Raingauge Network Optimization and GIS
A Case Study of the Mananga Basin

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1 Introduction

1.1 The Mananga basin

The study area of this case study is the river basin of the Mananga river, one of the main rivers on Cebu-island, the Philippines. Today the Mananga is used as discharge river, in the near future this river may be used for drinking water purposes of the region around Cebu-city, some 25 kilometres east of the Mananga catchment. This catchment area comprises about 102 square kilometres, and is surrounded by a chain of sharp-edged mountains which reach to a maximum height of 700 meter. The total length of the Mananga-river is 24.5 kilometres, the drainage area upstream Camp-4 is about 64 km² (see the front page figure). According to the Köppen classification the climate of Cebu is classified as TC; tropical characterized by high temperatures and humidity, and heavy rainfall. There are, however, pronounced regional and, in most parts, seasonal variations. Average annual rainfall ranges from 1300 to 1700 mm; average annual temperatures ranges from 26°C to 29°C.

1.2 Rainfall analyses

The characteristics of the rainfall-processes of the basin can be analyzed with the raingauges in the basin. However, in the Mananga basin there are only four operational raingauge stations, a too small number to describe the characteristics from. Therefore, eight other stations lying in the surrounding mountain ranges are included in the analyses of the rainfall process.

The yearly rainfall distribution over the basin exists through a variety of weather patterns inducted by different oceanic and continental air streams. Dominating weather patterns are the a) Inter Tropical Convergence Zone (ITCZ), b) easterly waves, c) tropical cyclones and, d) convective cells.

1.3 The Mananga river

One can classify the discharge pattern of the Mananga river as a braided stream (anastomosed river). This means that the stream is divided into an interlacing system of channels, which sediment contain a heavy load due to accelerated erosion. The rock situation in the bed itself, prevents the river from incision and promotes lateral current. In spite of the relatively young geological age of the Philippines, the width of the Mananga riverbed is considerable (more than 100 m in some parts). In those parts, the river can develop and really does develop the channel system. During high discharges, all these channels will be filled with water and form one complete water body.

1.4 Cases

The Mananga basin will be used to demonstrate the construction of a Digital Elevation Model, some applications of geostatistics, and raingauge network optimization in combination with GIS. Use is made of the GIS software package ILWIS.

Three cases will serve as example:

- a digital elevation map will be made of the Mananga basin,
- an overall rainfall map (annual values) will be made with the use of detrending Kriging,
- an optimization of the raingauge network will be performed.

The raster maps of the different phenomena will be made on a grid with a grid spacing of 100*100 meter, resulting in a raster of 106 columns and 136 rows (pixel size = 10000 m²).

1.5 Ilwis

Ilwis (the Integrated Land and Water Information System) is a GIS that integrates image processing capabilities, tabular databases and conventional GIS characteristics. The program was developed by the ITC (International Institute for Aerospace Survey and Earth Sciences) at Enschede in 1985. The conceptualization of the system takes into account that not all GIS users have a thorough knowledge of computers. Therefore all operations are performed through a user friendly menu. Experienced users can, on the other hand, perform operations directly through commands and/or command files.

Figure 1 presents an overview of the Ilwis main menu, this menu is subdivided in several modules and submodules. A short overview of the menus will be presented.

1.5.1 Input module

The input module enables the user to gather geographical information (in vector or raster form) and attribute data. This module also enables the user to convert files with other formats to files in Ilwis format.

1.5.2 Vector module

The vector module enables the user to digitize, display, update and rasterize vector data. A raster to vector conversion option and a stream ordering analysis facility are provided.

1.5.3 Raster module

The raster module enables the user to process, analyze and visualize the geographical information stored in raster format. The raster module also enables the user to georeference raster maps and link raster maps with the attribute data stored in the internal Ilwis database. The raster module consists of the sub-modules Visualization, Spatial Modelling and Image Processing.
Visualization
This module enables the visualization and storage of raster maps.

Spatial modelling
This module enables interactive modelling and analysis using one or more raster maps and/or tables.

Image Processing
This module contains all the standard digital image processing facilities and some extra statistical features. It can be used to process remotely sensed data, but also data derived from other sources can be processed digitally.

1.5.4 Tables module
The table manipulation module can be used to manipulate attribute data, i.e. the non-spatial information used in a geographic information system. The module allows the user to create database queries and perform standard database operations.

1.5.5 Points module
The points module provides facilities to convert point data to vector or raster maps.

1.5.6 Output module
The output module provides possibilities to plot or print maps, graphs and tables. It is also possible to create, display or update annotation such as legends, symbols and text.

1.5.7 Command option
This option proceeds to the command line. In the command line mode Ilwis can be executed without interervention of menus.

1.5.8 Dos option
This option calls Dos and allows the user to execute Dos commands. Return to Ilwis by typing Exit.

2 Creating the digital elevation model (DEM)

With a digitizer the hundred meters isolines of an analogue topographic map (1:50.000) are digitized and stored in three vector files:

- altitude.crd (coordinates file)
- altitude.seg (file with line segments)
- altitude.slg (segment log file)

These three files contain the altitudes with their coordinates. The digitized points with the
same altitudes are connected and are called segments. These segments have to be converted into a raster model. A few procedures must be performed before a nice DEM is constructed; a sequence of the procedures that will be discussed are:

- Rasterize,
- Interpolation,
- Display&Store,
- PixelInfo,
- Classification,
- Colorlut.

The first procedure is to rasterize the points of the different segments. After this estimations of the altitudes have to be made for pixels where no value is present, this will be done by interpolating these values out of the known altitude values.

### 2.1 Rasterize

When converting a segment map into a raster map the pixel size and the coordinate system are user defined (in practice the coordinate system of the topographic map is adopted). Also the input- and output-filenames are asked. The output map, a raster map, contains two files; a MaP Data file with extension .MPD, and a MaP Information file with extension .MPI. Go to the Vector module and make a raster map of the segments with the following scheme:

<table>
<thead>
<tr>
<th>VECTOR =&gt; RASTERIZE =&gt; SegmentToRaster</th>
</tr>
</thead>
<tbody>
<tr>
<td>➔ Segment map: altitude</td>
</tr>
<tr>
<td>➔ create an attribute map: y</td>
</tr>
<tr>
<td>➔ enter values manual: y</td>
</tr>
<tr>
<td>➔ enter the missing values, 100 for _100, etc.</td>
</tr>
<tr>
<td>➔ Raster map: altitude</td>
</tr>
<tr>
<td>➔ coordinates from existing map: n</td>
</tr>
<tr>
<td>➔ meters per pixel: 100</td>
</tr>
<tr>
<td>➔ Enter minimum and maximum X and Y:</td>
</tr>
<tr>
<td>Lower Left Corner</td>
</tr>
<tr>
<td>X: 584500</td>
</tr>
<tr>
<td>Y: 1139000</td>
</tr>
<tr>
<td>Upper Right Corner</td>
</tr>
<tr>
<td>X: 595000</td>
</tr>
<tr>
<td>Y: 1152500</td>
</tr>
</tbody>
</table>

name of segment file to be converted
accept altitude as attribute values
type an attribute value for each code
name of output file
create raster coordinate system
pixel size defined.
Grid min and max.

A small map with the isolines is displayed on the high resolution screen. The map altitude.mpd is a map with altitude values on the pixels nearest to the isolines (figure 2).

If you have a sub-menu currently active you can exit it either by moving to the 'return' option in the menu and pressing return, or by pressing the 'escape' [ESC] key.
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2.2 Interpolation

The second step is to interpolate the isolines (100 meters altitude lines) to obtain an altitude value at every pixel. The interpolation will be done with the procedure FromIsolines. This procedure performs a linear interpolation; for each pixel the distances to two nearest isolines are calculated. Then a linear interpolation is performed for the unknown pixel. Because we have created a raster map we will leave the Vector module and go to the Raster module.

The raster map alt100 can be displayed on the high resolution screen, this is performed in the Visualization module.

2.3 Display&Store

The raster map alt100 can be displayed on the high resolution screen, this is performed in the Visualization module.
What we see is only a white mass with some colors at the bottom! This has to do with the way in which the high resolution screen is controlled. The high resolution screen can only display pixels with values within the 1 byte range (integer values 0-255). Every screen pixel will obtain a byte value. Our altitude map has attribute values (altitudes) which range between 95 and 805 meters, so the high resolution screen only recognises pixels with altitude values with a maximum of 255 meters. Pixels with values higher than 255 will automatically obtain the largest possible screen value, namely 255. The white color of most of the pixels depends on the color given to every possible byte value. There are 256 byte values, so also 256 possible color lut s. The default color for the byte value 255 is white, this causes an almost complete white screen.

When for stretching the answer would be \( y \), stretching of the altitude values will be performed. A histogram of the altitude values will be calculated and stored on disk. The raster map will now be stretched according to the 1 and 99% bounds of the histogram. Values within the 1 byte range will be assigned to the altitude values (see example below).

The values of file alt100 range between 95,0 and 805,0. This means that pixels with values 95,0 obtain values 0, and pixels with values 805,0 become 255. All other pixels will obtain new recalculated values ranging between 0 and 255.

<table>
<thead>
<tr>
<th>Altitudes</th>
<th>New Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>95,0</td>
<td>→</td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
<tr>
<td>( \downarrow )</td>
<td></td>
</tr>
<tr>
<td>805,0</td>
<td>→</td>
</tr>
</tbody>
</table>

For example a pixel with an altitude of 300,0 meters will get a value of 65, 400 becomes 103, 787 becomes 252, etc.

For the enlargement factor we chose the value 4, this means that the image will be displayed 4 times larger than the original size (106*136). The high resolution screen has a resolution of 800*600 screen pixels (the resolution depends on the type of screen; VGA, SVGA, etc.). So the largest possible displayed map can have 800 columns and 600 rows. If the columns or rows of a raster map are larger, the enlargement factor should be chosen smaller than 1. In our case we have a raster map with 106 columns and 136 rows, this makes it possible to enlarge the image to obtain a better view. Enlargement factor 4 means that for every pixel of the raster map 16 screen pixels will be taken (4*4).

2.4 Pixel information

There is an option to retrieve information of the pixels. Choose the procedure Pixel Info in the Visualization (Raster) menu. We see in the top left corner three columns, the first two show the row and column number of the pixel which is depicted on the screen, the third column shows the byte value of the pixel. Below these values the X-coordinate and Y-coordinate of the pixel are displayed. When we want to see more information of the pixels, choose \( R \) (raster map). Type alt100 when the raster map is asked. Choose \( N \) when a table is asked (we don’t have a table with values). Press enter if a second raster map is asked, if information of another (second or third) raster map is wanted the name of this map should
be entered. When moving to a pixel, the available information of this pixel is displayed. Note the difference between the pixel values from the top left corner and the raster map values column. The primer values are the byte values (range from 0 to 255).

It is also possible to view values in raster maps on the monochrome screen:

2.5 Classification

The problem that raster values greater than 255 can not be shown on the screen (except with stretching) can be solved by classification of the attribute values. Therefore the altitude values have to be classified (indexed) and provided with a color. ILWIS has a 'color set' with color index values ranging 0 to 255. Every index value can be provided with a color, build by the user in the 'color set' option. If a raster map pixel has a value of 20, ILWIS will look in the active color palette for the color assigned at the index value 20. If the value of a pixel in the raster map goes beyond the 1 byte range (integer value between 0-255), ILWIS will assign a color to this pixel with index number 255 (default value for 255 is white). Since most of the altitude values are higher than 255, the resulting raster map is mainly white. To systematize this we will introduce altitude classes, in such a way that the raster map has values within the 1 byte range.

Before a map can be classified we must make a classification table, this will be done in the Table module.

The proposed classification table is:

<table>
<thead>
<tr>
<th>Bound</th>
<th>Class</th>
<th>Bound</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0</td>
<td>500</td>
<td>9</td>
</tr>
<tr>
<td>100</td>
<td>1</td>
<td>550</td>
<td>10</td>
</tr>
<tr>
<td>150</td>
<td>2</td>
<td>600</td>
<td>11</td>
</tr>
<tr>
<td>200</td>
<td>3</td>
<td>650</td>
<td>12</td>
</tr>
<tr>
<td>250</td>
<td>4</td>
<td>700</td>
<td>13</td>
</tr>
<tr>
<td>300</td>
<td>5</td>
<td>750</td>
<td>14</td>
</tr>
<tr>
<td>350</td>
<td>6</td>
<td>800</td>
<td>15</td>
</tr>
<tr>
<td>400</td>
<td>7</td>
<td>850</td>
<td>16</td>
</tr>
<tr>
<td>450</td>
<td>8</td>
<td>2000</td>
<td>17</td>
</tr>
</tbody>
</table>
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The first column of the table represent the bounds of the raster values. The second column represent the new raster values. This means that altitudes with a value between 50 and 100 belong to class 1, values between 100 and 150 to class 2, etc.. An example of the classify procedure is given in figure 3.

| 452 | 455 | 480 | 510 | 535 |
| 480 | 495 | 505 | 540 | 570 |
| 510 | 527 | 563 | 593 | 603 |
| 549 | 572 | 589 | 622 | 634 |

| 9 | 9 | 9 | 10 | 10 |
| 9 | 9 | 10 | 10 | 11 |
| 10 | 10 | 11 | 11 | 12 |
| 10 | 11 | 11 | 12 | 12 |

**Figure 3: Classification**

Now we can classify the map alt100 with this classification table.

<table>
<thead>
<tr>
<th>RASTER == SPATIAL MODELLING == CALCULATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>= alt101:=clfy(alt100,altclass);</td>
</tr>
</tbody>
</table>

clfy is a Ilwis function which links a raster map to a classification table. The new map alt101 will be calculated by classifying map alt100 with the classification table altclass. Notice that first the name of the raster map should be given and second the name of the classification table.

Our new raster map alt101 is now ready to display on the high resolution screen.

### 2.6 Colors

To assign colors to the different classes (index values) the Colorlut module will be used. In this module one can choose between a standard palette, a predefined palette or a user defined palette. The changing of colors is an interactive operation you can perform while looking at an image at the high resolution screen. For the altitudes a color palette is already defined.

<table>
<thead>
<tr>
<th>RASTER == VISUALIZATION == Colorlut == Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>= color file: altcolor (.col)</td>
</tr>
</tbody>
</table>

The colors of the raster altitude map will now change from green to red in ascending altitude. With the classification and color procedures we achieved the following:
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<table>
<thead>
<tr>
<th>Before classification</th>
<th>After classification (indexed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>value</td>
<td>index</td>
</tr>
<tr>
<td>0-50</td>
<td>0-50</td>
</tr>
<tr>
<td>50-100</td>
<td>50-100</td>
</tr>
<tr>
<td>100-150</td>
<td>100-150</td>
</tr>
<tr>
<td>150-200</td>
<td>150-200</td>
</tr>
<tr>
<td>200-250</td>
<td>200-250</td>
</tr>
<tr>
<td>250-300</td>
<td>250-255</td>
</tr>
<tr>
<td>300-350</td>
<td>255 {white}</td>
</tr>
<tr>
<td>350-400</td>
<td>255 {white}</td>
</tr>
<tr>
<td>400-450</td>
<td>255 {white}</td>
</tr>
<tr>
<td>450-500</td>
<td>255 {white}</td>
</tr>
<tr>
<td>500-550</td>
<td>255 {white}</td>
</tr>
<tr>
<td>550-600</td>
<td>255 {white}</td>
</tr>
<tr>
<td>600-650</td>
<td>255 {white}</td>
</tr>
<tr>
<td>650-700</td>
<td>255 {white}</td>
</tr>
<tr>
<td>700-750</td>
<td>255 {white}</td>
</tr>
<tr>
<td>750-800</td>
<td>255 {white}</td>
</tr>
<tr>
<td>800-850</td>
<td>255 {white}</td>
</tr>
<tr>
<td>850-2000</td>
<td>255 {white}</td>
</tr>
</tbody>
</table>

3 Creating the catchment map

The next map we will create is a raster map of the catchment. With a digitizer the coordinates of the boundary (watershed) of the Mananga basin are digitized and stored in three vector files:

- boundary.crd
- boundary.seg
- boundary.slg

With the watershed segments in these files we will make a catchment raster map in order to reduce the full sized raster maps to only catchment area raster maps. For this purpose we will make a map with values 1 for points inside the basin and values 0 for points outside the basin. To make such a map we first have to construct a polygon from the segments.

VECTOR -> DISPLAY&CHANGE -> Segments

POLYGONIZE

- closed polygon: y
- polygon name: boundary
- mask: *

only one polygon of the total catchment
name output file
take all segments

We will display the polygon to show the shape of the Mananga basin. Display first the altitude map of the Mananga basin alt101 (this will be the coordinate reference basis of the screen), next the polygon will be displayed on top of this altitude raster map.
To combine the DEM with the catchment, the catchment polygon has to be rasterized. The pixels covering the polygon on the screen will be given the values 1, the other pixels will get values 0. For this we stay in the vector module and make a raster file of the polygon. This is done the same way as with segments, the difference is that we use the PolygonToRaster module.

The created raster map has to be reformatted to maintain a map with the values 0 and 1. The just created map only has values for points within the catchment, for points outside the catchment no value is defined. In the Raster module one can make calculations with different maps, also conditional statements can be made. We want pixels only to have the values 0 or 1, so we make the conditional statement that if values inside the catchment map are higher than zero (they have a value), they must take the value 1, else they have the value 0.

Finally we have created the file we wanted, bound100 (.mpd, .mpi). All the other files we created to realize this map can be deleted from the directory, we will not use them anymore. Display the catchment raster map on the screen and look at some of the values.

4 Creating the river map

As alike as making the catchment map, the coordinates of the river are digitized and stored in vector format. With the segments of the river we will make a raster map of the river. Display the DEM and display the river segments on top of this DEM (use the vector module with segments). The name of the river segments file is River.
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VECTOR → Display&Change → Segments → Display Segments

The screen shows a raster map of the altitudes overlaid with a vector map of the river. The segments of the river on the screen will be rasterized in order to merge this river map with other maps.

VECTOR → RASTERIZE → SegmentsToRaster

- segment file: river
- create an attribute map: y
- enter values manual: y
- enter value: 1000
- raster file: river
- coordinates from existing map: y
- map name: altitude

all river pixels have value 1000

use an existing reference system
reference system of the altitude raster map

To demonstrate this raster map of the river, display it on the screen in the raster module.

Figure 4: Raster map of the river, with the watershed displayed in vector mode

5 Digital elevation model with river at catchment level

With our created raster maps of the altitudes, catchment and river a nice representation of these topographical features of the Mananga basin will be made. Our basic altitude map alt100 with the altitude at all pixels will be used to start with.

First we will see what the altitudes are in the catchment; we are not interested anymore in values outside the Mananga basin. The only thing we have to do is multiply the altitude raster map (alt100) with the boundary raster map (bound100). Because the values of the boundary map are 1 inside the catchment and 0 outside the catchment, the resulting map will
be the altitude values inside the catchment. After multiplication this raster map has to be classified.

\[ alt_{102} = alt_{100} \times bound_{100}; \]
\[ alt_{103} = \text{classify}(alt_{102}, alt_{\text{class}}); \]

The next map we will make is a combined raster map of the river and the altitudes, these two maps will be merged. The second map is glued to the first one. Pixel values of the altitude map (first map) will be assigned to all those pixels of the river map (second map) where no value is defined (for an integer map), or where a value zero exists (for a byte map).

\[ \text{merge: first map: } alt_{100} \]
\[ \text{second map: } \text{river} \]
\[ \text{output map: } alt_{104} \]
\[ \text{enlarge factor: } 1 \]
\[ \text{ignore zero values: } y \]

This map will now be classified using the classify table \text{alt}_{\text{class}}, and reduced to catchment scale using the file \text{bound}_{100}.

\[ alt_{105} = \text{classify}(alt_{104} \times bound_{100}, alt_{\text{class}}); \]

Display this map (\text{alt}_{105}) on the high resolution screen. Our final step is to add a legend to this map with altitudes. Therefore we go to the output module and make a legend.

<table>
<thead>
<tr>
<th>Legend table</th>
</tr>
</thead>
<tbody>
<tr>
<td>Text</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>50-100m</td>
</tr>
<tr>
<td>100-150m</td>
</tr>
<tr>
<td>150-200m</td>
</tr>
<tr>
<td>200-250m</td>
</tr>
<tr>
<td>250-300m</td>
</tr>
<tr>
<td>300-350m</td>
</tr>
<tr>
<td>350-400m</td>
</tr>
<tr>
<td>400-450m</td>
</tr>
<tr>
<td>450-500m</td>
</tr>
</tbody>
</table>
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Enter the legend table in the edit mode. Move to the column named Text, press ins to insert a row and type the first row of the legend table (50-100m). Move to Fill and enter value 1 for the class assigned to this text line. Continue this procedure for all classes. After this press escape, save the legend as altleg, and display the legend on the screen (figure 5).

Figure 5: Topography of the Mananga Basin
What we have accomplished so far is the generation of a few maps, altitude, river and catchment. A resume of the maps is given below:

### Altitude raster maps

- `altitude`: isolines map of the altitudes
- `alt100`: interpolated map of altitude isolines
- `alt101`: classified map of `alt100`
- `alt102`: altitudes in the Mananga basin
- `alt103`: classified map of `alt102`
- `alt104`: altitudes and river
- `alt105`: classified map of `alt104` in the Mananga basin

### Catchment raster maps

- `bound100`: catchment map with values 0 and 1

### River raster maps

- `river`: river map with values of 1000

After these first exercises it is assumed one can rasterize vector maps, merge two maps, classify these maps, use colors and display the maps on the screen.
6 Yearly rainfall of the Mananga basin

With a Geographical Information System we can undertake some statistical operations on data sets. There is also some mathematical modelling capacity, among which regression models. This tool will be used to estimate the correlation between altitude and precipitation in the Mananga basin.

For this exercise two data sets are available:

- the mean annual precipitation values at 12 raingauge stations in and around the Mananga basin,
- the altitudes of those 12 stations.

In the previous exercises we constructed already a raster map containing the altitude values in the Mananga basin, namedaltl02.

The goal of this exercise is to determine the relation between altitude and precipitation, and to construct, with this information, a mean annual rainfall map of the Mananga basin. Data from 12 raingauges are present to establish this relation.

<table>
<thead>
<tr>
<th>Station</th>
<th>Altitude (m)</th>
<th>Rainfall (mm)</th>
<th>Station</th>
<th>Altitude (m)</th>
<th>Rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>395</td>
<td>1666</td>
<td>7</td>
<td>250</td>
<td>1345</td>
</tr>
<tr>
<td>2</td>
<td>225</td>
<td>1514</td>
<td>8</td>
<td>154</td>
<td>1146</td>
</tr>
<tr>
<td>3</td>
<td>220</td>
<td>1695</td>
<td>9</td>
<td>730</td>
<td>1589</td>
</tr>
<tr>
<td>4</td>
<td>190</td>
<td>1412</td>
<td>10</td>
<td>460</td>
<td>1636</td>
</tr>
<tr>
<td>5</td>
<td>420</td>
<td>1534</td>
<td>11</td>
<td>540</td>
<td>1478</td>
</tr>
<tr>
<td>6</td>
<td>370</td>
<td>1399</td>
<td>12</td>
<td>50</td>
<td>1371</td>
</tr>
</tbody>
</table>

From these data we can in general say, "the higher the raingauge, the higher the rainfall value". However, we need a more precise technique for specifying this relation. In statistics a procedure called regression analysis will do this, for which IIwis provides a module named Statistics. This procedure analyses the relation between two raster maps or two data sets. The data set with the altitudes and precipitation data is stored in a (table) filestations.dat. The rainfall values $Z(x)$ can now be thought of as the sum of two components, a deterministic component $(\text{trend}, a_0 + a_1 A(x))$ calculated with linear regression, and a variability component $(\alpha(x))$:

$$Z(x) = a_0 + a_1 A(x) + \alpha(x)$$

where $a_0$ and $a_1$ are the parameters of the altitude effect, $A(x)$ are the altitudes, and $\alpha(x)$ are the residuals.

The parameters $a_0$ and $a_1$ will be calculated with linear regression:
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**TABLES — Table Calculation**

- **Enter Table name:** stations.dat

**Special Features — Statistics — Least Squares**

- **Select X-axis:** altitude
- **Select Y-axis:** precipitation

<table>
<thead>
<tr>
<th>Polynomial</th>
<th>Order: 1</th>
<th>Display: y</th>
<th>Window name:</th>
<th>Clear window:</th>
<th>7 times enter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**After running this regression procedure we see that there is a distinct relation between the altitude and the rainfall values, we have a $a_0$ of 1346.77 mm, and a $a_1$ of 0.455 mm/m.**

![Linear Regression](image)

**Figure 6: Linear regression**

With the parameters $a_0$ and $a_1$, and the altitude values $A(x)$ the deterministic component of the rainfall values are calculated. The differences between the deterministic rainfall values and the measured values, the residuals $\alpha(x)$ can be used to estimate the variability of the rainfall process in space (variability around the deterministic trend). This variability is caused by scale effects, it can be decomposed in a large-scale, a micro-scale, and measurement errors. The assumption is made that the closer the stations, the more rainfall values become alike; some kind of correlation is expected between the rainfall values depending only on the distance, the lag vector $h$, between two measurement stations. The basic theory by which such relations are explained comes from Geostatistics. For this exercise it must be understood that the rainfall values are not purely random; rainfall values consists of a certain spatial relation.
6.1 The semivariogram

When a graph is made of the distance between two stations on the X-axis and the rainfall variance differences between those stations on the Y-axis, the relation becomes clear. Such a graph is called a semivariogram. Different mathematical models are made to fit the experimental semivariogram (i.e. the calculated semivariances from the measuring points). In figure 7 a spherical model is drawn, with three parameters determining the shape of it. $C_o$ is the nugget effect, representing the random variance, a variance caused by measuring errors and micro-scale variations (variations over a distance smaller than the average distance between measuring stations). $a$ is the range, representing the maximum distance when two stations still have some correlation. The stations with a distance larger than the range are assumed to be independent. The maximum semivariance of the phenomenon, reached at the range distance, is called the sill $C_o + C$.

![Figure 7: Spherical model](image)

In the following table the measured rainfall values, the deterministic (altitude depending) components, and the variability (residuals) are presented.

<table>
<thead>
<tr>
<th>Station number</th>
<th>Measured value</th>
<th>Deterministic comp. $(a_o + a_1 A(x))$</th>
<th>Variability comp. $(a(x))$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1666</td>
<td>1527</td>
<td>139</td>
</tr>
<tr>
<td>2</td>
<td>1514</td>
<td>1499</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>1695</td>
<td>1445</td>
<td>250</td>
</tr>
<tr>
<td>4</td>
<td>1412</td>
<td>1433</td>
<td>-21</td>
</tr>
<tr>
<td>5</td>
<td>1534</td>
<td>1538</td>
<td>-4</td>
</tr>
<tr>
<td>6</td>
<td>1399</td>
<td>1515</td>
<td>-116</td>
</tr>
<tr>
<td>7</td>
<td>1345</td>
<td>1461</td>
<td>-116</td>
</tr>
<tr>
<td>8</td>
<td>1146</td>
<td>1417</td>
<td>-271</td>
</tr>
<tr>
<td>9</td>
<td>1589</td>
<td>1679</td>
<td>-90</td>
</tr>
<tr>
<td>10</td>
<td>1636</td>
<td>1556</td>
<td>80</td>
</tr>
<tr>
<td>11</td>
<td>1478</td>
<td>1593</td>
<td>-115</td>
</tr>
<tr>
<td>12</td>
<td>1371</td>
<td>1370</td>
<td>1</td>
</tr>
</tbody>
</table>

A semivariogram of the residuals is shown in figure 8. The model of the semivariogram, fitted through the calculated semivariances, is used in geostatistics to show the spatial...
dependency of a phenomenon. This spatial dependency on its turn is used for interpolation with the Kriging method.

6.2 Kriging

The Kriging method gives estimates of a phenomenon at non-measured locations with a prediction of the reliability of the estimation. In our case we can calculate the expected rainfall values on a grid of 100*100 meters, with for each estimate a standard deviation representing the accuracy of the estimate.

Kriging is a 'linear' type of estimator, that is, it gives a weighted average from the measuring points. This estimator is denoted by $Z^*$ and is equal to:

$$Z^* = \lambda_1 * Z_1 + \lambda_2 * Z_2 + \ldots + \lambda_n * Z_n = \sum_{i=1}^{n} \lambda_i * Z_i$$

where the $\lambda_1, \lambda_2, \ldots, \lambda_n$ are the weights assigned to each measuring point.

The weights are calculated using the semivariogram, this makes that the assigned weights depend on the distance between an estimated point and a measuring point, and the distance between the measuring points themselves, this to prevent the overweighing of clustered data. An example of the distribution of the weights is given in figure 9.

For further information about semivariances and the Kriging method see the references.
6.3 Detrending Kriging

In the original Kriging equations, there is a restriction for the phenomenon under study; no trend is allowed. In our case we assume the existence of a trend of the yearly precipitation depending on the altitude values. We have to subtract the trend from the original values and interpolate the residuals over the whole domain. In this case we speak about detrending (or residual) Kriging.

With the spherical model of the semivariogram, Kriging estimates and their standard deviation are calculated and stored in a table file: detr.pnt. This file containing four columns (X-coordinates, Y-coordinates, estimates of the rainfall variabilities, and standard deviations of the variability estimates) can be read by ILWIS in the Point module.

This raster file must be classified with the underlying table (detrprec.clt), fitted to the watershed and stored in the file detrprec.

<table>
<thead>
<tr>
<th>Bound</th>
<th>Class</th>
<th>Bound</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>-50.0000</td>
<td>1</td>
<td>75.0000</td>
<td>6</td>
</tr>
<tr>
<td>-25.0000</td>
<td>2</td>
<td>100.0000</td>
<td>7</td>
</tr>
<tr>
<td>-0.0001</td>
<td>3</td>
<td>125.0000</td>
<td>8</td>
</tr>
<tr>
<td>0.0001</td>
<td>0</td>
<td>150.0000</td>
<td>9</td>
</tr>
<tr>
<td>25.0000</td>
<td>4</td>
<td>175.0000</td>
<td>10</td>
</tr>
<tr>
<td>50.0000</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Show the map of the interpolated residuals (detrprec.mpd) with the color file detrprec.col and legend detrprec.leg on the high resolution screen (figure 10).

With these residuals the rainfall values at every pixel can be calculated using the altitude map and the parameters \(a_0\) and \(a_1\).

\[
Z(x) = 1347 + 0.455 \times A(x) + \alpha(x)
\]

In the calculation function of the spatial modelling module, the new rainfall map, calculated from the altitudes and the residuals can be made. The following function can be applied:

\[
\text{precyear} := \text{if}(\text{alt102} > 0, 1347 + 0.455 \times \text{alt102} + \text{detr}, 0)
\]

Use a scale factor of \(-1\). The conditional statement performs the following: if the altitude values are positive (inside the watershed), the calculation of the rainfall values should be
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Figure 10: Residuals interpolated with detrending Kriging

performed, otherwise the rainfall values should be set to zero. The rainfall raster map can be classified with table \textit{precyear.clt} and displayed with legend \textit{precyear.leg}. The classification table \textit{precyear.clt} looks like this:

<table>
<thead>
<tr>
<th>Bound</th>
<th>Class</th>
<th>Bound</th>
<th>Class</th>
<th>Bound</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>1450</td>
<td>0</td>
<td>1575</td>
<td>5</td>
<td>1675</td>
<td>9</td>
</tr>
<tr>
<td>1475</td>
<td>1</td>
<td>1600</td>
<td>6</td>
<td>1700</td>
<td>10</td>
</tr>
<tr>
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<tr>
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<td>3</td>
<td>1650</td>
<td>8</td>
<td>1750</td>
<td>12</td>
</tr>
<tr>
<td>1550</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We now have a map incorporating the mean annual rainfall values with altitude effect over the Mananga basin (figure 11).

Together with the interpolated rainfall values a plot of the variances of the rainfall estimates can be made; this consists of the Kriging standard deviations, a measure of accuracy of the estimates. A pixel with a high value for the standard deviation represent a pixel where the estimate must be interpreted with caution. These standard deviations are stored in the fourth column of the file \textit{detr.pnt}. From this column a raster map must be made using the same procedures as with the variability estimates, store this map in a file \textit{(detrvar)}. This raster file must be classified with table \textit{detrvar.clt}, fitted to the watershed and stored in the file \textit{varrain}. 
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yearly rainfall
Detrending Kriging

Figure 11: Rainfall values calculated with detrending Kriging

The classification table detvar.cl1 looks like this:

<table>
<thead>
<tr>
<th>Bound</th>
<th>Class</th>
<th>Bound</th>
<th>Class</th>
<th>Bound</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>70.0</td>
<td>0</td>
<td>90.0</td>
<td>4</td>
<td>110.0</td>
<td>8</td>
</tr>
<tr>
<td>75.0</td>
<td>1</td>
<td>95.0</td>
<td>5</td>
<td>115.0</td>
<td>9</td>
</tr>
<tr>
<td>80.0</td>
<td>2</td>
<td>100.0</td>
<td>6</td>
<td>120.0</td>
<td>10</td>
</tr>
<tr>
<td>85.0</td>
<td>3</td>
<td>105.0</td>
<td>7</td>
<td>125.0</td>
<td>11</td>
</tr>
</tbody>
</table>

A legend is made, named varrain.leg. Show the map of the Kriging standard deviations (varrain.mpd) with the colorfile varrain.col and legend on the high resolution screen.

Figure 12: Kriging estimation variances
From this image (figure 12) one can clearly see the locations where the raingauges are stationed, this by the much lower standard deviations. The Northern part of the area, without raingauges, is less trustworthy than the middle part, resulting in an error standard deviation of above 100 mm.

7 Network optimization

It is clear that the estimated variance is an important factor for determining the location of raingauges, the variance depends only on the geometrical location of the raingauges. Obviously, the choice of the variogram model and its parameters is conditioned by the particular set of available data. But once the variogram model is chosen, the variance can be viewed as depending exclusively on the location of the raingauges. Hence it becomes possible to compute the error variance associated with any set of hypothetical data points without getting actual data at these points.

The estimation variance is thus a very suitable tool for network optimization. The existing network of raingauges can be replaced or supplemented by the best representative new set of raingauges at specified locations.

In our case the standard deviations are highest in the northern part of the area. The best places to add a new raingauge would be on that particular place where the estimation variance is highest. If two stations are added, the estimation variance in the northern part is reduced considerable (figure 13).

![Figure 13: Kriging estimation variances with two additional stations](image)

The two added stations are only known by coordinates from the rainfall map. A topographic map should be analyzed to check if it is possible to place the new stations at or close to the chosen locations in order to satisfy other criteria like reachability. For this exercise we have to our disposal a road map of the Mananga basin from which the distances to the new locations can be calculated. The road map is stored in a file `road.mpd`. From this file a distance map will be calculated and classified:
Figure 14 shows a distance map with a vector model of the watershed and a legend. Classes of distances are: 0 → 100, 100 → 250, 250 → 500, 500 → 1000, and 1000 → ∞ meters. If the distance map and the variance map (without extra stations) are combined, the best locations for additional stations become visible. The problem is now what weight to assign to the distance and what weight to assign to the estimation variance for optimization. This is very subjective and will be different for every hydrologist.

Make a map which calculates the best place for additional raingauges. An example is given in figure 15, which has been made by the calculation \( \text{map} := \frac{\text{maxdist} - \text{dist}}{10 + \text{detrvar} * 5} \), and classified. In the distance map the maximum distance is 5885 meters.
Figure 15: Optimal locations for additional raingauges
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