Detrended Kriging Program (DK)
User's Guide

1 Introduction

The purpose of this program is to estimate spatial fields of precipitation, temperature, and snow water equivalent by interpolating among point measurements from standard surface stations. The program was written with daily time series data in mind, but it can also be used to interpolate data at other temporal resolutions. The algorithm is based on detrended kriging and is documented in Garen et al. (1994), Garen (1995), and Garen (2013). It has found use in several studies, including Garen and Marks (1996), Schumann and Garen (1998), Susong et al. (1999), Geyer et al. (2001), and Garen and Marks (2005).

The motivation for the development of this program was to create a better way of calculating mean areal inputs for spatially lumped hydrologic simulation models and to create a method for estimating spatial fields of these inputs for spatially distributed models, especially in mountainous areas. Traditional methods, such as Thiessen polygons and other station weighting procedures, do not adequately account for orographic effects nor do they make use of modern spatial estimation (geostatistical) techniques. This program is an attempt to account for the most important factors affecting hydrometeorological variables, taking advantage of topographic information, and to create usable software for operational applications.

The program is most appropriate for mesoscale watersheds, approximately 100 - 10000 km^2. The implicit assumption is that there is a homogeneous relationship between the hydrometeorological variable and elevation within this domain, hence other factors such as slope, aspect, differing orographic regimes, etc. are not considered. For large regions where climatic regimes do differ, the DK program should probably be applied to sub-regions where homogeneity could be assumed, or other methods would have to be applied, such as the procedure in the PRISM program (Daly et al., 1994; PRISM Group, 2009) used to identify homogeneous areas within a large region. Some evidence suggests, however, that even if DK is applied in a region that is not homogeneous with respect to the orographic regime, the kriging can compensate for this to a significant degree, and one can still obtain good interpolated results (Garen et al., 1994; Jarvis and Stuart, 2001).

The program is written in the C programming language and has been successfully compiled and run on PCs and on UNIX workstations (Hewlett-Packard, IBM, Sun, Macintosh). On a PC, the author has been using the Microsoft Visual C++ compiler for a number of years, whereas the GNU C compiler has been used in UNIX (but it also can be used on a PC). Makefiles have been created for both systems, although the makefile concept does not really apply with Visual C++.

Users must bear in mind that this program was originally written primarily for the author's own use, and as such, it is not a commercial software product. It does not contain extensive error-trapping features, so it is possible for the program to terminate abnormally if the input data are not prepared exactly as required. One must also exercise caution when entering file names during the program dialog, as the program opens files without checking first if the file already exists (thereby destroying any existing information). Finally, while the author believes that the program functions properly, there is no guarantee that it is bug-free. If users discover problems, or if they would like enhancements or modifications, they are encouraged to contact the author (see information near the end of this document before the Appendices).

2 Algorithm description

Spatial fields on a grid cell basis for precipitation, temperature, and snow water equivalent are calculated by interpolating point measurements at hydrometeorological stations for a given time period. Grid cells are represented by latitude or northing, longitude or easting, and elevation. These are most easily defined by a digital elevation model (DEM).

This algorithm was originally developed with daily data in mind. It can, however, be applied to data of any time resolution. The implementation described below explicitly allows for four time resolutions: hourly, daily, monthly, and yearly.

Spatial interpolation is done by detrended kriging, which carries out the interpolation by dividing the variability into a vertical and a horizontal component. The vertical component is described by time-varying linear relationships between the hydrometeorological quantity and elevation. The detrending is then accomplished by subtracting the line from the observations, thus yielding the residuals, which are used in the kriging calculations. Ordinary kriging is used as a station weighting scheme to describe the horizontal variability (although the option does exist to weight the stations equally). Kriging weights are calculated from the distances among stations and distances between stations and grid cells. This is equivalent to using a linear semivariogram, which greatly speeds up the calculations and does not require the estimation of a semivariogram for each time step, but rather the kriging weights become constant over the entire simulation period. The implicit assumption here is that within the spatial extent of the domain, the semivariogram does not reach a sill and that a line adequately approximates the rising portion of the semivariogram.

For calculating the relationships of the data with elevation, the data can be aggregated into periods of a specified number of time periods in length. For daily precipitation only, there is another option of aggregating into storms, which are defined as consecutive sequences of days where, on each day, at least three stations have precipitation and at least one of these has more than 5 mm. This aggregation affects only the way the detrending regression equations are calculated, not the aggregation of the output. An aggregation period of one time period is generally recommended for most purposes. This allows the maximum flexibility to follow the actual elevation trend for any given time period. More robust (i.e., less temporally variable) estimates of the elevation trends can be obtained by aggregating, if this information is more important to the user. In this case, there are no clear rules for choosing an aggregation period, but storms for precipitation and a few days for temperature would be the most reasonable. An aggregation of one time period should always be used for snow water equivalent, because this is an accumulated variable and the others are not. An aggregation period of one should always be used when using the program to interpolate fields of long-term averages or monthly and annual time series (see section “Hydrometeorological Input Data Format”).

There are constraints placed on the detrending lines (except for the generic data type of “other”, for which there are no constraints). For precipitation, the slope of the line must be positive, otherwise it is set to zero. This is to ensure that the detrending is in fact dealing with orographic influences, for which precipitation increases with elevation. By setting the slope to zero if it is negative, the detrending step is in effect not done, thereby saying that there is no trend with elevation, and the interpolation consists only of kriging in the horizontal. Similarly, for temperature, the slope of the regression line must be negative, otherwise it is set to zero. The program deals only with the normal cooling with elevation and hence does not handle temperature inversions or other unusual atmospheric conditions that would cause temperature to increase with elevation. Here again, a zero slope reduces the interpolation to purely kriging in the horizontal.

Detrending for snow water equivalent is handled like precipitation, except that the program takes an extra step to identify an approximate snow line elevation and do the detrending only for stations above this elevation. This is particularly important early and late in the snow season, when the lower elevations are snow-free. For each day, the snow water equivalent measurements are examined, in order of low to high elevation, to identify the first nonzero value. All measurements above this in elevation are used to calculate the detrending line. The elevation at which this line predicts zero snow water equivalent is the estimated snow line. No detrending is used for stations or grid cells below this snow line. Users should be cautioned that during the initial snow accumulation period and during the latter part of the melt period, the detrending can be unstable due to stations switching from snow-free to snow-covered and vice versa. This causes stations to enter or leave the group used for detrending, which usually causes an abrupt change in the detrending line. During the main part of the winter, after the snowpack is well-established, the interpolation algorithm performs well.

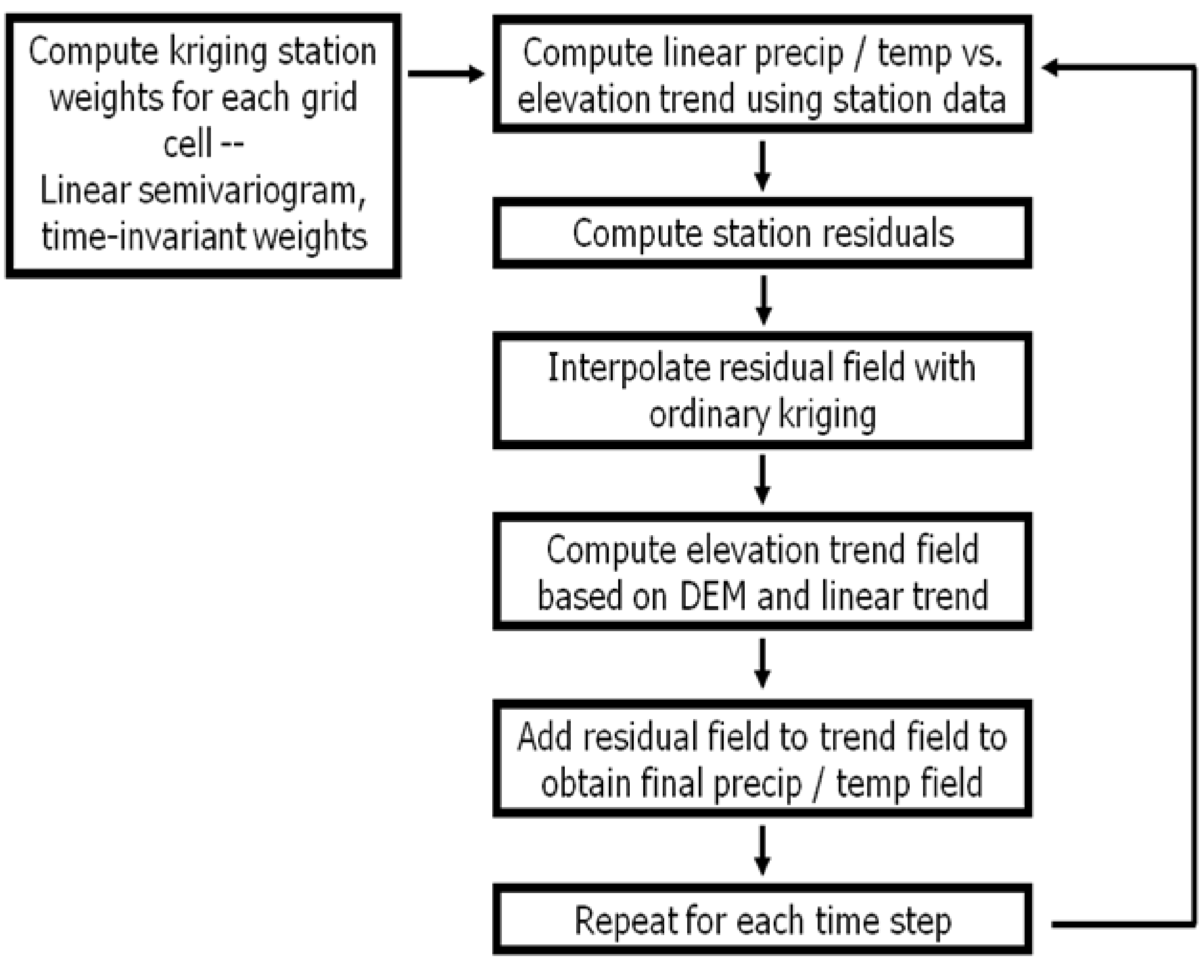
For estimating the detrending line, the program can use either the usual least squares regression, or it can use least absolute deviations regression (algorithm taken from Press et. al., 1988). The latter is a robust regression technique that is less influenced by so-called “outliers”, that is, values that are significantly different from most of the others in the regression data set. From the author’s experience, least absolute deviations regression is preferable for precipitation data. For temperature, least squares generally performs fine. Either method can be successfully applied for snow water equivalent.

Ordinary kriging is used for the horizontal part of the interpolation. Each estimate of the residual at a grid cell is calculated as a weighted sum of the station detrending residuals. The weights are determined by solving a system of linear equations, where the weights are constrained to sum to one. With the use of a linear semivariogram, the kriging weights are independent of the slope and intercept of the function, so one set of weights suffices for all days (as long as no stations have missing data). Sometimes, due to the particular configuration of distances among the stations and the grid cell, the kriging algorithm will give small negative weights for some stations. In this case, the stations having the small negative weights are considered in effect to have a zero weight (i.e., they are of no value in the interpolation). The program handles this by removing the negatively weighted stations from the kriging weight calculation, setting their weights to zero, and recalculating the weights using the remaining stations. This process is repeated until all the kriging weights are positive. This ensures a physically meaningful interpolation and uses only those stations that have significant value for estimating the hydrometeorological variable at the grid cell.

Sometimes, one or more stations will have missing data for a given time period. If this is the case, DK recalculates the kriging weights using only those stations that have data.

The final estimate at a grid cell on a particular day is obtained by adding the estimated residual from the kriging step to the estimated elevation trend for the grid cell from the detrending line.

The algorithm is summarized in the following flowchart. (This does not depict the situation of missing station data for a given time step, where the kriging weights are recalculated.)



3 Program operation

There are two ways to operate the DK program:

1) Executing from the command-line and going through a scrolling question-and-answer dialog to specify the information required by the program.
2) Executing from the command-line and passing a configuration file, which specifies all information required by the program.

These two options are described below.

3.1 Command-line execution with scrolling dialog

The program is invoked by entering the program name (DK) followed by any desired command line switches at a Windows command prompt or UNIX prompt or using the RUN feature in Windows. Double clicking on the executable file name in Windows will launch the program, but you will not be able to enter any command line switches. You are then led through a question-and-answer session before the program begins its computations. Specification of input and output files and other program options occurs during this dialog.

3.1.1 Command-line switches

Command-line switches turn on extra output options that can sometimes be helpful for debugging or further analysis. Experience has shown that most of these switches are not commonly used except for the -e switch for detrending regression statistics.

Any or all of the following command line switches can be given to obtain extra output:

-d or /d	gives printout of distances among stations
-e or /e	gives printout of data element vs. elevation regressions
-i or /i	gives printout of input data
-o or /o	reads data in OMS-compatible csv format
-r or /r	gives printout of detrended residuals
-w or /w	gives printout of kriging weights

An option for reading kriging weights from a file (from the output of the -w option above) rather than the program calculating them can be selected with the switch (and following argument)

-f or /f *krigingweightfilename*

Also available is the switch (and following argument)

-k or /k *configfilename*

which passes the configuration file to the program and bypasses the scrolling dialog. This is described further below.

3.1.2 Scrolling dialog

When the program is invoked in this manner, the user will be prompted sequentially for the following information:

1) Input file name
2) Type of data (precipitation, temperature, snow water equivalent, other)
3) Time step of data (hourly, daily, monthly, yearly)
4) Coordinate system and grid format
   a) Latitude and longitude, column grid format
   b) Easting and northing, column grid format
   c) Easting and northing, GRASS grid format
   d) Easting and northing, ARC/INFO grid format
5) Elevation grid file name
6) Mask grid file name (optional -- GRASS and ARC/INFO format only)
7) Zone grid file name (optional -- GRASS and ARC/INFO format only)
8) Output format
   (a) Mean areal values -- tabular
   (b) Daily fields, GRASS format, plus table of mean areal values
   (c) Daily fields, ARC/INFO format, plus table of mean areal values
   (d) Daily fields, IPW format, plus table of mean areal values
   [If b, c, or d is chosen, additional prompts for the beginning and ending day numbers appear, which apply to all years in the input data set. In addition, if b or c is chosen, another prompt appears, which asks for the precision of the values in the output grid files.]
9) Main output file name
10) Zone output file name (optional)
11) Method to handle elevation (detrending)
    a) Least squares regression
    b) Least absolute deviations regression
12) Station weighting (kriging or equal)
13) Number of days per aggregation period (or storm periods for daily precipitation)

An example of the full dialog is given in Appendix 7.

3.2 Command-line execution with configuration file

If a configuration file exists, and it contains the desired information, this file can be passed to the DK program so that the scrolling dialog is bypassed. The program can be invoked as

```
DK -k configfilename
```

where *configfilename* is the name of the configuration file. This is a text file that should be modified based on the template that is supplied with this program package. This file is described in the next section.

3.2.1 Configuration file

The configuration file is a text file that contains a keyword name, an equals sign, and the value of the keyword. The keyword names are intended to be self-descriptive, corresponding to each piece of information needed by the DK program, as appears in the scrolling dialog.

A configuration file template is supplied with the program package and is shown in Appendix 8. It is recommended that the configuration file be created from this template by editing the relevant keyword values. While the keywords can appear in any order, the template file presents them in the same order as they are asked for in the scrolling dialog.

There must not be any spaces between the keyword, the equals sign, and the value. The configuration file can contain comments, if the first character of the line is #. The template already has many comment lines describing each keyword, but the user can add other comment lines as well, if desired.

4 Hydrometeorological input data format

4.1 Original column format

The format of the input precipitation, temperature, or snow water equivalent data is described below. Examples of data files are given in Appendices 1 and 2. There are three sections in the input file: the first line, which gives values describing the data in the file; a station description block; and a data block.

First line: Free format, integer values, specifying the following:
1) Number of stations in the data set
2) Number of years of data in the data set
3) For each year, a pair of numbers indicating the beginning and ending time period in the data set

Example:
```
10 2 1 304 30 150
```
(Ten stations, two years, first year has data for time periods 1 through 304, second year has data for time periods 30 through 150)

Station block: Free format, one line per station, specifying the following:
1) Station name (no blanks in name)
2) Station elevation (meters)
3) Northing (meters) or latitude (ddmmss) of station location (same units as digital elevation data)
4) Easting (meters) or longitude (dddmmss) of station location (same units as digital elevation data)

Data block: Free format, one line per time period, specifying the following:
1) Year (four-digit)
2) Time period (sequential number, i.e., water year or calendar year hour, Julian day, etc.)
3) Data, separated by one or more spaces or a tab, in the same order as the stations are listed in the station block

PLEASE NOTE: It is ESSENTIAL that the data in the data block be given in the same order as the stations are listed in the station block. There also must be NO BLANK LINES within or at the end of the data file.

The intended standard data units are millimeters for precipitation and snow water equivalent and °C for temperature. However, English units can also be used, with the one exception that the storm aggregation mode for precipitation will not work correctly due to the 5 mm criterion in the program code (see 4th paragraph under section 2 above).

The program can explicitly handle data at four time resolutions: hourly, daily, monthly, and yearly. (This is specified by the third question in the scrolling dialog.)

Data at other time resolutions can be used by "tricking" the program a bit. By putting data of the desired aggregation into the data file and (arbitrarily) using one of the four time period designations, the program will think the data are at this resolution. For example, one could run the program with long-term annual averages by specifying only one day in the input file. But as long as the user knows what the data are, it will not matter, as the algorithm operates the same, provided that an aggregation period of 1 is used for the detrending.

4.2 Object Modeling System csv format

An alternative input format was included in late 2012 to allow compatibility with a general data file format used in the Object Modeling System (http://www.javaforge.com/project/oms), a simulation modeling development and operational environment developed by the U. S. Department of Agriculture. This is based on a spreadsheet-style comma-separated value (csv) format. This is intended for daily data only.

The file sections are described below.

@T block:
Specifies starting and ending dates (yyyy mm dd hh mm ss) and missing data value. For example:

```
@T,obs,,,,,,,
 date_start,1998 10 1 0 0 0,,,,,,,
 date_end,2000 9 30 0 0 0,,,,,,,
 missing_value,-99
```

@H block:
Specifies: (a) data type (precip, tmax, or tmin) of each station, with a sequential subscript number (beginning with zero); (b) station names; (c) elevation of each station; (d) easting and northing of each station's location in coordinates used for digital elevation model; and (e) numerical data type designations. For example:

```
@H,date,precip[0],precip[1],precip[2],precip[3],precip[4],precip[5],precip[6]
name,,Klamath,Gerber,Taylor,Quartz,Silver,Strawberry,Summer
elevation,,1245,1490,1533,1743,1750,1759,2164
easting,,602845.2,654100.0,628930.8,679211.6,648343.4,678863.9,680073.3
northing,,4668601.7,4674133.8,4727500.4,4687290.3,4757330.7,4665799.9,4729136.2
type,Date,Real,Real,Real,Real,Real,Real,Real
```

Data block:
Specifies date and data values in station ordering. For example:

```
,1998 10 1 0 0 0,0,0,0,2.5,0,15.2,0
,1998 10 2 0 0 0,0,0,0,0,2.5,0,2.5
,1998 10 3 0 0 0,0,0,0,0,0,0,0
,1998 10 4 0 0 0,0,0,0,0,0,0,0
,1998 10 5 0 0 0,0,0,0,2.5,0,0,0
,1998 10 6 0 0 0,0,0,0,2.5,0,0,2.5
,1998 10 7 0 0 0,0,0,0,0,0,0,0
,1998 10 8 0 0 0,1.3,0,2.5,0,2.5,0,0
```

5 Digital elevation data format

The most convenient formats for the digital elevation data are the GRASS and ARC/INFO GIS formats. These are both ASCII column-and-row formats and are very similar.

For the GRASS format, the coordinates of the corners of the rectangle and the number of rows and columns are specified, followed by rows and columns of the elevations for each grid cell. For example:

```
north: 2503075.0
south: 2446075.0
east: -1503075.0
west: -1579075.0
rows: 228
cols: 304
```

```
1272 1307 1338 1341 1262 ...
1397 1341 1315 1289 1313 ...
.
.
```

The keywords `north`, `south`, `east`, `west`, `rows`, and `cols` must be given. The coordinates come from the map projection used within the GIS. Standard units are meters for the coordinates and elevations. Although the GRASS program handles only integer data, DK allows the elevations to be given either as integers or as floating point values (i.e., the elevations above could have a decimal point).

For the ARC/INFO format, only the first six header lines differ; the rows and columns of elevation data are the same:

```
ncols 304
nrows 228
xllcorner -1579075.0
yllcorner 2446075.0
cellsize 250
nodata_value -9999
1272 1307 1338 1341 1262 ...
1397 1341 1315 1289 1313 ...
.
.
```

The keywords `ncols` and `nrows` are self-explanatory and are the same as `cols` and `rows` for the GRASS format. The values of `xllcorner` and `yllcorner` are again from the map projection used in the GIS and specify the coordinates of the lower left corner of the grid. The `cellsize` gives the length of a side of the grid squares in meters, while `nodata_value` specifies the missing data value (which is typically -9999).

An optional mask file can be used to indicate which grid cells within the rectangle to include in the interpolation calculations. This is particularly useful to delineate a catchment. The format of the mask file is the same as above for the digital elevation data, except that the elevations are replaced by a 0 (zero) if the grid cell is outside the mask and a 1 (one) if the grid cell is within the mask.

Another optional mask file is a grid that specifies zones. This option was created for the purpose of computing mean areal values for subcatchments or hydrologic response units (HRUs). The value in each cell in the zone grid is the assigned number of the subcatchment or HRU. After the interpolation is complete, DK will average the values for all grid cells with the same zone number and create a text output file (the user must specify this file name) containing mean zonal values for each zone for each time step.

Two older, column-style formats are still in the program for specifying the digital elevation data, in which the latitude or northing, longitude or easting, and elevation are given, one grid cell per line. That is, each line could be either

```
latitude longitude elevation
```

or

```
northing easting elevation
```

where latitudes and longitudes are given as ddmmss (dd = degrees, mm = minutes, ss = seconds), and northings and eastings are in meters according to the appropriate coordinate system. The grid cell coordinates must be in the same units as the hydrometeorological station coordinates. Latitude-longitude coordinates at present can only be used for locations in the United States.

6 Regular model output

The output that appears in the regular output file depends on the command line switches, the aggregation period, and the variable analyzed. Examples are given in Appendices 3, 4, and 5.

If the -e command line switch is used (which is generally recommended), elevation detrending regression results for each aggregation period are written to the output file. The following values are given:

Period: Sequential number of aggregation period

if a fixed-length aggregation period was selected, or:

Storm: Sequential storm number
Year: Year
Day: Beginning day number of storm
Length: Length of storm in days

if storm-period aggregation was selected (for precipitation). The following values are always given:

Intercept: Regression intercept (constant)
Slope: Regression slope, given as mm or °C per 1000 m of elevation
N: Number of stations used in regression

For least squares regression, the following regression statistics are also given:

R: Regression correlation coefficient

SE: Regression standard error
T: T-statistic of regression slope

For least absolute deviations regression, the following value is given instead:

MAE: Mean absolute error

For snow water equivalent, the following additional values are also given:

Snow Line: Elevation of estimated snow line
SCA: Snow covered area in percent

If other command line switches are used, the requested additional output appears at the beginning of the output file and is self-explanatory.

The output file will always contain the mean areal values, computed as the arithmetic average of the values for all grid cells in the region, for each day and year in the data set. If a mask is used, these values are for the area within the mask, otherwise they are for the entire area specified by the digital elevation data. The format is self-explanatory and is shown in Appendices 3, 4, and 5.

7 Spatial field output

Spatial fields can be output in the ASCII column-and-row formats used by the GRASS or ARC/INFO GISs or in the encoded format used by the Image Processing Workbench (IPW) software package (Marks et al., 1999).

The file naming convention consists of a prefix, *vvv_yyyy_ddd_tttt*, where *vvv* = variable (prc, tmp, or swe), *yyyy* = year, *ddd* = sequential day number, and *tttt* = sequential time period number, followed by a suffix of *.grs*, *.asc*, or *.ipw* for GRASS, ARC/INFO, and IPW files, respectively.

Three options are available for the precision of the values in the GRASS and ARC/INFO files. The first is floating point values with one decimal place accuracy. This is a reasonable precision for all three data types handled by this program and is the most generally useful precision option. It cannot be used, however, if the files are intended to be processed with the GRASS program itself, as GRASS handles only integer data. The second option is integer output. The third option is integer output, but with the values multiplied by 10, which allows the files to be used with the GRASS program without losing precision, as happens with regular integer output. None of these precision problems exist if the ARC/INFO GIS is used.

IPW output is encoded according to a quantization scheme based on dividing the range of values into a number of discrete intervals. The precision is determined by the number of bits used in the encoding. DK uses 8 bits for all three variables, which gives 255 intervals. The quantization is based on the maximum and minimum values found in each image.

8 Zone output

If a zone grid is used as input (item 7 in the scrolling dialog, as given in Section 3.1.2), a separate output file is created containing mean areal values for each zone for each time step. This option was designed primarily with semi-distributed hydrologic models in mind, where each zone is a hydrologic response unit (HRU) and each time step is a day. The the value of each cell in the input zone grid is the (integer) sequential zone/HRU number.

The output for each zone and day is the arithmetic average of the precipitation or temperature value for all grid cells in the zone. This average for each zone is then written to the output file in a csv format essentially the same as the csv input format described in Section 4.2. An example of this output is given in Appendix 6.

9 Program author

Please direct any questions, comments, and suggestions to:

Dr. David Garen
United States Department of Agriculture
Natural Resources Conservation Service
National Water and Climate Center
1201 NE Lloyd Boulevard, Suite 802
Portland, Oregon 97232
USA
Phone: +1-503-414-3021
E-mail: David.Garen@por.usda.gov
Internet: http://www.wcc.nrcs.usda.gov

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Appendix 1: Example precipitation data

This data set is for eight stations, one year (1998), time periods (days in this case) 1-365.

```
8 1 1 365
ARROWROCK_DAM          1070  2458086.55  -1589509.15
IDAHO_CITY             1219  2481190.01  -1577449.94
ATLANTA_TOWN           1649  2466414.97  -1523914.63
GRAHAM_GUARD_STATION   1761  2484877.93  -1530823.30
MORES_CREEK_SUMMIT     1883  2488855.03  -1561993.38
JACKSON_PEAK           2131  2498204.50  -1541897.48
ATLANTA_SUMMIT         2338  2462734.19  -1532511.07
TRINITY_MOUNTAIN       2377  2451997.63  -1551029.43
1998   1    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998   2    0.3    2.0    2.3    5.1    0.0    2.5    0.0    7.6
1998   3    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998   4    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998   5    1.0    1.3    0.8    0.0    0.0    0.0    0.0    7.6
1998   6    0.0    0.0    4.6    7.6    5.1    7.6    5.1    2.5
1998   7    0.0    0.0    1.3    0.0    0.0    2.5    0.0   10.2
1998   8    0.3    0.0    0.5    0.0    0.0    2.5    2.5    0.0
1998   9    4.1   14.2   13.7   12.7   15.2   22.9   22.9   27.9
1998  10    0.3    0.5    8.4    5.1    0.0    2.5   12.7    5.1
1998  11    1.5    0.5    2.8    0.0    2.5    0.0    0.0   10.2
1998  12    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998  13    0.0    0.3    0.5    2.5    5.0    2.5    5.1    0.0
1998  14    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998  15    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998  16    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998  17    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998  18    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998  19    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998  20    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998  21    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998  22    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998  23    0.0    2.6    5.9    5.1    5.1    7.6    2.5   12.7
1998  24    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998  25    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998  26    0.0    0.0    0.0    2.5    0.0    0.0    2.5    0.0
1998  27    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998  28    0.0    0.5    0.0    0.0    0.0    2.5    2.5    0.0
1998  29   13.0   18.8   23.1   33.0   40.6   25.4   25.4   27.9
1998  30    6.4    8.6   18.3   15.2   12.7    7.6   25.4   15.2
1998  31    0.0    1.8    4.6    2.5    2.5    0.0    0.0   12.7
1998  32    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998  33    0.0    0.6    0.0    2.5    2.5    0.0    0.0    0.0
1998  34    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998  35    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
                                .
                                .
                                .
1998 363    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998 364    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
1998 365    0.0    0.0    0.0    0.0    0.0    0.0    0.0    0.0
```

Appendix 2: Example temperature data

This data set contains the daily maximum temperatures for the same stations and time period as the precipitation data set in Appendix 1.

```
8 1 1 365
ARROWROCK_DAM         1070  2458086.55  -1589509.15
IDAHO_CITY            1219  2481190.01  -1577449.94
ATLANTA_TOWN          1649  2466414.97  -1523914.63
GRAHAM_GUARD_STATION  1761  2484877.93  -1530823.30
MORES_CREEK_SUMMIT    1883  2488855.03  -1561993.38
JACKSON_PEAK          2131  2498204.50  -1541897.48
ATLANTA_SUMMIT        2338  2462734.19  -1532511.07
TRINITY_MOUNTAIN      2377  2451997.63  -1551029.43
1998   1   30.8   28.9   26.4   23.2   18.6   18.9   16.4   15.1
1998   2   18.1   16.0   13.7   11.2    7.9    5.1    4.0    4.4
1998   3   21.3   19.4   15.6   12.3    8.8    8.7    6.5    6.1
1998   4   18.6   17.3   14.2   11.3    8.6    5.5    4.2    4.7
1998   5   14.5   13.4   10.3    6.8    3.5    2.0    0.9   -0.1
1998   6   14.6   13.7   16.7   10.3    6.2    4.0    4.9    4.0
1998   7   10.7    8.3    3.7    3.2    0.3   -1.2   -3.0   -2.8
1998   8   14.5   12.7   10.2    6.7    3.5    1.9    0.1    0.7
1998   9   14.3   12.2    6.9    3.5    1.4    0.3   -1.1   -1.2
1998  10   11.0    8.8    3.2    2.8    1.1   -0.1   -2.2   -1.5
1998  11    7.7    5.8    2.3   -0.4   -2.1   -3.9   -5.6   -5.2
1998  12    8.2    7.1    4.9    1.8   -1.6   -2.8   -5.2   -5.0
1998  13   14.5   13.4   11.3    6.6    3.1    2.0    0.1   -0.3
1998  14   19.4   18.8   17.2   11.2    6.6    6.8    3.7    1.7
1998  15   20.0   19.9   18.8   12.9    8.5    8.7    6.0    3.2
1998  16   22.0   22.7   21.9   14.1   10.1   10.6    8.7    4.4
1998  17   21.4   21.3   19.7   13.6    9.0    9.6    6.3    3.6
1998  18   18.3   17.3   15.5    9.9    6.7    5.4    3.8    2.6
1998  19   16.5   17.3   16.7   11.1    8.1    6.6    5.1    4.4
1998  20   14.9   17.1   16.6   10.5    6.6    6.3    5.3    2.1
1998  21   15.8   17.0   15.5   10.2    5.8    5.5    4.1    1.4
1998  22   15.7   15.2   13.7    8.5    4.3    3.8    2.7    2.5
1998  23    7.3    2.9    1.0   -1.7   -1.7   -4.6   -6.3   -5.9
1998  24    9.8    8.7    5.2    1.2   -0.9   -3.4   -4.7   -6.6
1998  25    8.3    9.2    7.4    3.3   -0.6   -1.8   -2.4   -4.1
1998  26   12.6   10.0    8.5    5.9    3.6    2.4    0.8    0.8
1998  27   10.8   10.4    9.1    6.3    3.0    1.5   -0.2   -0.6
1998  28   12.2    9.6    8.3    6.6    3.4    2.0    0.7    1.6
1998  29    7.7    6.3    2.4    2.1    1.7    0.0   -0.7    0.2
1998  30   11.0    9.6    5.7    4.7    3.5    2.8    1.5    2.4
1998  31   10.9    8.5    4.7    2.5    1.3   -1.2   -2.6   -2.2
1998  32    9.6    8.0    5.3    2.7   -0.2   -1.2   -1.7   -2.8
1998  33   11.0    8.9    7.1    5.0    2.2    1.8    0.4    0.1
1998  34   11.2    9.2    8.9    7.4    5.6    5.6    4.6    5.9
1998  35   13.1   11.5    8.9    6.9    3.9    3.6    1.9   -0.3
                                  .
                                  .
                                  .
1998 363   24.7   23.5   20.8   17.6   15.8   13.3   11.5    8.7
1998 364   25.2   25.8   25.3   19.4   16.0   14.2   13.1    9.9
1998 365   25.5   24.3   24.0   19.3   14.9   13.5   12.5   10.7
```

Appendix 3: Example output for precipitation

In this example, the one-year period of daily precipitation shown in Appendix 1 was analyzed, using a 1-day aggregation period and least absolute deviations regression. The first section containing the regression results is from the -e command line switch. Note that the regression slopes are in terms of elevations divided by 1000.

```
Detrended Kriging (DK) Program

Input file:       prc98.dat
Elevation file:   boise_dem.asc
Mask file:        boise_msk.asc


Precipitation-elevation regressions (least absolute deviations regression)
for individual years and aggregation periods:
(Note:  Slopes based on elevation / 1000)

YEAR 1998

AGG.
PERIOD  INTERCEPT      SLOPE      MAE    N

     1     0.0000     0.0000   0.0000    8
     2     1.3490     0.5379   1.8053    8
     3     0.0000     0.0000   0.0000    8
     4     0.0000     0.0000   0.0000    8
     5     0.0000     0.0000   0.0000    8
     6    -6.7254     6.2820   1.8345    8
     7    -3.3531     2.7481   1.7426    8
     8     0.0000     0.0000   0.0000    8
     9   -13.6311    16.5731   2.3038    8
    10    -3.6111     3.6618   2.6660    8
                        .
                        .
                        .
   363     0.0000     0.0000   0.0000    8
   364     0.0000     0.0000   0.0000    8
   365     0.0000     0.0000   0.0000    8


Mean areal precipitation:

Time
Period    1998

   1      0.00
   2      3.03
   3      0.00
   4      0.00
   5      1.40
   6      5.24
   7      2.14
   8      0.64
   9     18.23
  10      5.16
            .
            .
            .
 363      0.00
 364      0.00
 365      0.00
```

Appendix 4: Example output for temperature

In this example, the one-year period of daily maximum temperatures shown in Appendix 2 was analyzed, using a 1-day aggregation period and least squares regression. The first section containing the regression results is from the -e command line switch. Note that the regression slopes are in terms of elevations divided by 1000.

```
Detrended Kriging (DK) Program

Input file:      tmp98.dat
Elevation file:  boise_dem.asc
Mask file:       boise_msk.asc


Temperature-elevation regressions (least squares regression)
for individual years and aggregation periods:
(Note:  Slopes based on elevation / 1000)

YEAR 1998

AGG.
PERIOD  INTERCEPT      SLOPE        R       SE        T    N

     1    43.7666   -11.9097   -0.972   1.5073  -10.099    8
     2    30.2117   -11.1792   -0.980   1.1799  -12.109    8
     3    33.7281   -11.8606   -0.979   1.2772  -11.869    8
     4    31.5314   -11.6337   -0.985   1.0813  -13.751    8
     5    27.3803   -11.6262   -0.979   1.2550  -11.840    8
     6    25.8816    -9.1941   -0.856   2.8947   -4.059    8
     7    21.1535   -10.3984   -0.992   0.7040  -18.879    8
     8    26.7835   -11.3646   -0.978   1.2646  -11.486    8
     9    26.5099   -12.1832   -0.979   1.3365  -11.651    8
    10    20.3394    -9.6767   -0.984   0.9282  -13.324    8
                                  .
                                  .
                                  .
   363    38.0384   -11.6723   -0.982   1.1588  -12.874    8
   364    40.3577   -12.0572   -0.933   2.4329   -6.334    8
   365    39.0784   -11.6390   -0.947   2.0690   -7.190    8


Mean areal temperature:

Time
Period    1998

   1     20.60
   2      8.63
   3     10.50
   4      9.03
   5      4.77
   6      8.39
   7      0.86
   8      4.72
   9      2.50
  10      1.29
            .
            .
            .
 363     15.42
 364     17.15
 365     16.67
```

Appendix 5: Example output for snow water equivalent

In this example, a one-year period of daily snow water equivalent values was analyzed, using a 1-day aggregation period and least squares regression. The first section containing the regression results is from the -e command line switch. Note that the regression slopes are in terms of elevations divided by 1000.

```
SWE-elevation regressions for individual years and periods:
(least squares regression)

YEAR 1997

PERIOD  INTERCEPT      SLOPE        R       SE         T    N  SNOW LINE    SCA (%)

                                 .
                                 .
                                 .
   110  -686.3140   725.9266    0.671 251.8690    1.569    5        945      100.0
   111  -690.9299   728.3746    0.672 252.2369    1.572    5        949      100.0
   112  -704.4225   735.5302    0.674 253.3365    1.580    5        958      100.0
   113  -725.4463   748.6970    0.676 256.5696    1.588    5        969      100.0
   114  -734.1939   757.2325    0.675 260.3716    1.583    5        970      100.0
   115  -775.5280   780.7950    0.684 261.5666    1.625    5        993      100.0
   116  -780.1438   783.2430    0.685 261.9694    1.628    5        996      100.0
   117  -789.0205   787.9507    0.686 262.7554    1.632    5       1001      100.0
   118  -833.2131   821.8652    0.684 275.4590    1.624    5       1014      100.0
   119  -910.2210   871.6401    0.696 282.9968    1.677    5       1044      100.0
   120  -921.9427   879.1528    0.699 282.9564    1.691    5       1049       99.9
                                 .
                                 .
                                 .


Mean areal snow water equivalent:

Day    1997

         .
         .
         .
110   767.0
111   767.3
112   768.1
113   773.4
114   781.7
115   787.7
116   788.0
117   788.5
118   812.1
119   835.0
120   837.7
         .
         .
         .
```

Appendix 6: Example zone output

In this example, daily maximum temperature data were analyzed with a zone (hydrologic response unit) grid specified and output by zone requested. Notice that the zone numbering starts with 0 rather than 1. This watershed has more than the 9 zones shown; the lines are truncated to fit on the page. This is in the same spreadsheet-compatible csv format as the Object Modeling System csv input format described in Section 4.2. The header information shown is the result of using the csv input format; if the column input format is used instead (Section 4.1), the header information will be less complete, as the necessary information is not available.

```
@T,obs
date_start, 1999 4 1 0 0 0
date_end, 2004 9 30 0 0 0
date_format, yyyy MM dd H m s
@H,date,tmax[0],tmax[1],tmax[2],tmax[3],tmax[4],tmax[5],tmax[6],tmax[7],tmax[8],  ...
type,Date,Real,Real,Real,Real,Real,Real,Real,Real,Real,  ...
,1999 4 1 0 0 0,1.51,4.89,4.85,6.44,6.52,7.22,6.57,3.60,6.79,  ...
,1999 4 2 0 0 0,5.65,7.90,7.82,8.99,9.11,9.57,9.16,6.26,8.35,  ...
,1999 4 3 0 0 0,-3.35,-1.00,-1.08,0.29,0.52,1.07,0.65,-1.55,  ...
,1999 4 4 0 0 0,1.45,3.03,2.99,3.79,3.86,4.18,3.89,1.75,3.29  ...
,1999 4 5 0 0 0,0.58,2.73,2.73,3.65,3.64,4.08,3.65,1.61,3.81,  ...
,1999 4 6 0 0 0,3.07,5.80,5.76,7.08,7.18,7.75,7.23,4.91,7.43,  ...
,1999 4 7 0 0 0,7.56,9.94,9.88,11.14,11.30,11.82,11.38,8.76,10.94,  ...
,1999 4 8 0 0 0,-2.50,-0.75,-0.81,0.20,0.36,0.75,0.45,-1.74,-0.22,  ...
,1999 4 9 0 0 0,-1.20,0.71,0.65,1.65,1.75,2.15,1.80,-0.76,1.04,  ...
,1999 4 10 0 0 0,1.43,2.50,2.46,3.15,3.30,3.58,3.40,2.58,3.40,  ...

                              .
                              .
                              .
```

Appendix 7: Example program dialog

Below is the question-and-answer dialog with the DK program. Program prompts are given in `typewriter-style font`, and example user responses are given in **bold normal font**.

```
Detrended Kriging Program (DK)
Version 4.8     15 May 2015

Please enter input data file name (q to quit):
```
==> **prec.txt**

```
What type of data are in this file (q to quit)?
   1) Precipitation
   2) Temperature
   3) Snow water equivalent
   4) Other (no restrictions on detrending)
```
==> **1**

```
What is the time step of the data in this file (q to quit)?
   1) Hourly
   2) Daily
   3) Monthly
   4) Yearly
```
==> **2**

```
What is the coordinate system and elevation grid format (q to quit)?
   1) Latitude and longitude, column grid format
   2) Easting and northing, column grid format
   3) Easting and northing, GRASS grid format
   4) Easting and northing, ARC/INFO grid format
```
==> **4**

```
Please enter elevation grid file name (q to quit):
```
==> **elevation.asc**

```
Please enter watershed mask file name --
GRASS or ARC/INFO format only, must be same as elevation grid
(q to quit, blank for no mask):
```
==> **watershed_mask.asc**

```
Please enter zone grid file name --
GRASS or ARC/INFO format only, must be same as elevation grid
(q to quit, blank for no mask):
```
==> **zones.asc**

```
Please enter desired output format (q to quit):
   1) Mean areal values -- tabular (one column per year)
   2) Daily fields -- GRASS format, plus (1) above
   3) Daily fields -- ARC/INFO format, plus (1) above
   4) Daily fields -- IPW format, plus (1) above
```
==> **3**

```
Please enter beginning day number for ARC/INFO output
```
==> **13**

```
Please enter ending day number for ARC/INFO output
   ==> 150

Please enter desired ARC/INFO output precision (q to quit):
   1) Floating point, one decimal place (default)
   2) Integer
   3) Integer, values multiplied by 10
   ==> 1

Please enter main output file name (q to quit):
   ==> main.out

Please enter zone output file name (q to quit):
   ==> zone.out

Please select regression method for elevation detrending (q to quit):
   1) Least squares regression
   2) Least absolute deviations regression
   ==> 2

Please select station weighting method (q to quit):
   1) Distance weighting (linear semivariogram)
   2) Equal weighting
   ==> 1

Please enter the number of days per period you desire
or enter 0 or s to use storm periods (q to quit):
   ==> 1
```

This is the end of the dialog. At this point the program has all the information it needs to proceed. You will see messages like these below as the program goes through its various steps. Be advised that the calculation of the kriging weights can take a bit of time if the domain is large.

```
Now reading input data ...

Now reading grid data ...

Now calculating kriging weights ...

Now calculating prec/temp-elevation regressions by analyzing 1-day periods ...

Now calculating grid cell precipitation ...
                     .
                     .
                     .
```

Appendix 8: Configuration File

Below is a template for the configuration file:

```
#dk_config.txt
#
#Input data file
input-data-file-name=precip_data.txt
#
#Type of data: 1=precipitation; 2=temperature; 3=swe; 4=other
type-of-data=1
#
#Time step of data: 1=hourly; 2=daily; 3=monthly; 4=yearly
#This must appear before "timesteps-per-period"
time-step=1
#
#Coordinate system and format: 1=lat-lon column; 2=easting-northing column;
#3=GRASS grid; 4=ARC/INFO grid
coord-system=4
#
#Elevation grid file
elevation-grid-file-name=dem.txt
#
#Watershed mask grid (optional)
watershed-mask-file-name=mask.txt
#
#Zone grid (optional)
zone-grid-file-name=zone.txt
#
#Output format: 1=mean areal values table; 2=GRASS grid plus 1;
#3=ARC/INFO grid plus 1; 4=IPW grid plus 1
#If 2, 3, or 4, must also specify "beginning-period-number"
#and "ending-period-number"
output-format=1
#
#Sequential period number for beginning of grid output
beginning-period-number=
#
#Sequential period number for end of grid output
ending-period-number=
#
#Grid output precision: 1=floating point with one decimal place;
#2=integer; 3=integer*10
output-precision=1
#
#Main output file
output-file-name=main.out
#
#Zone output file (optional)
zone-output-file-name=zone.out
#
#Regression method: 1=least squares; 2=least absolute deviations
#(2 is recommended for precipitation)
regression-method=2
#
#Station weighting method: 1=distance (kriging); 2=equal weights
station-weighting-method=1
```

```
#
#Timesteps per period for detrending (usually 1)
timesteps-per-period=1
#
#Command-line switch option for OMS-csv input format: if true,
#csv format is read; if false, standard column input format is read
input-format-csv=false
#
#Command-line switch option for reading kriging weights from
#file rather than calculating them -- file name given if
#option desired
kriging-weights-file-name=kriging_weights.txt
#
#Command-line switch options for extra diagnostic output (true/false)
#-c switch: write input data to output file and quit
print-input=false
#-d switch: write distances among stations
print-distances=false
#-e switch: write detrending regressions (usually set to true)
print-regressions=true
#-r switch: write detrended residuals
print-residuals=false
#-w switch: write kriging weights
print-weights=false
```

Appendix 9: DK version history

The original program was first coded in June 1992 and was called MAP_D (Mean Areal Precipitation -- Daily data). It underwent numerous changes and enhancements between then and the first version with a number.

Version 2.0, 8 May 1997:
First version called SDHV. Version number of 2.0 was used because this is not a new program, being derived from MAP_D, which would be considered to be version 1.x.

25 September 1997: Name of program changed to SPAM.

Version 2.1, 28 October 1997:
Small bug fix to modules swe1.c and swe2.c (added -1 to index jj calculation)
Modified handling of snow line and trend between highest zero and lowest nonzero swe

Version 2.2, 3 November 1997:
Added IPW output option.

Version 2.3, 7 November 1997:
Added watershed mask option.

Version 2.4, 16 December 1997:
Changed variable type for grid[i].mask to long instead of short int so that huge model for PC could be used (each element of array has to have a size in bytes equal to a power of 2, 16 bytes in this case).

Version 2.5, 23 December 1997:
Added precision options for GRASS output files.

Version 2.51, 9 March 1999:
Fixed small bug in line 465 -- from nper=365/dpp to nper=366/dpp. This is used to dimension some arrays but crashed in leap years. Problem reported by Joachim Geyer.

Version 2.6, 24 January 2000:
Added ARC/INFO grid format and changed IPW precipitation resolution to 0.5 mm from 1.0 mm.

Version 2.7, 26 May 2000:
Changed method of solving for kriging weights from Gauss-Jordan to LU decomposition (much faster).

Version 2.8, 14 April 2003:
Name of program changed to DK.

Version 2.81, 9 May 2003

Function readgrid.c modified to use strnicmp() instead of strncmp() to do a better job of non-case-sensitive reads of grid headers.

Version 2.82, 28 March 2005

Changed output grid file naming convention for IPW and ARC formats.

Version 2.9, 8 November 2005

Added computation and output of zone means.

Version 2.91, 15 May 2006

Changed precision for IPW output by computing quantization interval based on maximum and minimum in each image rather than using generic values.

Version 2.92, 6 November 2006

1) Added day fraction field to input file and added day fraction to grid output file names.
2) Added run information to top of main output file (input file names, day fraction).
3) Changed strnicmp() back to strncmp() in readgrid.c because strnicmp() function for case-insensitive reads exists only in PC Visual C++ compiler and not in UNIX GNU C compiler. Thus un-does the modification made for Version 2.81. The read now assumes that all the letters are lower case or all are upper case; it will fail for mixed case keywords.

Version 3.0, 8 November 2006

Created "other" data category to allow detrending without screening or restrictions on the slope

Version 3.01, 22 November 2006

Fixed bug in calculation of delta in ipwout.c

Version 3.1, 29 May 2007

Modified zoneout.c and period2.c to write a line of zone output for every day, even if all values are zero

Version 4.0, 20 April 2009

Modified to read parameters from a "configuration" file (in addition to the interactive, scroll-up prompting). This enables, among other things, for the use of a GUI input form that writes the user's choices to the configuration file. The program can then be invoked with the -k option to read a given configuration file. Reading the configuration file is typically created by a GUI front end (that can also read the file). This front end can also be used to invoke this program.

Version 4.1, 1 August 2011

Modified zone output to produce OMS-compatible csv format

Version 4.2, 17 October 2012

Added option to read input data in OMS-compatible csv format

Version 4.3, 28 November 2012

1) Added variable dataname to contain name of data type in OMS-csv data input file (precip, tmax, or tmin)
2) Added zoneseq array to contain index for output of zones in numerical order
3) Changed keyword in OMS-csv input read from "x" to "easting" and "y" to "northing"

Version 4.4, 29 November 2012

1) Added variables yr_start, mo_start, dy_start, yr_end, mo_end, dy_end, read in readcsv.c, to write out in OMS-csv formatted zone output
2) Renamed function getline.c to getln.c to avoid conflict with built-in function "getline" in gcc compiler

Version 4.5, 5 December 2012

Added reading of missing data code in OMS-csv input

Version 4.6, 14 February 2013

Added recognition of NODATA in ARC/INFO elevation grid and assignment of use flag to those that are non-NODATA

Version 4.6.1, 10 July 2013

Slight changes to OMS-csv reading and output formats

Version 4.7, 13 March 2014

Added capability for hourly, monthly, and yearly data, in addition to existing daily data, by handling time periods more generically; added variable mtper to support this

Version 4.8, 15 May 2015

Various clean-up and minor modifications, including:

- Remove -g command line switch (GeoEAS output -- obsolete)
- Minor output formatting and wording clarifications

More significant changes:

- Added -f command line switch to allow reading of kriging weights from file instead of calculating them
- Changed readgrid.c to exclude from use any grid cells that have a valid elevation but are outside of the watershed and zone grids

Regarding Java user interface:

This has not been maintained and at this point is no longer supported. The previous double backslash requirement for filenames in config file (a Java user interface idiosyncracy) is therefore no longer necessary.

Appendix 10: DK C source code files and notes

The source code for the program is contained in the following files:

arcout.c
array.c
caldate.c
dist.c
dk.c
dk_m.h
dk_x.h
getln.c
grassout.c
index.c
interp.c
ipwout.c
isleap.c
krige.c
lusolv.c
medfit.c
period1.c
period2.c
readcnfg.c
readcsv.c
readdata.c
readgrid.c
sca_grid.c
sreg.c
storm1.c
storm2.c
swe1.c
swe2.c
wyjdate.c
zoneout.c

The file dk_m.h contains five variables that set the maximum limits of number of grid cells (MGRID), number of stations (MSTA), number of storms (MSTORM), number of time periods per year (MTPER), and number of zones (MZONE). If the user needs different limits from those in the distributed version, this file can be edited, new values put in, and the program recompiled. As of this writing, the values set for these variables are:
MGRID = 16000000
MSTA = 100
MSTORM = 300
MTPER = 8784

MZONE = 300

The file dk_x.h contains declarations of all external variables and arrays, which are used extensively in the source files to make data available to all functions in the program.

There is also a makefile, set up for use with the GNU C compiler (gcc) on either a PC or a UNIX machine.

D. Garen dk.doc

Substantial edits on:
23 April 2009
14 January 2013
16 March 2015
21 April 2015
19 May 2015