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This project has received European Regional Development Funding through INTERREG IV B.
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Low flow regionalisation in the Walloon region

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Université de Liège
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Title	Low flow regionalisation in the Walloon region
Authors	Maud Grandry, Arnaud Verstraete, Sébastien Gailliez, Aurore Degré
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Lead partner	ULg Gembloux Agro-Bio Tech
Partners involved	ULg Gembloux Agro-Bio Tech
Work package	1
Action	3

AMICE *Adaptation of the Meuse to the Impacts of Climate Evolutions*
is an INTERREG IVB North West Europe Project (number 074C).
Climate change impacts the Meuse basin creating more floods and more droughts.
The river managers and water experts from 4 countries of the basin join forces in this EU-funded transnational project to elaborate an innovative and sustainable adaptation strategy. The project runs lasts from 2009 through 2012.
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1. Introduction

Floods have always been the main concern resulting from extreme weather conditions. Now, low flows and droughts are more and more recognised as risk situations due to the huge consequences of water shortage. Furthermore, climate change constitutes a new threat, even though the uncertainty about the evolution of low-flows remains high.

Moreover, being able to estimate low flows at any point of a river is really important nowadays for a good integrated management of rivers. Indeed, low flow estimates are needed in projects related, for example, to the construction of hydroelectric dams, the conservation of aquatic habitats, water abstraction licensing, discharge management, commercial navigation or the management of bathing areas.

It becomes essential to know the magnitude as well as the frequency of such extreme events. The frequency actually indicates the severity of low flow events. And, in case of droughts, different measures to maintain a minimum flow in rivers are usually taken by the environmental department of the Government according to this severity (e.g. “Plan d’Action Sécheresse” in France, drought plans in the UK).

In Wallonia, low flows have never been studied in details, and no method exists to estimate them. Therefore, Gembloux Agro-Bio Tech (University of Liège) aims at filling this knowledge gap.

The first step is to select the gauging stations that have sufficient homogeneous flow data. Then, a frequency analysis is carried out for each station. This aims at fitting a frequency distribution to low flow data in order to calculate low flows for return periods of 5, 10, 20 and 50 years. Physical and climatic parameters characterising the catchments of the gauging stations are also determined for each catchment. These are subsequently used to delineate hydrologically homogeneous regions and develop regression equations to estimate low flows.

2. Hydrological data

The MAM7 was chosen, by the partners within the framework of the AMICE project (WP1 AC3), as the index characterising low flows. It represents the mean annual minimum of 7-day average flows. It is used in the Netherlands, in Germany and also in the United-States and United Kingdom, and is less sensitive to measurement errors.

The main problem in Wallonia is the short history of hydrological monitoring (Figure 1). Most first monitoring site were installed in 1960. It consisted in a staff gauge and daily manual readings. Since 1974, hourly data have been recorded. The number of gauging stations reached 244 in 2011.

A qualitative analysis of the monitoring stations led us to disregard 187 stations. The main quality problems were short recording periods, important extrapolation of the discharge rating curve, algae development in summer, human influence on flows (dams, abstraction, etc), MAM7 below 5 l/s, and flow values extrapolated from nearby stations. In order to try to get back a few monitoring sites or data years, three analyses were performed.

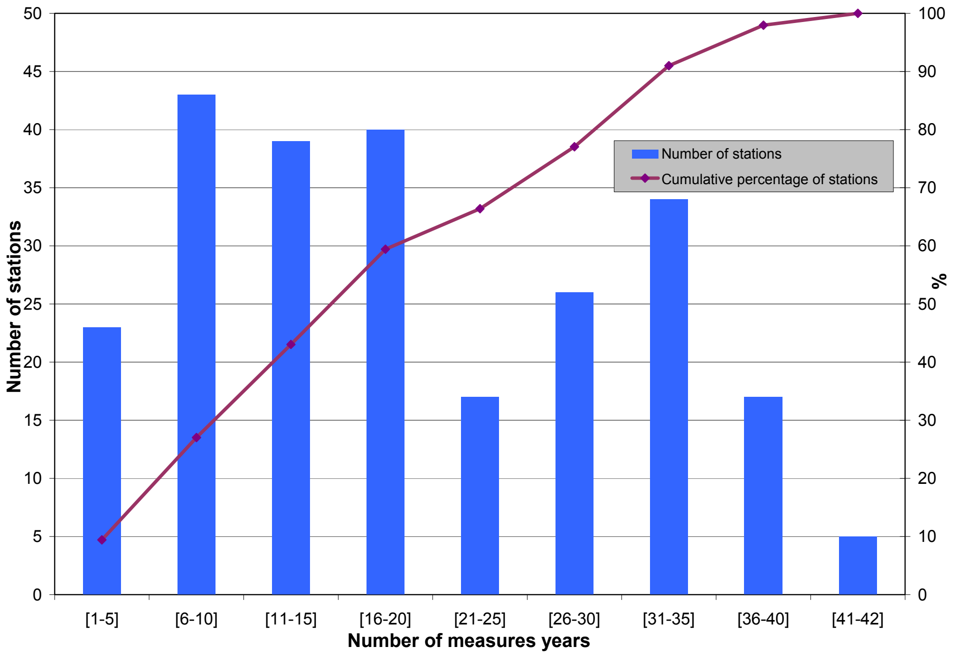


Figure 1. The number of stations in function of data length.

Firstly, the old manual daily readings were analysed. In the past, water heights were read daily by an operator at a set time (8am) and were then converted in discharges using a rating curve (stage-discharge relationship). Unusable in high flow situations, they still hold practical and usable information during low flow periods. The variability during a day in a period of low flows is indeed low. These data were validated from sites with 25 years of data. A test for the equality of means was done to compare the MAM7 obtained from the daily data and the MAM7 from hourly data at 8 am (Dagnélie, 1975). The latest data are equivalent to discharges that would be converted from the water heights read by the operator. This analysis allowed us to extend the recording period of 7 stations and to recover 16 stations.

Secondly, a lot of data were missing during the 1960-1994 period, due to a poor management of the monitoring network. A yearly hydrograph analysis led us to keep some years when the gaps were out of the low flow period. The treatment permitted to increase the data length of 51 stations. A few monitoring sites have gained up to 10 years of data.

Thirdly, in Wallonia, about 60% of the monitoring sites have less than 20 years of hourly data (see Figure 1) which is the data length recommended in the literature for the characterisation of low flows (Laaha and Blöschl, 2005). A methodology based on the mean and standard deviation of MAM7 was applied on monitoring sites situated in different catchment areas of the Walloon region and with at least 20 years of data. For each site, the number of recording years necessary for the minimum data length was calculated in such a way that the relative deviation between the sample mean and the general mean as well as the relative deviation between the sample variance and the general variance were both inferior to a predefined tolerance (10%). The minimum data length resulting from this method was about 20 years. No site with a short data length could therefore be recuperated.

After the selection of gauging stations for frequency analysis, a homogeneity test was performed on the data. The goal of this test was to verify if all the low flows of a station came from one population in a statistical sense. The most frequent causes of heterogeneities were: a displacement of a measuring site, a change in the discharge rating curve, a change in the catchment area management. The test consisted in a test for the equality of means (Student test). The samples were considered to have the same variance. The total population of one site was represented by the annual minimum 7-day average flow series of that site.

Three homogeneity tests were carried out depending on the division of the population. The population was divided into two samples of the same size, at the year 1992 (change in the management team), and at the transition year between staff gauges and level recorders.

⇘ Finally, 59 out of 244 monitoring sites were selected for frequency analysis.

3. Frequency analysis

Frequency analysis consists in the adjustment of a statistic law to hydrologic observations. The goal is to calculate, for each station, the critical low flow Q_T that corresponds to a given return period T. The return period is defined as the mean time between two occurrences of a specific flow. To do so, we used probabilistic models. These models are mathematical formulations that aim at simulating natural hydrological phenomenon such as probabilistic processes based on the probabilistic analysis of the considered random variables (in this study, MAM7).

The laws currently used in hydrology are the following: Normal, Lognormal, Gumbel, Generalized Extreme Value, Weibull, Gamma, and Pearson. After having chosen the law, the parameters must be estimated by the method of moments, the method of maximum likelihood or even the L-moments method and probability-weighted moments (Ashkar and Mahdi, 2006; Condie and Nix, 1975; Galea *et al.*, 1999; Greenwood *et al.*, 1979; Gumbel, 1954; Hosking *et al.*, 1985; Hosking, 1986; Joseph, 1970; Landwher, 1979; Leppajarvi, 1989; Matalas, 1963; Nathan, 1990; Tasker, 1987). A test of adequacy (the examination of the skewness and kurtosis coefficients, the khi² test, the Kolmogorov-Smirnov test or the Cramer-Smirnov-Von mises test) is then performed in order to verify the good fit between observations and the corresponding probability laws (Joseph, 1970; Prakash, 1981; Shao *et al.*, 2008). Several distributions can give statistically acceptable adjustments but this test does not permit to draw conclusions on the choice of the best law. To determine the law that best fits the data, the graphical method is the most efficient tool.

Adjustment methodology

Five distributions often used for low flow discharge analysis were tested with the HYFRAN software: Weibull (2 parameters), 2-parameter lognormal (LN2) and 3-parameter lognormal (LN3), Gamma and Pearson type III. The Fréchet distribution was also tested manually. The parameters of the laws were estimated by the maximum likelihood estimation (MLE). The selection of the three best laws was performed for each site thanks to three Bayesian criterions proposed by HYFRAN. These three criterions permitted to build a classification of statistical laws taking into account the parsimony principle that favours the 2-parameter laws. The khi² test was applied to verify the adequacy of these distributions for the sample of observed values. To be selected, the null hypothesis must be accepted for the distribution.

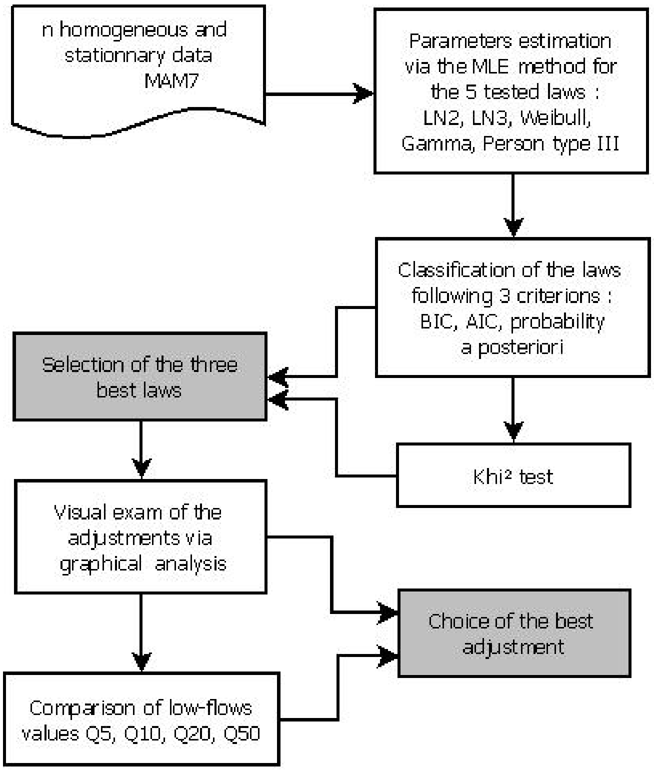


Figure 2 : Diagram of the methodology used in the choice of the best adjustment for each station

Finally, the distribution that best fits the data was visually chosen. The Fréchet distribution was also compared to these 3 distributions. The incertitude associated to the choice of the law was considered for the estimation of the quantiles. Indeed, the theoretical occurrence probabilities of studied events were unknown and we searched a probability law that gave a good approximation. That is why, for each adjustment, the quantiles of return period were estimated with a confidence interval of 95%.

Results

The Gamma and the lognormal distributions were the most used. The Gamma was the most frequently appropriated, followed closely by the lognormal. In some cases, a three-parameter law best fitted the data. The Weibull law proved to be unadapted for low flow discharges in Wallonia.

The table below (Table 1) gives the best adjustment for all the monitoring sites. We also calculated the values of low flows for different return periods (5, 10, 20 and 50 years) with their 95% confidence interval. Fifty years is the maximal period in view of the number of working years of the measurements sites.

Table 1. Choice of the best adjustment for the gauging stations, with the values of MAM7 for the considered return periods and their 95% confidence interval.

Station (River)	Distribution	MAM7							
		T5	CI (95%)	T10	CI (95%)	T20	CI (95%)	T50	CI (95%)
Trois-Ponts (Salm)	Lognormal 3	0.464	0.397 - 0.531	0.412	0.353 - 0.470	0.378	0.322 - 0.434	0.348	0.288 - 0.407
Lorcé (Lienne)	Lognormal	0.224	0.176 - 0.273	0.181	0.135 - 0.226	0.151	0.108 - 0.195	0.124	0.083 - 0.165
Harnoncourt (Ton)	Gamma	1.900	1.710 - 2.080	1.690	1.490 - 1.890	1.530	1.310 - 1.740	1.360	1.140 - 1.590
Ruette (Vire)	Gamma	0.194	0.162 - 0.226	0.163	0.130 - 0.196	0.140	0.107 - 0.174	0.118	0.084 - 0.152
Athus (Messancy)	Gamma	0.106	0.082 - 0.130	0.083	0.059 - 0.106	0.066	0.043 - 0.089	0.051	0.029 - 0.073
Latour (Vire)	Gamma	0.218	0.181 - 0.255	0.176	0.139 - 0.213	0.146	0.109 - 0.182	0.117	0.081 - 0.153
Irchonwelz (Dendre occidentale)	Lognormal	0.110	0.095 - 0.124	0.095	0.081 - 0.110	0.085	0.070 - 0.099	0.074	0.060 - 0.089
Ath (Dendre orientale)	Pearson type III	0.254	0.199 - 0.308	0.195	0.136 - 0.254	0.149	0.081 - 0.217	0.101	0.016 - 0.187
Isières (Sille)	Gamma	0.017	0.013 - 0.022	0.013	0.009 - 0.017	0.010	0.006 - 0.014	0.007	0.004 - 0.010
Brugelette (Dendre orientale)	Lognormal 3	0.163	N/D	0.121	N/D	0.086	N/D	0.047	N/D
Bierges (Dyle)	Gamma	1.190	1.100 - 1.280	1.090	0.999 - 1.190	1.020	0.917 - 1.120	0.939	0.828 - 1.050
Suzeril (Thyle)	Gamma	0.221	0.191 - 0.252	0.188	0.156 - 0.220	0.163	0.131 - 0.196	0.139	0.105 - 0.172
Amougies (Rhosnes)	Gamma	0.101	0.074 - 0.128	0.075	0.050 - 0.101	0.058	0.034 - 0.082	0.043	0.021 - 0.064
Bergilers (Geer)	Lognormal	0.305	0.258 - 0.352	0.263	0.216 - 0.310	0.233	0.185 - 0.280	0.203	0.155 - 0.251
Opheylissem (Petite Gette)	Lognormal	0.461	0.413 - 0.508	0.410	0.361 - 0.459	0.372	0.322 - 0.423	0.334	0.282 - 0.386
Haine (Boussoit)	Gamma	0.517	0.446 - 0.588	0.441	0.368 - 0.515	0.385	0.309 - 0.461	0.328	0.250 - 0.406
Baisieux (Grande Honnelle)	Lognormal	0.221	0.206 - 0.237	0.205	0.189 - 0.222	0.193	0.175 - 0.211	0.180	0.161 - 0.200
Hastière (Hermeton)	Pearson type III	0.171	0.154 - 0.187	0.153	0.140 - 0.167	0.143	0.132 - 0.154	0.135	0.126 - 0.143
Modave (Hoyoux)	Lognormal	0.359	0.313 - 0.406	0.319	0.271 - 0.367	0.289	0.240 - 0.339	0.259	0.208 - 0.310

Table 1. Choice of the best adjustment for the gauging stations, with the values of MAM7 for the considered return periods and their 95% confidence interval.

Station (River)	Distribution	MAM7							
		T5	CI (95%)	T10	CI (95%)	T20	CI (95%)	T50	CI (95%)
Daverdisse (Lesse)	Lognormal	0.428	0.355 - 0.500	0.346	0.278 - 0.414	0.291	0.226 - 0.356	0.239	0.178 - 0.301
Resteigne (Lesse)	Lognormal	0.426	0.339 - 0.512	0.340	0.259 - 0.420	0.282	0.206 - 0.358	0.229	0.158 - 0.300
Ochamps (Lesse)	Gamma	0.017	0.013 - 0.022	0.013	0.008 - 0.017	0.010	0.006 - 0.014	0.007	0.003 - 0.010
Graide (Ruisseau de Graide)	Gamma	0.007	0.003 - 0.010	0.004	0.001 - 0.006	0.002	0.001 - 0.004	0.001	N/D
Our (Eau d'Our)	Lognormal	0.117	0.093 - 0.140	0.095	0.073 - 0.117	0.080	0.059 - 0.101	0.066	0.046 - 0.086
Lavaux-Saint-Anne (Wimbe)	Lognormal	0.040	0.026 - 0.054	0.027	0.016 - 0.038	0.019	0.010 - 0.028	0.013	0.006 - 0.020
Grupont (Lhomme)	Gamma	0.217	0.128 - 0.306	0.139	0.065 - 0.214	0.093	0.030 - 0.155	0.055	0.007 - 0.104
Eprave (Lhomme)	Lognormal	0.698	0.581 - 0.814	0.585	0.471- 0.699	0.506	0.394 - 0.618	0.430	0.320 - 0.539
Moha (Mehaigne)	Fréchet	0.595	0.470 - 0.721	0.528	0.402 - 0.654	0.483	0.357 - 0.609	0.447	0.321 - 0.573
Wanze (Mehaigne)	Fréchet	0.673	0.549 - 0.798	0.605	0.481 - 0.730	0.561	0.436 - 0.685	0.525	0.401 - 0.649
Upigny (Mehaigne)	Pearson type III	0.014	0.009 - 0.018	0.009	0.004 - 0.014	0.006	-0,0003 - 0,011	0.002	-0,006 - 0,009
Ambresin (Mehaigne)	Gamma	0.266	0.218 - 0.314	0.213	0.165 - 0.260	0.175	0.128 - 0.222	0.139	0.093 - 0.185
Felenne (Houille)	Lognormal	0.145	0.121 - 0.169	0.118	0.095 - 0.141	0.099	0.078 - 0.121	0.082	0.061 - 0.103
Warnant (Molignée)	Gamma	0.484	0.444 - 0.524	0.436	0.393 - 0.480	0.399	0.353 - 0.446	0.361	0.311 - 0.410
Rhisnes (Houyoux)	Gamma	0.022	0.017 - 0.027	0.016	0.011 - 0.021	0.012	0.008 - 0.017	0.009	0.005 - 0.013
Gedinne (Houille)	Fréchet	0.068	0.042 - 0.094	0.045	0.019 - 0.071	0.027	0.001 - 0.053	0.009	-0,017 - 0,036
Dalhem (Berwinne)	Lognormal 3	0.196	0.144 - 0.248	0.139	0.085 - 0.193	0.096	0.035 - 0.157	0.052	-0,022 - 0,126
Hamoir (Néblon)	Gamma	0.128	0.105 - 0.151	0.103	0.080 - 0.126	0.085	0.062 - 0.108	0.068	0.045 - 0.090
Erneuville (Ourthe)	Gamma	0.273	0.196 - 0.349	0.192	0.123 - 0.261	0.140	0.078 - 0.202	0.095	0.042 - 0.148

Table 1. Choice of the best adjustment for the gauging stations, with the values of MAM7 for the considered return periods and their 95% confidence interval.

Station (River)	Distribution	MAM7							
		T5	CI (95%)	T10	CI (95%)	T20	CI (95%)	T50	CI (95%)
Baillonville (Ruisseau d'Heure)	Gamma	0.030	0.023 - 0.037	0.023	0.016 - 0.029	0.018	0.012 - 0.024	0.013	0.008 - 0.019
Cerfontaine (Eau d'Heure)	Lognormal	0.030	0.027 - 0.033	0.027	0.024 - 0.030	0.025	0.022 - 0.028	0.023	0.020 - 0.026
Wihéries (Hantes)	Lognormal	0.174	0.148 - 0.200	0.149	0.123 - 0.174	0.131	0.105 - 0.156	0.113	0.087 - 0.139
Bersillies-l'abbaye (Thure)	Lognormal	0.105	0.093 - 0.116	0.094	0.082 - 0.107	0.087	0.074 - 0.100	0.079	0.065 - 0.092
Aiseau (Biesme)	Gamma	0.150	0.120 - 0.176	0.125	0.098 - 0.153	0.107	0.082 - 0.137	0.089	0.067 - 0.122
Walcourt (Ry d'Yves)	Lognormal 3	0.120	0.091 - 0.149	0.087	0.058 - 0.116	0.063	0.031 - 0.095	0.040	0.002 - 0.077
Thy-Le-Château (Thyria)	Fréchet	0.090	0.078 - 0.102	0.069	0.057 - 0.080	0.050	0.038 - 0.062	0.028	0.016 - 0.040
Membre (Semois)	Lognormal	1.630	1.330 - 1.920	1.300	1.030 - 1.570	1.080	0.823 - 1.340	0.877	0.636 - 1.120
Sainte-Marie (Semois)	Gamma	0.230	0.180 - 0.280	0.180	0.131 - 0.229	0.146	0.098 - 0.193	0.113	0.067 - 0.158
Tintigny (Semois)	Fréchet	0.429	0.305 - 0.554	0.315	0.191 - 0.439	0.229	0.105 - 0.354	0.148	0.024 - 0.272
Straimont (Vierre)	Gamma	0.164	0.110 - 0.218	0.111	0.064 - 0.158	0.078	0.037 - 0.118	0.049	0.016 - 0.083
Tintigny (Rulles)	Lognormal	0.152	0.110 - 0.194	0.111	0.075 - 0.147	0.086	0.054 - 0.118	0.065	0.037 - 0.092
Marbehan (Mellier)	Lognormal	0.034	0.021 - 0.047	0.022	0.012 - 0.032	0.016	0.008 - 0.023	0.010	0.004 - 0.016
Ronquières (Samme)	Gamma	0.314	0.278 - 0.349	0.283	0.244 - 0.322	0.259	0.218 - 0.301	0.235	0.190 - 0.279
Tubize (Senne)	Weibull (MM)	0.278	0.229 - 0.328	0.234	0.181 - 0.288	0.199	0.144 - 0.255	0.161	0.106 - 0.216
Martelange (Sûre)	Lognormal	0.127	0.080 - 0.174	0.087	0.049 - 0.124	0.063	0.032 - 0.094	0.044	0.019 - 0.069
Brouffe (Mariembourg)	Lognormal	0.011	0.008 - 0.014	0.008	0.006 - 0.011	0.007	0.004 - 0.009	0.005	0.003 - 0.007
Nismes (Eau Blanche)	Gamma	0.190	0.156 - 0.223	0.152	0.119 - 0.185	0.125	0.092 - 0.158	0.099	0.067 - 0.131
Couvin (Eau Noire)	Gamma	0.168	0.132 - 0.204	0.132	0.097 - 0.167	0.106	0.072 - 0.141	0.083	0.050 - 0.115

Table 1. Choice of the best adjustment for the gauging stations, with the values of MAM7 for the considered return periods and their 95% confidence interval.

Station (River)	Distribution	MAM7							
		T5	CI (95%)	T10	CI (95%)	T20	CI (95%)	T50	CI (95%)
Treignes (Viroin)	Gamma	0.557	0.467 - 0.647	0.453	0.362 - 0.543	0.378	0.287 - 0.468	0.305	0.216 - 0.394
Bruly (Ry de Pernelle)	Lognormal	0.062	0.050 - 0.073	0.051	0.040 - 0.062	0.044	0.033 - 0.054	0.037	0.027 - 0.047

4. Calculation of the catchment parameters

4.1. Altitude (Alt)

The “0” level of the staff gauge was considered as the altitude of each gauging station. It was measured (in m) with a GPS or by levelling, by the Public Service of Wallonia.

4.2. Map coordinates (X and Y)

The map coordinates (in m) were also measured with a GPS or by levelling, by the Public Service of Wallonia. The Belgian Lambert 1972 coordinate system was used.

4.3. Area (A)

Catchment boundaries were defined by the ALBA project (Xanthoulis and Debauche, 2010) using the 1/10000 Digital Terrain Model (DTM) created for the ERRUISSOL project (Dautrebande *et al.*, 2008). For the transboundary catchments, the 1/50000 DTM from the Belgian National Geographic Institute was used. The area (in km²) was calculated using ArcGIS.

4.4. Drainage density (DD)

Drainage density is the length of all streams included in a catchment divided by the catchment area (in km/km²). A GIS map of Walloon streams was provided by the Public Service of Wallonia and the stream lengths were calculated with ArcGIS. The parts of streams outside Wallonia were determined using the DTM from the Belgian National Geographic Institute.

4.5. Slope (Sl)

The 10th, 50th and 90th percentiles of the slope (Sl_{10}, Sl_{50} and Sl_{90} in %) of each catchment were determined from the ERRUISSOL DTM using ArcGIS. The same DTM was used for the transboundary catchments, considering only the Walloon part of these catchments.

4.6. Land use (L)

The area percentages of urban lands (L_u), forests (L_f), arable lands (L_a), permanent crops (L_p) and grasslands (L_g) were calculated from the Walloon land use map created in 2007, and from the European CORINE map updated in 2006 for the catchment parts outside Wallonia.

4.7. Soil type (S)

The hydrological types of soil determined by the ERRUISSOL project with the Soil Conservation Service method (Demarcin *et al.*, 2011) were utilised: S_A, S_B, S_C, S_D in percentage of catchment area. Soils from the hydrological group A are characterised by a high infiltration rate and an excellent to good drainage. On the other hand, soils from the hydrological group D have very low infiltration rate and very bad drainage. For this study, group D also contains urban areas which are considered as impermeable. S_{NM} represents the area percentage of soils that were not mapped.

4.8. Meteorological parameters: precipitation (P) and temperature (T)

Meteorological data were simulated by the hydrological model EPICgrid (Sohier *et al.*, 2009; Sohier, 2011). Input data were provided by the Royal Meteorological Institute of Belgium and the Hydrology Study Service of the Public Service of Wallonia. The model uses the Thiessen polygon method. Mean annual (October to September), summer (July to September) and winter (October to April) precipitation were considered (AP, SP and WP in mm). For temperature, only the summer mean was taken into account (ST in °C).

4.9. Evapotranspiration (PET)

Mean summer evapotranspiration (in mm) was also calculated for all catchments by the hydrological model EPICgrid (Sohier *et al.*, 2009; Sohier, 2011) which uses Penman and Penman-Monteith equations.

4.10. Percolation (Pe)

Mean annual percolation (in mm) was simulated by the hydrological model EPICgrid (Sohier *et al.*, 2009; Sohier, 2011).

4.11. Recession coefficient (RC)

The recession coefficient was chosen as a feature to characterise the hydrogeology of the streams. Low flows are influenced by aquifer properties such as the quantity of water that can be released and the releasing velocity.

Recession is defined as the part of stream flow in which discharge depletes gradually and there is no rainfall or human influence (Dacharry, 1997; Tallaksen, 1995).

It is usually described mathematically by Maillet's formula in which discharge decreases exponentially through time:

$$Q_t = Q_0 e^{-\alpha t}$$

in which Q_t is the discharge at time t, Q_0 is the discharge at the beginning of the recession and t is the time since the beginning of the recession. The parameter α is the recession coefficient.

Methodology

The method chosen to calculate recession coefficients is one developed by the University of Metz (Lang C. and Gille E., 2006). Indeed, study zones were comparable in regards to climate and catchments. However, it has been adapted to the particularities of Wallonia.

The first step was to define recession periods.

Firstly, all discharge values above the 75th percentile were discarded because they are not characteristic of recession.

Secondly, a threshold of 1 mm/day was set for significant precipitation, which means that remaining discharges occurring during a rainfall of more than 1 mm/day were not taken into account.

Thirdly, recession periods had to last at least 5 days.

Fourthly, in order to avoid the influence of overland flow, a period of time, dependent on catchment area, was allowed between the end of the rainfall event and the beginning of the recession sequence.

Moreover, the first discharge of the sequence (Q_0) was determined using the last values of the sequence. The slope of each sequence was calculated using the 3 last values of the sequence and extrapolated to previous days. Discharge values that were different by more than 1.5% from the extrapolated line were not considered for the final sequence.

It appeared sometimes that the slope was negative because of some consecutive raising values at the end of the sequences. Then, these values were deleted until the recalculated slope was positive.

Finally, only the sequences of at least 3 values were taken into consideration.

The second and final step was to construct a mean recession curve for each station, called master recession curve, in order to calculate the recession coefficient.

The method consists in correlating all Q_0 discharges with all Q_t discharges for every t value from 1 to t_{max} (maximum recession length), for each station, in order to obtain $a_t = Q_t / Q_0$ for each length t (Figure 3).

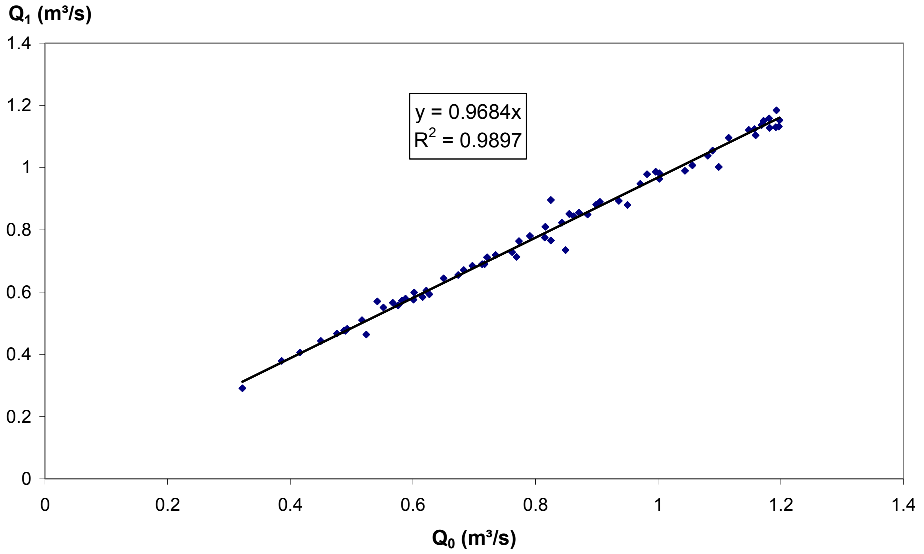


Figure 3. Correlation plot between Q_0 and Q_1 for Trois-Ponts station on the Salm: The a_t ratio is here equal to 0.9684.

Table 2 shows a_t ratios for Trois-Ponts station on the Salm as well as corresponding determination coefficients R².

Table 2. Decreasing a_t ratios when the length t increases.

t (days)	a_t	R²
0	1	
1	0.968	0.990
2	0.951	0.990
3	0.926	0.979
4	0.903	0.971
5	0.890	0.973
6	0.876	0.937
7	0.858	0.897
8	0.846	0.875
9	0.817	0.860

A a_t ratio of 0.951 at t = 2 means that the discharge after 2 days was 95.1% of the original one.

Then, a_t ratios were plotted against the length t and an exponential curve was fitted to the graph. Indeed, the descending behaviour of the ratio over time was considered to represent the recession and the exponential curve could be characterised by Maillet's equation:

$$a_t = e^{-\alpha t}$$

where α is the recession coefficient and t is the recession length.

Figure 4 shows an example of application of this method for Trois-Ponts station on the Salm.

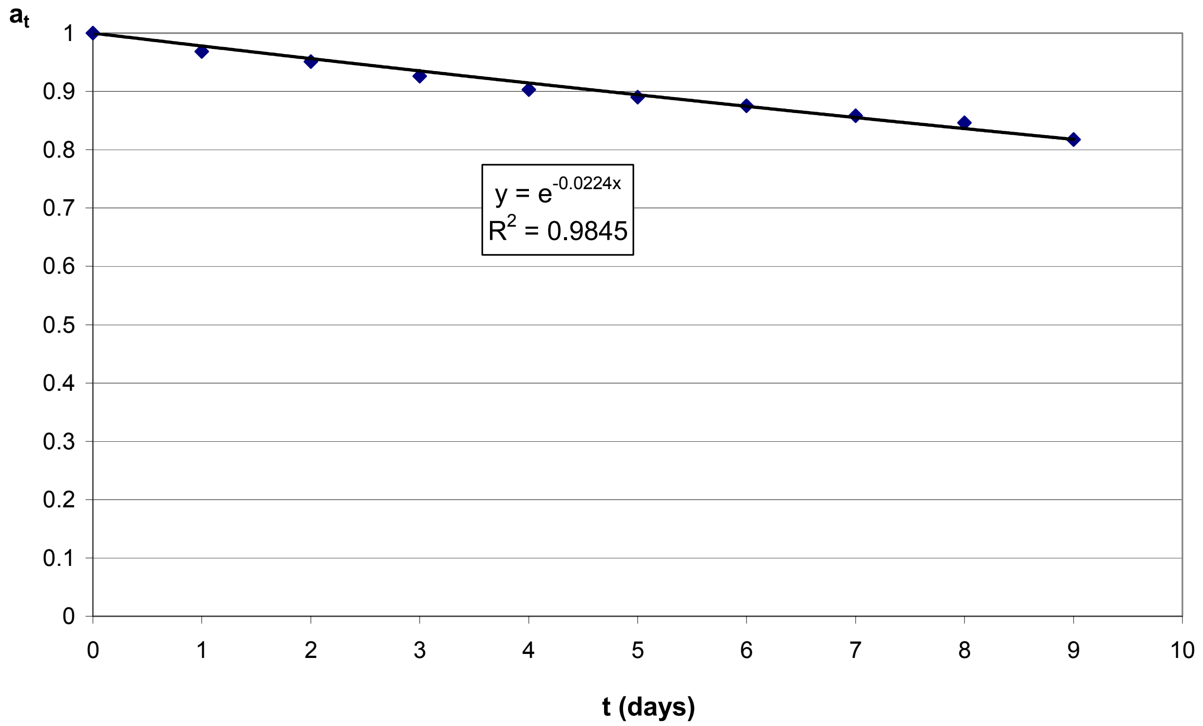


Figure 4. Example of construction of the master recession curve for Trois-Ponts station on the Salm: The recession coefficient is here equal to 0.0224 day^{-1}.

Results

Table 3 shows the recession coefficients for each gauging station selected in the study. The lower the coefficient is, the more the aquifer sustains low flows.

Table 3. Recession coefficient (day^{-1}) for each gauging station.

Station	Stream	Catchment	Recession coefficient (day^{-1})
Trois-Ponts	Salm	Amblève	0.022
Lorcé	Lienne	Amblève	0.019
Harnoncourt	Ton	Chiers	0.008
Ruette	Vire	Chiers	0.010
Latour	Vire	Chiers	0.012
Irchonwelz	Dendre occidentale	Dendre	0.014
Ath	Dendre orientale	Dendre	0.025
Isières	Silles	Dendre	0.015
Brugelette	Dendre orientale	Dendre	0.013
Bierges	Dyle	Dyle	0.005
Suzeril	Thyle	Dyle	0.004
Amougies	Rhosnes	Escaut	0.025
Opheylissem	Petite Gette	Gette	0.002
Boussoit	Haine	Haine	0.011
Baisieux	Grande Honnelle	Haine	0.010
Hastière	Hermeton	Hermeton	0.015
Daverdisse	Lesse	Lesse	0.025
Resteigne	Lesse	Lesse	0.010
Ochamps	Lesse	Lesse	0.021

Table 3. Recession coefficient (day^{-1}) for each gauging station.

Station	Stream	Catchment	Recession coefficient (day^{-1})
Graide	Ruisseau de Graide	Lesse	0.037
Our	Eau d'Our	Lesse	0.022
Lavaux-Sainte-Anne	Wimbe	Lesse	0.035
Grupont	Lhomme	Lesse	0.015
Eprave	Lhomme	Lesse	0.018
Moha	Mehaigne	Mehaigne	0.014
Wanze	Mehaigne	Mehaigne	0.014
Upigny	Mehaigne	Mehaigne	0.013
Ambresin	Mehaigne	Mehaigne	0.009
Felenne	Houille	Meuse amont	0.024
Warnant	Molignée	Meuse amont	0.008
Bruly	Ry de Pernelle	Meuse amont	0.027
Rhisnes	Houyoux	Meuse amont	0.011
Gedinne	Houille	Meuse amont	0.025
Bergilers amont	Geer	Meuse aval	0.008
Modave	Hoyoux	Meuse aval	0.006
Dalhem	Berwinne	Meuse aval	0.007
Hamoir	Néblon	Ourthe	0.007
Erneuville	Ourthe occidentale	Ourthe	0.021
Baillonville	Ruisseau d'Heure	Ourthe	0.024
Cerfontaine	Eau d'Heure	Sambre	0.023
Wiheries	Hantes	Sambre	0.024
Bersillies-l'abbaye	Thure	Sambre	0.019
Aiseau	Biesme	Sambre	0.010
Walcourt	Ry d'Yves	Sambre	0.018
Thy-le-Château	Thyria	Sambre	0.012
Membre	Semois	Semois	0.042
Sainte-Marie	Semois	Semois	0.020
Tintigny	Semois	Semois	0.027
Straimont	Vierre	Semois	0.036
Tintigny	Rulles	Semois	0.041
Marbehan	Mellier	Semois	0.054
Athus	Messancy	Semois	0.012
Ronquières	Samme	Senne	0.011
Tubize	Senne	Senne	0.025
Martelange	Sûre	Sûre	0.040
Mariembourg	Brouffe	Viroin	0.039
Nismes	Eau Blanche	Viroin	0.018
Couvin	Eau noire	Viroin	0.037
Treignes	Viroin	Viroin	0.028

Discussion

Figure 5 represents the values of recession coefficient on a map of Wallonia, together with the main aquifers. The more permeable the substratum is, the lower the coefficient is (Lang and Gille, 2006).

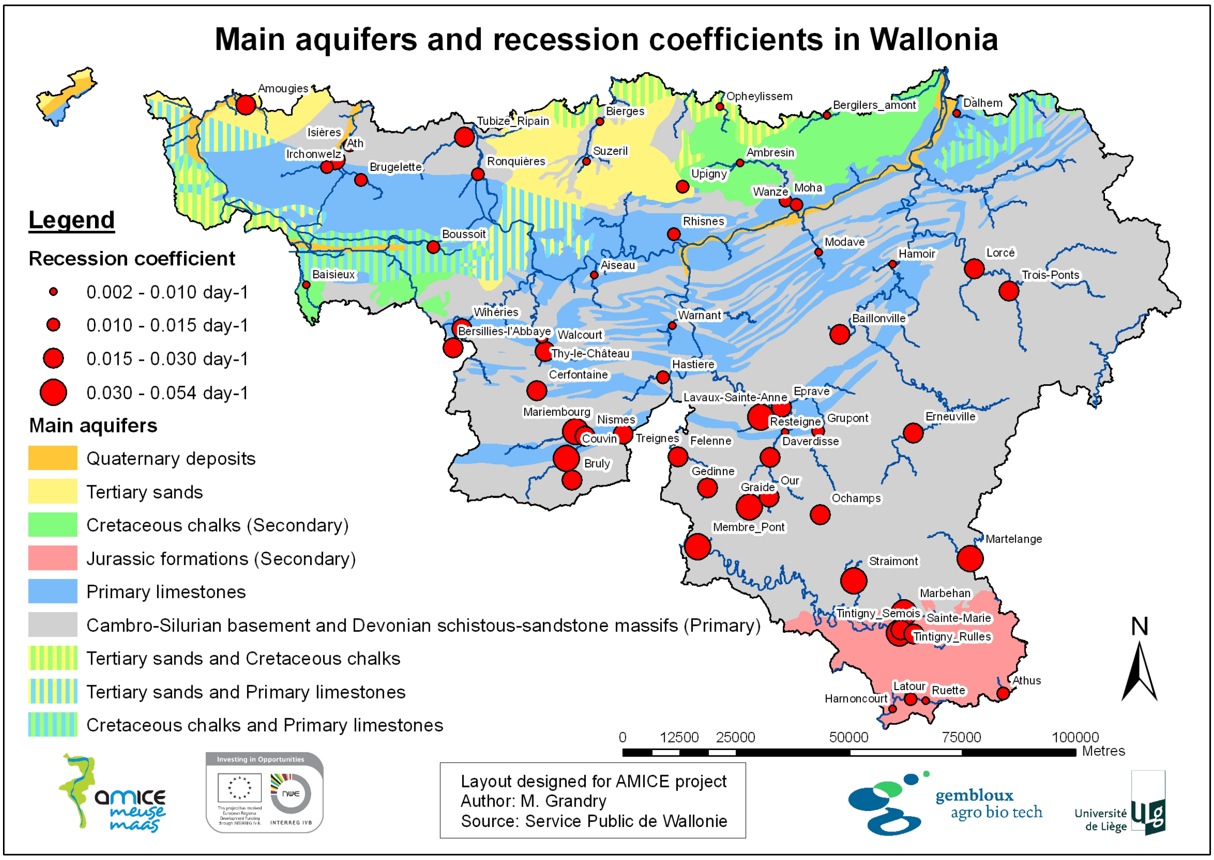


Figure 5. Map of main aquifers and spatial distribution of recession coefficients of some gauged catchments in Wallonia: The more permeable the substratum is, the lower the coefficient is.

Catchments with the highest recession coefficient values are situated on the Cambro-Silurian basement and Devonian schistous-sandstone massifs (in grey). This formation is constituted by schists, phyllites, quartz phyllites, sandstones, and cracked quartzites, and is characterised by a low capacity (Derouane and Meus, 2012). These catchments are, among others, Semois from its confluence with the Rulles, Sûre, Viroin, Rulles and Vierre.

Primary limestones (in blue), which are more permeable, consist of Carboniferous and Devonian limestones, and represent the most important aquifer in Wallonia (Derouane and Meus, 2012). Catchments on this formation are characterised by low coefficients (e.g. Molignée, Hoyoux, Néblon, Resteigne station on the Lesse and Dendre orientale).

Permeable (limestone and sandstone sands) and impermeable (marls or schistous sands) alternate in Jurassic formations (in red) (Derouane and Meus, 2012). Recession coefficients values vary from low to moderate.

Cretaceous chalks (in green) are carbonate formations which are more or less permeable (Derouane and Meus, 2012). Recession coefficients values are low (e.g. Baisieux, Bergilers, Ambresin and Boussoit).

Tertiary sands (in yellow) include Brusselian sands and Landenian and Ypresian sands. The Brusselian ones are constituted by loose rocks such as quartz sands, sandstone concretions, and calcariferous sands and sandstones. Streams in that region (Dyle and Senne) are in direct contact with the water table and drain it (Derouane and Meus, 2012). Recession coefficients values are very low.

Therefore, it seems interesting to classify the gauged catchments of the study by type of aquifer. The main type of aquifer that underlies the catchment (according to the area) has been attributed to each catchment. However, it is important to remember that these catchments correspond to surface water and might be different from the groundwater ones. Results are presented in Table 4 and Figure 6.

Table 4. Minimum, median and maximum recession coefficients by type of aquifer.

Type of aquifer	Number of observations	Recession coefficient (day^{-1})		
		Minimum	Median	Maximum
Tertiary sands	3	0.004	0.005	0.013
Cretaceous chalks (Secondary)	5	0.008	0.010	0.014
Primary limestones	12	0.006	0.011	0.025
Jurassic limestones-sands-sandstone (Secondary)	5	0.008	0.012	0.020
Devonian schists-sandstones and Cambro-Silurian basement	31	0.010	0.024	0.054

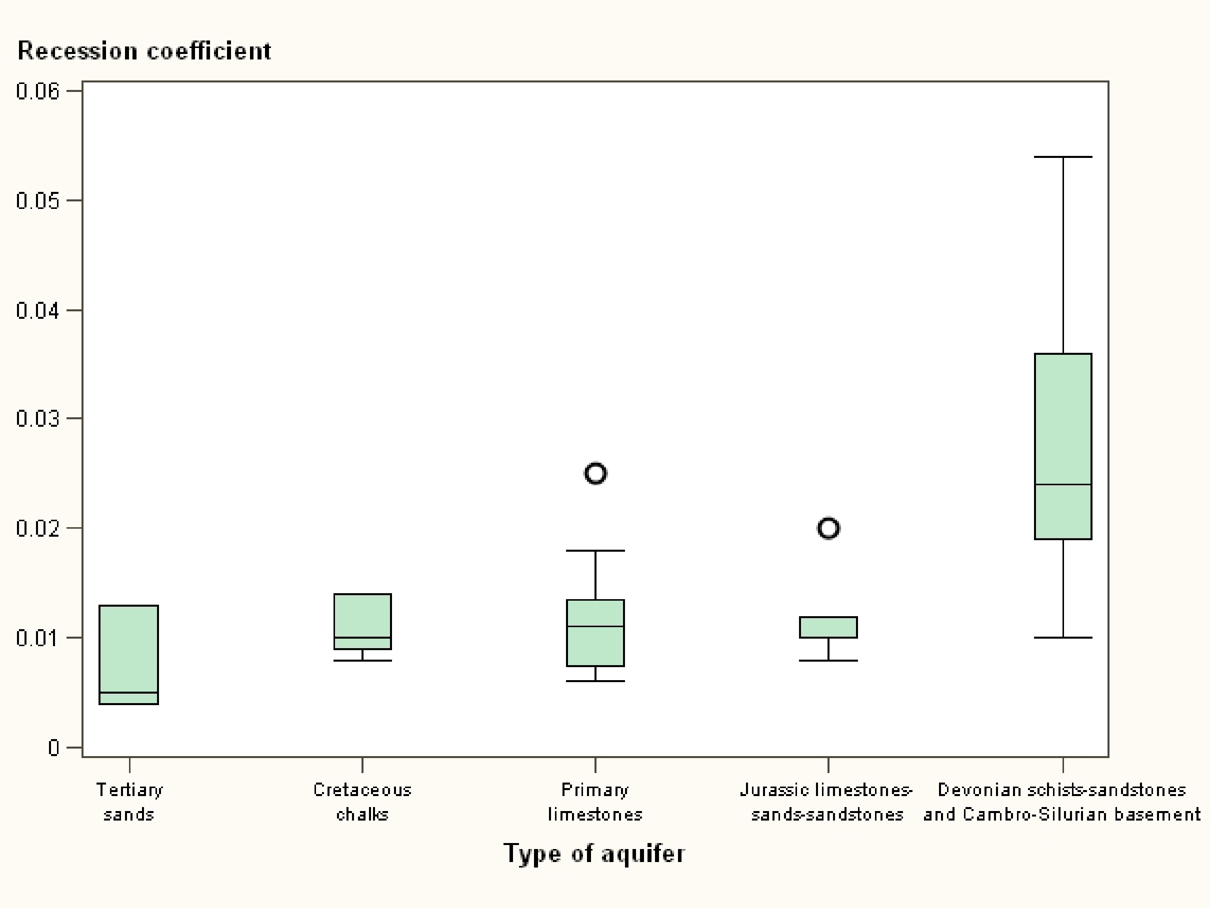


Figure 6. Boxplot of recession coefficients by type of aquifer.

Tertiary sands are characterised by the lowest median (0.005 day^{-1}), while the Cambro-Silurian basement and Devonian schistous-sandstone massifs have the highest median (0.024 day^{-1}). As the permeability of chalks and limestones is intermediate between the ones of sands and shists, they are characterised by a middle value (0.011 day^{-1}). This means that, during low flows, rivers on sands will be more sustained by groundwater than rivers on shists or sandstones.

5. Low flow regionalisation in Wallonia

Low flow regionalisation has been carried out in two steps:

- delineation of homogeneous regions using the physical features of the catchments related to the gauging stations
- development of regression models

5.1. Delineation of homogeneous regions

Methodology

The gauged catchments which had similar physical features and therefore similar hydrological responses were gathered in a region thanks to a cluster analysis. It will then be possible to assign the ungauged catchments to a region according to their features (Smakhtin, 2001). The features taken into account were the position and the altitude of the stations, catchment area, drainage density, slope, land use, hydrological type of soil, precipitation, temperature, evapotranspiration, percolation, and recession coefficient.

The variables were standardised and weighted for the analysis (Palm, 1998).

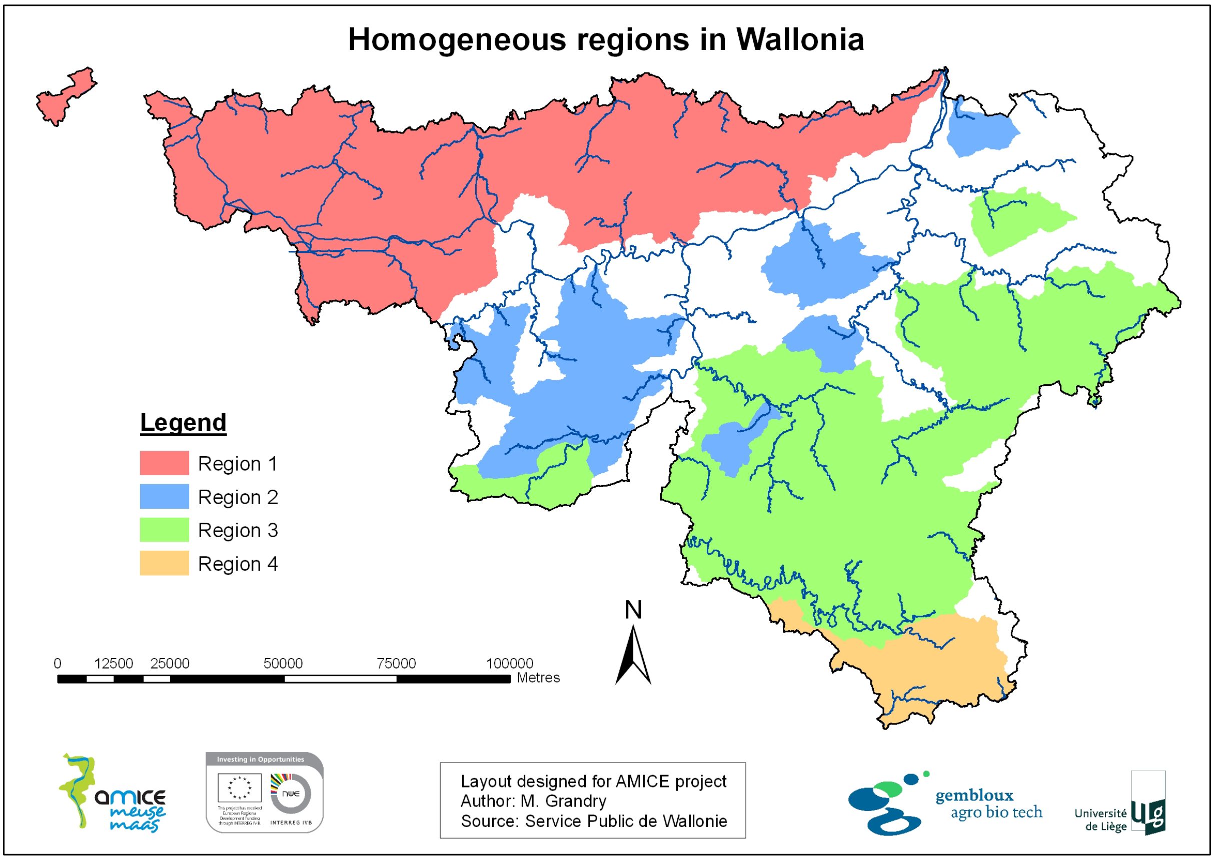
The clustering method used was the agglomerative hierarchical clustering which merges two small groups into a bigger one. The starting clusters were *n* groups of one observation each. Since all variables were quantitative, Ward's algorithm was chosen as the merging strategy. Each merger was then carried out in order to have the smallest difference of R^2 between two groupings. Indeed, R^2, the determination coefficient, represents the proportion of information kept after the fusion of clusters. The fusions were stopped before this difference of R^2 became large (Palm, 1998). A group of catchments form a homogeneous region.

Then, to interpret the results of clustering and characterise the regions, a Principal Component Analysis (PCA) was carried out, which helps understand the main differences between groups. A component is a linear combination of standardised variables. The mean and standard deviation of all variables for each group were also calculated and boxplots were drawn. This allowed locating groups in the plane of variables and compare groups according to these 25 variables.

Cluster and principal component analyses were carried out using SAS (Statistical Analysis System) software.

Results and interpretation

The map below shows the four homogeneous regions that result from the cluster analysis (Figure 7). White zones correspond to catchments that are influenced by humans (dam, abstraction) or ungauged.



Layout designed for AMICE project
Author: M. Grandry
Source: Service Public de Wallonie

Figure 7. Map of homogeneous regions in Wallonia.

Concerning the characterisation of these regions, the two first components of PCA already give a lot of information to distinguish the four groups of catchments (Figure 8 and Figure 9).

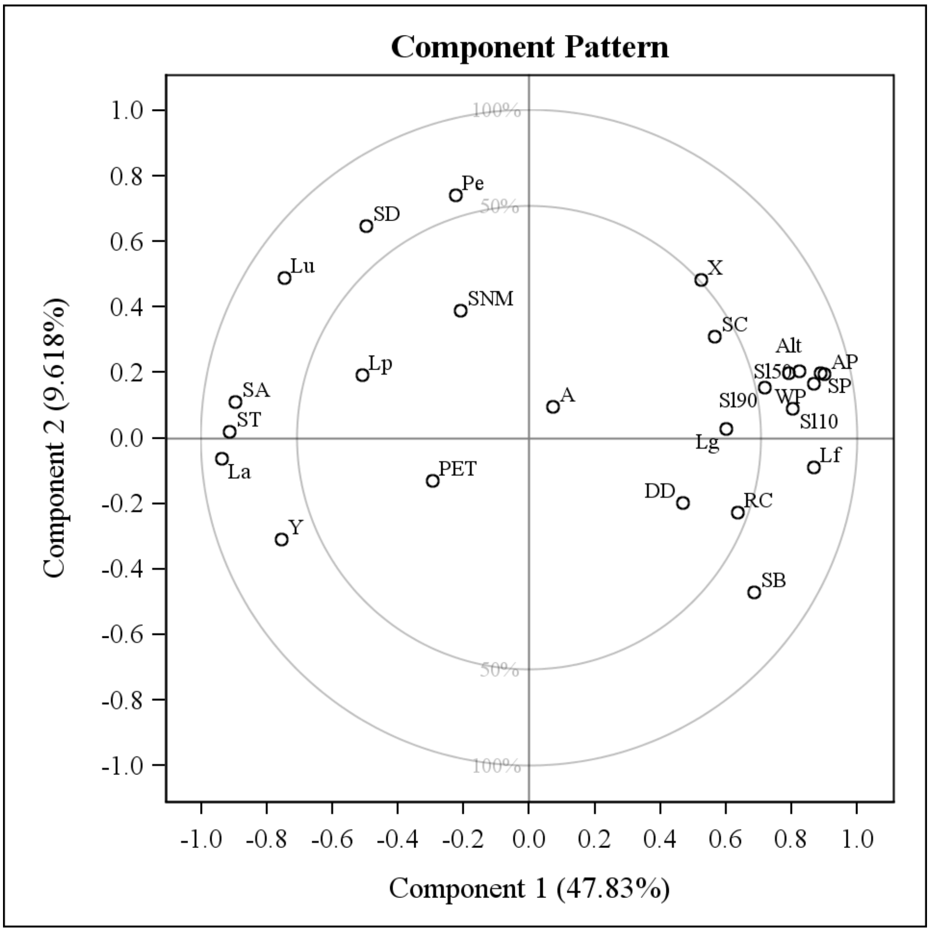


Figure 8. Correlation circle in the plane of the two first principal components.

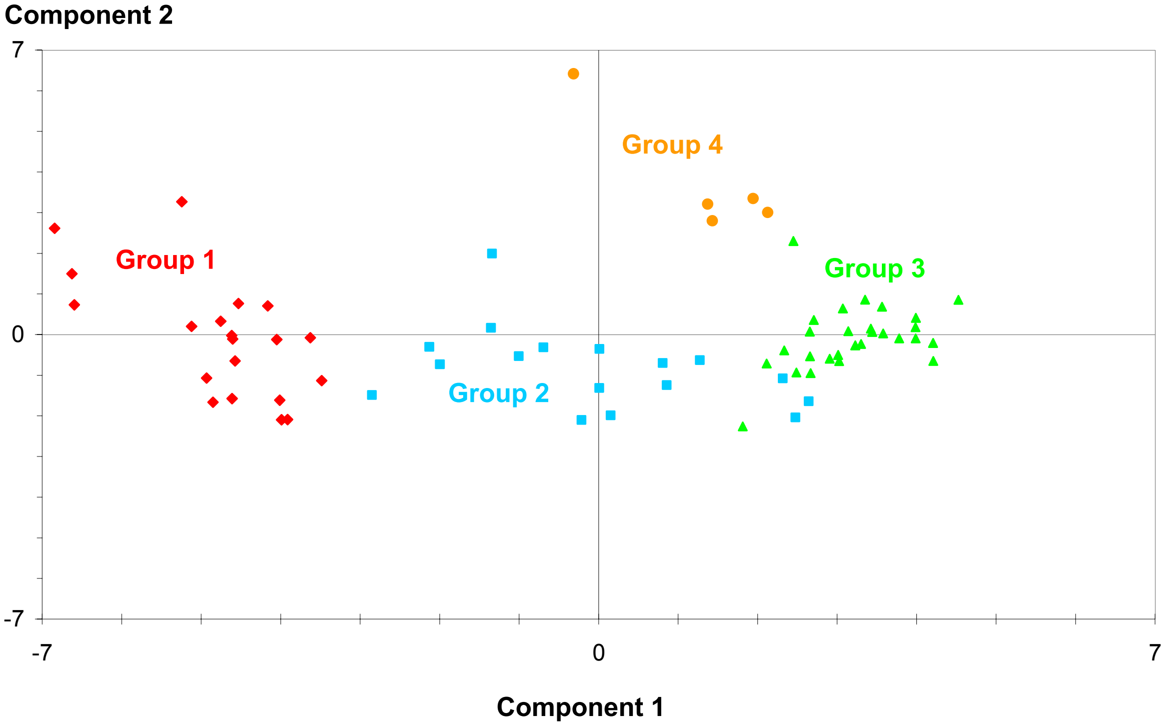


Figure 9. Groups of catchments in the plane of the two first components: The two first components allow distinguishing the four groups of catchments.

According to the first component, group 1 is different from groups 3 and 4. Group 1 is characterised by higher percentages of soils of hydrological group A, arable lands, and urban lands, higher summer temperature and Y Lambert coordinates but lower precipitations, altitudes, slopes, recession coefficients, and percentages of forests and soils of hydrological group B, than groups 3 and 4.

Group 4 can be differentiated from the others with the second component. This group has higher percolations and percentage of soil of hydrological group D.

Group 2 is located near the centre and is then characterised by average features. This corresponds to its central spatial location in Wallonia (region 2 on Figure 7).

Figure 10, Figure 11 and Figure 12 show some examples of the spatial distribution of some important catchment features that allow distinguishing regions.

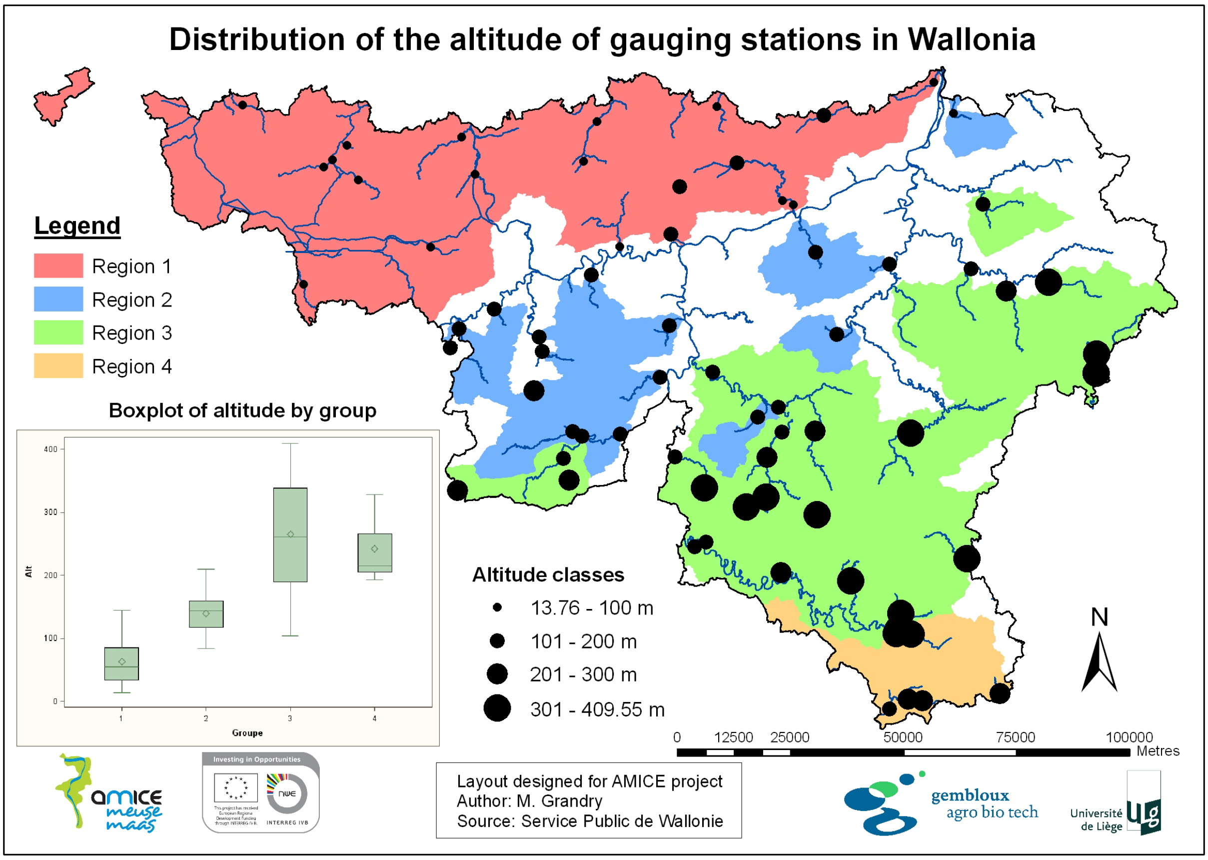


Figure 10. Map of the spatial distribution of the altitude of gauged stations used for cluster analysis in Wallonia and boxplot by group: Altitude increases from North-West to South-East.

Altitude in Wallonia increases from North-West to South-East, but with a little diminution between groups 3 and 4. A similar trend can also be observed for the slope and precipitation. But temperature follows an opposite trend.

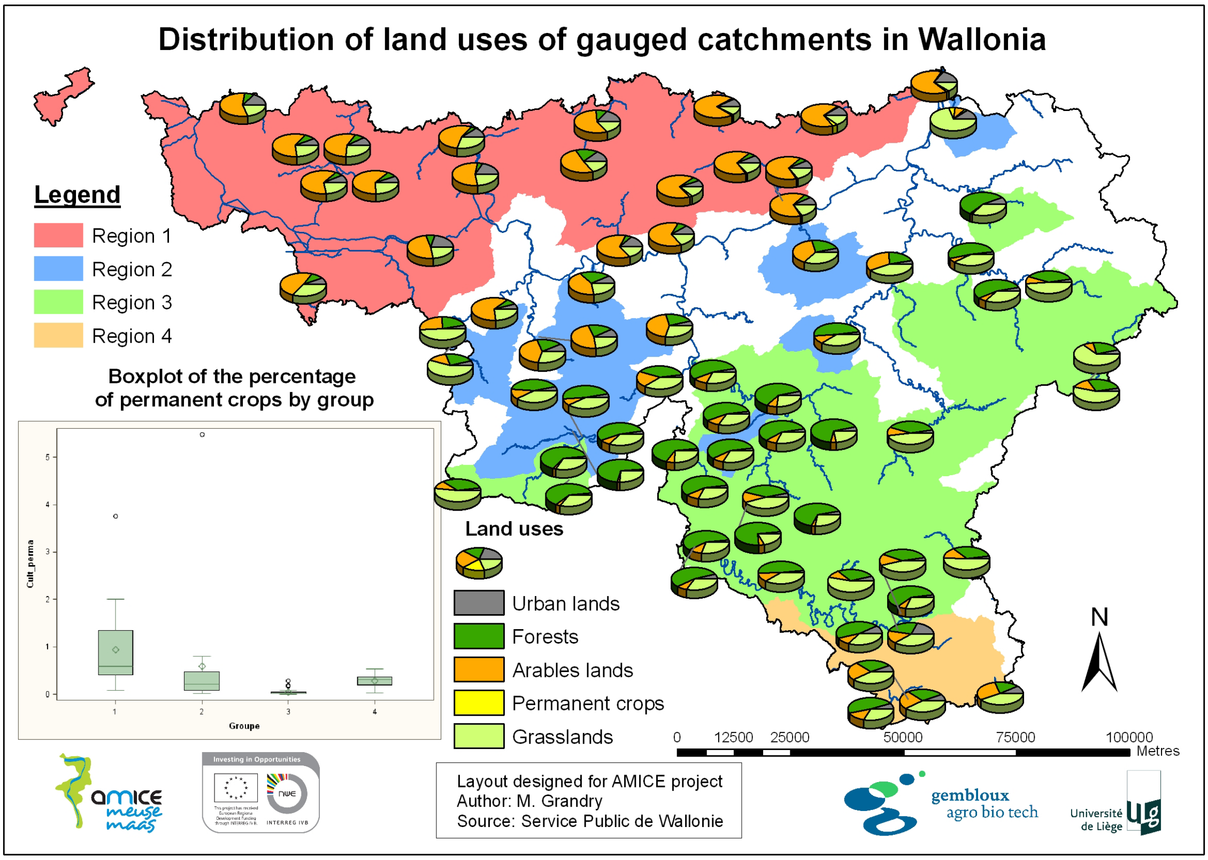


Figure 11. Map of the spatial distribution of land uses of gauged station catchments in Wallonia and boxplot of the percentage of permanent crops by group.

Regarding land use, group 1 can be distinguished from the three other groups by a higher percentage of urban and arable lands, and a lower percentage of forests and grasslands. However, the percentage of urban lands in group 4 is intermediate between group 1, and groups 3 and 4. As for the percentage of permanent crops, it is higher for group 1 and a little lower for group 3. It can also be noticed that the variability in the proportions of the different land uses is high for group 2.

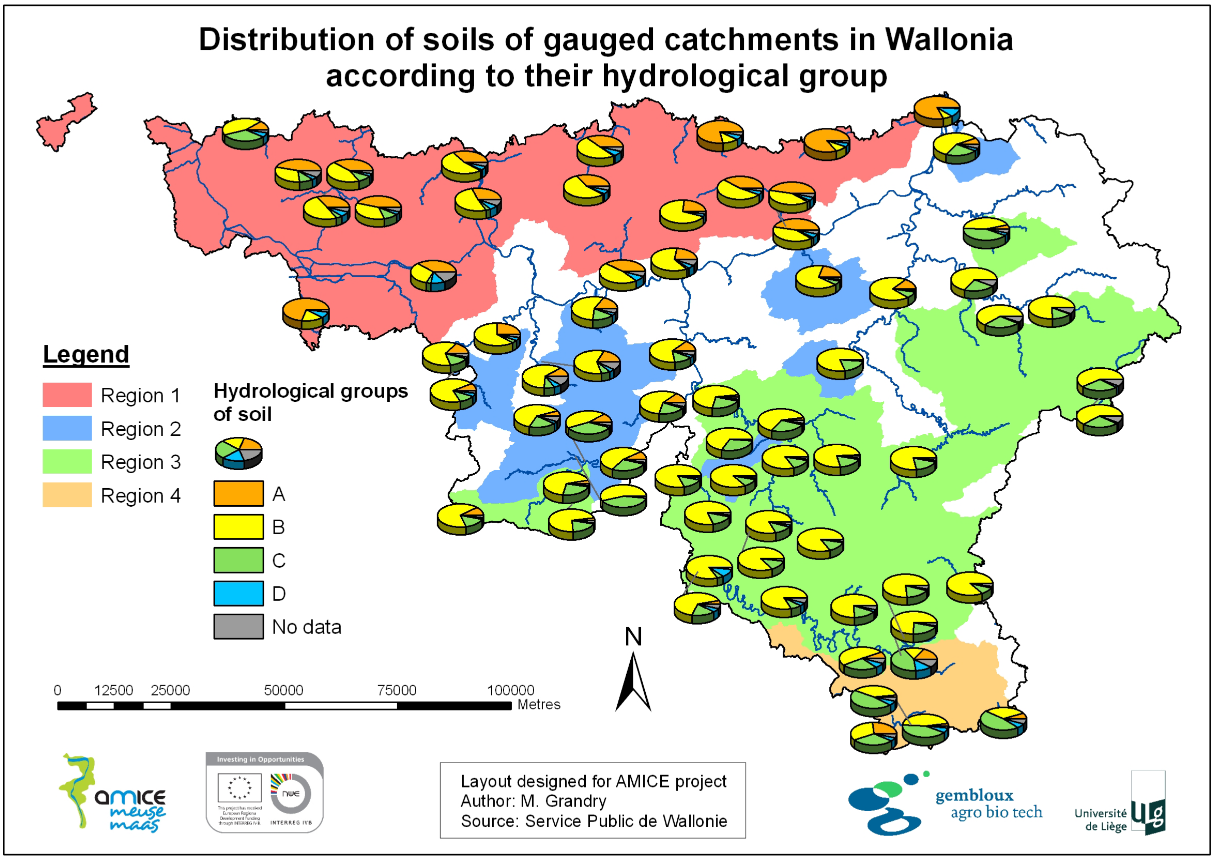


Figure 12. Map of the spatial distribution of the hydrological groups of soil of gauged station catchments in Wallonia.

Group 1 is characterised by a higher proportion of soils from the hydrological group A and a lower proportion of soils from the hydrological group C. Groups 2 and 3 are characterised by a higher proportion of soils from the hydrological group B and a lower proportion of soils from the hydrological group D. Group 3 has a very low proportion of soils from the hydrological group A but the highest proportion of soils from the hydrological group B. Group 4 is characterised by a high proportion of soils from the hydrological group C.

The table below summarises the low and high values of features for each group, which allow differentiating and characterising the four regions.

Table 5. Summary of differentiating features.

	Features with high values	Features with low values
Region 1	- urban lands - arable lands - permanent crops - soil of group A - temperature	- altitude - pentes - forests - grasslands - soil of group C - precipitation - recession coefficient
Region 2	- soil of group B	- urban lands - soil of group D

Region 3	- altitude - forests - soil of group B - precipitation - recession coefficient	- urban lands - arable lands - permanent crops - soil of group A - soil of group D - temperature
Region 4	- altitude - soil of group C - precipitation - percolation	- evapotranspiration - recession coefficient

The interpretation of the boxplots and PCA allow describing these regions according to the different catchment characteristics used for the analyses.

➥ Region 1 is a region of low altitude, gentle slopes, receiving less precipitation, where summer temperatures are higher, rather agricultural and urban, with soils of good infiltration capacity and permeability predominating.

➥ Region 2 is a region characterised mainly by intermediate values of features: medium altitude, steep slopes, receiving average precipitation, where summer temperatures are average for Belgium, fairly urbanised and agricultural, rather forested and grassy, with soils of moderate infiltration capacity and relatively low permeability predominating.

➥ Region 3 is a region of higher altitude, steep slopes, receiving a lot of precipitation, where summer temperatures are lower, not much urbanised, with soils of relatively good infiltration capacity and moderate permeability predominating, where forests and grasslands prevail.

➥ Region 4 is a region of higher altitude, steep slopes, receiving a lot of precipitation, where summer temperatures are average, not much urbanised, rather forested and grassy, with soils of low infiltration capacity but good permeability predominating.

5.2. Development of regression models

Developing a regression model aims at finding a relationship between Mean Annual 7-day Minimum flows (MAM7), which is the index chosen to characterise low flows, and catchment and/or climatic characteristics, in order to be able to calculate low flows in any ungauged river.

As some groups contained only a few observations, a global model for whole Wallonia was preferred. However, the use of regions remains a promising route for the future, when more data are available (minimum 20 years of data per gauging station).

The stepwise method was used to select a few explanatory variables that were not correlated to each other and that could explain the most of the variability of specific MAM7 (MAM7 divided by catchment area) (Claustriaux, 2007). A log transformation was also applied to the specific MAM7 to improve the normality of residuals. This was done for the four return periods (5, 10, 20 and 50 years). The selected explanatory variables were percolation and the recession coefficient:

$$MAM7\_T5 = Area10^{-2.7851+0.0017 Percolation-13.4274 \operatorname{Re} cessionCoefficient}$$

$$MAM7\_T10 = Area10^{-2.8396+0.0016 Percolation-15.5904 \operatorname{Re} cessionCoefficient}$$

$$MAM7\_T20 = Area10^{-2.8939+0.0016 Percolation-17.3211 \operatorname{Re} cessionCoefficient}$$

$$MAM7\_T50 = Area10^{-2.9808+0.0016 Percolation-19.0192 \operatorname{Re} cessionCoefficient}$$

This matches with other results from the literature such as Vogel and Kroll (1992) who found that low flow characteristics were highly correlated to catchment area, average basin slope and baseflow recession constant, and Smakhtin (2001) who considers geology as one of the natural factors that most influence low flows.

The models were checked for applicability conditions (normality and equality of variances of residuals) and robustness (absence of leverage points and multicollinearity). Their performance was evaluated by the coefficient of determination (R^2) and Root-Mean-Square Error (RMSE) (Laaha and Blöschl, 2006; Vezza *et al.*, 2010). R^2 represents the part of the variance of MAM7 explained by the model and RMSE quantifies the difference between observed and predicted MAM7 (Claustriaux, 2007). A validation with another set of data including 19 catchments was also performed. The table below shows R^2 and RMSE for calibration (adjustment of the model using the 59 catchments) and validation:

Table 6. Performance of models according to different indices.

	T5	**T10**	**T20**	**T50**
Calibration R²	0.670	0.623	0.578	0.508
Calibration RMSE	0.201	0.187	0.177	0.170
Validation RMSE	0.205	0.188	0.179	0.177
Validation R²	0.796	0.754	0.703	0.608

The R^2 and RMSE of the calibration decrease when the return period increases, which means that the part of the variance of MAM7 explained by the model and residuals both decrease. This seems contradictory but can be explained by the diminution in the variance of observed MAM7 when T increases, this diminution being relatively bigger than the reduction in MSE. From a validation point of view, R^2 is quite high but decreases also when T increases. RMSE decreases also but is in the same range of values as the RMSE of the calibration. Therefore, R^2 is higher because the variance of observed MAM7 of validation stations is higher. In conclusion, the model performs generally well and even better for predicting. This performance is detailed in the following paragraphs.

Figure 13 shows scatter plots of predicted versus observed values of MAM7 for the four return periods. They are also useful to interpret the models (Vezza *et al.*, 2010). The adjustment of the models seems quite good, except for 3 observations. These correspond to higher values of MAM7.

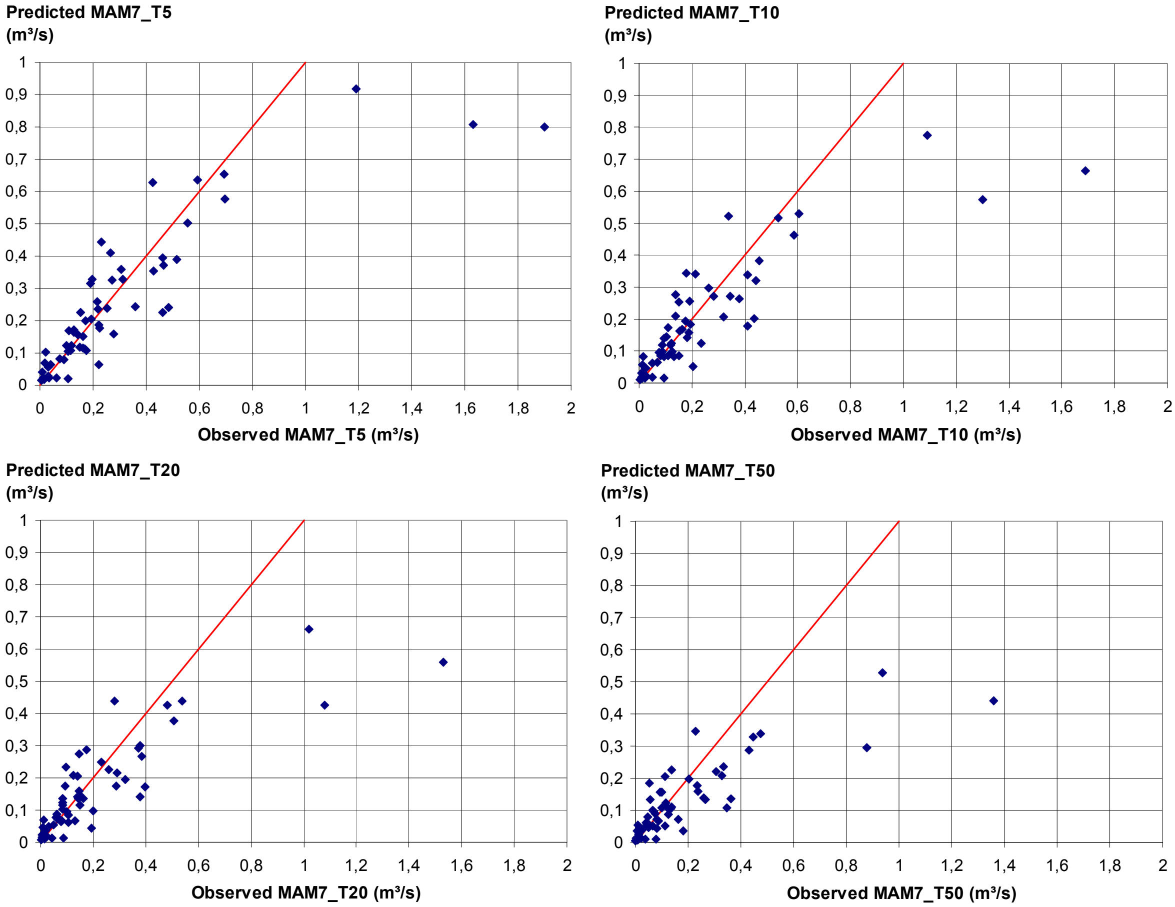


Figure 13. Scatter plots of predicted versus observed values of MAM7: The model is less well calibrated for high values of observed MAM7.

Residuals increase linearly with observed specific MAM7, as it can be observed on Figure 14 for T5. Therefore, the model overestimates low values of specific MAM7 (especially under 0.001 m³/s.km² for T5 and T10, and under 0.0005 m³/s.km² for T20 and T50) and underestimates higher values of specific MAM7 (especially over 0.003 m³/s.km² for T5 and T10, and over 0.002 m³/s.km² for T20 and T50). This problem of lack of calibration for extremes is due to the little number of observations for this range of specific MAM7, especially for specific MAM7 over 0.004 m³/s.km² for T5 and T10 and over 0.003 m³/s.km² for T20 and T50. This can explain the low R² of the model, and can be solved by adding data but they are not available yet in Wallonia. It could be useful to recalibrate the model in 10 years, when more stations have at least 20 years of data.

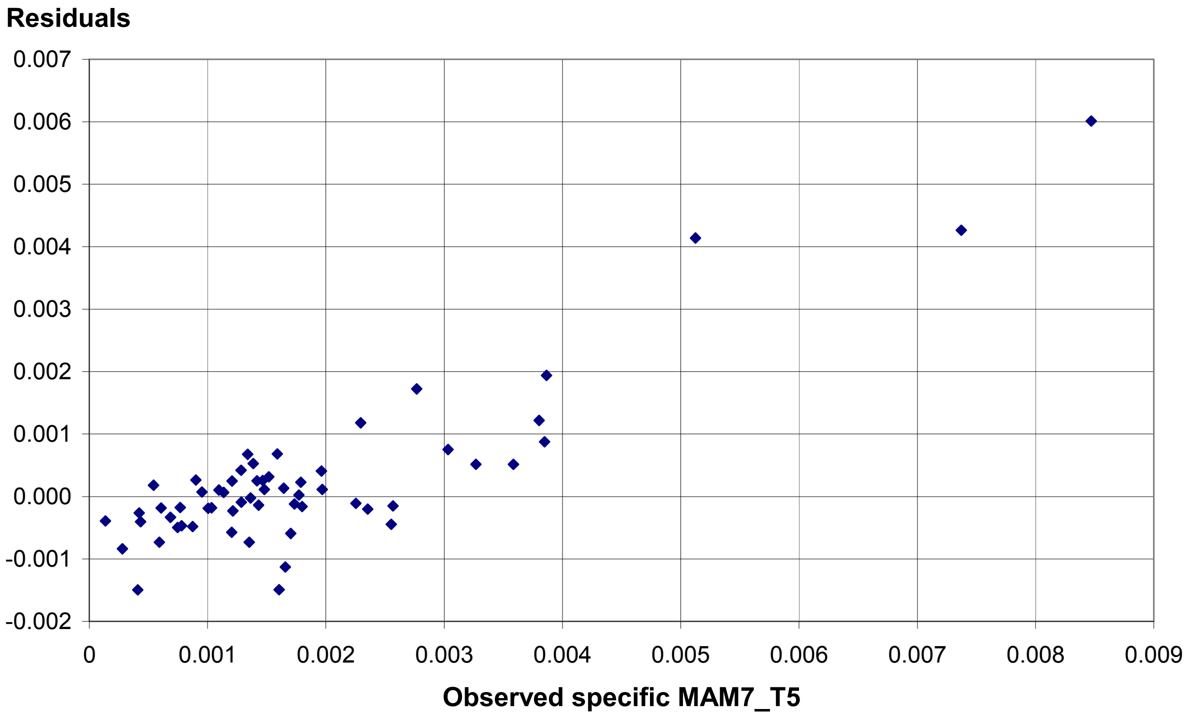
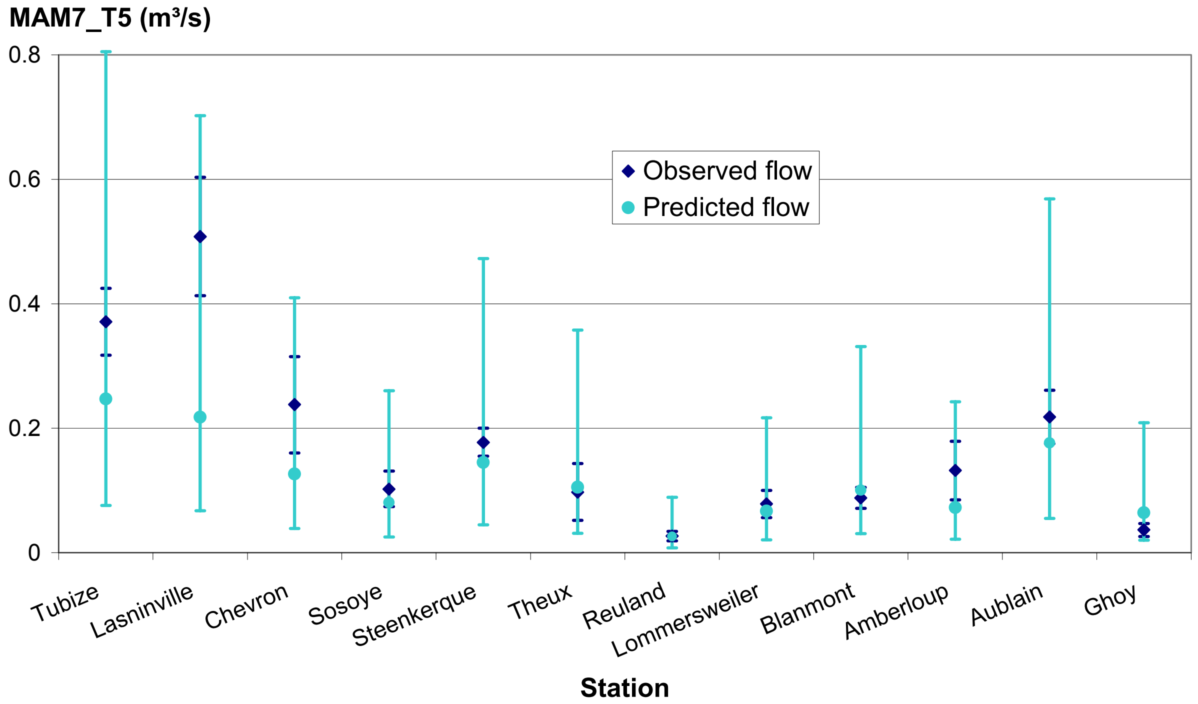


Figure 14. Plot of residuals against observed specific MAM7_T5: Residuals increase linearly with observed specific MAM7.

Graphics below (Figure 15) represent, for validation stations, observed and predicted MAM7_T5 with their 95% confidence interval. Most of predicted values are within or near the limits of the confidence interval of the observed values. The exceptions are Tubize, Lasninville, Chevron, Ghoy, Eben-Emael and Virton. The overestimation in Eben-Emael can be explained by water abstraction in the aquifer which is in direct contact with the river, this abstraction reducing the natural observed flow (Rouxhet *et al.*, 1996). As for Virton, its observed specific MAM7 (0.0096 $m^3/s.km^2$) is out of the range of specific low flows used for the calibration of the model (0.00014 - 0.0085 $m^3/s.km^2$).

It can also be seen that confidence intervals for predicted values are large. This is due to the low R^2 of the model.



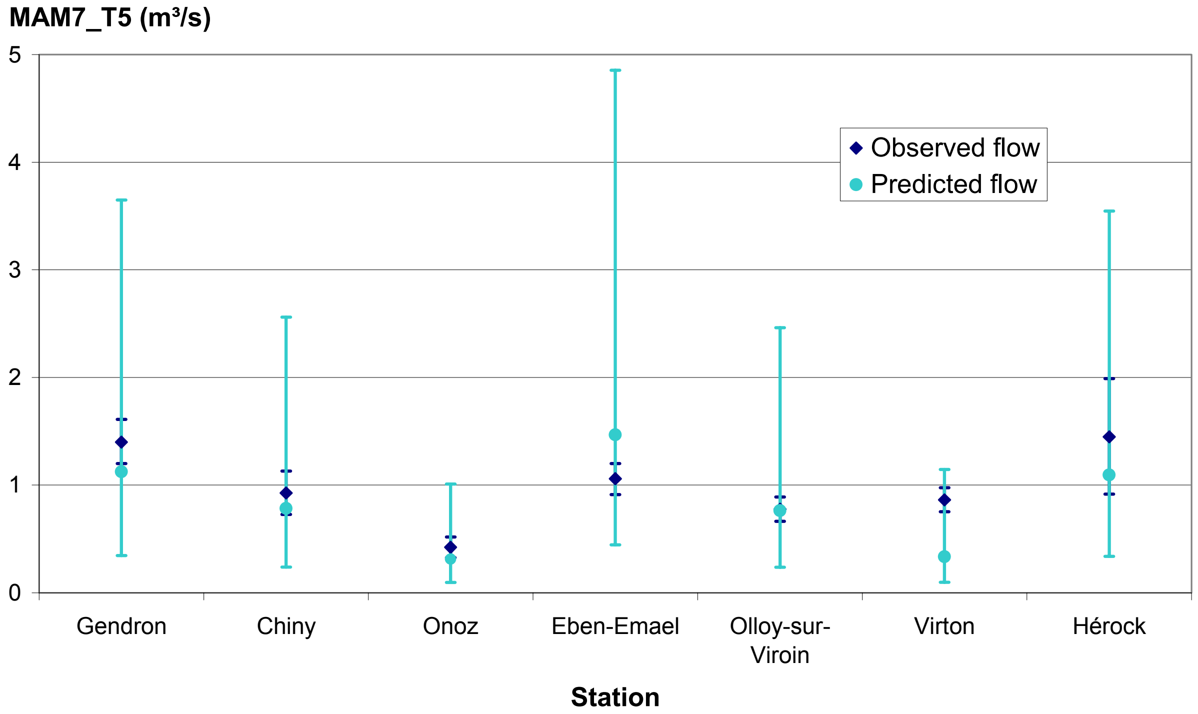


Figure 15. Observed and predicted MAM7_T5 included within their 95% confidence interval, for each validation station: Most of predicted MAM7_T5 values are within or near the limits of the confidence interval of the observed values.

Moreover, plotting regression coefficients against return period, Figure 16 shows that regression coefficients are linked to return period by a logarithmic relationship.

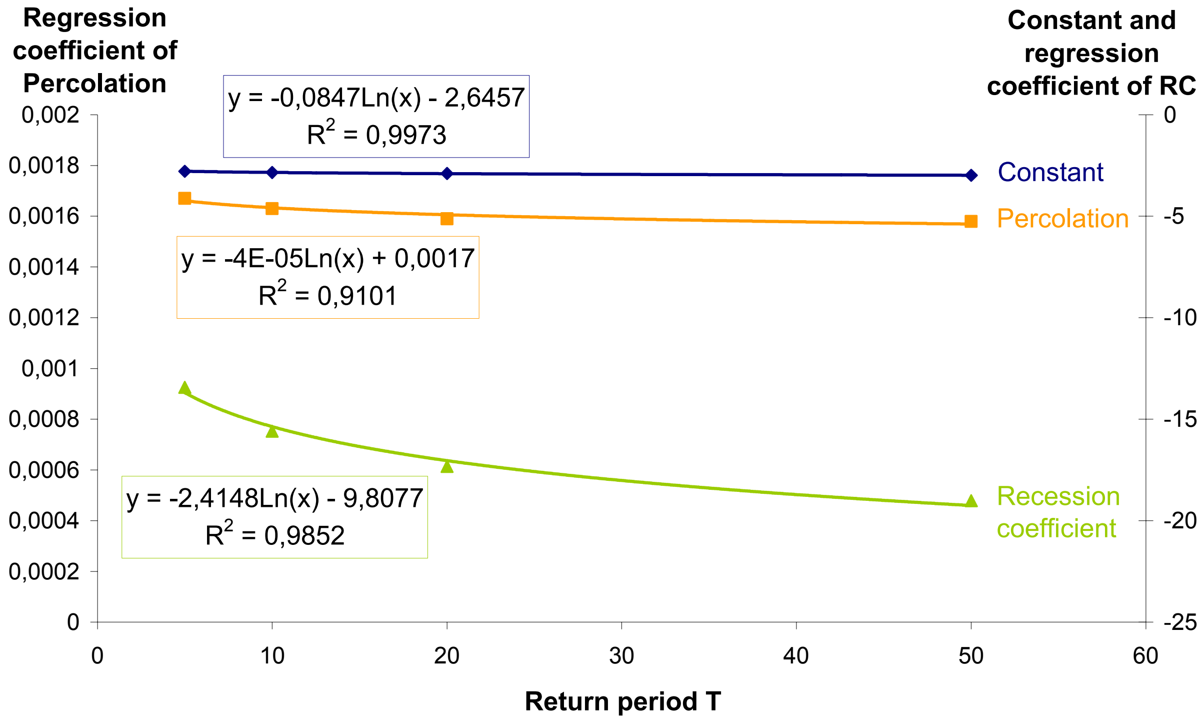


Figure 16. Constant and regression coefficients plotted against the return period: There is a logarithmic relationship between regression coefficients and return period.

➩ It is therefore possible to calculate MAM7 for any return period T with this formula:

$$MAM7 = Area.10^{-2.6457-0.0847\ln T+0.0017\,Percolation-9.8077\,RC-4.10^{-5}\,Percolation\ln T-2.4148\,RC\ln T}$$

in which RC is the recession coefficient.

Compared to MAM7 predicted with the models for each return period, values estimated by this model are lower by 0.5 to 3% for 5-year and 50-year return periods. For 10-year and 20-year return periods, the difference is even lower (between 0.1 and 2%) and estimate values are generally higher for a 10-year return period and generally lower for a 20-year return period. This means that, for 5-year and 50-year return periods, this model slightly underestimates MAM7 that are already underestimated but improves the estimation of MAM7 overestimated by the models for each return period. For a 10-year return period, it is generally the opposite: overestimation of overestimated MAM7 but improvement of the estimation of underestimated MAM7. This is also sometimes the case for a 20-year return period.

In practice: Using the equation

The last step before being able to calculate low flows for any ungauged site is to be able to estimate the percolation and recession coefficient for the study catchment. Indeed, since flow values are needed to determine the recession coefficient, this coefficient cannot be estimated for ungauged sites. And percolation is obtained from a time-consuming simulation by the EPICgrid model (Sohier *et al.*, 2009; Sohier, 2011).

➩ For the recession coefficient, values from calibration and validation catchments that are spatially close and hydrogeologically similar to the study catchment can be used (Tsakiris *et al.*, 2011). The map in Figure 17 gives the values of recession coefficients and shows the main aquifers of Wallonia. It also shows the length of data available when calculating the recession coefficient, which gives an idea of the precision of the coefficient. Indeed, the longest the data are, the largest the number of recession periods is and the most precise the recession coefficient is.

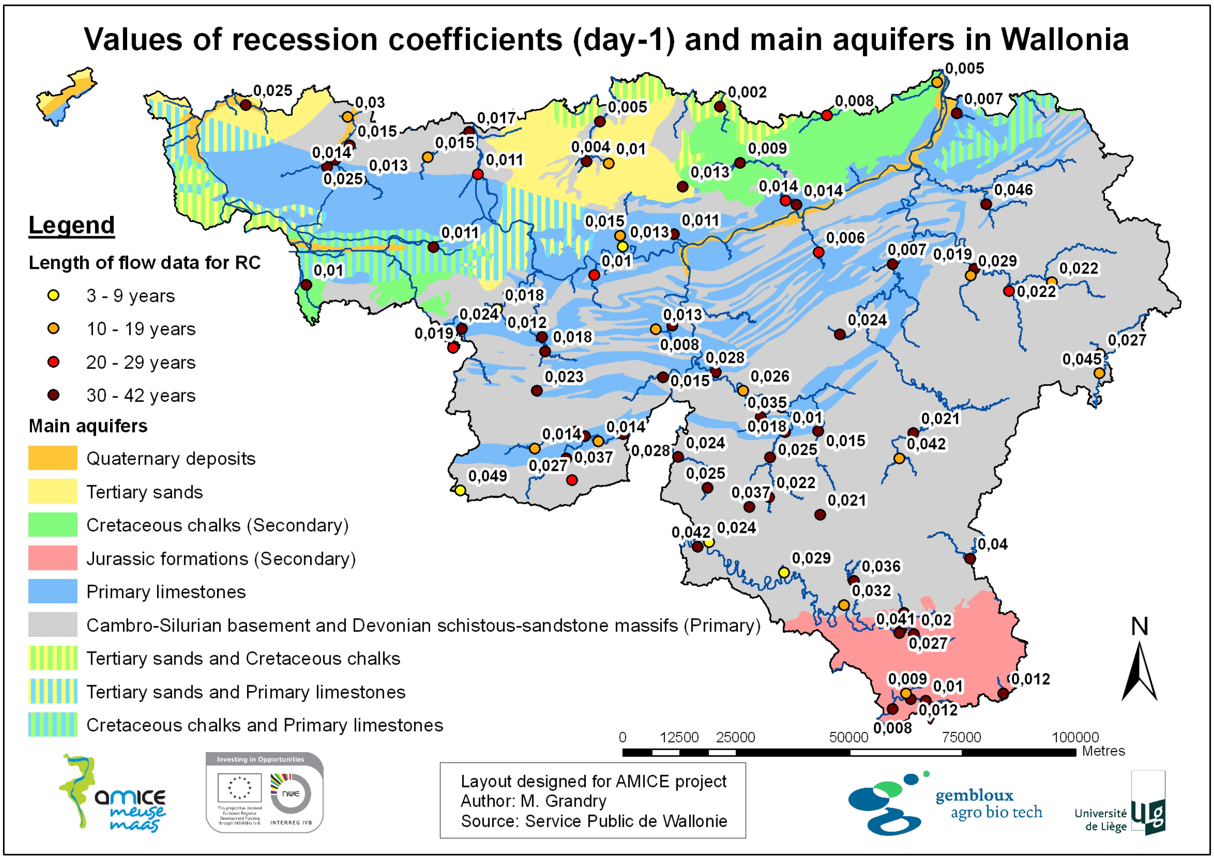


Figure 17. Map showing recession coefficient values for studied catchments and the main aquifers of Wallonia: For the estimation of low flows for an ungauged site using the regression equation, the value of the recession coefficient of a spatially close and hydrologically similar catchment can be used.

➯ As for percolation, the average of the percolation of the small catchments that are included in the study catchment can be used. The map in Figure 18 shows the values of percolation simulated by small catchment.

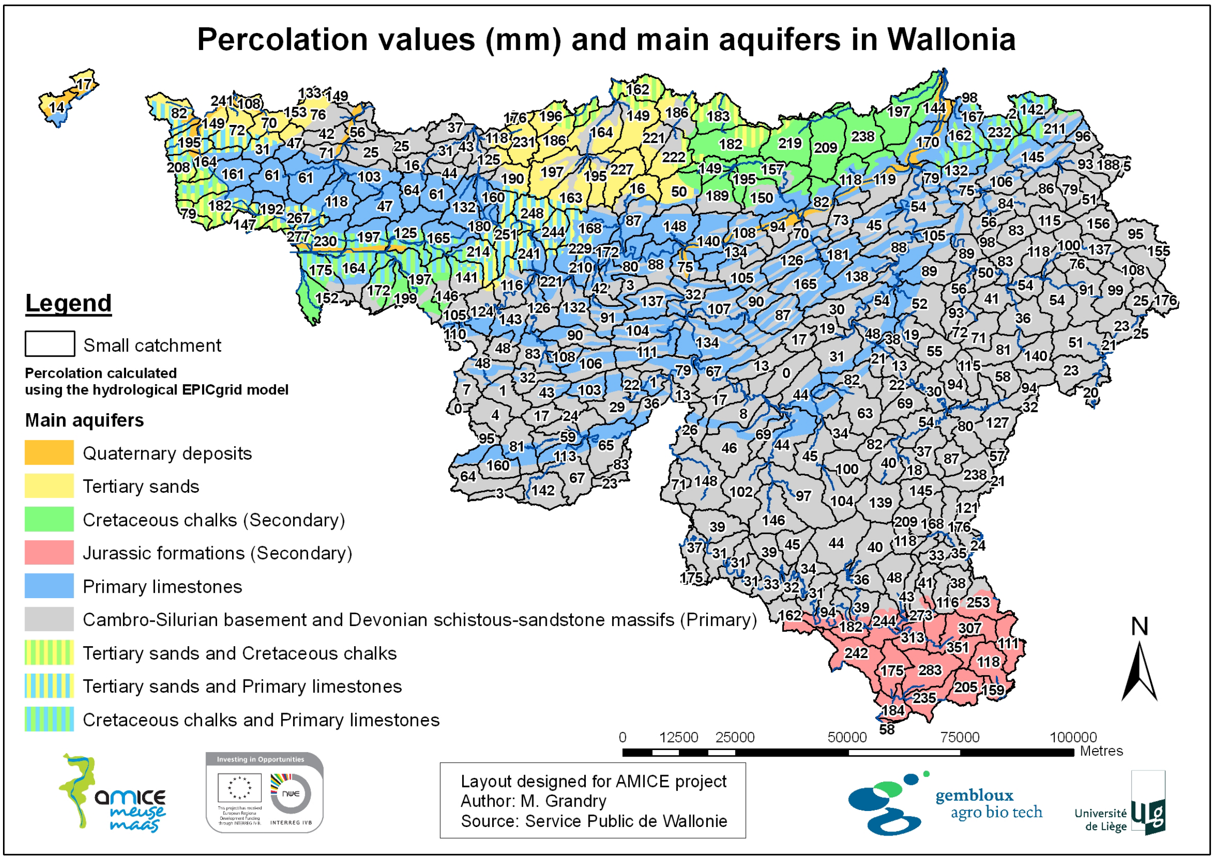


Figure 18. Map showing percolation values by small catchment and the main aquifers of Wallonia: For the estimation of low flows for an ungauged site using the regression equation, the average of the percolation of the small catchments that are included in the study catchment can be used.

Some small catchments are lying over two different aquifers (mainly Cambro-Silurian basement and Devonian schistous-sandstone massifs, and Jurassic formations). Therefore, care should be taken when using percolation values of these catchments.

6. Conclusion

The aim of the study has been reached: being able to estimate low flows anywhere in an ungauged catchment of Wallonia. It is even possible to calculate low flows for any return period.

Knowing the magnitude and the frequency of such extreme events will help Walloon managers to improve the management of low flows in rivers and the management of droughts.

Wallonia has a quite young monitoring network for river discharges. The present report showed that only 59 out of 244 stations were sufficiently robust to provide good data for such analyses. This situation will improve gradually during the coming years.

A regionalisation analysis was performed and four homogeneous regions were identified. In regards to the current length of data and in order to obtain a model sufficiently robust, a single regression was carried out for the whole Wallonia.

The model can predict MAM7 from catchment area, percolation and recession coefficient, the two last ones being related to substrate permeability. This means that geology plays an important role in determining low flows in Wallonia.

The model developed gives good predictions but can be improved with a re-calibration using more data, especially for lower and upper limits of low flows. This will be possible in around 10 years, when more stations have at least 20 years of data. This increase in number of stations will also allow carrying out a new classification and developing one model per region, which will probably also improve estimate precision.

7. References

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