PC practical 4
Topography-based models

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1 Introduction

This practical focuses on the importance of the catchment geomorphology for the catchment response to rainfall. Digital elevation models (DEMs) are relatively easily available (compared to e.g. soil maps or the location of river branches) and are often used as a first tool to characterize catchments. A detailed analysis of a digital elevation model will give a first idea of which processes play a role in streamflow generation and, therefore, how the discharge will respond to rainfall events.

1.1 The Ourthe catchment

We will focus specifically on the catchment of the Ourthe upstream of Tabreux (1600 km^2). Both topography and geomorphology play an important role in the hydrological response of the Upper Ourthe catchment. The catchment is situated in the hilly plateaus of the Ardennes in the eastern part of Belgium* (Figure 1.1). The elevation of the catchment varies between 150 and 650 m above sea level. The soil mainly consists of sandstone, shale and limestone, which have been eroded by small river systems that drain into the river Meuse. The region can be characterized as mostly rain-fed with some snow during the winter period. This results in a runoff regime that can be classified as highly variable, with low discharges in summer and high peaks in winter.

2 Getting DEM data

The data and scripts can be found on Blackboard in the ZIP file `P4.zip`. Download the file and unzip the folder. This will generate the folder `DEM_Analysis_Ourthe`, containing the subdirectories `R_scripts`, `DEM` and `Data`.

*a well-known area for those who followed Hydrogeology

3 Using digital evelation models

The DEM you will use today was obtained by the Shuttle Radar Topography Mission (SRTM) which generated a near global elevation map. For Europe the resolution of this dataset is about 90 meter and can be downloaded from the internet (`http://www2.jpl.nasa.gov/srtm/`).

Your DEM file is called `ourthe_90m.asc` and is located in the folder `DEM`.

Open this file in Notepad and try to understand how this ASCII format is set up. What do the numbers in the big matrix signify?

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3.1 Preprocessing

Before you can use the DEM for hydrological applications, the DEM has to be preprocessed. In this preprocessing step, pits in the topography field are filled, flow directions are computed and contributing areas and slope gradients are computed.

For this preprocessing, multiple GIS programs can be used (e.g. ArcGIS, SAGA GIS, GRASS). For this practical these preprocessing steps have already been performed using the TAUDEM package. TAUDEM is a terrain analysis package developed by David G. Tarboton of Utah State Univerity and can be applied inside ArcGIS. For more information concerning the specific aspects of TAUDEM, please consult the following website: `http://hydrology.usu.edu/taudem/taudem5.0/index.html`.

The following sections explain what happens during the preprocessing phase.

3.1.1 Sink / pit filling

The main assumptions behind spatial hydrological analyses is that the water will flow from higher to lower cells. To obtain a continuous flow direction map, the lowest cell in a DEM should be situated at the boundary of a DEM. Unfortunately, local topography or erroneous measurements by the satellite can result in local depressions (also called sinks or pits) in a DEM. Because the cells surrounding the pits are higher in elevation, water will never flow out of them and will never reach the river.

Although sinks may represent real terrain features, they hinder the analysis of drainage networks.

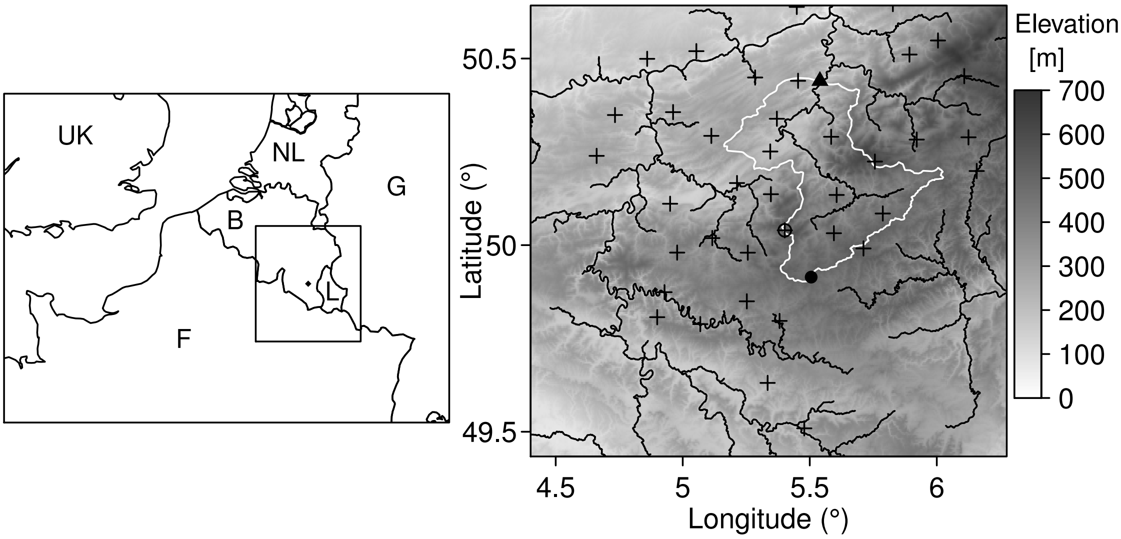
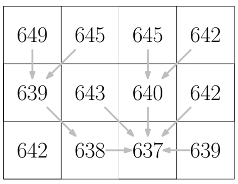


Figure 1 Left: a map of Belgium with the study area. Right: a 200x200-km box with a topographic map of the Ardennes with the main channel network (black), the Ourthe catchment boundary (white), the catchment outlet (▲), the meteorological station (○), rain gauges (+) and weather radar (●).

Local depressions should therefore be filled before making a flow direction map. Using TAUDEM, the original DEM file `ourthe_90m.asc` was corrected for pits. This generated the new DEM file `ourthe_90mfel.asc`, which can also be found in the `DEM` folder.

3.1.2 Flow direction, slope and contributing area

There are many ways to compute flow directions. In this practical the simplest and oldest method will be applied. For each pixel, the 8 neighbouring cells are evaluated and water will flow in the direction of the steepest descent:



This method is known as the D8 flow direction method. The D8 algorithm inside TAUDEM gives a local flow direction for each pixel. The flow direction numbering as performed by TAUDEM is as follows:

4	3	2
5		1
6	7	8

Boundary pixels for which no downstream direction could be obtained receive the value of -1. The output of this step was saved in the file `ourthe_90mp.asc`.

Once these directions have been determined, TAUDEM immediately generates the file `ourthe_90msd8.asc`, containing the local slopes for all pixels.

Based on the flow direction, it is possible to calculate the upstream area for each pixel. TAUDEM starts at the highest points of the DEM and moves downward. In `ourthe_90mad8.asc` the number of upstream pixels is given for each pixel.

Open `ourthe_90mp.asc`, `ourthe_90msd8.asc` and `ourthe_90mad8.asc` in Notepad and try to understand what the numbers mean.

3.2 Getting started

After these preprocessing steps, R can be used for spatial hydrological analyses. Open RStudio and load the script `DEM_analyses.R`. Set the working directory name, so it points to the proper folder `P4` on your computer. Run the part under "Getting started".

3.3 Extra functions

In the folder `R_scripts` many other scripts are located. You don't have to open these scripts now. They contain functions which are used by the main R script `DEM_analyses.R`:

- `SetGeo.R` gives pixel size and extent of the DEM.
- `nbrtable.R` Within R a DEM matrix is internally represented as a vector. Therefore, for every pixel within the grid this function calculates the vector index value for the 8 neighbour points.
- `downnbr.R` gives the vector index number of a pixel's downstream neighbour based on the D8 flow direction method.
- `mainbasin.R` gives the upstream area for a given pixel.
- `GetNewCoordinates.R` zooms in to the catchment when the catchment area covers a small part of the DEM.
- `flowdistance.R` calculates the distance to the channel network for each pixel.
- `plotflowdistance.R` draws a map of the distance to the channel for each pixel obtained by `flowdistance.R`.
- `channeldistance.R` gives the distance to the outlet (measured along the channel) for each pixel (given a certain channel network).
- `channelpixelsize.R` computes for each channel pixel how many metres of channel it contains.
- `strahler_order.R` gives Strahler order numbers for each channel link.
- `shreve_order.R` gives Shreve order numbers for each channel link.
- `TOPMODEL.R` runs the hydrological model TOPMODEL.
- `NSeff.R` computes the Nash-Sutcliffe efficiency.

Run the part under "Extra functions". You then load all extra functions. For example, when you run the line `source("R_scripts/SetGeo.R")` in the `DEM_analyses.R`-script, R runs the whole `SetGeo.R`-script at once in the background. Because the `SetGeo.R`-script contains the definition of the function `SetGeo`, you will see this function with the argument `A` appear in the workspace window.

4 DEM analyses

4.1 Read data

Next, run the part of the script under "Read Data". This part of the script generates a map with the pit filled DEM. Check if your figure is similar to Figure 1.1.

Read the part of the script under "Catchment Area". If you run this part in R, only the part of the DEM that lies upstream of Tabreux is selected. This part belongs to the Upper Ourthe catchment.

Click on `basin` in the workspace window. What do the TRUE and FALSE mean?

TRUE: ______

FALSE: ______

Make sure you understand what happens in the line `Elevation[basin == FALSE] = NA`. If you don't know what the square brackets do, reread Section 11.1 of the (Very) short introduction to R.

What can you tell about the topography in the Ourthe catchment?

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How many pixels belong to this catchment and what is the corresponding area?

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4.2 Channel network

Because we do not have information on where the channels are (which is almost always the case), we will predict the location of the channels with the DEM. We will assume that a river branch will develop when the upstream area exceeds a certain value representing the soil's flow capacity; excess water will start to flow overland instead, creating a channel. It is assumed that for a pixel to be part of the channel network, the upstream area has to be equal to or exceed 0.1 km^2.

Run the part of the script under "Channel Network". This will generate the channel network.

How many pixels are part of the channel network?

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How many pixels are part of the network when you change the upstream area to 0.03, 0.3 and 1 km^2.

0.03 km^2: ______

0.3 km^2: ______

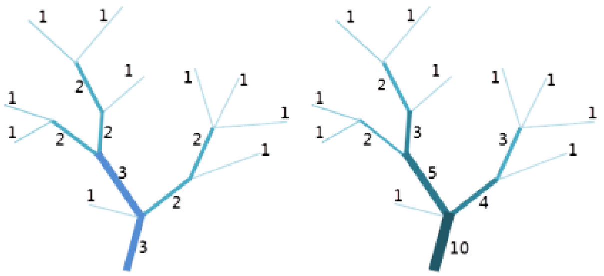
1 km^2: ______

What can you conclude from these numbers?

Change the upstream area back to 0.1 km^2 for the next assignments.

4.3 Channel network ordering

The shape of channel network can be analyzed with several ordering systems. Today we will focus on the Strahler (left) and Shreve (right) ordering systems:



Use the function **shreve** to calculate the Shreve order for each channel pixel.

What is the maximum Shreve value for the Ourthe catchment? (Look at the arguments of the function `max` to find out how you can exclude non-channel pixels from your computation.)

To what catchment characteristic does this maximum correspond?

Do the same for the Strahler order.

What is the maximum Strahler number for the Ourthe catchment?

How would this value change when you increase the upstream area which defines the channel network? (i.e. what you did in section 4.2)

4.4 Drainage density and hillslope length

The function `channelpixelsize` calculates for every channel pixel how many metres of channel it contains.

Click on `Channel_Length_Per_Pixel` in the workspace window. What do NA, 90 and 127 tell you about the flow direction?

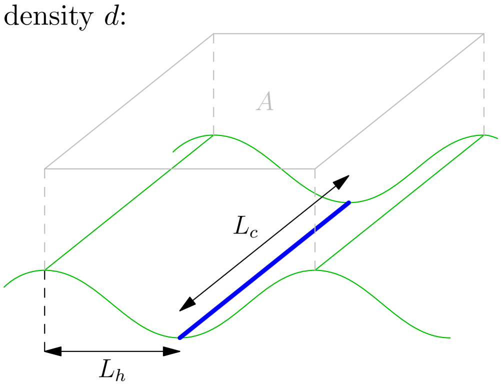
NA:

90:

127:

Where do the numbers 90 and 127 come from?

A rectangular valley with a channel in the middle and the local water divide at the edges, can be characterized by several measures: the channel length L_c, the area A, the hillslope length L_h and the drainage density d:



Give the equation to compute the area of the valley in the figure above from L_h and L_c.

$A =$

Give the equation to compute the drainage density from area A and channel length L.

$d =$

Give the equation to compute the drainage density from the hillslope length L_h.

$d =$

Give the equation to compute L_h from d.

$L_h =$

What is the unit of drainage density?

Compute the drainage density of the Ourthe catchment (for $Ac = 0.1$)

$d =$

What is the average hillslope length?

4.5 Distance to outlet

Compute for each pixel the distance to the outlet. This is preprogrammed in `channeldistance`.

What is the distance from the most upstream channel pixel to the outlet?

Plot the average channel elevation versus distance to the outlet. What do the slopes of the curves show?

What can you say about the relation between the slopes of the curves and the distance to the outlet?

4.6 Channel width function

From the channel network you can compute the network width function. This function gives the fraction of channel pixels at a given distance from the outlet. Plot the width function.

Make a sketch of the width function below.

Can you explain the shape of the width function with the spatial distribution of the channel network?

4.7 Channel travel time distribution

The velocity of the water in the river is generally between 0.3 and 3.0 $\mathrm{m\,s^{-1}}$. Here a value of 0.8 $\mathrm{m\,s^{-1}}$ is assumed for every stretch of river. With the flow velocity you can convert the distance-to-outlet-map into a channel travel time map.

What can you say about the pattern and variability in flow times and their relation to the shape of the catchment and the channel network?

Different channel velocities lead to different travel time distributions. Compute the maximum and median travel time with different channel velocities ranging from 0.3 to 3.0 $\mathrm{m\,s^{-1}}$ and plot the results (channel velocity on the x-axis and travel time on the y-axis).

What is the relation between flow velocity and maximum channel travel time?

If all rain would fall on the channel network directly, what do the maximum and median travel time then represent?

5 Rainfall-runoff modelling

5.1 Time series

Before you start modelling, you should get a better feeling of the water balance terms in the Ourthe catchment. The file `PEQ_Ourthe_2002_2003.txt` in the folder `Data` contains 2 years of basin averaged hourly precipitation [$\mathrm{mm\,h^{-1}}$], potential evaporation [$\mathrm{mm\,h^{-1}}$] and discharge [$\mathrm{m^3\,s^{-1}}$] data.

Comparing fluxes is easier when they have the same units. Use the catchment area to convert the discharge to $\mathrm{mm\,h^{-1}}$ and plot the time series.

To remove the hourly variability, the data can be averaged over monthly periods. This is preprogrammed in the script. In addition, the 10^{th} and 90^{th} percentiles are computed.

What can you say about the inter- and intra-monthly variation (inter: between for example January and July; intramonthly: between all January values)?

What are the main differences in water balance terms between the Ourthe and Hupsel Brook catchment that you analysed during practical 2?

For the models in the next sections, we need input. We could just use P, but of course, part of the precipitation evaporates. Unfortunately, the amount of actual evaporation was unknown for the period 2002–2003. As a quick fix, a factor f is introduced to close the water balance over the two year period:

$$f \cdot \Sigma P - \Sigma Q = 0 \ .$$

Hourly values of effective precipitation can then be computed as:

$$P_{\text{eff}} = f \cdot P \ .$$

5.2 Channel travel time distribution model

From the channel width function in section 4.6 you can make a simple rainfall-runoff model. In this model you assume that all precipitation enters the channel network directly.

The function `Q_geomorph_channel` converts the width function to a travel time distribution model with a convolution integral. Try to understand the different aspects of this function (look in the file `Q_geomorph_channel.R`).

Run this function with the effective precipitation time series and flow velocity parameter.

How does the simulated discharge compare to the observed discharge? What happens if you change the velocity?

5.3 Hillslope width function

The assumption that all precipitation immediately enters the channel network does of course not hold: the simulated discharge response is too fast. This illustrates that the response of a catchment is not only characterized by the channel network but also by the soil, slope and vegetation on the hillslopes.

Compute for each pixel the distance to the nearest channel, plot the map and make a histogram of the fraction of pixels with a certain distance to the nearest channel: the hillslope width function.

What is the average distance to the channel?

How does the average distance to the channel compare to the average hillslope length you computed in Section 4.4?

What can you tell from the width function?

5.4 Channel and hillslope travel time distribution model

A catchment's travel time distribution is determined by the amount of time a water droplet spends in both the hillslope and the channel network. You already obtained the channel travel time distribution from the width function. In the same way, you can make a hillslope travel time distribution from the histogram of the distances to the nearest channel. Just as in the channel, we assume that the flow velocity in the hillslope is constant.

Why is the assumption of a constant (no variation in time) flow velocity in the hillslope not realistic?

The functions `Q_geomorph_hillslope` and `Q_hillslope_parts` have a similar set-up as the previously used function `Q_geomorph_channel`.

As a first estimate, the effective[†] velocity in the hillslope is assumed to be 0.001 $\mathrm{m\,s^{-1}}$ and the channel network velocity 0.8 $\mathrm{m\,s^{-1}}$.

During which part of the year do the simulated discharge peaks fit the observed ones well? Why is this?

What happens to the baseflow? Why?

Play around with different effective hillslope velocity values.

Which values for the effective hillslope velocity yield good results in the winter period and which in the summer?

You probably found that in winter the hillslope velocity is higher than in in summer. Explain this with the dominant processes that occur during winter.

5.5 Flow routes

The route a water droplet takes through the hillslope to the channel depends on many factors, such as the soil type, presence of macropores, vegetation and wetness of the catchment. Because many of these factors change during the year, the flow routes change, and therefore the travel times change.

We will make the model a bit more complex by assuming that the hillslope can be modelled with three different hillslope velocity values, $v = 10^{-3}$, $v = 10^{-5}$ and $v = 10^{-7}$ $\mathrm{m\,s^{-1}}$, indicating the fast, intermediate and slow hillslope response. Run the model with the defined fractions for the fast, medium and slow response velocity.

Play around with the fractions of the different velocity values. Which fractions did you get for which part of the year?

For which part of the year were you able to obtain proper discharge estimates?

6 TOPMODEL

As you probably noticed, the simple model was only able to simulate a proper response behaviour for some events. It is very difficult to simulate the hydrological response of a catchment with a few fixed velocities. It is impossible to grasp the temporal variations in the complex hydrological interactions between vegetation and the unsaturated and saturated zones using this simple approach.

The next step is to use a more complex (but still relatively simple) hydrological model: TOPMODEL. TOPMODEL is a well-known model based on the topographic properties of the catchment.

6.1 Topographic index

The main assumption behind TOPMODEL is that the response behaviour of a given pixel, can be estimated by its topographic index value λ:

$$\lambda = \ln\left(\frac{a}{\tan\beta}\right) ,$$

where a is the upstream area per unit contour length (pixel length) [m] and β the local slope [°]. More information on TOPMODEL is given in the paper by Beven and Kirkby in the literature section of the reader.

Use the script to compute and plot the topographic index for each pixel.

[†] The word effective is added because the actual flow velocity of the water particles through the soil is much slower than the response caused by pressure changes.

How are the topographic indices distributed?

When is the parameter uncertainty large? In other words, when is the spread of the grey lines, caused by different parameter sets, large?

6.2 Running TOPMODEL

To run TOPMODEL (and almost all other rainfall-runoff models), you need to specify parameter values and initial conditions. TOPMODEL has 5 parameters of which the values are different for each catchment and can be found by model calibration (also called parameter estimation or optimization). Calibration is often difficult because different parameter sets may lead to more or less equally good results. TOPMODEL has already been calibrated for the Ourthe catchment and 20 parameter sets are given in `TOPMODEL_Parameters.dat`.

The initial conditions which have to be specified are estimates of the total catchments unsaturated zone deficit (`Dbar`) and the total catchment root zone deficit (`Drzone`).

First we will use only the first parameter set (first row in `TOPMODEL_Parameters.dat`). Run TOPMODEL and simulate the discharge response for the period 1 October 2002–31 March 2003.

Describe the performance of the model. When did the model succeed and when and how did it fail?

6.3 Effect of parameters

To analyze the effect of uncertainty in the parameter values, run the model with all 20 parameter sets and make an ensemble of the simulations. This may take a few minutes.

What is the effect of the different parameter sets?

6.4 Effect of initial conditions

The results show that it is especially difficult to simulate the response of the Ourthe for the first main runoff peak in November 2002. This is caused by a wrong estimation of the initial storage, given by `Dbar` and `Drzone`.

Change the values of `Dbar` and `Drzone` and run the model again.

What is the effect of the initial conditions?

Some models use a warming-up period to compensate for bad initial conditions. For example, when you want to forecast discharge from April to September, you may start the simulations in March and neglect the output of the first month.

How long would you advise the warming-up period to be for TOPMODEL in the Ourthe catchment and why?

What is the relation between `Dbar` and `Drzone`?