quad [\text{rad}]$$

Position of the sun in respect to a horizontal plane:

$$\sinh_0 = C_{31} \cos T + C_{33} \quad (\text{A.60})$$

$$\cos A_0 = \frac{C_{11} \cos T + C_{13}}{\sqrt{(C_{22} \sin T)^2 + (C_{11} \cos T + C_{13})^2}} \quad (\text{A.61})$$

where:

$$\begin{aligned} C_{11} &= \sin \varphi \cos \delta \\ C_{13} &= -\cos \varphi \sin \delta \\ C_{22} &= \cos \delta \\ C_{31} &= \cos \varphi \cos \delta \\ C_{33} &= \sin \varphi \sin \delta \end{aligned}$$

Position of the sun in respect to an inclined plane:

$$\sin \delta_{exp} = C'_{31} \cos(T - \lambda') + C'_{33} \quad (\text{A.62})$$

where:

$$\begin{aligned} C'_{31} &= \cos \varphi' \cos \delta \\ C'_{33} &= \sin \varphi' \sin \delta \\ \sin \varphi' &= -\cos \varphi \sin \gamma_N \cos A_N + \sin \varphi \cos \gamma_N \\ \tan \lambda' &= -\frac{\sin \gamma_N \sin A_N}{\sin \varphi \sin \gamma_N \cos A_N + \cos \varphi \cos \gamma_N} \end{aligned}$$

Sunrise/sunset over a horizontal plane:

$$\cos(Th_{r,s}) = -\frac{C_{33}}{C_{31}} \quad (\text{A.63})$$

Sunrise/sunset over an inclined plane:

$$\cos(Tp_{r,s} - \lambda') = -\frac{C'_{33}}{C'_{31}} \quad (\text{A.64})$$

**Extraterrestrial irradiance on a plane perpendicular to the solar beam  $G_0$  [ $W/m^2$ ]**

$$G_0 = I_0 \epsilon \tag{A.65}$$

where:

$$\epsilon = 1 + 0.03344 \cos(j - 0.048869)$$

values  $j$  and  $0.048869$  are in radians.

**Extraterrestrial irradiance on a horizontal plane  $G_{0h}$  [ $W/m^2$ ]**

$$G_{0h} = G_0 \sin h_0 \tag{A.66}$$

**Beam irradiance on a horizontal plane  $B_h$  [ $W/m^2$ ]**

$$B_h = G_0 e^{(-0.8662 T_{LK} m \delta_R(m))} \sin h_0 \tag{A.67}$$

where:

$$p/p_0 = e^{(-z/8434.5)}$$

$$\Delta h_0^{ref} = 0.061359(0.1594 + 1.123h_0 + 0.065656h_0^2)/(1 + 28.9344h_0 + 277.3971h_0^2)$$

$$h_0^{ref} = h_0 + \Delta h_0^{ref}$$

$$m = (p/p_0)/(\sin h_0^{ref} + 0.50572(h_0^{ref} + 6.07995)^{-1.6364})$$

where values  $h_0^{ref}$  and  $6.07995$  are in degree

$$\delta_R(m) = 1/(6.6296 + 1.7513m - 0.1202m^2 + 0.0065m^3 - 0.00013m^4)$$

if  $m \leq 20$

$$\delta_R(m) = 1/(10.4 + 0.718m)$$

if  $m > 20$

**Beam irradiance on an inclined plane  $B_i$  [ $W/m^2$ ]**

$$B_i = G_0 e^{(-0.8662 T_{LK} m \delta_R(m))} \sin \delta_{exp} \tag{A.68}$$

**Diffuse irradiance on a horizontal plane  $B_h$  [ $W/m^2$ ]**

$$D_h = G_0 F_d(h_0) Tn(T_{LK}) \tag{A.69}$$

where:

$$Tn(T_{LK}) = -0.015843 + 0.030543 T_{LK} + 0.0003797 T_{LK}^2$$

$$F_d(h_0) = A_1 + A_2 \sin h_0 + A_3 \sin^2 h_0$$

$$A'_1 = 0.26463 - 0.061581 T_{LK} + 0.0031408 T_{LK}^2$$

$$A_1 = 0.0022/Tn(T_{LK})$$

$$\begin{aligned}
 A_1 &= A'_1 && \text{if } A'_1 Tn(T_{LK}) < 0.0022 \\
 A_2 &= 2.04020 + 0.018945 T_{LK} + 0.011161 T_{LK}^2 && \text{if } A'_1 Tn(T_{LK}) \geq 0.0022 \\
 A_3 &= -1.3025 + 0.039231 T_{LK} + 0.0085079 T_{LK}^2
 \end{aligned}$$

*Diffuse irradiance on an inclined plane  $D_i$  [ $W/m^2$ ]*

$$D_i = D_h F_x \quad (\text{A.70})$$

where:

if plane is in shade (e.g.  $\delta_{exp} < 0$  and  $h_0 \geq 0$ ):

$$\begin{aligned}
 F_x &= F(\gamma_N) \\
 F(\gamma_N) &= r_i(\gamma_N) + \left( \sin \gamma_N - \gamma_N \cos \gamma_N - \pi \sin^2 \left( \frac{\gamma_N}{2} \right) \right) 0.252271
 \end{aligned}$$

if plane is sunlit under clear sky:

if  $h_0 \geq 0.1 \text{ rad}$ :

$$F_x = F(\gamma_N)(1 - K_b) + K_b \sin \delta_{exp} / \sin h_0$$

if  $h_0 < 0.1 \text{ rad}$ :

$$F_x = F(\gamma_N)(1 - K_b) + K_b \sin \gamma_N \cos A_{LN} / (0.1 - 0.008h_0)$$

$$A_{LN}^* = A_0 - A_N$$

$$A_{LN} = A_{LN}^*$$

$$\text{if } -\pi \leq A_{LN}^* \leq \pi$$

$$A_{LN} = A_{LN}^* - 2\pi$$

$$\text{if } A_{LN}^* > \pi$$

$$A_{LN} = A_{LN}^* + 2\pi$$

$$\text{if } A_{LN}^* < -\pi$$

$$\begin{aligned}
 F(\gamma_N) &= r_i(\gamma_N) \\
 &+ \left( \sin \gamma_N - \gamma_N \cos \gamma_N - \pi \sin^2 \left( \frac{\gamma_N}{2} \right) \right) (0.00263 - 0.712K_b - 0.6883K_b^2)
 \end{aligned}$$

$$K_b = B_h / G_{0h}$$

$$r_i(\gamma_N) = (1 + \cos \gamma_N) / 2$$

*Diffuse ground reflected irradiance on an inclined plane  $R_i$  [ $W/m^2$ ]*

$$R_i = \rho_g G_h r_g(\gamma_N) \quad (\text{A.71})$$

where:

$$r_g(\gamma_N) = (1 - \cos \gamma_N) / 2$$

$$G_h = B_h + D_h$$

with  $G_h$  in [ $W/m^2$ ]

**Symbols**

- Position of the grid cell (solar plane):
  - $\varphi$  geographical latitude [rad],
  - $z$  elevation above sea level [m],
  - $\gamma_N$  slope angle [rad],
  - $A_N$  aspect (orientation, azimuth) – angle between the projection of the normal on the horizontal plane and east [rad],
  - $\varphi'$  relative geographical latitude of an inclined plane [rad],
  - $\lambda'$  relative geographical longitude [rad].
- Parameters of the surface (plane):
  - $\rho_g$  mean ground albedo.
- Date-related parameters:
  - $day$  day number 1-365 (366),
  - $j$  Julian day number expressed as a day angle [rad],
  - $T$  time of computation [decimal hours/rad],
  - $Th_{r,s}$  time of sunrise and sunset over the local horizon,
  - $Tp_{r,s}$  time of sunrise and sunset over the inclined grid cell (plane),
  - $\delta$  solar declination [rad],
  - $\epsilon$  correction of the variation of sun-earth distance from its mean value.
- Solar position:
  - $h_0$  solar altitude – an angle between sun and horizon [rad],
  - $A_0$  solar azimuth – an angle between sun and meridian measured from east [rad],
  - $A_{LN}$  angle between the vertical plane containing the normal to the surface and vertical plane passing through the center of the solar disc [rad],
  - $\delta_{exp}$  solar incidence angle - an angle between sun and the (inclined) plane [rad].
- Solar radiation:
  - $I_0$  solar\_const = 1367 W/m<sup>2</sup>,
  - $G_0$  extraterrestrial irradiance on a plane perpendicular to the solar beam [W/m<sup>2</sup>],
  - $G_h$   $G_h = B_h + D_h$  – global solar irradiance on a horizontal plane [W/m<sup>2</sup>],
  - $G_i$   $G_i = B_i + D_i + R_i$  – global solar irradiance on an inclined plane [W/m<sup>2</sup>],
  - $B_h$  beam irradiance on a horizontal plane [W/m<sup>2</sup>],
  - $B_i$  beam irradiance on an inclined plane [W/m<sup>2</sup>],
  - $D_h$  diffuse irradiance on a horizontal plane [W/m<sup>2</sup>],
  - $D_i$  diffuse irradiance on an inclined plane [W/m<sup>2</sup>],
  - $R_i$  diffuse ground reflected irradiance on an inclined plane [W/m<sup>2</sup>].
- Parameters of the atmosphere:
  - $p/p_0$  correction of station elevation [-],
  - $T_{LK}$  Linke turbidity factor [-],
  - $T_L$  corrected Linke turbidity factor ( $T_L = 0.8662 T_{LK}$ ), see Kasten (1996),
  - $m$  relative optical air mass [-],
  - $\delta_R(m)$  Rayleigh optical thickness [-].

- Parameters of the radiation transmission:
  - $F_d(h_0)$  diffuse solar elevation function,
  - $Tn(T_{LK})$  diffuse transmission function,
  - $F(\gamma_N)$  function accounting for the diffuse sky irradiance distribution,
  - $K_b$  proportion between beam irradiance and extraterrestrial solar irradiance on a horizontal plane,
  - $r_i(\gamma_N)$  fraction of the sky dome viewed by an inclined plane [-],
  - $r_g(\gamma_N)$  fraction of the ground viewed by an inclined plane [-].

### Walking person

Anisotropic movement of a person between different geographic locations:

$$T = a.\Delta S + b.\Delta H_u + c.\Delta H_d + d.\Delta H_s \quad (\text{A.72})$$

where  $T$  is time of movement in seconds,  $\Delta S$  is the distance covered in meters,  $\Delta H_u, H_d, H_s$  is the altitude difference in meters when going uphill, downhill, and steep downhill respectively. The  $a, b, c, d$  parameters represent speed under different conditions and are linked to  $a$  underfoot condition ( $a=1/\text{walking\_speed}$ ),  $b$  underfoot condition and cost associated to movement uphill,  $c$  underfoot condition and cost associated to movement moderate downhill,  $d$  underfoot condition and cost associated to movement steep downhill. Moving downhill is beneficial up to a specific slope value threshold, after that it becomes unfavourable. The default slope value threshold (slope factor) is -0.2125, corresponding to  $\tan(12)$  downslope. The default values for  $a, b, c, d$  are those proposed by Langmuir (0.72, 6.0, 1.9998, -1.9998), based on man walking effort in standard conditions. Total cost is estimated as a linear equation combining movement and friction costs using the  $\lambda$  parameter:

$$TC = MC + \lambda * FC \quad (\text{A.73})$$

where  $TC$  is total cost,  $MC$  is movement time cost and  $FC$  is friction costs, (see Aitken, 1977; Fontanari, 2001).

## A.2 Landscape process modeling

### *Wetness index*

$$W = \ln \frac{A}{\tan \beta} \quad (\text{A.74})$$

where  $A$  is the upslope area per unit contour width [m] and  $\beta$  is the slope angle in [deg].

**Universal Soil Loss Equation (USLE, RUSLE)**

$$A = RKLSCP \quad (\text{A.75})$$

where  $A$  is average annual soil loss in  $\text{ton}/(\text{acre}\cdot\text{year})=0.2242\text{kg}/(\text{m}^2\cdot\text{year})$ ,  $R$  is rainfall factor in  $(\text{hundreds of ft}\cdot\text{tonf.in})/(\text{acre}\cdot\text{hr}\cdot\text{year})=17.02(\text{MJ}\cdot\text{mm})/(\text{ha}\cdot\text{hr}\cdot\text{year})$ ,  $K$  is soil erodibility factor in  $(\text{ton acre}\cdot\text{hr})/(\text{hundreds of acre ft}\cdot\text{tonf.in})=0.1317(\text{ton}\cdot\text{ha}\cdot\text{hr})/(\text{ha}\cdot\text{MJ}\cdot\text{mm})$ ,  $LS$  is a dimensionless topographic (length-slope) factor,  $C$  is a dimensionless land cover factor, and  $P$  is a dimensionless prevention measures factor. The modified factor, representing topographic potential for erosion at a point on the hillslope, is a function of the upslope area per unit width and the slope angle:

$$LS = (m + 1) \left( \frac{U}{22.1} \right)^m \left( \frac{\sin \beta}{0.09} \right)^n \quad (\text{A.76})$$

where  $U$  is the upslope area per unit width (measure of water flow) in meters ( $\text{m}^2/\text{m}$ ),  $\beta$  is the slope angle in degree, 22.1 is the length of the standard USLE plot in meters and  $0.09 = 9\% = 5.15^\circ$  is the slope of the standard USLE plot. The values of exponents range for  $m = 0.2 - 0.6$  and  $n = 1.0 - 1.3$ , where the lower values are used for prevailing sheet flow and higher values for prevailing rill flow. When nothing is known about the type of flow,  $m = 0.4$  and  $n = 1.3$  are usually used (see RUSLE for ArcView<sup>1</sup>).

**Unit Stream Power Based Erosion/Deposition model (USPED)**

The *Unit Stream Power Based Erosion/Deposition model (USPED)* (Mitasova and Mitas, 2001) estimates a simplified case of erosion/deposition using the idea originally proposed by Moore and Burch (1986). It combines the RUSLE parameters and upslope contributing area per unit width  $A$  to estimate the sediment flow  $T$ :

$$T \approx RKCPA^m(\sin\beta)^n. \quad (\text{A.77})$$

The upslope area and slope are not normalized, because  $T$  is an estimate of sediment flow [ $\text{kg}/(\text{ms})$ ] (rather than soil detachment [ $\text{kg}/(\text{m}^2\text{s})$ ]). The net erosion/deposition  $D$  [ $\text{kg}/(\text{m}^2\text{s})$ ] is then computed as a divergence of sediment flow:

$$D = \nabla \cdot (T\mathbf{s}_0) = \frac{d(T \cos \alpha)}{dx} + \frac{d(T \sin \alpha)}{dy}, \quad (\text{A.78})$$

where  $\alpha$  in degrees is the aspect of the terrain surface (direction of flow). The exponents  $m, n$  control the relative influence of water and slope terms and reflect the impact of different types of flow. The typical range of values is  $m = 1.0 - 1.6, n = 1.0 - 1.3$ , with the higher values reflecting the pattern for

<sup>1</sup> RUSLE for ArcView,

<http://abe.www.ecn.purdue.edu/~engelb/agen526/gisrusle/gisrusle.html>



prevailing rill erosion with more turbulent flow when erosion sharply increases with the amount of water. Lower exponent values close to  $m = n = 1$  better reflect the pattern of compounded, long term impact of both rill and sheet erosion and averaging over a long term sequence of large and small events.

### A.3 Definition of SQLite-ODBC connection

At time of this writing, there is only OpenOffice.org Base which can be used as powerful graphical user interface to SQL databases. While GRASS can be directly connected to SQLite, OpenOffice.org Base needs an ODBC based driver, the “sqliteodbc” library<sup>2</sup> and of course ODBC. In this example, we define a sample SQLite-ODBC connection.

After installation of the “sqliteodbc” library, on UNIX-based systems, add the driver to `/etc/odbcinst.ini` (either add next lines or create as new file if the file does not yet exist):

```
[SQLite]
Description=SQLite ODBC Driver
Driver=/usr/local/lib/libsqlite3odbc.so
Setup=/usr/local/lib/libsqlite3odbc.so
```

Now the SQLite driver is available for ODBC. The next step is to add the definition(s) of the database you want to connect to. Add an ODBC Data Source Name (DSN) to your definition file at `$HOME/.odbc.ini` (replace “user” and “mymapset” with the correct entries):

```
[nc_sqlite]
Description=North Carolina SQLite DB
Driver=SQLite
Database=/home/user/grassdata/nc_spm/mymapset/sqlite.db
# optional lock timeout in milliseconds
Timeout=2000
```

See Section 6.2.1 for GRASS related usage notes of the SQLite driver. For installation under MS-Windows see the “sqliteodbc” Web page.

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<sup>2</sup> Web site of “sqliteodbc” library, <http://www.ch-werner.de/sqliteodbc/>

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