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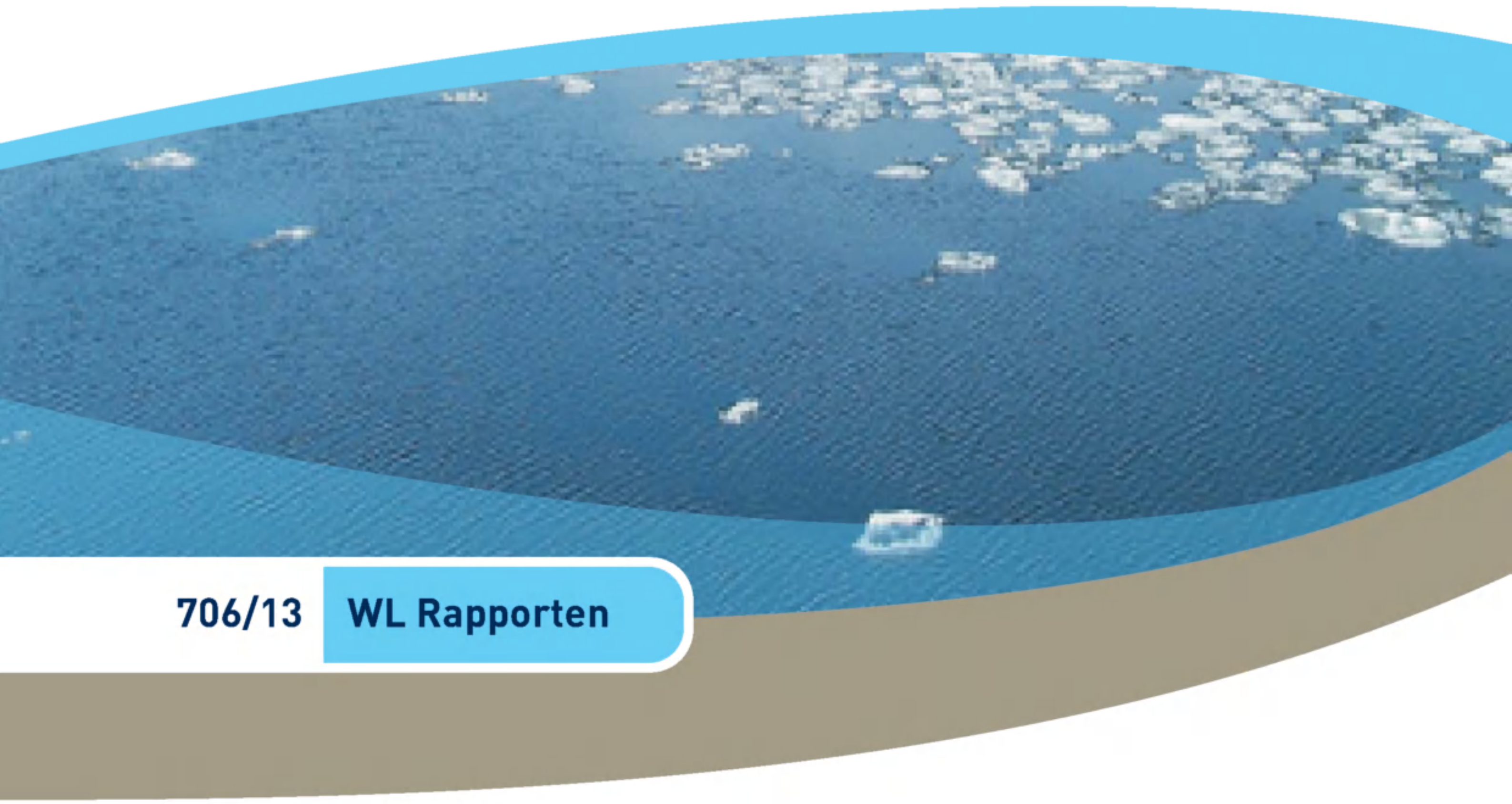
Climate change impact on hydrological extremes in Flanders: Regional differences



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INTERNE NOTA

datum	17-7-2008
van	Katrijn Holvoet en Wouter Vanneuville
titel	Addendum bij het rapport "Climate change impact on hydrological extremes in Flanders: Regional Differences"

In het rapport "Climate change impact on hydrological extremes in Flanders: Regional Differences" zijn enkele fouten geslopen. Deze worden hierbij rechtgezet.

- bladzijde 13

De tekst horende bij figuur 1 dient vervangen te worden door volgende onderschrift:
Figure 1: Area of the river basins of the *International Scheldt District* *(%) (ISC, 2005)*

- bladzijde 49 t.e.m. 52

Het onderschift bij de figuren 16 t.e.m. 19 dient aangevuld te worden als volgt:
Figure …, …, regional differences *compared to the actual situation*.

- bladzijde 53

In hoofdstuk *5.2 Correlation results and discussion* dient in de tweede paragraaf de tekst vervangen te worden door onderstaande:
*While being based on a DTM (Digital Terrain Model) with a grid resolution of 25m * 25m*, …

Ir. Katrijn Holvoet   Wouter Vanneuville

KATHOLIEKE UNIVERSITEIT LEUVEN

Climate change impact on hydrological extremes in Flanders: Regional differences

Faculteit Ingenieurswetenschappen
Afdeling Hydraulica

Vlaamse Overheid
Waterbouwkundig Laboratorium

Climate change impact on hydrological extremes in Flanders: Regional differences

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Samenvatting

Inleiding

Voorliggend rapport beschrijft het onderzoek naar de invloed van klimaatverandering op de neerslagafstroming, de rivierdebieten en de overstromingskansen en –risico’s voor een groot aantal hydrografische deelbekkens in het Vlaams gedeelte van het Schelde-stroomgebiedsdistrict. De studie is uitgevoerd door de Afdeling Hydraulica van de K.U.Leuven in samenwerking en met financiering van het Waterbouwkundig Laboratorium van de Vlaamse Overheid. Ze bouwt verder op de resultaten van een eerdere studie [Boukhris et al., 2006; Willems et al., 2007a, 2007b] waarbij een methode werd ontwikkeld om op basis van klimaatveranderingsscenario’s voor neerslag (waaronder extreme neerslag) en potentiële evapotranspiratie de impact door te rekenen naar rivierafvoeren en overstromingskansen. De methode werd afgestemd op de specifieke methodologie van het Waterbouwkundig Laboratorium voor het hydrologisch en hydrodynamisch modelleren van rivieren, de berekening van overstromingskansen en de opmaak van overstromingskaarten [zie Willems et al., 2000], alsook voor de berekening van overstromingsschades en –risico’s [zie Vanneuville et al., 2002]. De klimaatveranderingsscenario’s zijn afgeleid door K.U.Leuven – Afdeling Hydraulica en het Koninklijk Meteorologisch Instituut van België in een onderzoeksproject rond de “impact van klimaatverandering op hydrologische extremen” (het CCI-HYDR project) voor Federaal Wetenschapsbeleid. Deze laatste studie is nog lopend tot einde 2009. De klimaatveranderingsscenario’s worden daarom nog continu bijgestuurd. De voorliggende studie heeft gebruik gemaakt van de mei 2007 versie van deze scenario’s, zoals gerapporteerd in Boukhris et al. [2007].

Methode

De impact van klimaatverandering op rivierhydrologie en –hydrodynamiek wordt doorgerekend via een combinatie van klimaatmodellering en hydrologische modellering. De methode maakt gebruik van continue lange-termijn simulaties. Gecombineerde hydrologische en hydrodynamische modellen worden voor alle bestudeerde deelbekkens doorgerekend voor zowel een referentieperiode in het verleden (de zogenaamde controleperiode 1960-1990) als voor een periode in de toekomst (de scenarioperiode 2070-2100). De invloed van de klimaatverandering (van de controle- tot de scenarioperiode) wordt ingerekend voor zowel de neerslag als de potentiële evapotranspiratie (ETo). Neerslag en ETo zijn immers de voornaamste invoervariabelen in de hydrologische modellen. Voor beide variabelen zijn klimaatveranderingsscenario’s opgebouwd. Ze zijn gebaseerd op de A2 en B2 scenario’s van het IPCC m.b.t. de toekomstige uitstoot aan broeikasgassen. De impact van deze toekomstige uitstoot op neerslag en ETo is hierbij ingeschat op basis van bestaande simulaties met regionale klimaatmodellen voor Europa. 24 simulaties met dergelijke klimaatmodellen werden bekomen via het Europese PRUDENCE project, en in samenwerking met het Koninklijk Meteorologisch Instituut van België verwerkt voor Ukkel (ter hoogte van het voornaamste meteorologisch meetstation in België). Na statistische analyse van deze klimaatmodelsimulaties werden seizoensafhankelijke kwantielperturbatiefactoren afgeleid (factoren verandering in neerslag- en ETo-kwantielen van de controle- tot de scenarioperiode). Voor de uitbijters in deze factoren werd voor de controleperiode een consistentiecontrole uitgevoerd van de neerslag- en ETo-kwantielen met de historische neerslag te Ukkel, en de inconsistente factoren werden verwijderd. Op basis van de consistente factoren werden drie scenario’s weerhouden: laag, midden en hoog scenario, en dit voor zowel de gemiddelde seizoenscondities als voor de uitzonderlijke gebeurtenissen (de extremen). Ook werd de afhankelijkheid van deze scenario’s met de tijdschaal onderzocht (dag-, week-, maand- en seizoensschaal) en geëxtrapoleerd naar de uurlijkse tijdschaal. De neerslag- en ETo invoertijdreeksen van de hydrologische modellen worden overeenkomstig geperturbeerd, doorgerekend in de modellen, en de impact geanalyseerd voor uurlijkse piekdebieten (representatief voor overstromingskansen en –risico’s), uurlijkse laagwaterdebieten (representatief voor de problematiek van watertekorten), cumulatieve neerslagafstromingsvolumes, oppervlakteafstromingsvolumes en evapotranspiratievolumes. Ook word de invloed op uurlijkse piekdebieten verder doorgerekend naar overstromingskaarten en overstromingsrisicokaarten. Voor dit laatste worden de hydrologische en hydrodynamische riviermodellen verder uitgebreid met modellen voor de overstromingsgebieden, met digitale hoogte-informatie, en met modellen die overstromingskansen en -schades combineren tot overstromingsrisico's.

Resultaten voorgaande studie voor het Denderbekken als testcase

In de voorgaande studie van Boukhris et al. [2006] werd de hoger samengevatte methode ontwikkeld en getest voor drie deelbekkens in het Denderbekken. Uit deze analyse bleek dat toekomstige klimaatverandering door de sterke daling in de zomerneerslag en de toename in de verdamping zal leiden tot een daling van de laagwaterdebieten. Tijdens droge zomers kunnen de laagste grondwaterafstromingen naar de Dender en zijn zijbeken met meer dan 50% dalen. Het is duidelijk dat dit de kans op watertekorten aanzienlijk kan doen toenemen, wat nadelige gevolgen kan hebben voor de drinkwaterproductie, de diepgang voor de scheepvaart, voor de waterkwaliteit, enz.

De toename van de kans op overstromingen, die vaak met klimaatverandering wordt geassocieerd, blijkt uit de resultaten minder duidelijk. Piekafvoeren in een rivier zoals de Dender nemen in het meest extreme scenario met niet meer dan 15% toe.

De impactresultaten bleken verder een grote onzekerheid te kennen, ten gevolge van vooral de onzekerheid in de impactresultaten van de klimaatmodellen t.g.v. de toegenomen en nog verder toenemende uitstoot van broeikasgassen op toekomstige neerslag- en verdampingshoeveelheden.

Regionale analyse voor het Schelde-stroomgebiedsdistrict

De methode die in voorgaande studie werd uitgewerkt en getest voor het Denderbekken is in voorliggende studie verder toegepast op alle hydrografische deelbekkens van het Vlaams gedeelte van het Schelde-stroomgebiedsdistrict waarvoor modellen voorhanden zijn bij het Waterbouwkundig Laboratorium (WL). Deze analyse had tot doel na te gaan of de resultaten voor het Denderbekken ook geldig zijn voor andere streken van Vlaanderen, en of er eventuele regionale verschillen worden waargenomen.

Figuren 16, 17, 18 en 19 in het rapport vatten de regionale resultaten samen. De ingekleurde deelbekkens zijn deze die werden doorgerekend (dus waarvoor modellen beschikbaar waren bij het WL). Fig. 16 beschrijft de invloed op uurlijkse piekafvoeren. Deze afvoeren stellen de ruimtelijk gemiddelde neerslagafstromingsdebieten voor per hydrografisch deelbekken (VHA-zone) zoals bekomen als uitvoer van de NAM hydrologisch modellen van het WL. Fig. 17 geeft de invloed op de cumulatieve oppervlakteafstromingsdebieten (opnieuw gebaseerd op de uurlijkse neerslagafstromingsdebieten van de NAM hydrologische modellen). Fig 18 beschrijft de impact op de cumulatieve werkelijke evapotranspiratievolumes (de ruimtelijk gemiddelde volumes aan verdamping en transpiratie van vegetatie per VHA-zone, zoals gesimuleerd in de NAM hydrologische modellen). Fig. 19 tenslotte geeft de invloed op de uurlijkse laagwaterdebieten (opnieuw gebaseerd op de uurlijkse neerslagafstromingsdebieten van de NAM hydrologische modellen). De uurlijkse piekafvoeren van Fig. 16 en de laagwaterdebieten van Fig. 19 stellen onafhankelijke debieten voor die via een tijdreeksanalysetechniek en een onafhankelijkheidscriterium uit de continue tijdreeks gehaald zijn (volgens de methode beschreven in Willems et al. [2000]). Bovendien gaat het om "uitzonderlijke" waarden aangezien enkel waarden boven een bepaalde drempel (voor de piekdebieten) en waarden onder een bepaalde drempel (voor de laagwaterdebieten) beschouwd zijn (zie rapport voor meer details). De percentages die in Figuren 16, 17, 18 en 19 weergegeven zijn, stellen het gemiddelde % verandering voor in piekafvoer, oppervlakteafstromingsvolume, werkelijk evapotranspiratievolume en laagwaterafvoer tussen het huidig klimaat (gebaseerd op de referentie- of controleperiode 1961-1990) en het toekomstige klimaat tot 2100 (gebaseerd op de scenarioperiode 2071-2100 voor de klimaatmodellen).

De Figuren 16, 17, 18 en 19 geven aan dat er regionale verschillen bestaan in de impactresultaten. De grootteordes van de impacts zijn evenwel vergelijkbaar met deze die eerder voor de Dender werden bekomen. Voor het middenscenario vertonen de piekafvoeren een kleine daling (in het laagste geval tot -14% daling t.o.v. de huidige klimaatcondities). Voor het laag scenario daalt dit percentage tot -70% in het laagste geval. Voor het hoog scenario wordt telkens een toename van piekafvoeren en van de overstromingskansen gevonden, met percentages die afhankelijk van het deelbekken tot maximaal ongeveer 35% oplopen. Oppervlakteafstromingsvolumes volgen een gelijkaardig patroon als de piekafvoeren. Evapotranspiratievolumes nemen in alle scenario's toe (tot maximaal 17%), en laagwaterdebieten nemen in alle scenario's af.

Men moet evenwel voorzichtig zijn met de interpretatie van de regionale verschillen, zoals gepresenteerd in de figuren. De regionale verschillen zijn immers niet enkel het gevolg van regionale verschillen in gebiedseigenschappen, waardoor hydrologische impacts van klimaatverandering variëren. Ze zijn ook het gevolg van onzekerheden en inconsistenties in de gebruikte modellen. De modellen van verschillende rivierbekkens zijn immers door andere experten opgebouwd en afgeijkt, wat subjectiviteit introduceert in de calibratie van de parameterwaarden en voor verschillen in de resultaten zorgt (ook al is de impact in werkelijkheid identiek). Om dit verder te onderzoeken werden de impactpercentages uitgezet t.o.v. de gebiedseigenschappen: topografie, landgebruik en bodemtype (zie figuren in paragraaf 5.2 van het rapport). Er werd bijvoorbeeld een toename verwacht van de impact op piekafvoeren voor meer verstedelijkte deelbekkens. Deze trend blijkt evenwel niet uit de resultaten. De correlatie van de impact met landgebruik en andere gebiedseigenschappen blijkt bovendien in de meeste gevallen zeer zwak te zijn. Dit doet vermoeden dat onzekerheden en subjectiviteit in de calibratie van de hydrologische NAM-modellen belangrijke factoren zijn in de verklaring van de regionale verschillen. Bij de verbanden met bodemtype en topografie worden wel logische trends gevonden: een toename van de piekafvoer bij een hoger percentage leem in tegenstelling met het percentage zand, een toename van de piekafvoer bij steilere deelbekkens (alhoewel ook hier correlaties eerder zwak zijn).

De impact op de piekafvoeren (toename in het hoog scenario, afname in het laag scenario) vertaalt zich naar overeenkomstige variaties in de uitgestrektheid van overstroomde gebieden (de overstromingskaarten) en in de grootte van de overstromingsschades en risico's (zie de Appendix voor de overstromingsgebieden bij bepaalde terugkeerperioden en voor het hoog, midden en laag klimaatveranderingsscenario, en voor de bijhorende overstromingsrisicokaarten).

Aanbevelingen en vervolgtraject

De studie heeft nieuwe inzichten gegeven in de regionale Vlaamse effecten van toekomstige klimaatverandering op rivierafvoeren. Het is duidelijk dat bij toekomstige ontwerpen en/of maatregelen voor waterbeheer best rekening wordt gehouden met de invloed van deze mogelijke klimaatverandering (via het laag, midden en hoog scenario). Voor de toename in het overstromingsrisico zijn de onzekerheden nog zeer groot. Daarom moeten de evoluties van het klimaat de volgende jaren verder nauwgezet opgevolgd worden, en moet bij nieuwe waterbeheersingsprojecten rekening worden gehouden met de mogelijkheid om preventieve maatregelen te nemen. Vooral de verwachte problematische waterbeschikbaarheid in de zomer vraagt verdere aandacht. Om deze waterbeschikbaarheid verder onder de loep te nemen wordt vanaf het najaar 2008 een vervolgstudie uitgevoerd waarbij via ruimtelijk verdeelde hydrologische bekkenmodellen de invloed op grondwaterstanden en laagwaterdebieten in rivieren meer gedetailleerd en nauwkeuriger wordt doorgerekend.

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List of symbols

AOGCMs	Atmospheric-Ocean General Climate Models.
CCCma	Canadian Centre for Climate modelling and analysis.
Cclov	Cloud covering.
CCSR	Centre for Climate System Research.
CSIRO	The Commonwealth Scientific and Industrial Research Organization.
DKRZ	The Service Centre for Climate Modelling in Germany.
ETo	Evapo(transpi)ration.
FAR	First Assessment Report of IPCC.
FOAR	FOurth Assessment Report of IPCC.
GCMs	General Climate Models.
H	Humidity.
IPCC	Intergovernmental Panel on Climate Change.
MSLP	Mean Sea Level Pressure.
NCAR	the National Centre for Atmospheric Research in America.
P	Precipitation.
POT	Peak Over Threshold.
PRPM	the Poisson Rectangular Pulses Model.
PRUDENCE	Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects.
RCMs	Regional Climate Models.
RMI	Royal Meteorological Institute of Belgium.
SAR	Second Assessment Report of IPCC.
Sdown	Total radiation Balance.
SRES	Special Report on Emission Scenarios.
TAR	Third Assessment Report of IPCC.
T2m	2-meter temperature.
UKMO	Met Office and Hadley Centre for Climate prediction and research.
UNEP	United Nations Environment Program.
UNFCCC	United Nations Framework Convention on Climate Change.
WL	Waterbouwkundig Laboratorium of the Flemish government.
WMO	World Meteorological Organization.
W-10m	10- meter wind.

1. Introduction

Human activities (primarily the burning of fossil fuels and changes in land use and land cover) are increasing the atmospheric concentrations of greenhouse gases, which alter radiative balances and tend to warm the atmosphere and along with the effects of aerosols. These changes in greenhouse gases and aerosols, taken together, are projected to lead to regional and global changes in temperature, precipitation and other climate variables, resulting in global changes in soil moisture, an increase in global mean sea level, and prospects for more severe extreme high temperature events, floods and droughts.

Based on the range of sensitivities of climate to changes in the atmospheric concentrations of greenhouse gases (IPCC FOAR, 2007) and to plausible changes in emissions of greenhouse gases and aerosols, climate models project that the mean annual global surface temperature will increase by 1.3 to 5.8°C by 2100, that global mean sea level will rise by 9-88 cm, and that changes in the spatial and temporal patterns of precipitation would occur (IPCC, TAR). The average rate of warming probably would be greater than any seen in the past 10 000 years, together the warming and melting of continental ice sheet would have the capacity to increase the average sea level by up to 8 m (!) over the next 1000 years in average scenario (Marbaix and van Ypersele, 2005). Although the actual annual to decadal rate would include considerable natural variability, regional changes could differ substantially from the global mean value.

These mid/long-term human-induced changes will interact with natural variability differently depending on spatial scales (i.e. large scale, regional scale, catchment scale...) and on time scales of days to decades (i.e. the El Nino-Southern Oscillation (ENSO) phenomenon) and thus influence social and economic well-being. Possible local climate effects that are due to unexpected events like climate change impact on flow pattern of rivers and on flood risks.

Scientific studies show that environmental systems like hydrology and water resources which is vital to sustainable development, is very sensitive to changes in climate including both the magnitude and rate of climate change as well as to changes in climate variability (Boukhris et al., 2006). Climate change represents an important additional stress to systems already affected by increasing resource demands, unsustainable management practices and pollution, which in many cases may be equal or greater than climate change threat. These stresses will interact in different ways across regions but can be expected to reduce the ability of some environmental systems (i.e. hydrological system) to provide, on a sustained basis, goods and services needed for successful economic and social development.

Flanders, which is the northern region of Belgian, took a very important economical and industrial position in the country and in west Europe. The physical geography as regards to Flanders has totally changed due to population growth and ribbon development dating back to the 17th and 18th century, but by far the most important factor is initiations of towns and urban planning. In Flanders huge densities of population and urban sprawling are the main factors responsible for land use change and life behaviour and hence responsible for changes in several natural systems. Facing these changes and their potential impacts, only few years ago Flanders started to draw up spatial plans at the regional level.

This report assesses the impact of climate change on hydrology in the region of Flanders giving its regional differences. The degree to which the hydrological system will respond to a given change in climate, including both beneficial and harmful effects will be discussed in this report for the different catchment forming the Flemish region in Belgium. It is obvious that the results of this study would lead to the degree to which adjustments in practices, processes or structures can moderate or offset the potential for damage or take advantage of opportunities created, due to given changes in climate. Under this framework, it is possible also to assess whether regional hydrological systems would be highly sensitive to modest changes in climate, where the sensitivity includes non-climatological factors as the degree of urbanity and the land use changes.

A number of quantitative estimates of impacts of climate change are cited below in the report. Such estimates are dependent on the specific assumptions employed regarding future changes in climate, as well as upon the particular methods and models applied in the analyses. For this reason, this study comes as a continuation of a previous study implemented by the

Waterbouwkundig Laboratorium (WL) of the Authorities of Flanders and done by the Hydraulics Laboratory of K.U.Leuven and IMDC titled: "Methodology of climate change impacts on hydrological extremes" (Boukhris et al., 2006) where the methodology of climate impact assessment was set and results were produced for the some sub-catchments of the Dender basin.

This study continues the steps with applying the same methodology on the total Flemish area with investigations on sub-catchments scale. The methodology is based on three scenarios of perturbation factors derived from downscaling the results of the European climate project PRUDENCE "Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects" and applied upon the hydrological variables (i.e. precipitation and evapo(transpi)ration) serving for hydrological estimations. The PRUDENCE results cover small grid cells (144 – 2500 km²) over the Belgian area with daily to seasonal time scales.

This study is also in close relation with a parallel project of the BELgian Science Policy Office entitled: "CCI-HYDR: climate change impacts on the hydrological extremes and drainage systems in Belgium" where a new perturbation approach has been developed (Boukhris et al., 2007) and implemented in this project and that will be presented throughout this report.

Hence, estimates of future climate changes will be taken in accordance to the methodology adopted by the Waterbouwkundig Laboratorium (WL) presented in the study of Boukhris et al (2006) and following the latest developments in deriving perturbations within the science of climate change impact estimation. However, to interpret these estimates, it is important to bear in mind that uncertainties regarding the answer, magnitude and rates of future climate change impacts remain. These uncertainties might be big particularly at regional and smaller scales where lots of physical phenomena and factors interfere.

In Chapter 2 of this report, the research goal, the study area and the availability of data and models are presented. In Chapter 3, a short overview is presented on the methodology of climate change impact assessment. For more information, the reader can get back to Boukhris et al. (2006). Then, in Chapters 4 and 5, the impact analysis results are presented and discussed for the different sub-basins.

From the other side and due to the absence of models for the upstream (Walloon) area of the Meuse basin, a special bibliography review has been made for this basin in order to try to gather all needed information serving to build a picture of the impact of climate change on the Meuse.

2. Research Goal

Most people understand that significant climate changes are predicted this century, but they may not be aware that these changes will likely vary regionally.

The nature, rate and extent of climate change are expected to differ across Flanders. Combined with variations in population, development and natural resources, it is likely that different regions will experience differing levels of vulnerability to climate change.

The Intergovernmental Panel on Climate Change (IPCC) stated several times that the impact of climate change on regional basis will be totally different on the environmental systems (hydrological system) than the one of global scale especially with respect to the extreme events where their frequency is expected to increase. The Belgian area is highly vulnerable to climate change because of its border location to the North Sea. Regarding the hydrological system, the impacts of climate change will depend on the baseline condition of the water and the ability of water resources managers to respond to climate change regional associated factors as population growth and changes in demands, change in land use and practices, technology, social and legislative conditions. Changes in climate could exacerbate periodic and chronic water.

Consequently, it is very important to investigate each regional condition apart through the different sub-basins of Flanders in order to have a general overview of the patterns of hydrological changes due to climate change.

The catchments of Flanders will act as case study depending on the availability of data and hydrological and hydro-dynamic tools which are applied in the current water management practice. An interpolation of impact is made for the areas suffering of absence of data or inexistence of gauged stations.

Below is a description of the studied area followed by an overview on the available data needed to climate change impact assessment.

2.1 Overview on the study area: Flanders

Flanders extends in northwestern Europe from the North Sea in the west to the Netherlands from north and east while the Walloon Belgian part is situated in the south with a surface of 13522 km^2. It is considered as one of the densest populated area in Europe with 442 inhabitants per km^2 with a total population of 6.058.368 inhabitants (Economie, 2006).

Flanders embraces several important European river basins. The largest part of the international Scheldt is situated in Flanders along with other international river basins like the MEUSE River. Other important river basins are included in the Scheldt district (Flanders) like the Ijzer (1 750 km^2), the Dender, the Demer and Nete basins…(ISC, 2005).

The total hydrological system of the Flemish area is distributed over different river basins of different sizes and land uses, where beside the Scheldt river basin, the Ijzer and the Polders cover a considerable part (Figure 1). A number of these river basins are further divided into hydrographical units; they form the basic units for water management. These hydrographical units are mainly delimited hydrographically, but they also take into account the national/regional boundaries (Table 1).

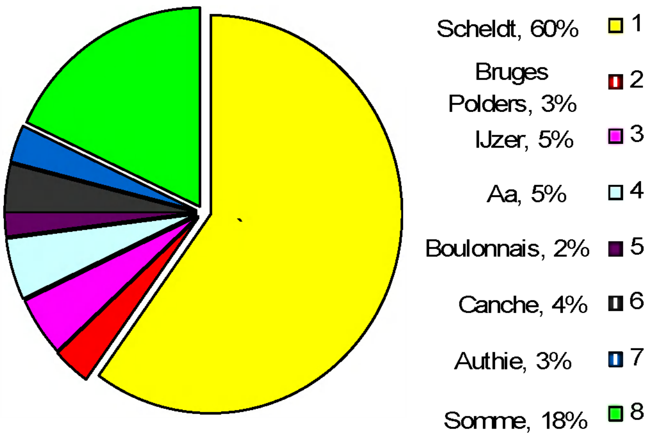


Figure 1. Area of the river basins in Flanders (%) (ISC, 2005).

River basin	Hydrographical unit (HU) name	Region	HU nature
Scheldt	"Leie"	VL	RP of SB
	"Bovenschelde"	VL	RP of SB
	"Dender"	VL	RP of SB
	"Zenne"	VL	RP of SB
	"Dijle"	VL	RP of SB
	"Demer"	VL	RP of SB
	"Gentse Kanalen"	VL	RP of SB
	"Benedenschelde"	VL	RP of SB
	"Nete"	VL	SB
IJzer	"Ijzer"	VL	RP of SB
Bruges Polders	"Brugse Polders"	VL	RB

Table 1. Hydrographical units per river basin (where RB = river basin; SB = sub-basin; RP of SB = regional part of sub-basin; VL =Flemish) (CIW, 2005).

Agriculture dominates land use in Flanders with 61% of total area, mainly livestock and arable farming, but also the basin still highly urbanized for commercial, communication inhabitants and transport needs. Main industrial areas include ports of Ghent, Terneuzen (The Netherlands), Antwerp and Vlissingen. In coastal areas tourism plays an import role. Part of the land used for transportation and communication is also shared with some watercourses. The land use in Flanders has been developing quite slowly with the beginning of the new millennium (Table 2).

Year	2000	2001	2002	2003	2004	2005
Total surface (km²)	**13552**	**13552**	**13552**	**13552**	**13552**	**13552**
Agricultural area	8473	8444	8422	8392	8369	8346
Built area	3303	3335	3361	3391	3416	3439
Industrial area	347	353	357	359	362	364
Area used for mines, wells…etc	14	14	14	14	14	14
Commercial area	88	89	89	90	90	90
Public service area	121	121	121	122	123	124
Mixture use area	63	63	63	63	63	63
Communication & transportation area	1029	1032	1035	1041	1044	1046
Technical infrastructural area	15	16	16	16	16	17
Free spaces area	237	238	238	239	240	242
Residential area	1385	1407	1424	1444	1460	1476
Diverse	1744	1742	1737	1738	1736	1736

Table 2. Percentage of land use in Flanders (Economie, 2006).

Figure 2 presents the location of the different Flanders basins that will be subject of the present study.

Figure 2. Location of the Flanders basins subject of this study.

2.2 Overview on data availability

Data needed to estimate climate change impact on the hydrological extremes in Flanders (Belgium) have to be sought within a much wider area than that delimited by the Flemish Water Authority. This is so because the impact of climate change is quite complicated and cannot be directly described by existing statistics or covered by easily organized additional data collection.

This is why, as is the case for a major part of hydrological studies, data will have to be assembled through field measurements, gauge stations, radar and satellite measurements etc.

The necessary data for this study have been organized into two fields: the perturbation factors necessary for the present investigation derived by the support climate study that should cover the studied area with different spatial resolutions and different aggregation time scales and which has been provided within the parallel CCI-HYDR research, and the hydrological data normally used by the water managers and local authorities in Flanders (Belgium).

The two data fields were provided for the present study as follows:

- The perturbation factors were fully provided through the parallel CCI-HYDR which processed the necessary climate data for Belgium from the European climate project PRUDENCE (see Chapter 3).

  The PRUDENCE project provides the necessary data to run hydrological applications in different spatial and temporal resolutions. It provides the variables of precipitation, evapo(transpi)ration, mean seal level pressure, total radiation balance, cloud covering, 2-meter temperature, 10-m wind and humidity. PRUDENCE simulation outputs give as well the great opportunity to calculate some hydrological variables according to specified schemes. For instance the variable of evapo(transpi)ration is calculated according to the Bultot equation which involves several parameters currently satisfied by PRUDENCE outputs.

  The Royal Meteorological Institute of Belgium (RMI) assured the extraction and processing of the PRUDENCE simulation outputs. RMI fed the CCI-HYDR research with daily precipitation and evapo(transpi)ration for more than 25 climate scenario simulations corresponding to the different regional climate models used within PRUDENCE project with their different physical concepts, different spatial resolution and different emission scenarios. The data were provided for current conditions (calibrated models) corresponding to the period (1960-1990) and for future conditions (2071-2100) and were extracted at the closest model grid point to Uccle station (Uccle station was considered as the station the most representative of Belgium) (Boukhris et al., 2006).

- The hydrological data were fully provided through the dense climatological and hydro-meteorological network of RMI and the rain gauge network of the WL. In Belgium, rainfall data and most of the climatological variables are recorded by RMI. Rainfall data are collected through rain gauges in the hydro-meteorological network (rain gauges with 10 min temporal resolution) and the climatological network (rain gauges with daily rainfall). RMI operates a rain-gauge network including more than 300 stations. These data are quality checked in a very detailed way. WL complemented these data with rain gauging data from their own network. The general data length used in this study had a time spam ranging from 30 to 35 years that is considered to be accurate for climate change impact analysis. The data are hourly times series.

All the necessary hydrological and hydrodynamic modelling tools were also provided for this study through the WL and the Hydraulics Laboratory of K.U.Leuven, which has carried out large number of hydrological and hydrodynamic modelling projects in the past for the Flemish area.

Hence, this study benefits of a huge database giving the possibility to deeply investigate climate change impact on the hydrological extremes for Belgium. In the following chapter, more focus is given to the necessary study data.

3. Review of climate change impact methodology

In order to investigate the link between the climate system and the hydrological system, one needs to go through several steps involving experiencing changes in climate variables. However, it is not feasible to experiment on the climate system itself, nor is it possible to reproduce the full complexity of the climate system in laboratories. That's why approaching the climate system changes and their impacts on the hydrological system, is done through two major methods:

- Empirical methods,
- Physically based methods.

The empirical methods are done through statistical analysis on the climate data in order to identify systematic behaviour and hence improve understanding the processes that drives such behaviour. The statistical analysis of climate data serves to compliment and support theories developed to explain the causes (and effects) of climate change.

As stated in the previous studies (Boukrhis et al., 2006) and (Boukhris et al., 2007), the physically based methods are done through the climate models (General climate models, GCMs and regional climate models, RCMs, with respect to the difference in spatial and temporal resolutions). The methodology that will be applied in this study is based on perturbation factors derived form climate models.

Hence, the methodology (that has been already set in previous study) should go through three major steps. They are: Climate modelling investigation, downscaling procedure and hydrological impact analysis. Below is a brief review on these steps while, for more information, the reader can consult Boukhris et al. 2006.

In this report, we are discussing the potential climate change impacts for Flanders driven by a complex system of 24 different scenarios extracted from PRUDENCE results. The scenarios are developed within the four SRES emission families using the A1 and A2 emission scenarios and concern the variables of rainfall and evapo(transpi)ration.

3.1 Climate modelling investigation: the PRUDENCE project

Regional climate modelling has been mainly elaborated within the tentative of enhancing spatial and temporal resolution of the General Climate models (GCMs). Most of the work in this direction has been made within different climate project as the European PRUDENCE project.

PRUDENCE (Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects) is a project with many European partners, funded by the EU 5^{th} Framework program for energy, environment and sustainable development and having as goal the evaluation of climate change risks over Europe in the end of the current century, as predicted by the most recent (at the project time) climate models. The project aimed to:

- Quantify the confidence and the uncertainties in predictions of future climate and its impacts over Europe;
- Interpret these results in relation to European policies for adapting to/or mitigating climate change.

To do so, PRUDENCE provides a series of high-resolution climate change scenarios for 2071-2100 for Europe. This is done through 10 different regional climate simulations with a high resolution coming up to 24 km in space and daily time scale. PRUDENCE chooses the period of 1961-1990 as a baseline for climate simulations and provides the predicted change for 2071-2100, mostly using A2 greenhouse gases emission scenario. Prudence results are valuable for different kind of impact analysis to be assessed with good resolutions, which can be compatible with the hydrological studies that require high resolutions (DMI, 2004).

PRUDENCE simulation data from its participants are freely available in public domain of the project host http://prudence.dmi.dk and have processed by RMI where they provide the CCI-HYDR project with daily series of precipitation and evapo(transpi)ration needed for the construction of future climate scenarios for Flanders. Due to the detailed and thorough data available, based on many climate models and covering the whole European continent, we will use the results of these simulations in the present study. With their different physical concepts, spatial resolution and emission scenarios used, the regional climate models used within PRUDENCE are valuable tools to assess degree of uncertainty in future climate predictions. Table 3 gives an overview on the RCMs processed in this study with their characteristics.

Regional climate models (RCMs)	Spatial resolution (km)	Temporal resolution	Control period	Scenario period	Emission scenario
DMI-HC1	50	Daily	1961-1990	2071-2100	A2
DMI-HC2	50	Daily	1961-1990	2071-2100	A2
DMI-HC3	50	Daily	1961-1990	2071-2100	A2
DMI-F25	25	Daily	1961-1990	2071-2100	A2
DMI-ECS	50	Daily	1961-1990	2071-2100	A2
DMI-ECC	50	Daily	1961-1990	2071-2100	A2
DMI-ECC	50	Daily	1961-1990	2071-2100	B2
METNO-HAD	53	Daily	1961-1990	2071-2100	A2
METNO-HAD	53	Daily	1961-1990	2071-2100	B2
CRNM-DC9	59	Daily	1961-1990	2071-2100	A2
CRNM-DE5	59	Daily	1961-1990	2071-2100	A2
CRNM-DE6	59	Daily	1961-1990	2071-2100	A2
CRNM-DE7	59	Daily	1961-1990	2071-2100	A2
ETH-HC	55	Daily	1960-1990	2070-2100	A2
GKSS	55	Daily	1961-1990	2071-2100	A2
GKSS-sn	55	Daily	1961-1990	2071-2100	A2
ITCP	52	Daily	1961-1990	2071-2100	A2
ITCP	52	Daily	1961-1990	2071-2100	B2
KNMI	47	Daily	1961-1990	2071-2100	A2
SMHI-HC	49	Daily	1961-1990	2071-2100	A2
SMHI-HC	49	Daily	1961-1990	2071-2100	B2
SMHI-HC22	24	Daily	1961-1990	2071-2100	A2
SMHI-MPI	49	Daily	1960-1990	2071-2100	A2
SMHI-MPI	49	Daily	1960-1990	2071-2100	B2

Table 3. PRUDENCE regional climate model simulations.

3.2 The downscaling method: the frequency perturbation method

The downscaling approach selected for this study is the combined dynamical – statistical downscaling method based on perturbations (Figure 3).

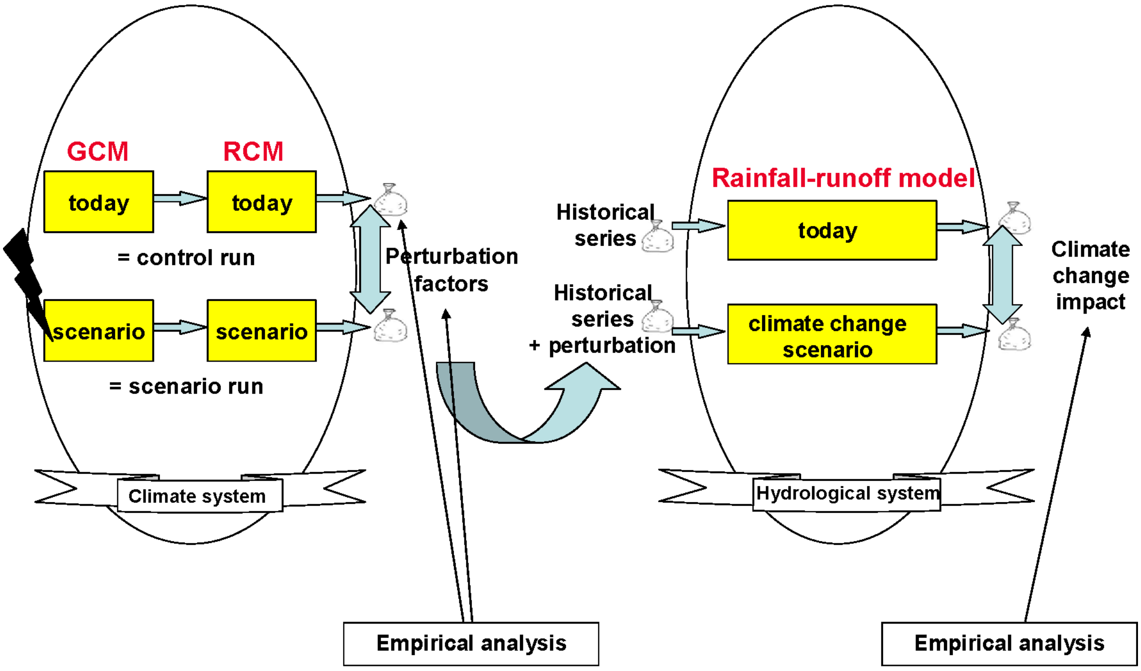


Figure 3. Schematic illustration of the selected perturbation approach (Boukhris et al., 2006).

The perturbations (differences between the current and future climate) are derived within the frequency perturbation approach, which is explained below.

The frequency perturbation approach consists on deriving the perturbations depending on the time scale and the intensity level or return period. For the rainfall variable, perturbations will furthermore be derived separately for the number or frequency of rainfall events (i.e. storm events) and the mean intensity per event. Both perturbations combined lead to perturbations in the mean intensity for a given aggregation level.

This approach is referred as the frequency analysis approach. It consists on comparing the complete frequency distribution between the RCMs control and scenarios simulations. The reason of applying such approach returns to the fact that when we compare hourly or daily times series between RCMs control and scenario simulations, we might compare a dry hour to a wet hour or a dry day to a wet day, and therefore the resulted perturbations would not be correct. Perturbations that are resulting from comparing day-to-day values are far from presenting climate change, as this last affects differently the extremes range and the normal range of each hydrological variable. Therefore, this approach has been adopted and it extracts the perturbation factors by comparing statistical properties of the same variables between the control and simulated time series (Boukhris et al., 2007).

The approach consists on five steps:

1. The selection of the RCM outputs to be processed (i.e. precipitation and ETo). The selection covers the control period results and the scenario period results. The control period results act as a baseline series, which present the current climate condition.
2. The control and scenario period simulation results are ranked in descending order giving the rank one to the highest value in the series. It is often used that statistically equal variable values get different ranks.

3. Perturbation factors of the ranked series are calculated as the ratio between the scenario variable value and the control variable value for the same rank.
4. A probability of occurrence (also exceedence probability) is assigned to each factor based on the rank of the variable values considered. The exceedence probability is a statistical measure of the empirically based frequency of being exceeded. This is referred here as the frequency. For example, events with low magnitudes have high frequencies, extreme events have low frequencies.
5. Plotting the frequency-perturbation relation to investigate the variation of the perturbation factors for the extremes and the low values. A threshold might be obtained above which the perturbation factor is approximately constant.

Figure 4 presents the frequency- perturbation plot for precipitation extracted from the control and A2 scenario simulations for the DMI-HC2 scenario. The perturbation factors seem to increase slightly for frequencies higher than 0.1 year. They strongly decrease for the lower events. A threshold of 0.1 year can be applied in this case and an average perturbation factor is calculated to represent the future extremes.

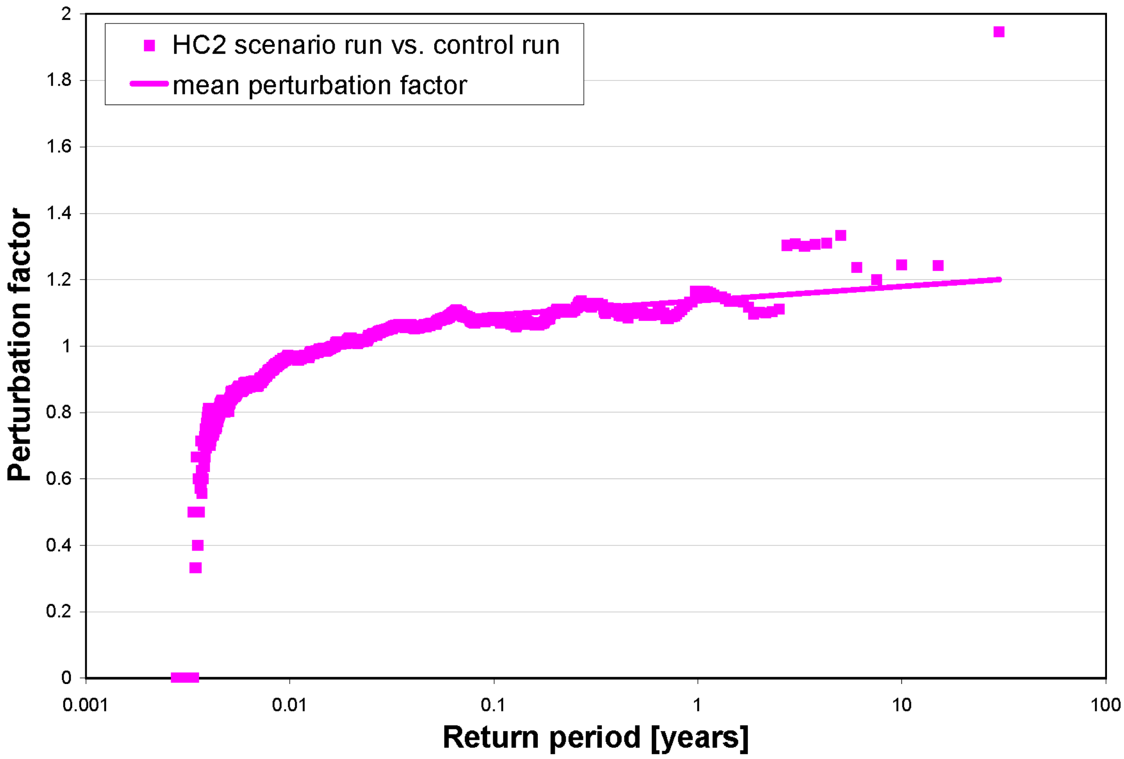


Figure 4. Frequency-perturbation plot for rainfall, DMI-HC2 scenario (Boukhris et al., 2007).

The method ensures that the perturbations are applied depending on the event's class. In fact, by carrying out a frequency perturbation analysis, events can be classified as low, medium, high and extreme. Such classification is very useful for modelling needs where some applications focus on a particular range of events. By plotting the derived perturbation factors assigned to their frequencies, it is possible to check whether the variable extremes tend to have higher perturbations than the variable medium or low values. It is possible as well to decide if the perturbations are frequency dependent and therefore to apply an average factor to a range of events having similar frequencies. In this project, a high variable threshold is selected in order to focus on the range of extremes.

Within the CCI-HYDR research, the PRUDENCE frequency perturbation factors have been calculated for winter and summer periods and for different aggregation levels (daily data, weekly, monthly, seasonally and yearly). After that, a selection procedure conforming to the previous WL research on climate change impact methodology has been performed to finalize three future climate scenarios (low, mean and high scenarios) for the variables of precipitation and ETo for Flanders (Boukrhis et al., 2007). The table 4 below presents the selected three scenarios. Within the CCI-HYDR research, it was found that the derived perturbations are independent of the time aggregation levels and thus it was decided to take an average constant factor for all aggregations (Boukhris et al., 2007).

Scenario	Low	Mean	High
Winter rainfall	1.00	1.08	1.16
Summer rainfall	0.83	0.99	1.11
Winter ETo	1.00	1.13	1.27
Summer ETo	1.10	1.16	1.29

Table 4. Climate change scenarios for Belgium for precipitation and ETo (Boukhris et al., 2007).

3.3 Climate change impact analysis: hydrological modelling and post-processing

Similarly to the settled methodology, after being derived, the perturbation factors serve to perturb the inputs variables of the calibrated hydrological model NAM implemented by the WL for hydrological management.

The hydrological models results are therefore extracted and processed and compared to the original results (representing the current climate conditions) in order to assess climate change impact on hydrological extremes. This processing contains the following steps:

- An estimation of the variations of the high flow QDFs and composite hydrographs throughout a peak over threshold method followed by an extremes value analysis.
- Elaboration of the flood maps and flood risk maps.
- An estimation of the variation on the low flow QDFs.
- A statistical summary on the percentage of variation of other variable (i.e. Overland flow, ETo).

All these steps are performed conforming to the methodology set in Boukhris et al (2006) where the reader should find all details. We proceed below with a short description of the NAM model and the extreme value analysis.

3.3.1 NAM model

NAM (recently called RR) is a hydrological module linked to the Mike11 software of the DHI Water & Environment, Denmark (DHI, 2004). NAM models simulate the rainfall-runoff generation at the catchment scale.

Totally based on the differences of water content, NAM describes the behaviour of the rainfall reaching the soil or the river in four different and interrelated storage systems. Figure 5 presents the structure of NAM, followed by a description of its concept.

The four storage systems of NAM are:

- Snow storage;
- Surface storage;
- Lower zone storage (root zone);
- Groundwater storage.

The surface storage and lower zone storage are mainly characterized by their actual soil water content presented respectively in Figure 5 by U and L and by their maximum capacity to hold the water, respectively U_{max} and L_{max}.

It is due to a continuous calculation of the ratios $\frac{U}{U_{\max}}$ and $\frac{L}{L_{\max}}$ that NAM calculates the amount of water percolating between each storage system, simulates the catchment runoff as well as it gives information about other elements of the land phase of the hydrological cycle, such as temporal variation of actual evapo-transpiration, ground water level, infiltration, percolation, overland runoff, interflow groundwater and recharge. The basic model inputs are meteorological data which are precipitation, potential evapo-transpiration and also temperature in case the modeler wants to rout the snow storage to the whole simulation.

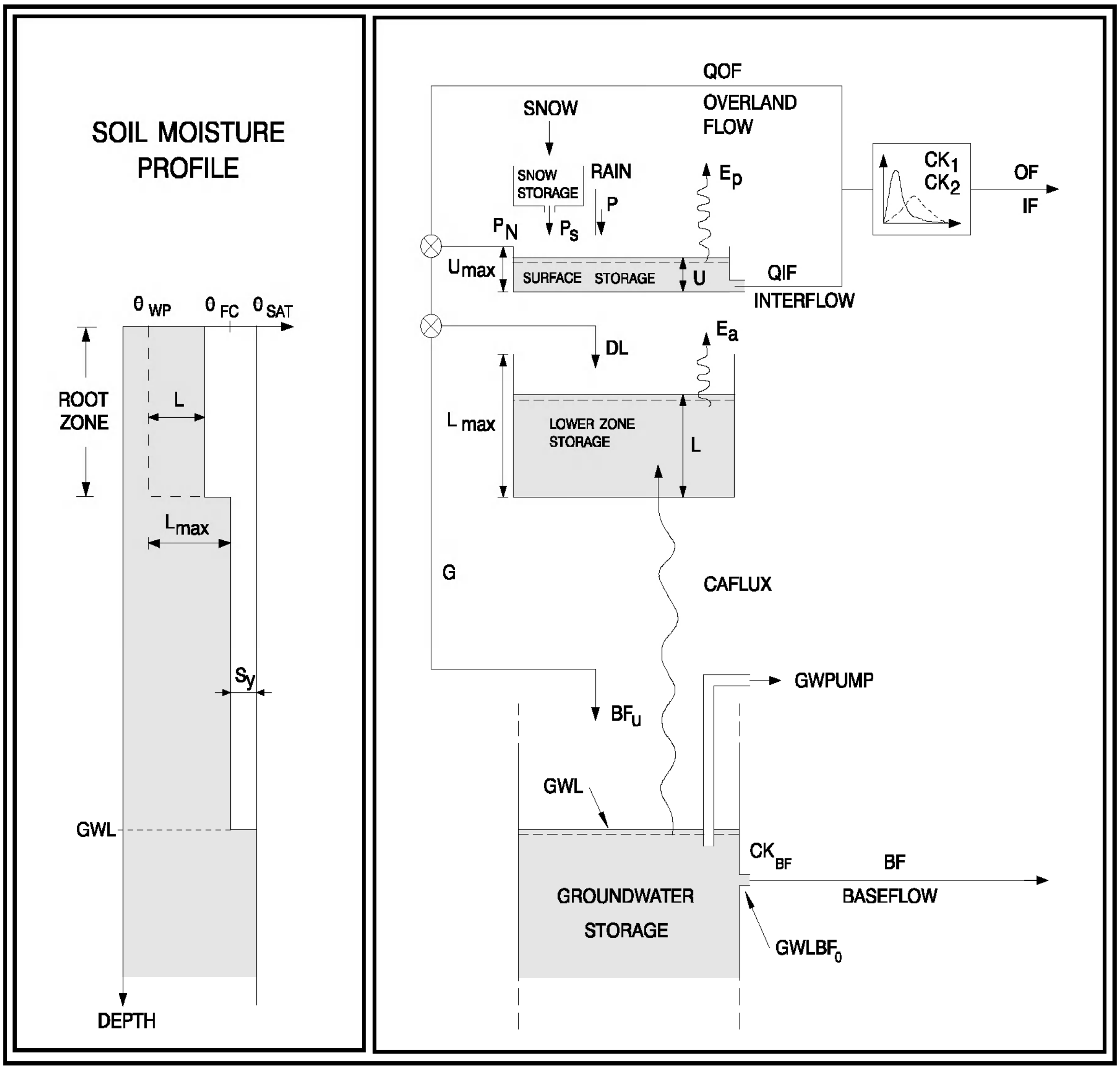


Figure 5. NAM model structure (DHI, 2004).

The part of rainfall that did not infiltrate, will runoff as an overland flow (top-right of Figure 5). The other part will be split into two fractions. The "DL" fraction will feed the root zone or the lower zone storage, as the fraction "G" will percolate deep towards the groundwater storage.

The interflow is assumed to be proportional to the soil moisture in the surface storage U and it is linearly dependent of the water content of the root zone. Both the surface zone and the root zone are subject of water loss due to actual evapo(transpi)ration which varies the water moisture content and the fraction "G" recharging the groundwater storage.

The following equations illustrate the basic calculations made within NAM for overland flow and interflow:

$$QOF = CQOF \frac{(\frac{L}{L_{max}}) - TOF}{1 - TOF} P_n, \quad for \frac{L}{L_{max}} > TOF$$

$$QOF = 0, \quad for \frac{L}{L_{max}} \leq TOF$$

$$QIF = (CKIF)^{-1} \frac{(\frac{L}{L_{max}}) - TIF}{1 - TIF} U, \quad for \frac{L}{L_{max}} > TIF$$

$$QIF = 0, \quad for \frac{L}{L_{max}} \leq TIF$$

In these equations, *QOF* and *QIF* denote the part of net precipitation (P_n) which contributes to overland flow or interflow, *CQOF* is the overland flow runoff coefficient ($0 \leq CQOF \leq 1$) and *TOF* is the threshold value for overland flow ($0 \leq TOF \leq 1$), *CKIF* is the time constant for interflow and *TIF* is the root zone threshold value for interflow ($0 \leq TIF \leq 1$).

The overland flow is simulated within the NAM model through two linear reservoirs plugged in series, having the property of the same time constant (*CK1*/*CK2*) (Figure 5) or reservoir constant. The reservoir constant equals the time during which the reservoir flow is reduced to a fraction exp (-1) = 0.37 of its original discharge. The interflow volumes are additionally routed through a third reservoir with reservoir constant *CKIF*.

From the other side, the groundwater storage behaves also as a linear reservoir storage where its input "G" and output "baseflow" are related with an exponential relation with a different time constant (*CKBF*, Figure 5) than the other storage systems.

The baseflow is generally qualified as a "slow flow". Its amount is dependent on the soil moisture content in the root zone too. A part of this groundwater storage feeds the lower zone as capillarity flux. Its amount depends on the soil moisture content $\frac{L}{L_{max}}$.

To conclude, NAM simulates the total catchment runoff through its different sub-flows: overland flow, interflow and baseflow. The aim of this simulation is the description of the behaviour of a plugged two linear reservoirs (surface zone), plus a second reservoir (root zone) and a third linear reservoir presenting the groundwater zone. This description is mainly based on variation of the water moisture content in each zone.

3.3.2 Peak Over Threshold (POT) approach

The old method adopted for estimating the return period value for specific runoff values used in water balance studies is commonly based on the adjustment of the yearly extreme runoff values to an extreme value distribution (Gumbel, 1958; Castillo, 1988). However, the main shortcoming for such an approach is the limited length of the available record. For example, if annual maximum extremes are used, the fitting of the probability distribution often relies on just 25-30 years long time series, which verifies the large uncertainties in the estimating results (Claps, 2003). To reduce these uncertainties, one might use short aggregation time data (daily, hourly data) of runoff within a Peaks-Over-Threshold (POT) framework, in which approach, the idea is to use more than one extreme runoff value per year.

By considering peak events instead of annual maximum extremes, the number of available data for statistical processing would be increased considerably. The POT method is therefore based on utilizing all peak events of the available time series exceeding a specified threshold. This approach suggests two main steps: the selection of the threshold or the selection of the peak values, and the estimation of the distribution properties using statistics above the threshold. The first step is very critical and can affect the efficiency of the method.

In practical applications, the POT method is done through:

- The identification of the peak events assigned to their magnitude. Several criteria exist in the literature to identify the peaks (instantaneous or aggregated values). In this study, the method of Willems (2000) is adopted, which is based on the runoff subflows. Firstly the total runoff is filtered in order to get the subflows (baseflow, interflow and overland flow), using a numerical digital filter technique, then a POT selection algorithm is simulated using three "independency" criteria depending on the subflows;
- A threshold is then applied to the obtained sequence of peak events. The problem of choosing the most appropriate threshold is still under analysis in many researches. The method is used as standard methodology for river flood modelling by the WL (Willems, 2000).

One of the basics of the POT method is the generalized Pareto distribution (GPD). In fact, the work made by Pickand (1975) showed that the probability distribution of the extremes converges to the GPD as the threshold becomes higher. The assumption of a Poisson process for the exceedence times combined with the GPD will lead to the generalized extreme value (GEV) distribution in case annual maximum extremes would be used (Willems, 1998).

The expression of the GPD is:

$$G(y) = p[Y \leq y] = 1 - (1 - \gamma \frac{y}{\beta})^{-\frac{1}{\gamma}}$$

Where β is a scale parameter, γ is called the extreme value index and determines the shape of the distribution. The cases of $\gamma > 0$, $\gamma = 0$ and $\gamma < 0$ correspond to Fréchet, Gumbel (Type I) or exponential and reverse Weibull respectively.

The asymptotic result followed by the GPD distribution above a high threshold (fact that was shown by Pickand, 1975) can be used within the equation to present the excess within the cumulative distribution function. To illustrate, let x be an observed variable and x_t a threshold. Given that $x > x_t$, for very large x_t, the excess $y = x - x_t$ can be presented by the cumulative distribution function GPD (Willems, 1998).

This study used a POT selection based on Willems' WETSPRO software. It is followed by a hydrological extreme value analysis procedure (Willems, 2004a, 2004b).

The method of Willems for POT selection is based on the different runoff subflows. Different "independency criteria" are assigned to extract the independent extremes (peak discharges) along the time series.

After filtering the discharge time series to separate the baseflow, interflow and overland flow, the following criteria are considered:

- POT selection based on baseflow (plus interflow): the independency criteria are (Figure 6):
    - Two peak events are considered independent and selected both if the difference of the minimum flow condition between them (q_{min}) and the baseflow (q_{base}) is lower than a fraction (f) of the maximum discharge (q_{max}):

$$\frac{q_{\min} - q_{base}}{q_{\max}} < f$$

    - The peaks should be higher than a limited flow:

$$q_{\max} > q_{\lim}$$

- POT selection independent on subflows: the independency criteria are (Figure 6):

- Two peak events are considered independent if the time delay (*p*) between the peaks is higher than the recession constant (*k*):

$$p > k$$

- The peaks should be higher than a limited flow:

$$q_{\max} > q_{\lim}$$

- The minimum flow between the two independent peak events should reach a small value:

$$\frac{q_{\min}}{q_{\max}} < f$$

By considering the recession constant *k* equal to the recession constant for overland flow (or quick flow), peak maxima during independent quick flow periods will be selected. After considering the recession constant of baseflow, longer nearly independent baseflow or slow flow periods are considered, and nearly independent low flows defined as the minima during these periods.

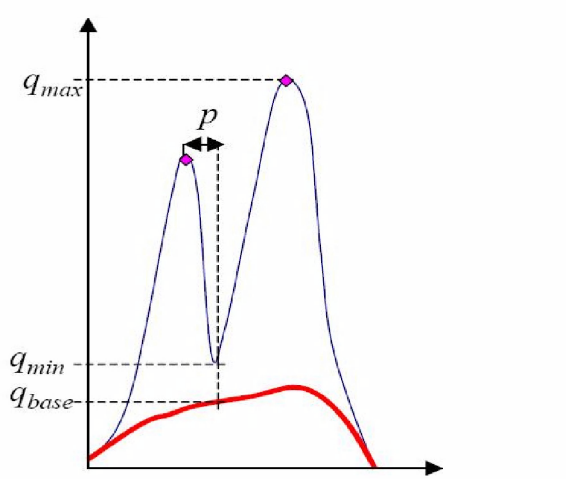


Figure 6. Independence criteria for defining independent peak flows (Willems, 2004a).

The use of Willems' independence criteria, which are hydrologic processes based, allows defining different hydrologic events that are nearly independent from a hydrological point of view. The hydrological events are split at the time moment of minimum flow in between two successively selected POT's, to derive nearly independent quick flow events when the recession constant for quick flow is applied, and nearly independent slow flow events when the recession constant of baseflow is used.

3.3.3 Extreme value analysis

After filtering the discharge time series and selecting the peaks with the POT approach, the next step consists on analyzing the extremes in order to define the type of distribution they present. To do so, one of the most efficient approaches is the method based on regression in "quantile-quantile plots" (QQR method; Willems, 2000).

The quantile-quantile (Q-Q) plot is a graphical technique for determining if two data sets come from populations with a common distribution. With the word "quantile", we mean the value corresponding to a fraction (or percent) of points below that given value. For example, the 0.4 (or 40%) quantile is the point at which 40% percent of the data fall below and 60% fall above the quantile.

In the QQR method for extreme value analysis, the empirical quantiles (the selected POT discharges) are plotted against the theoretical ones according to an assumed probability distribution, assuming the same empirical probability of exceedence for both. If the data are consistent with the assumed theoretical distribution, the points on the Q-Q plot lie approximately on a straight line. The distribution function tested with the Q-Q plot technique is generally named with the same distribution type. The normal, lognormal, exponential, Pareto, Weibull, etc. distributions can be used in the plot.

In this study, after sorting the extremes extracted by the POT selection, let y_i be the observed extremes, i=1,…,m with ($y_1 \leq \ldots\ldots \leq y_m$), their corresponding empirical exceedence probability is calculated by Willems (1998):

$$p_i = \frac{i}{(m+c)}$$

where c is a plotting position score number taken here equal to 1

In absence of the distribution parameter values, the extremes analysis can go then through the adopted Q-Q plot approach. In the last, the quantile function, a linear function to the exceedence probability that is totally independent of the distribution parameters, is plotted in abstraction to the distribution function. The quantile function for the case of exponential, Pareto and Weibull Q-Q plots are given respectively in the following (Willems, 1998):

- Exponential and Pareto quantile plots: $-\ln(\frac{i}{m+1})$
- Weibull quantile plot: $\ln(-\ln(\frac{i}{m+1}))$

The power of the Q-Q plot in examining the distributional shape seems to be easily applied with detecting the deviation from the linearity. In addition, other kind of difference between the shapes like skewness or shape in the tails can be identifiable too. Therefore the Q-Q plot technique is useful not only to determine the underlying distribution of the variables, but also to diagnostic what kind of deviations they might present.

3.3.4 Methodology for low flow extremes

After extracting the hydrological model results, the POT will be taken on $\frac{1}{Q}$ instead of Q, where Q refers to the simulated runoff time series. In this respect, the selected peaks by the POT are actually low flow extremes. In this study, this methodology has been applied using seasonal perturbation factors similar to Boukhris et al (2006) and therefore the results for low flows are the same. Further analyses are happening in the CCI-HYDR project.

4. Hydrological impact analysis: results and discussion

This chapter gives an overview of the obtained results after applying the methodology described above on the different catchments of Flanders. Thus we will go through the different basins separately to investigate climate change impact on a sub-basin scale where we will present respectively:

- The percentage of variation of the high flow peaks (hourly peaks) and changes into the composite hydrographs.
- The percentage of changes in the low flow.
- A statistical summary on the variation of the variables of overland flow and ETo
- A general overview on the variation of the flooded areas due to climate change scenarios.

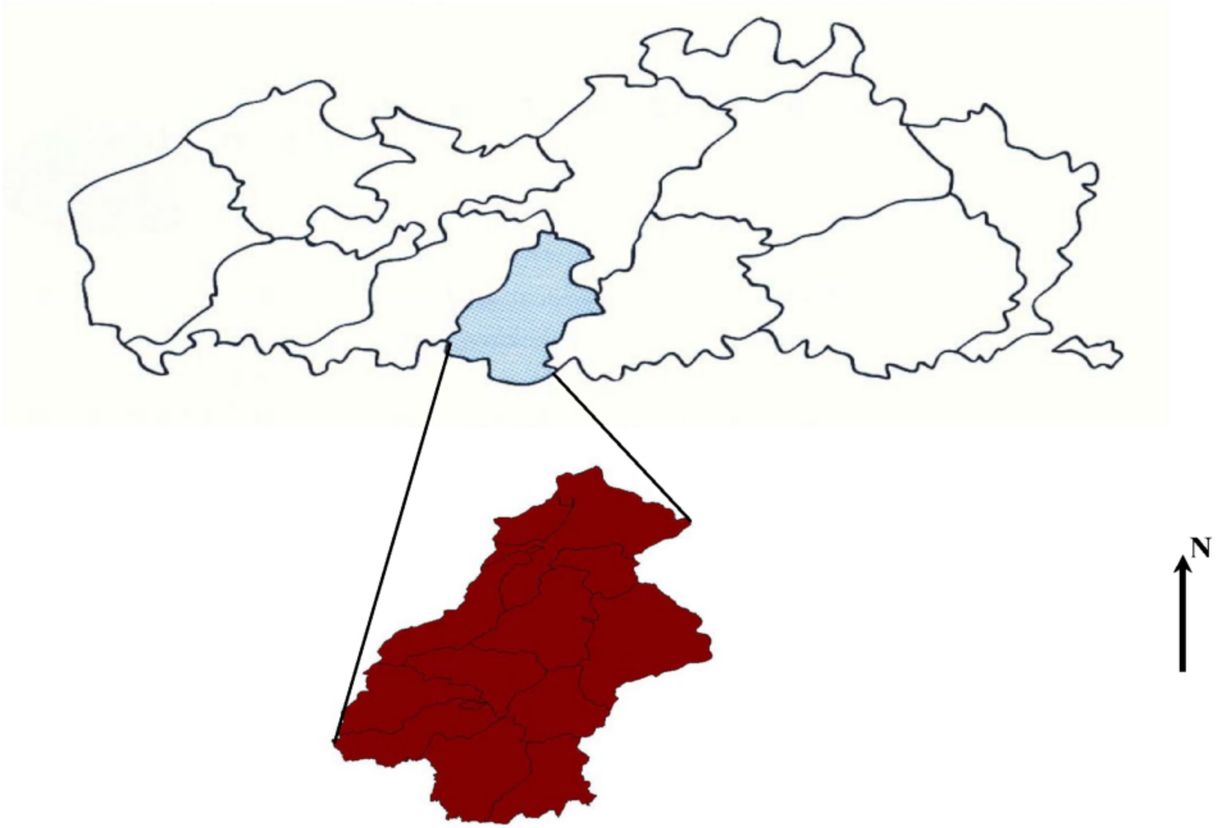
The following graphs present the methodology results of climate change impact on hydrological extremes for the Dender basin. Similar results for the remaining Flemish basins can be found in Appendix.

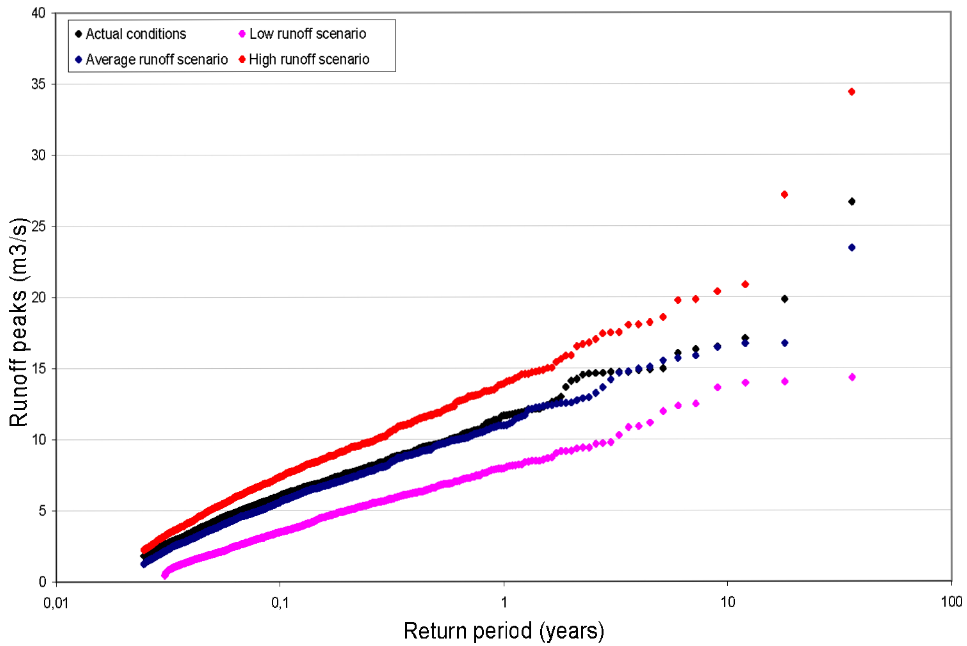
It is however very important to mention that due to data limitations in some areas and in order to reach an overall understanding of the variation of the hydrological answer of all Flemish sub-basins, an interpolation procedure has been followed for the ungauged areas in order to estimate their hydrological behaviour in response to climate change. The interpolation procedure consists that the hydrological answer of the un-gauged areas is considered to be similar to:

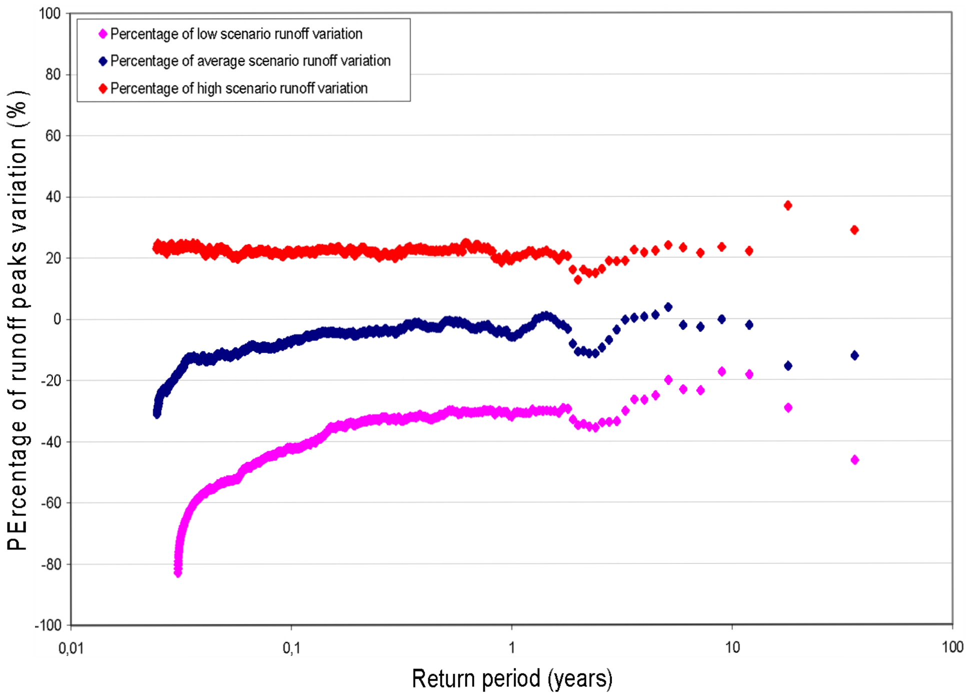
- The closest neighbor gauged sub-basin to the studied area (ungauged sub-basin) for which the surface is more or less the same with being included at the same catchment. This ensures that the studied area falls into the same hydrological system. It is obvious that many neighboring sub-basins might be chosen.
- The closest neighbor gauged sub-basin to the studied area (ungauged sub-basin) for which the geotechnical is more or less the same (soil type, soil layers depth, hydraulic conductivity...),
- The closest neighbor gauged sub-basin to the studied area (ungauged sub-basin) for which land use is more or less the same.

If the ungauged area is located in between neighboring sub-basins presenting different hydrological answers with respect to the geotechnical parameters and land use, an average value is taken for the un-gauged area.

4.1 The Dender basin

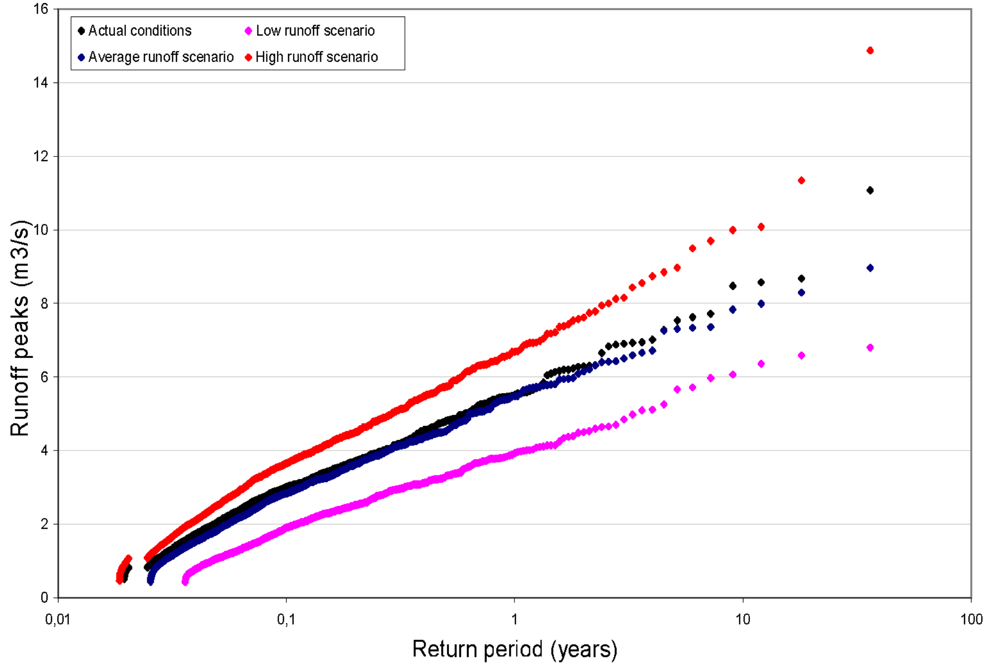




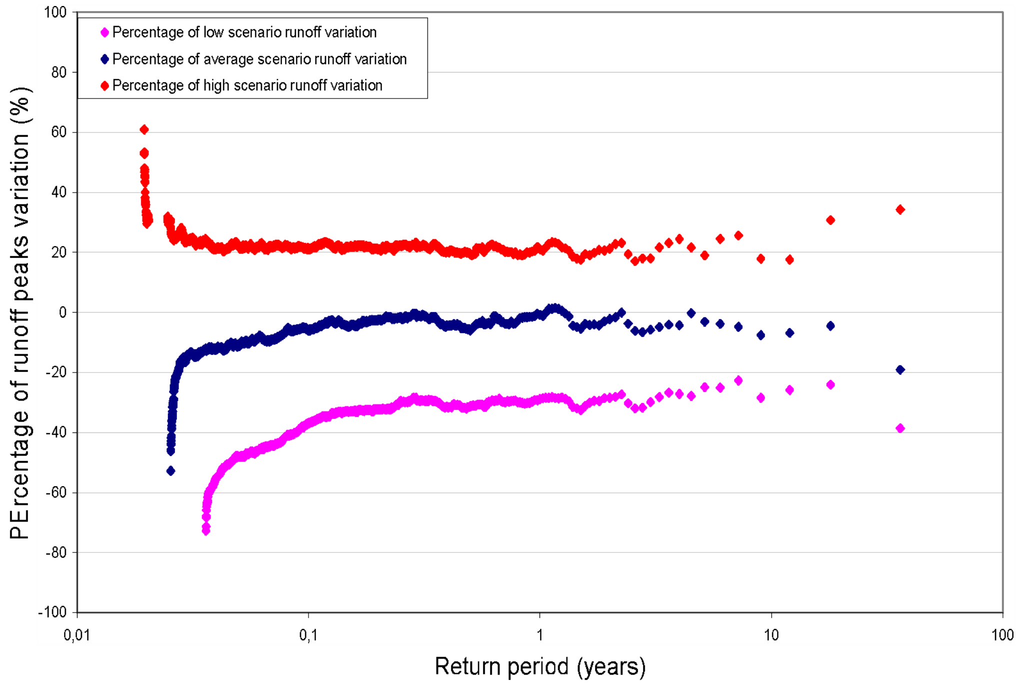


Sub-basin 400

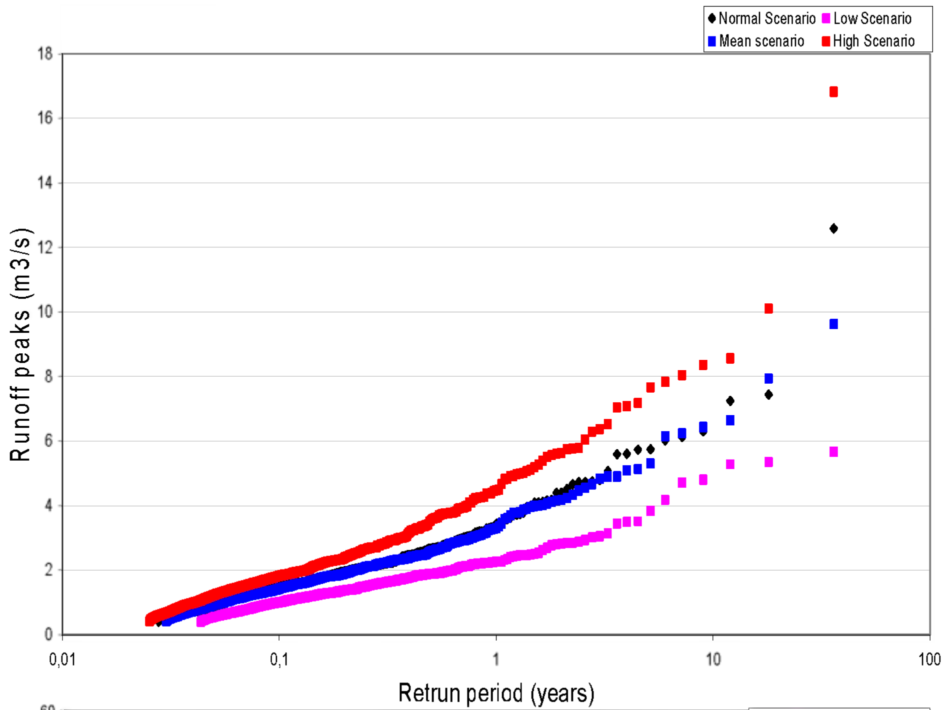
Average percentage of variation of high flow (%)	Low scenario	Mean scenario	High scenario
Sub-basin 400	-35	-4	22

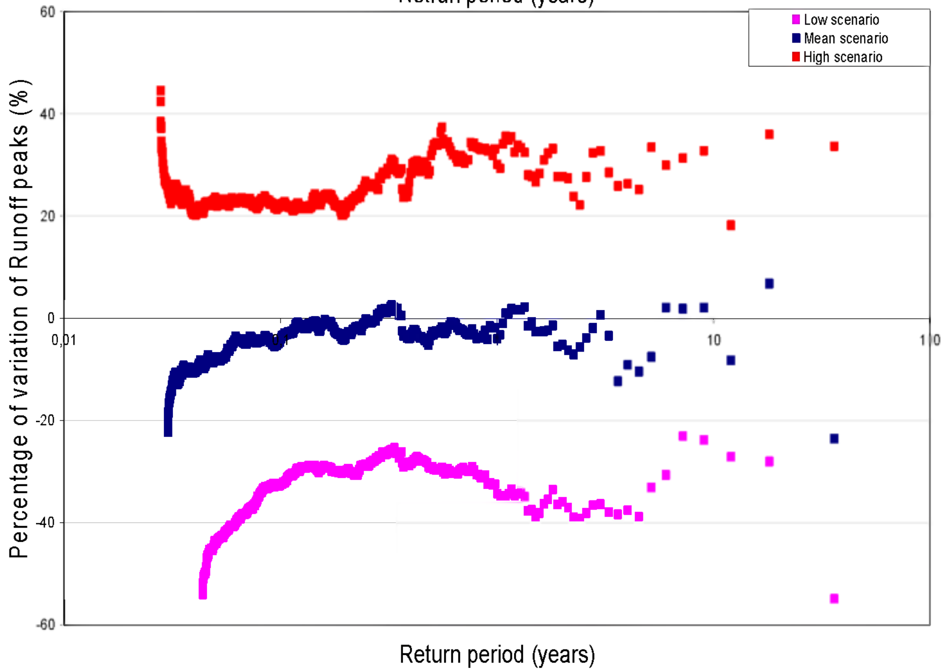


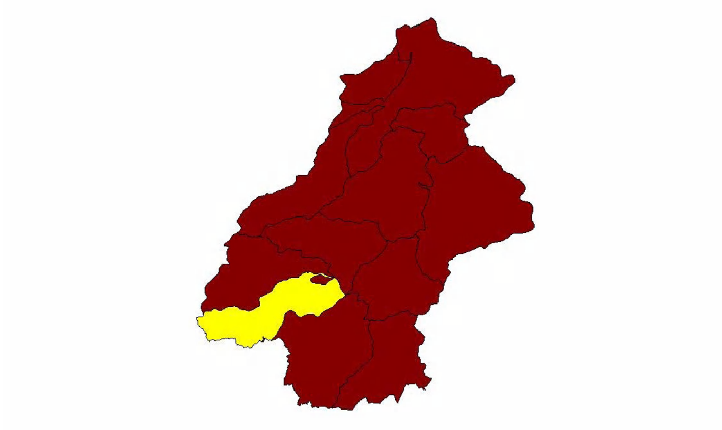
Sub-basin 401



Average percentage of variation of high flow (%)	Low scenario	Mean scenario	High scenario
Sub-basin 401	-32	-3	21

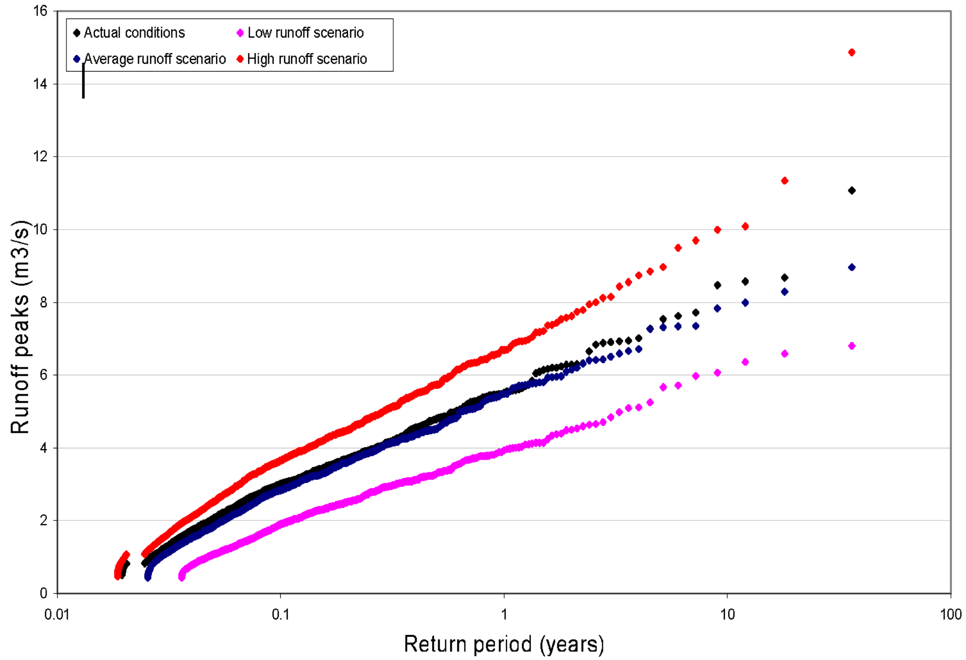




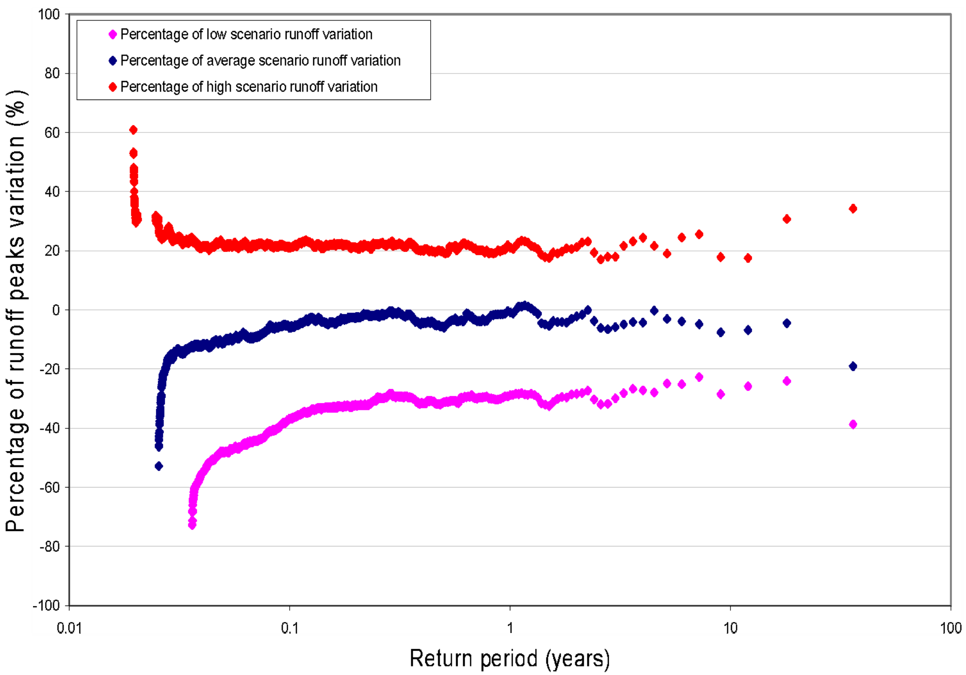


Sub-basin 410

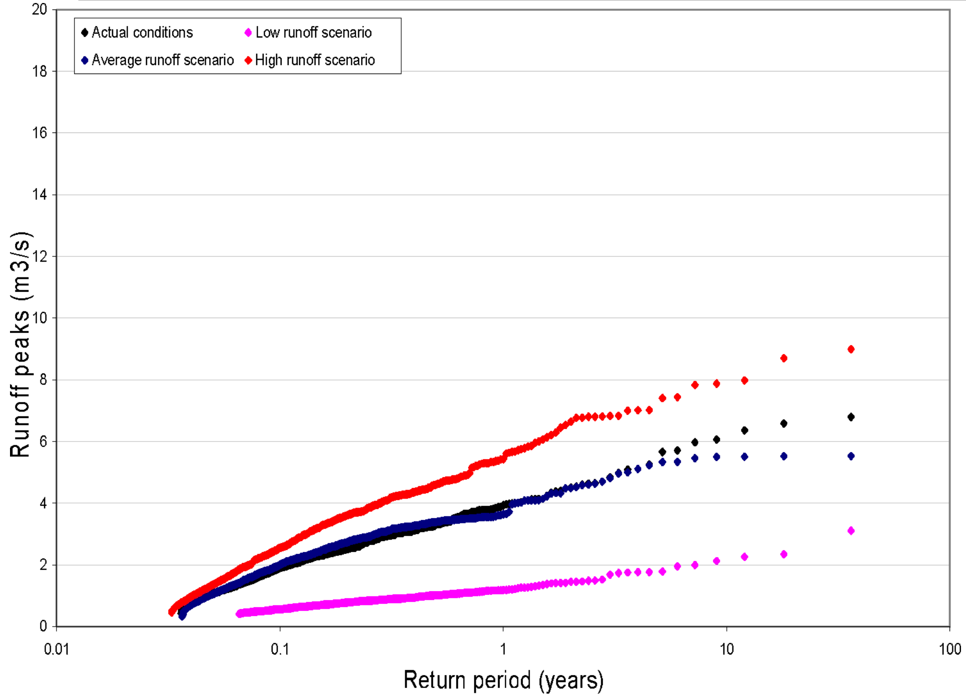
Average percentage of variation of high flow (%)	Low scenario	Mean scenario	High scenario
Sub-basin 410	-30	-2	25



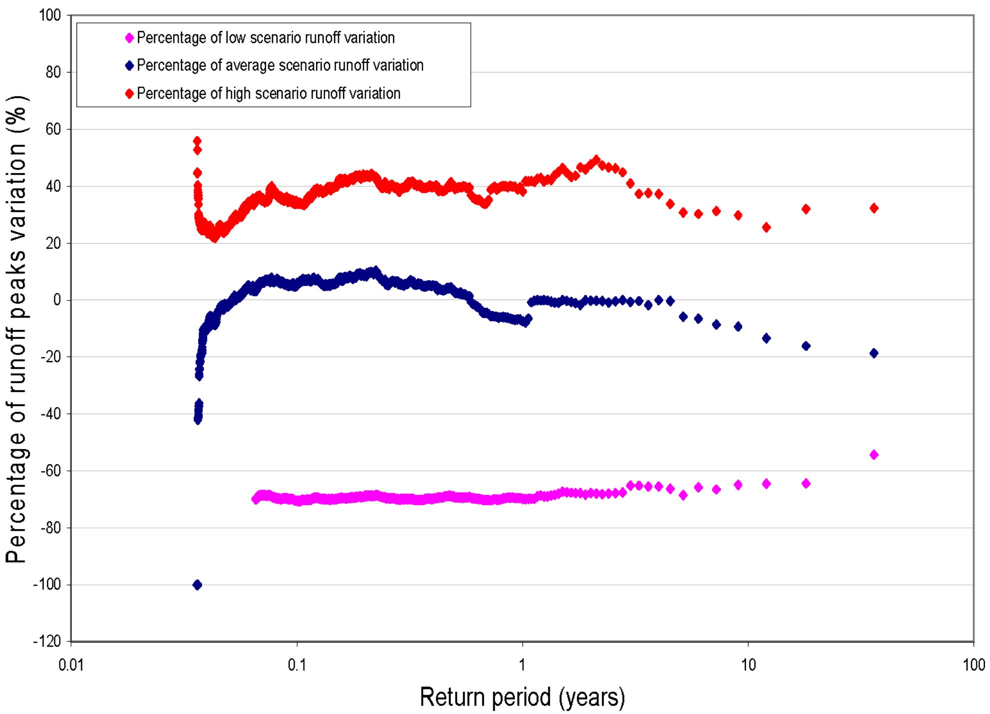
Sub-basin 420



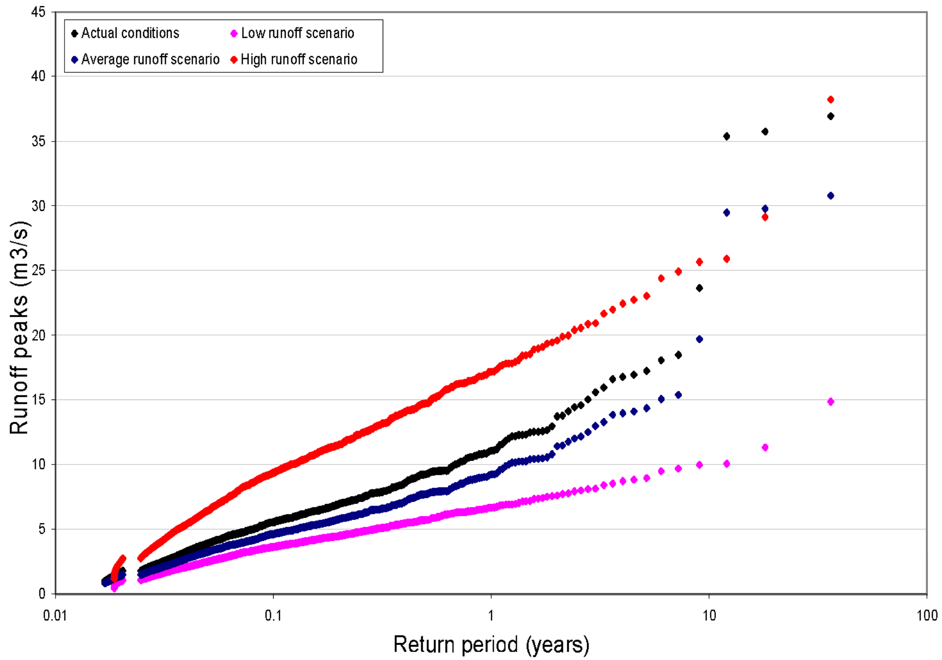
Average percentage of variation of high flow (%)	Low scenario	Mean scenario	High scenario
Sub-basin 420	-32	-3	22



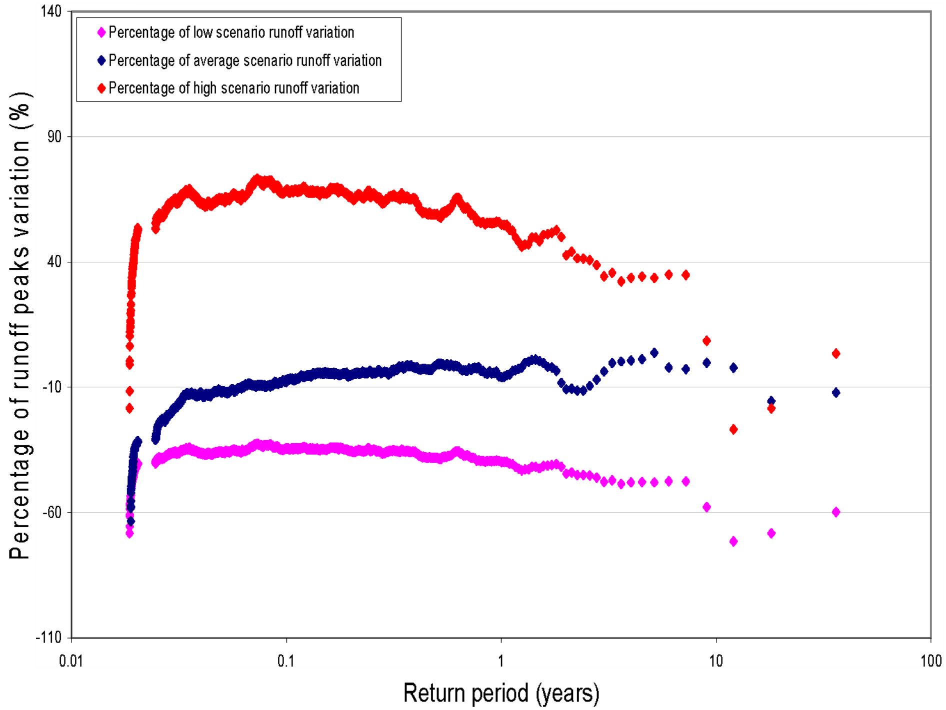
Sub-basin 421



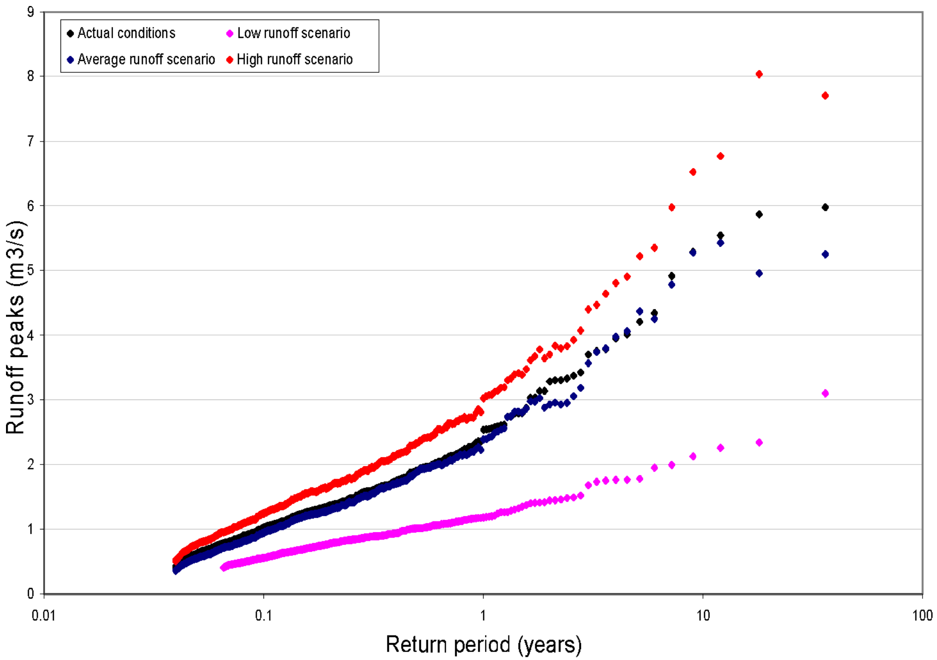
Average percentage of variation of high flow (%)	Low scenario	Mean scenario	High scenario
Sub-basin 421	-69	5	39



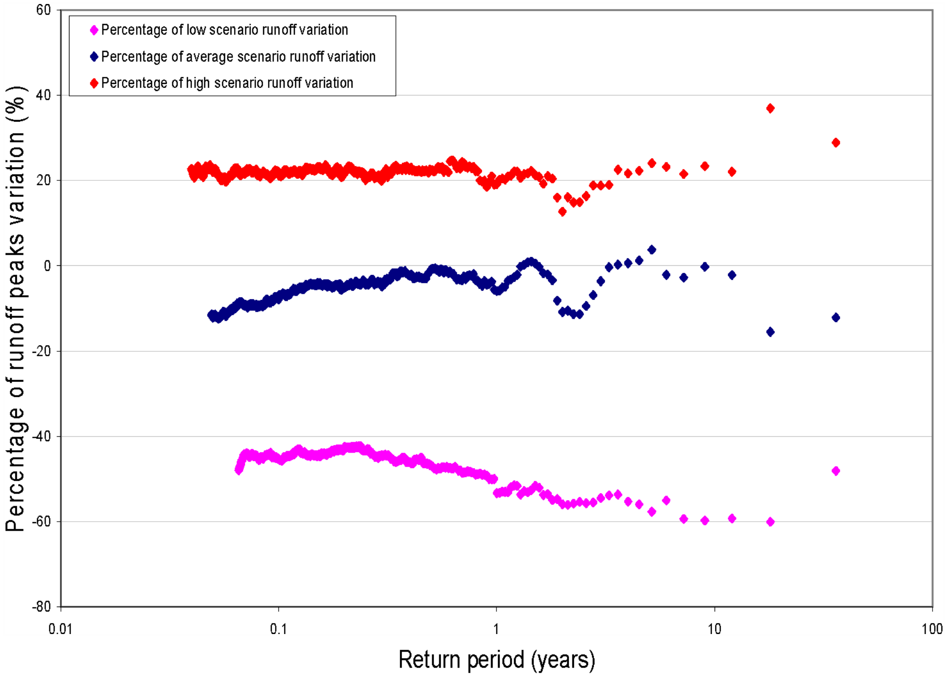
Sub-basin 422



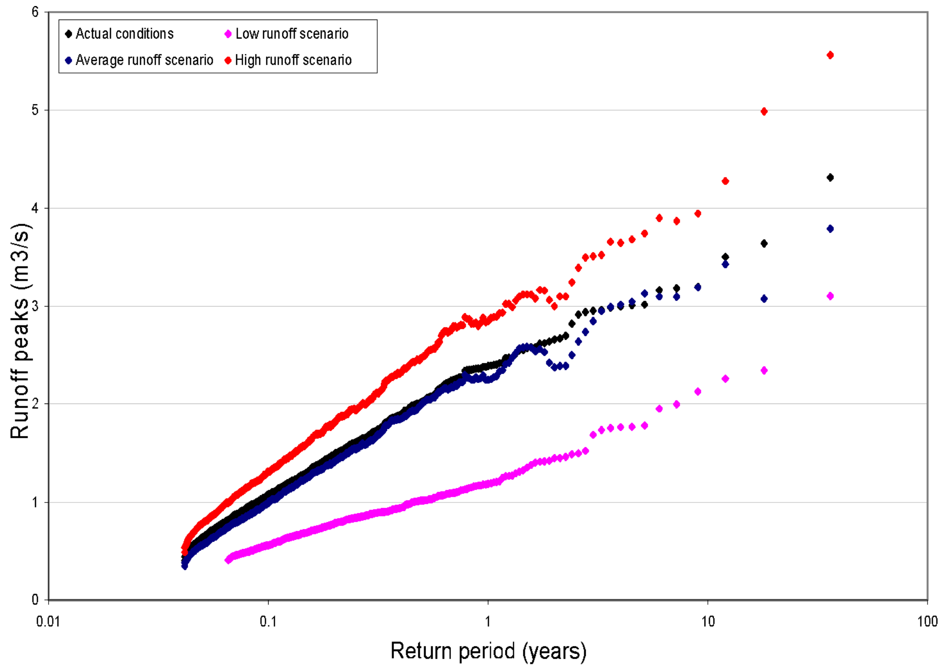
Average percentage of variation of high flow (%)	Low scenario	Mean scenario	High scenario
Sub-basin 422	-45	-8	32



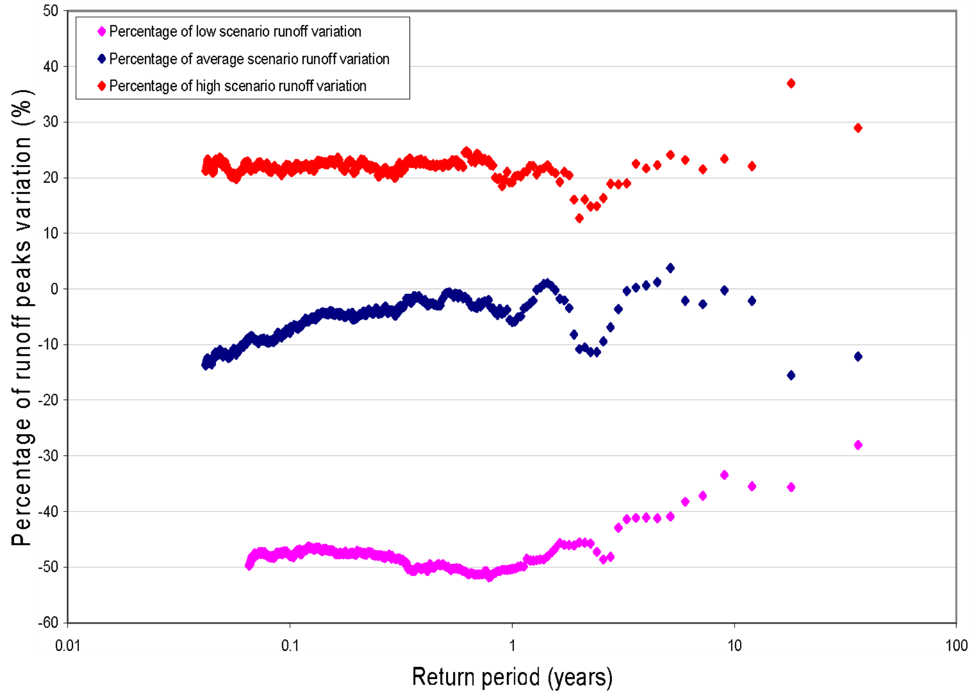
Sub-basin 423



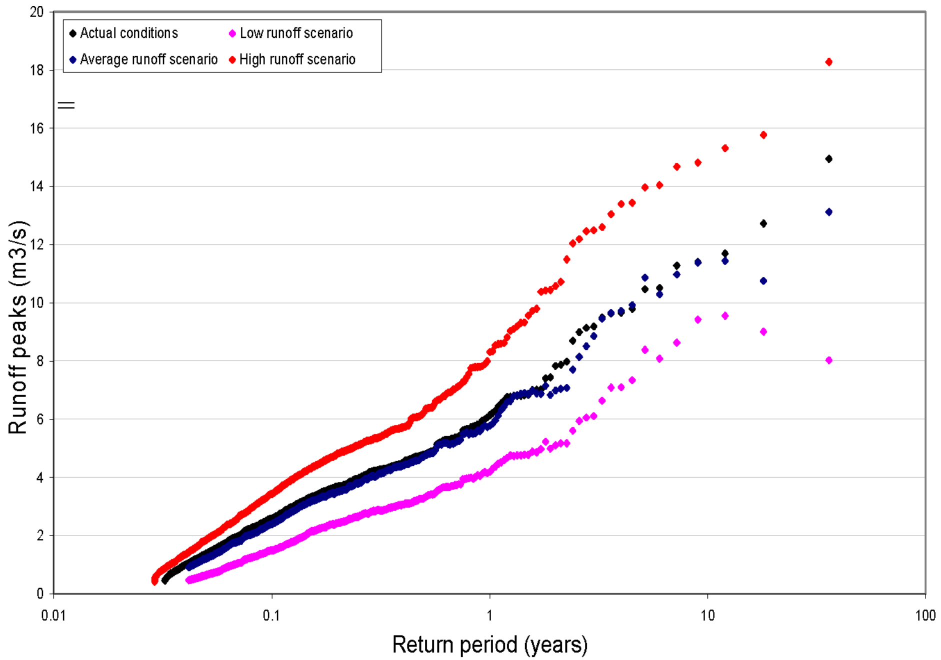
Average percentage of variation of high flow (%)	Low scenario	Mean scenario	High scenario
Sub-basin 423	-45	-4	22



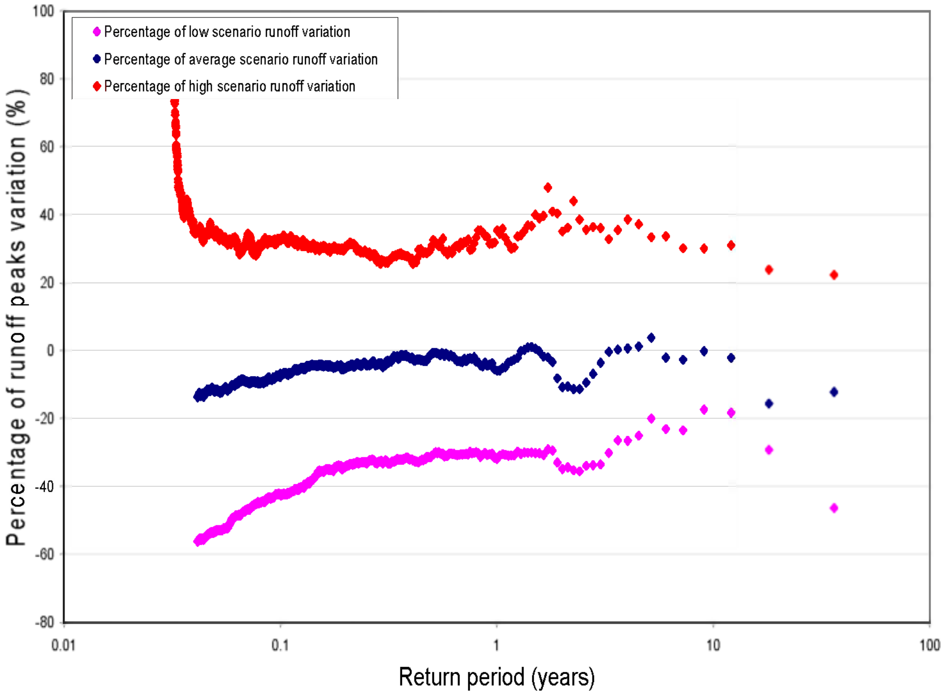
Sub-basin 430



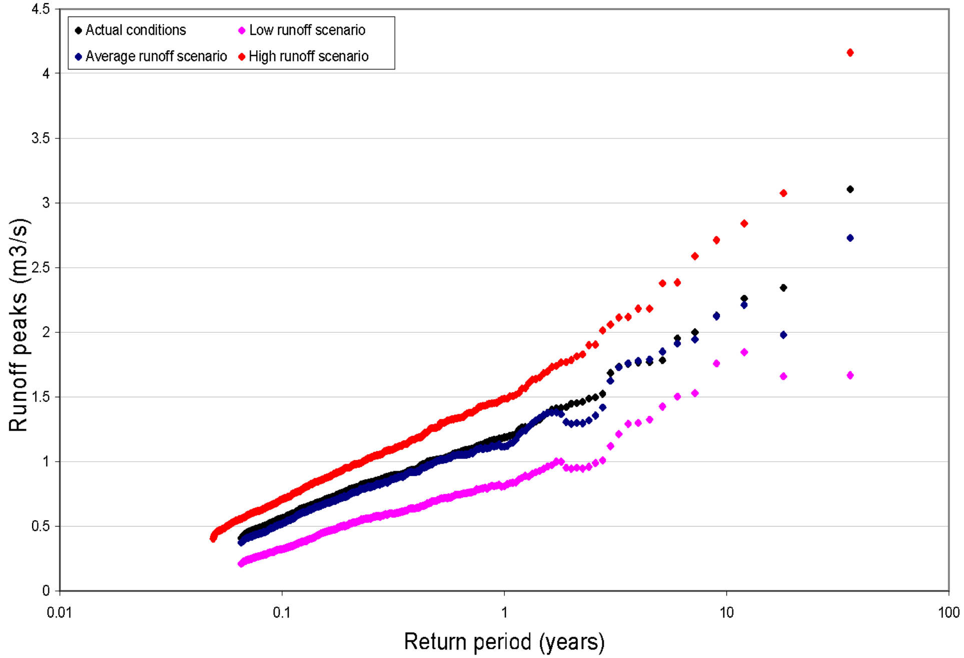
Average percentage of variation of high flow (%)	Low scenario	Mean scenario	High scenario
Sub-basin 430	-47	-4	22

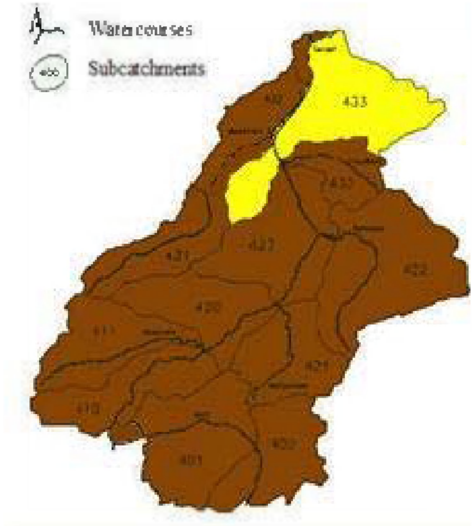


Sub-basin 431-2

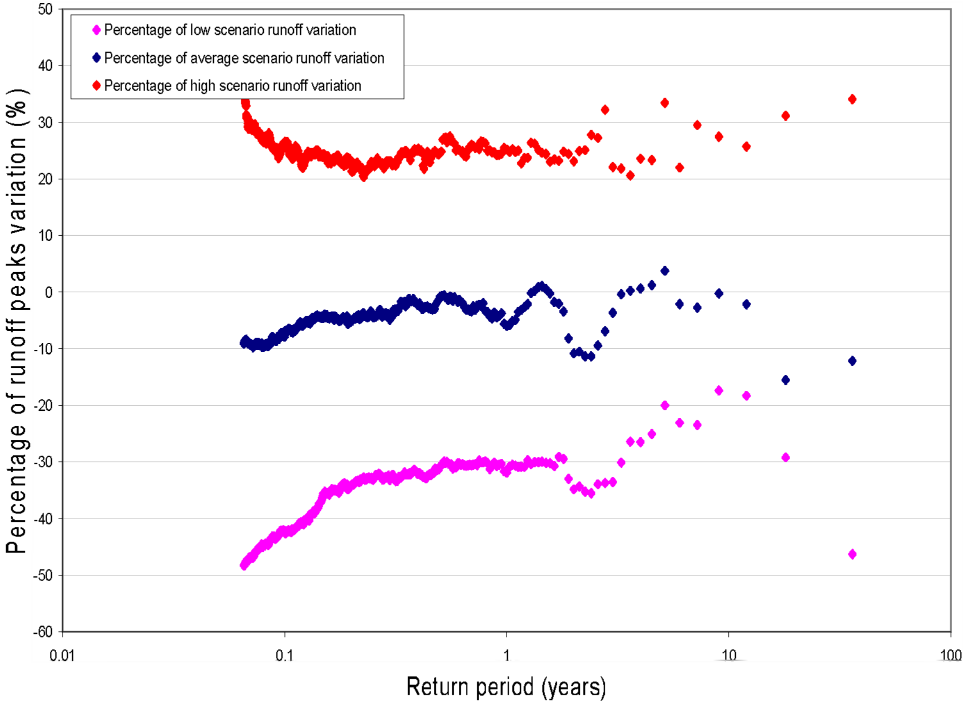


Average percentage of variation of high flow (%)	Low scenario	Mean scenario	High scenario
Sub-basin 431-2	-35	-4	30

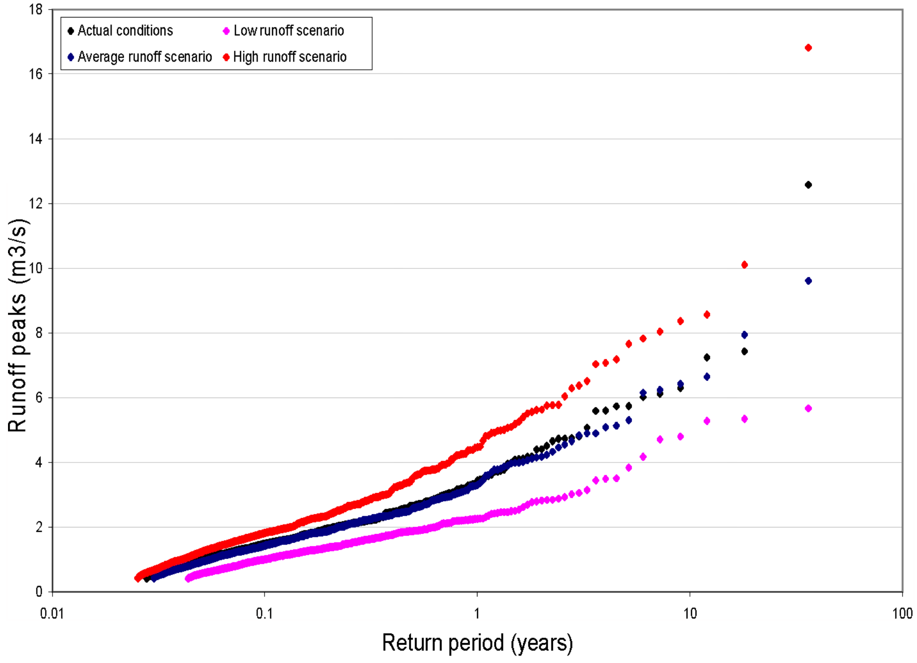




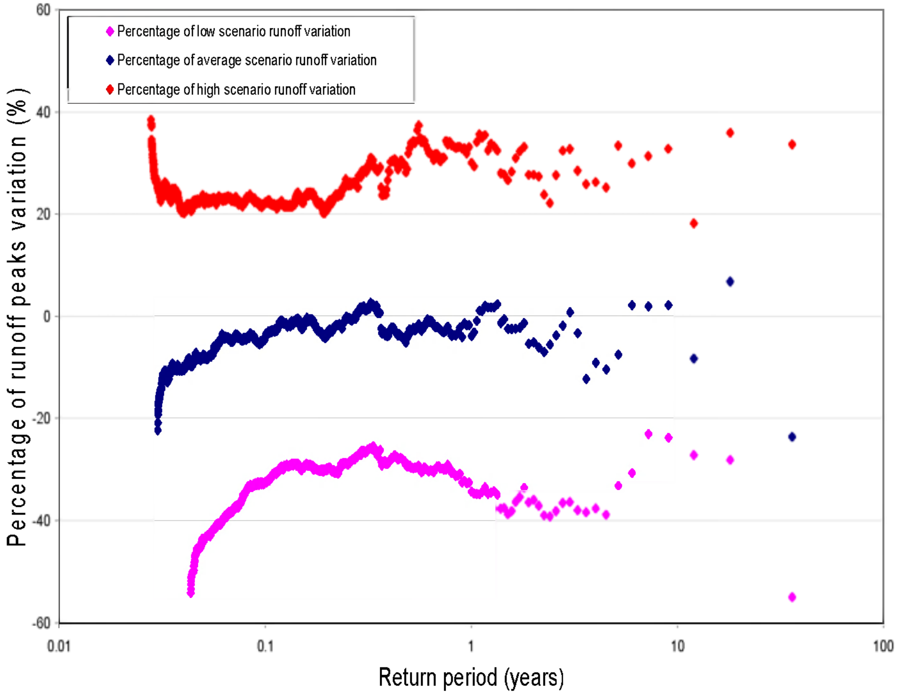
Sub-basin 433



Average percentage of variation of high flow (%)	Low scenario	Mean scenario	High scenario
Sub-basin 433	-35	-4	24



Sub-basin 411



Average percentage of variation of high flow (%)	Low scenario	Mean scenario	High scenario
Sub-basin 411	-30	-2	24

The figures above show respectively, for every sub-basin of the Dender, the NAM hourly (60min) runoff peaks behaviour after climate change scenarios forcing. The left top-panel of every sub-basin presents the Q-Q plot where for all the cases, the runoff peaks distribution remains unchanged after applying climate scenarios. However, the original distribution (Actual condition) shows a shift up or down depending on the applied scenario. This shift (difference between the peaks) is small for low return period but grows bigger for high return periods. These increases/decreases in the hourly peaks are clearly presented in the left down-panel for every sub-basin where the percentage of variation of the runoff peaks (difference between the new resulted runoff peaks after applying climate scenarios and the actual runoff peaks reported to the actual ones) are plotted depending on the return periods.

For the mean scenario, and in all the sub-basins, climate change would not introduce big variation where, in average, the runoff peaks would have -4% of change. In opposite the low and high scenarios, the sub-basins answer severely with respectively -40% and +28% changes in the runoff peaks increasing therefore the droughts and floods possibilities.

Overland flow volume shows similar behaviour to the runoff peaks (Figure 13), where big and moderate decreases in volumes are expected respectively for the low and mean scenarios. As for the evapo(transpi)ration (Figure 14), slight differences are seen between the three scenarios where the overall percentage of variation increases up to 15%, a result that is very expected as the majority of climate models predict global and regional warming and an increase in temperature.

Another important result from this analysis is the regional differences in the hydrological answer of every sub-basin in the Dender. Figures 12, 13, and 14 show that two neighbor sub-basins situating in the same hydrological system of the Dender provide different hydrological answer. This is issue is further investigated in this study.

4.2 Dender basin composite hydrographs factors

The percentages of variations in the high flows mentioned in the figures and tables above corresponding to different scenarios will automatically generate variations into the composite hydrographs for each sub-basin and indeed into the probabilities of flood risk. Estimating the variations of the composite hydrographs is very important with respect to assess the intensity of certain events corresponding to certain return periods. This is very important for dimensioning needs and for damage calculation assessment.

However, it has been remarked that the percentages of variation of the high flows present three important criteria that will have great impact on the composite hydrographs:

- Above certain threshold corresponding to the extremes, the factors vary independently of the return periods (Figures 8, 9, 10, 11),
- The factors vary nearly independently of time aggregation levels (Figures 8, 9, 10, 11),
- The average value of the factors above the ~0.1 year return period are nearly the same and constant for all the time aggregation levels (Table 5).

These three criteria mean that the percentages of variations of the composite hydrographs will be conforming in average to the variations seen in the high flows for each scenario. Indeed, for instance, the original composite hydrograph of the zone 410 of the Dender basin will have an increase of 25% for the high scenario, a decrease of 2% and of 30 % respectively for the mean and low scenarios. The original composite hydrographs (and QDF relationships) will then have a shift up or down independently on the return periods but only function of the climate scenarios (Figure 7). Therefore, it has been decided to use the average factor calculated for each time scale (aggregation levels) for each sub-basin. The factors of variation of the composite hydrographs for the Dender basin for each scenario are presented in Table 6.

It is to be mentioned that the table and figures below describe the tested procedure and results on the VHA zone 410 of the Dender basin although, the same procedure has been tested and applied for all other sub-basin of the Flemish area.

Time aggregation level (min)	Low scenario	Mean scenario	High scenario
60	-30.07	-1.98	25.43
180	-29.67	-1.87	24.67
720	-27.80	-1.55	21.92
1440	-26.54	-1.04	21.25
2880	-26.70	-1.21	20.91
43200	-30.96	-1.00	22.92
Average	**-28.16**	**-1.53**	**22.83**

Table 5. Percentage of variation of the high flow factors for different aggregation levels for the low, mean and high scenarios for the VHA zone 410 of the Dender basin.

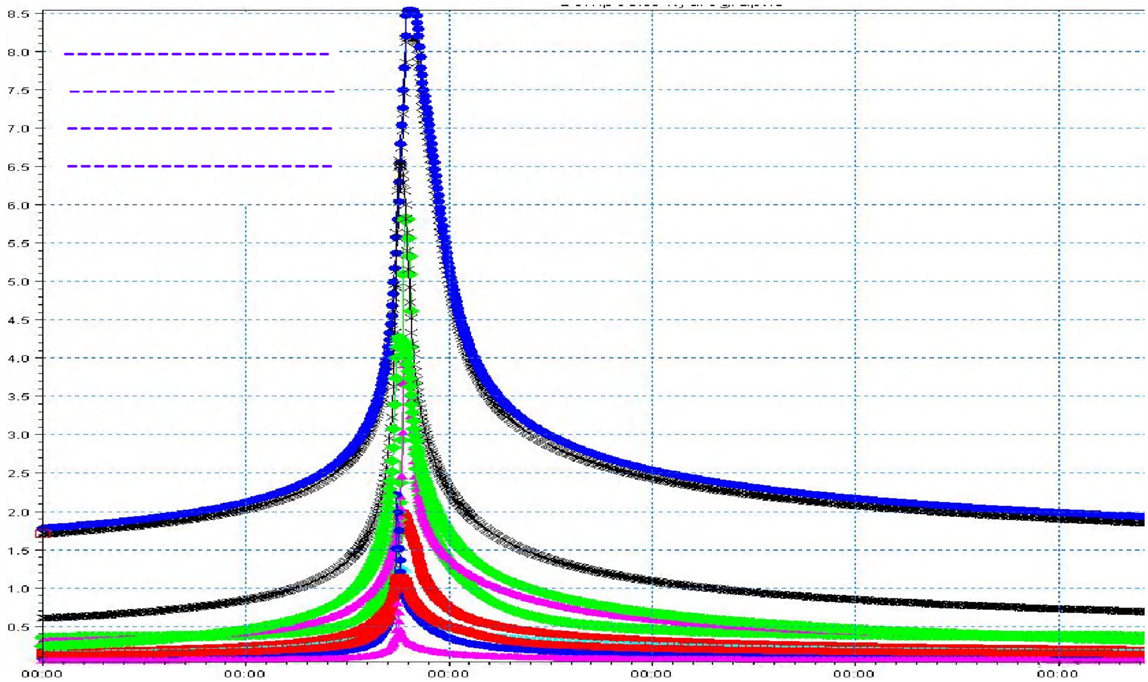


Figure 7. Perturbed composite hydrographs with the three composite hydrographs for the VHA zone 410 of the Dender basin.

Sub-basin	Low scenario	Mean scenario	High scenario
400	-34.08	-3.88	21.84
401	-31.21	-2.92	21.37
410	-28.16	-1.53	22.83
411	-27.15	-1.23	22.20
420	-31.21	-2.92	21.37
421	-71.64	5.84	35.74
422	-36.38	-4.32	32.07
423	-45.61	-4.32	22.02
430	-51.65	-25.72	23.54
431-2	-42.41	-4.30	26.93

Table 6. Percentage of variation factors of the composite hydrographs for the low, mean and high scenarios for the Dender basin.

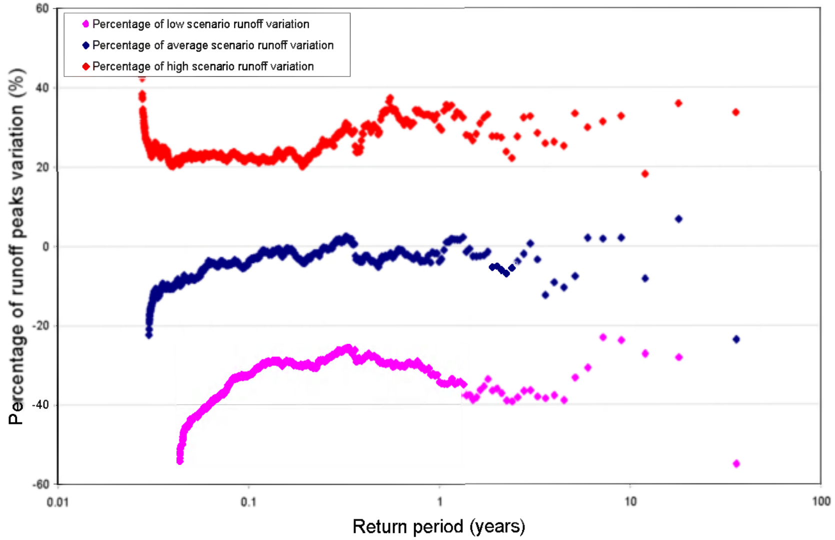


Figure 8. Percentage of variation of the (60 min) hourly high peaks for the low, mean and high scenarios for the VHA zone 410 of the Dender basin.

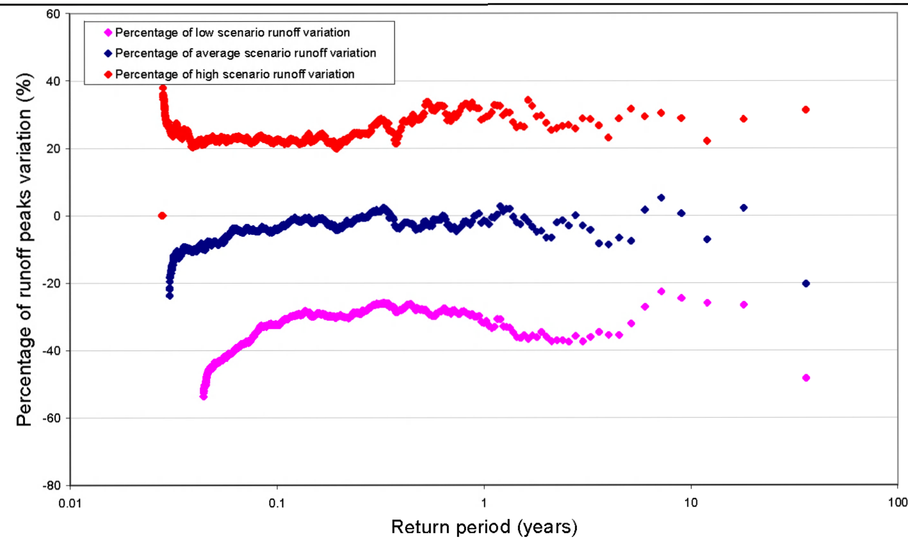


Figure 9. Percentage of variation of the (180 min) high peaks for the low, mean and high scenarios for the VHA zone 410 of the Dender basin.

Figure 10. Percentage of variation of the (720 min) high peaks for the low, mean and high scenarios for the VHA zone 410 of the Dender basin.

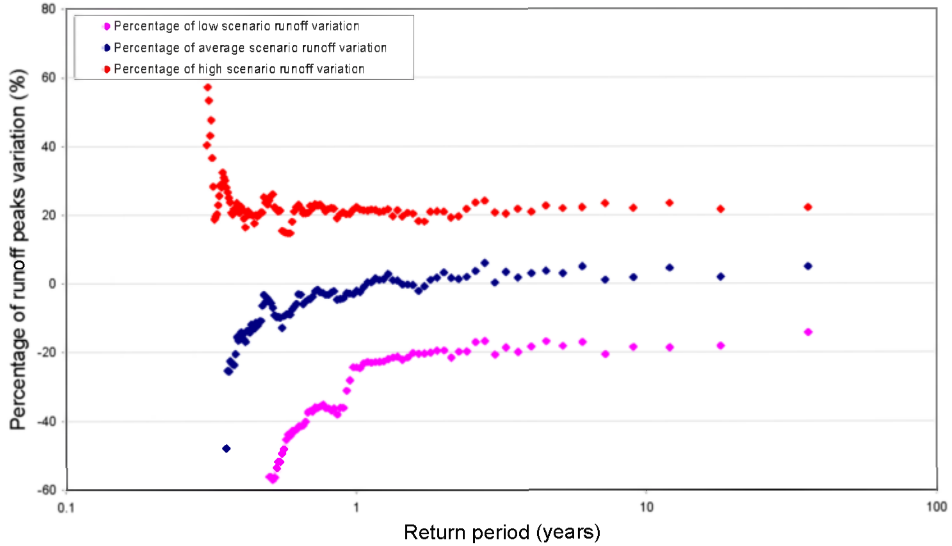


Figure 11. Percentage of variation of the (43200 min) high peaks for the low, mean and high scenarios for the VHA zone 410 of the Dender basin.

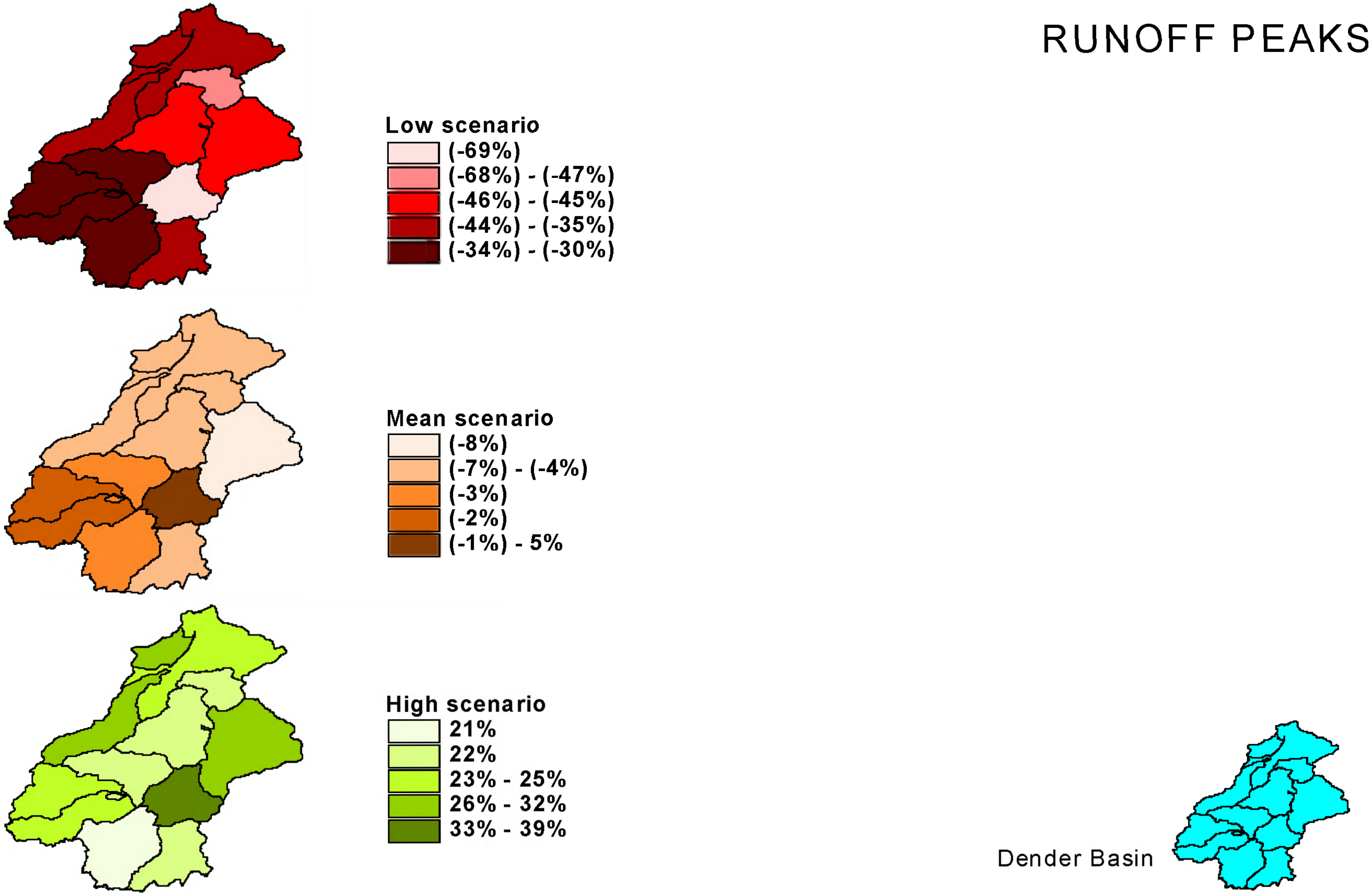


Figure 12. Percentage of variation of runoff peaks for the low, mean and high scenarios for the Dender basin, regional differences.

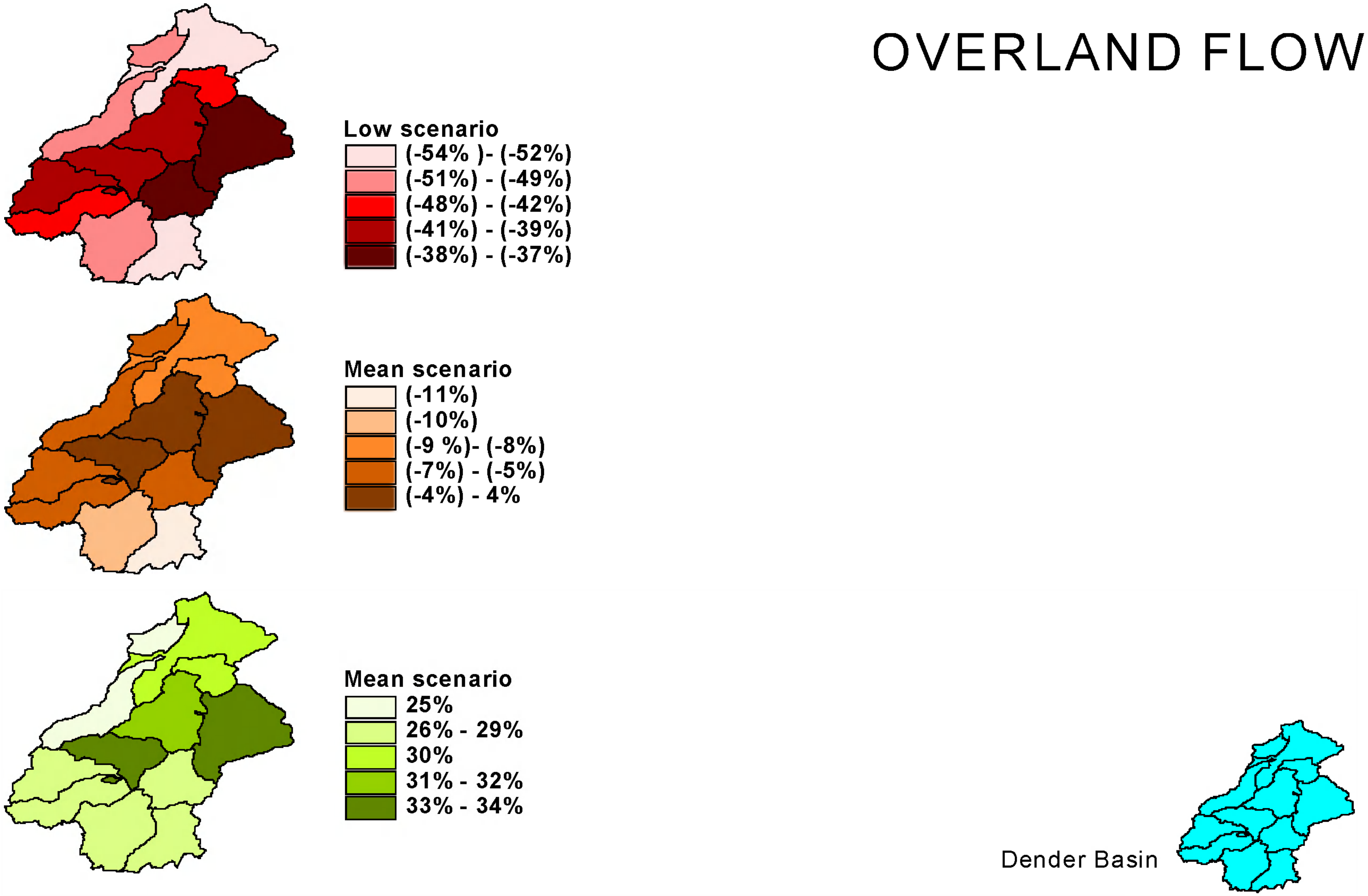


Figure 13. Percentage of variation of overland flow volume for the low, mean and high scenarios for the Dender basin, regional differences.

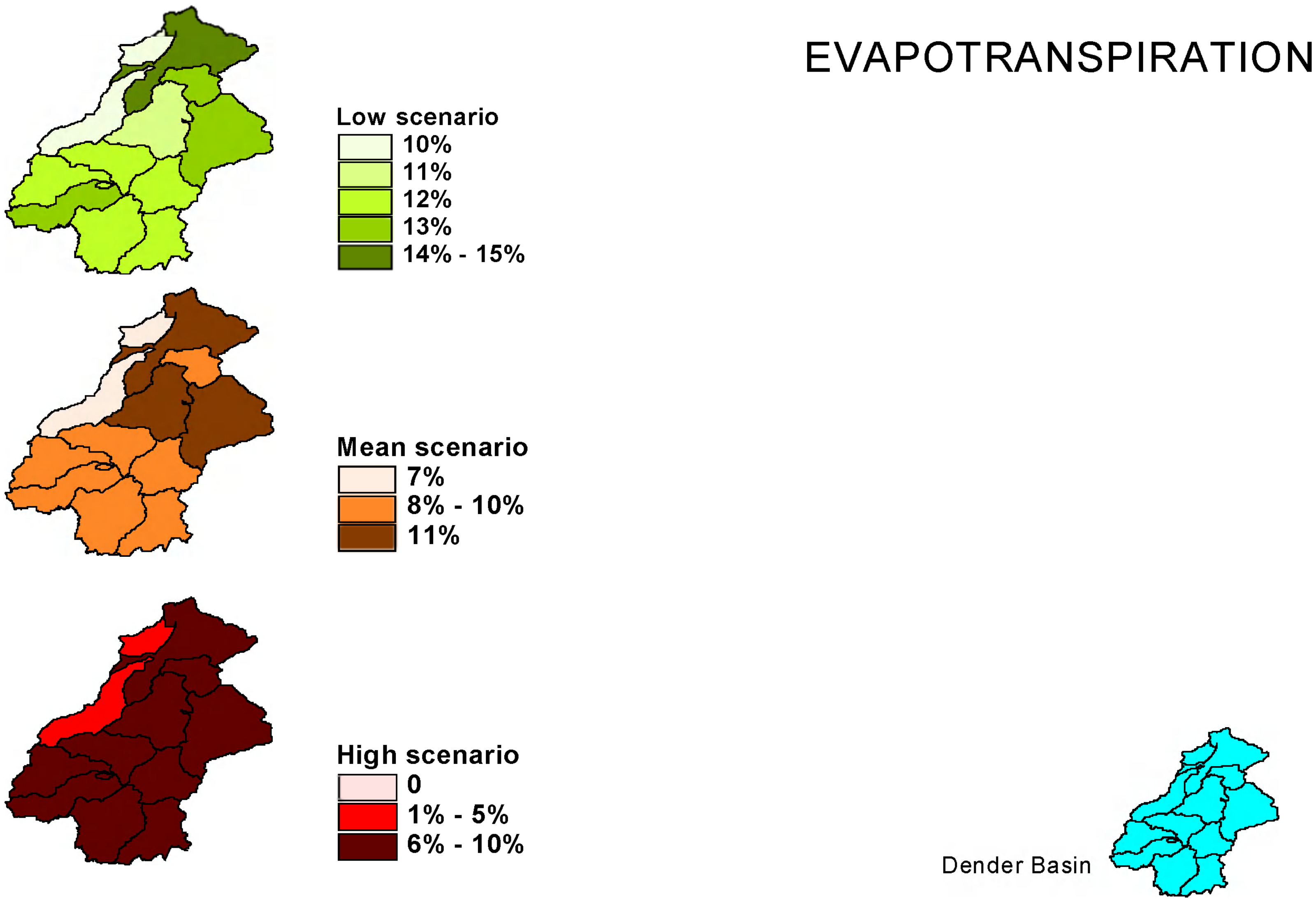
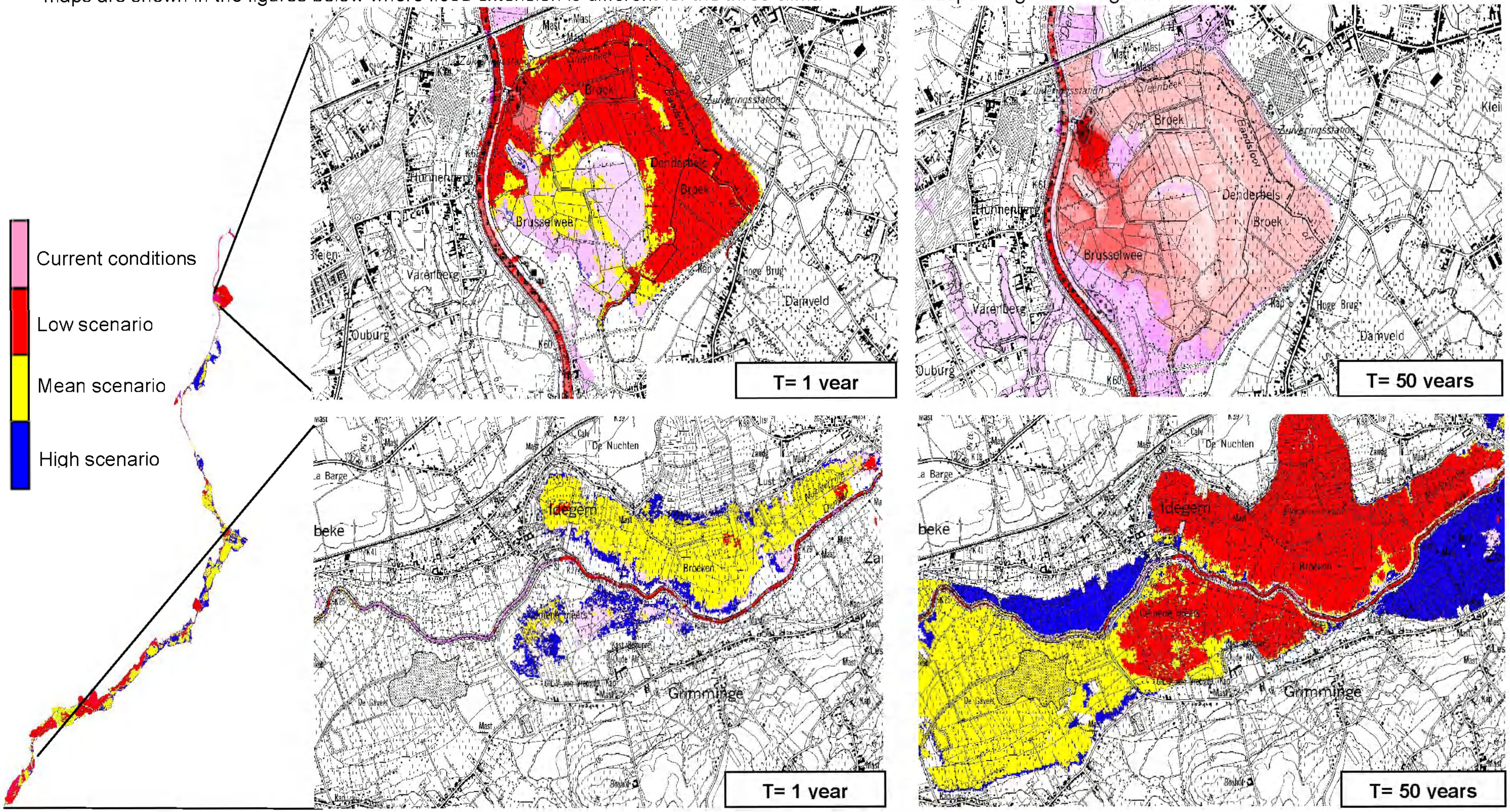


Figure14. Percentage of variation of evapo(transp)iration volume for the low, mean and high scenarios for the Dender basin, regional differences.

4.2 Dender basin flood maps

While proceeding with the previous results, flood maps have been generated for the Dender basin for different return periods (50, 100 and 500 years). The maps are shown in the figures below where flood extension is different for the three climate scenarios depending on the regions.



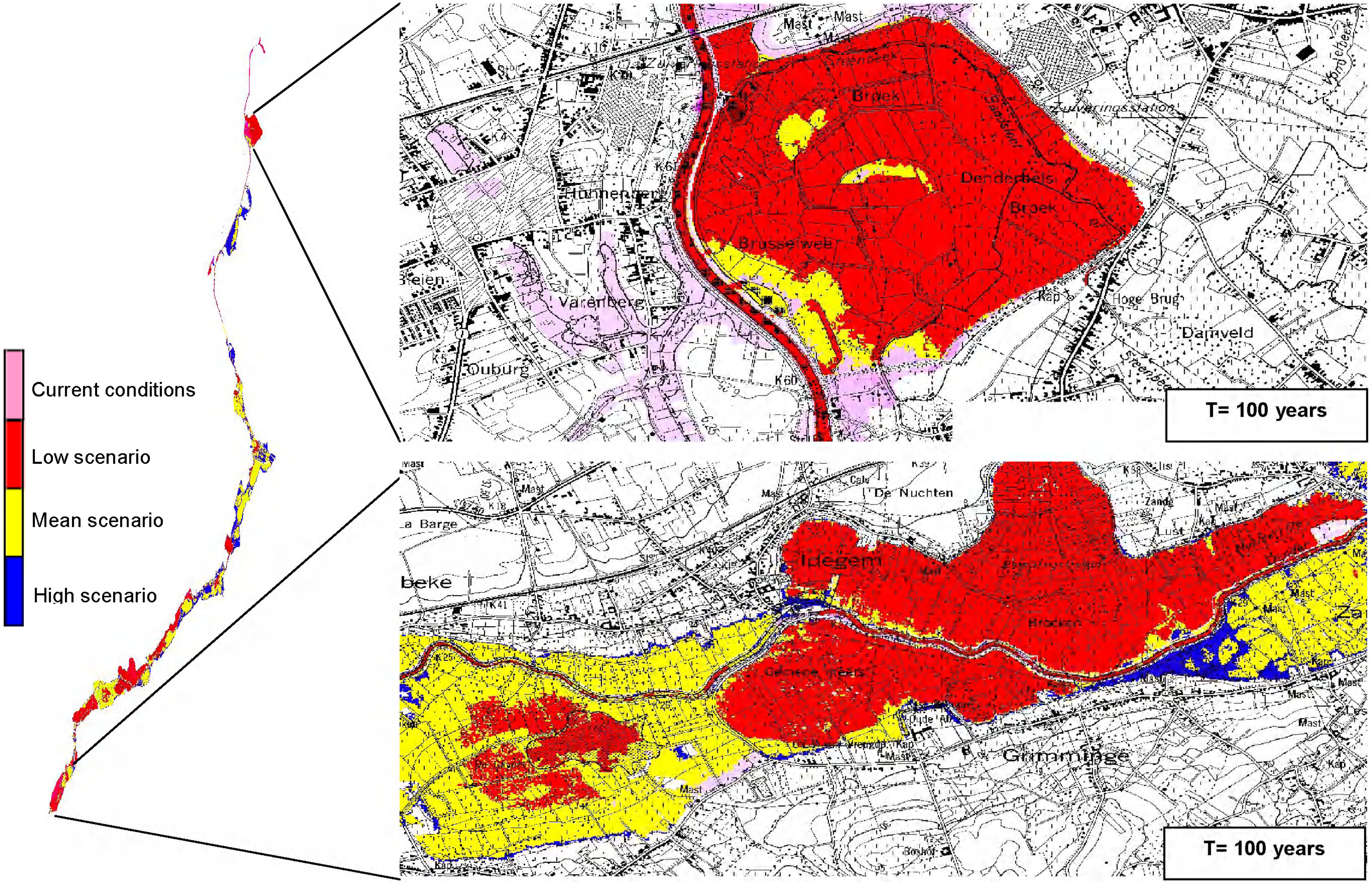


Figure15. Flood maps for sub-regions around Overboelare and Idegem in the Dender basin for the three climate scenarios and return periods of 1, 50 and 100 years.

4.3 Dender basin risk calculations

Damage maps for the different return periods have been issued for the Dender basin based on the flood maps. They serve as well to calculate the damage risk for the three climate scenarios. Table 7 presents the risk calculation values for the different reaches of the Dender based on different return periods.

Climate scenario	low	mean	high
Wallonië - Geraardsbergen	6 884	23 541	62 453
Geraardsbergen - Idegem	7 218	22 032	42 294
Idegem – Pollare	3 625	8 328	13 878
Pollare - Denderleeuw	15 547	46 756	123 020
Denderleeuw - Teralfene	7 267	18 902	64 914
Teralfene - Aalst	1 982	5 050	14 041
Aalst - Denderbelle	141 910	162 702	174 992
Denderbelle - Dendermonde	30 554	39 028	44 072

*Table 7. Risk in the Dender catchment for the 3 climate change scenarios (*25 Euro/year).*

For the different return periods, the mentioned values should be multiplied by:

- T1 : 0.92859
- T20 : 0.05765
- T100 : 0.00975
- T500 : 0.00401

5. Regional results for Flanders

Climate change impact on the hydrological extremes has been investigated for the modelled subbasins of the Flemish area (see results for other separate Flemish catchments in Appendix), where the results look to have general agreement with the ones found for the Dender basin in terms of hydrological mass balance.

In fact, while for the mean scenario, the runoff peaks look to experience slight decrease reaching a maximum of -14% comparing to the current runoff peaks condition, the decrease is very large for the low scenario to the level of -70%. For the high scenario, climate change acts positively where we expect an increase in runoff peaks to the order of ~35% depending on the sub-basin (Figure 16).

Overland flow volume results follow the same patterns as the runoff peaks (Figure 17). As for evapo(transpi)ration volumes, a maximum of additional 17% is expected for the low scenario, while this variable shows an increase for all the applied climate scenarios (consistency with general warming tendencies) (Figure 18). Low flow decreases dramatically for the entire Flemish area for all climate scenarios indicating that future low flow problems might be in more concern than flood problems (Figure 19).

The results indicate spatial heterogeneity of the hydrological answer in response to climate change forcing. Flanders, embraces then different hydrological systems that react in various ways to the same changes in climate. It seems that the different Flemish sub-basins are separated by physico-morphological boundaries forming the reasons behind the difference in hydrological behaviour. For instance, it was expected to find the highest variation of runoff peaks for the more urbanized areas of Flanders (for the major Flemish cities), which was not true in some cases throughout this analysis. This emphasizes the importance of hydrologic regionalization and the identification of the specific characteristics in each sub-basin. Understanding the spatial heterogeneity of the hydrological behaviour in Flanders due to climate change will be the subject of the next paragraph.

5.1 Sensitivity of the hydrological results to the physico-morphological characteristics in Flanders

Quantifying how local characteristics affect the hydrological response at a river basin scale due to climate change forcing is a current challenge in hydrological science. These impacts are significant in small scales, a fact that has been shown through the previous analysis. Understanding the relative role of natural and anthropogenic processes in the spatial hydrological heterogeneity generation is important for current management and future predictions. The objective of this paragraph is to analyze whether observed fluctuations in the runoff peaks over Flanders can be attributed to differences of the physico-morphological characteristics.

We identify three physico-morphological constraints, which may contribute to this heterogeneity. Using the means of correlations, we investigate the implication of the processes of soil type, land use and topographical slope into the spatial heterogeneity results of high scenario runoff peaks. For every catchment, different scheme were generated showing the possible correlations between predicted runoff peaks and the mentioned natural processes, results are presented in the upcoming paragraphs.

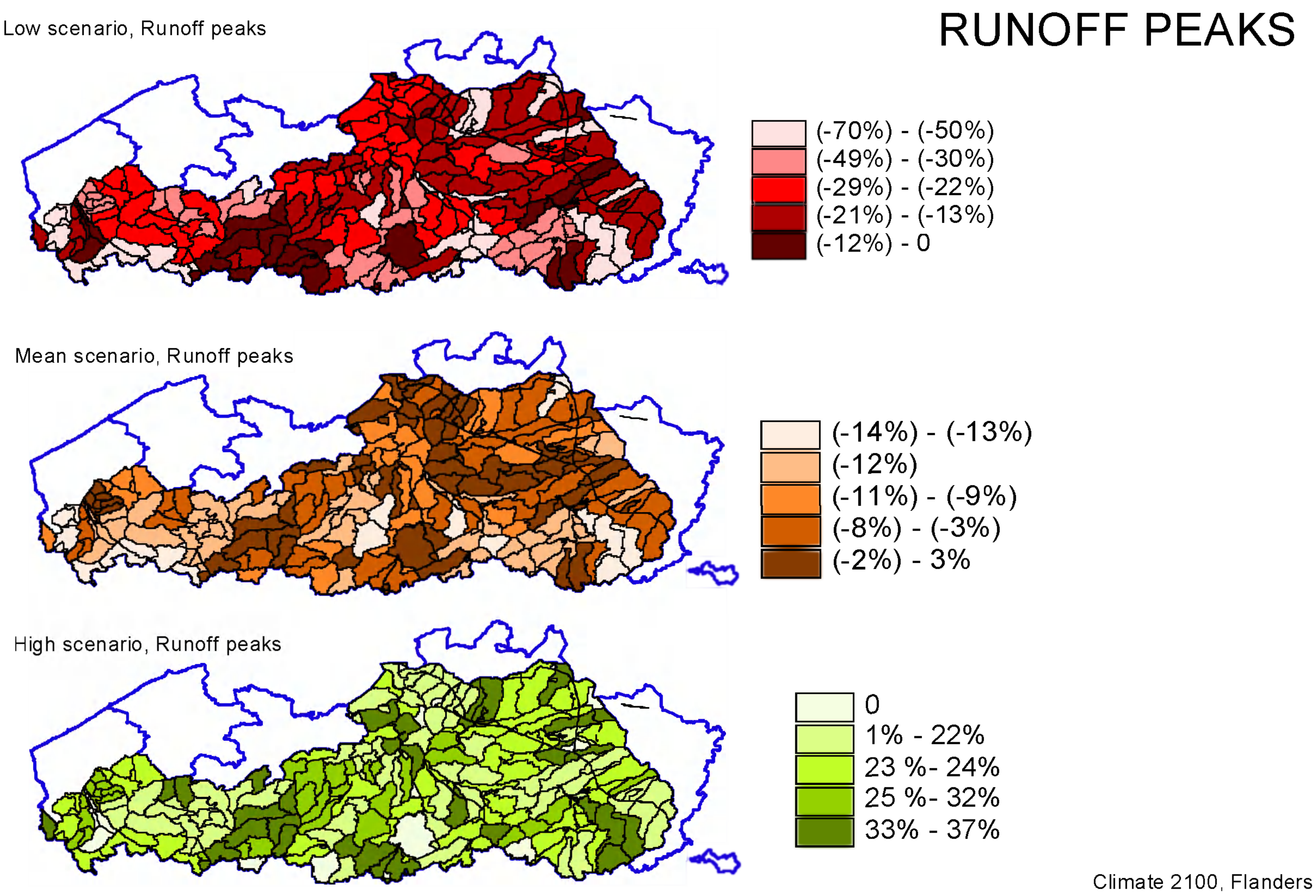


Figure 16. Percentage of variation of runoff peaks for the low, mean and high scenarios for the Flanders, regional differences.

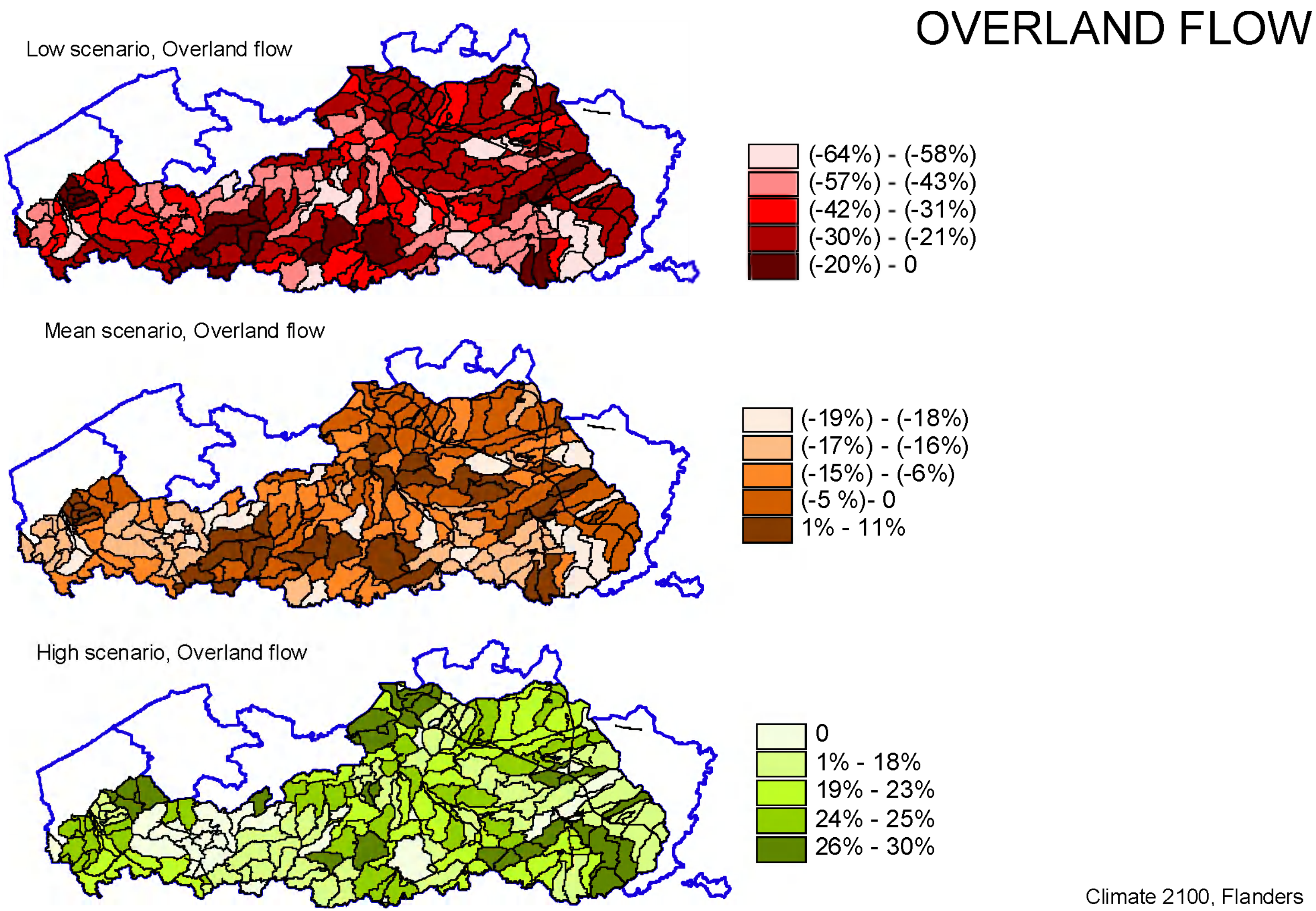


Figure 17. Percentage of variation of overland flow volume for the low, mean and high scenarios for the Flanders, regional differences.

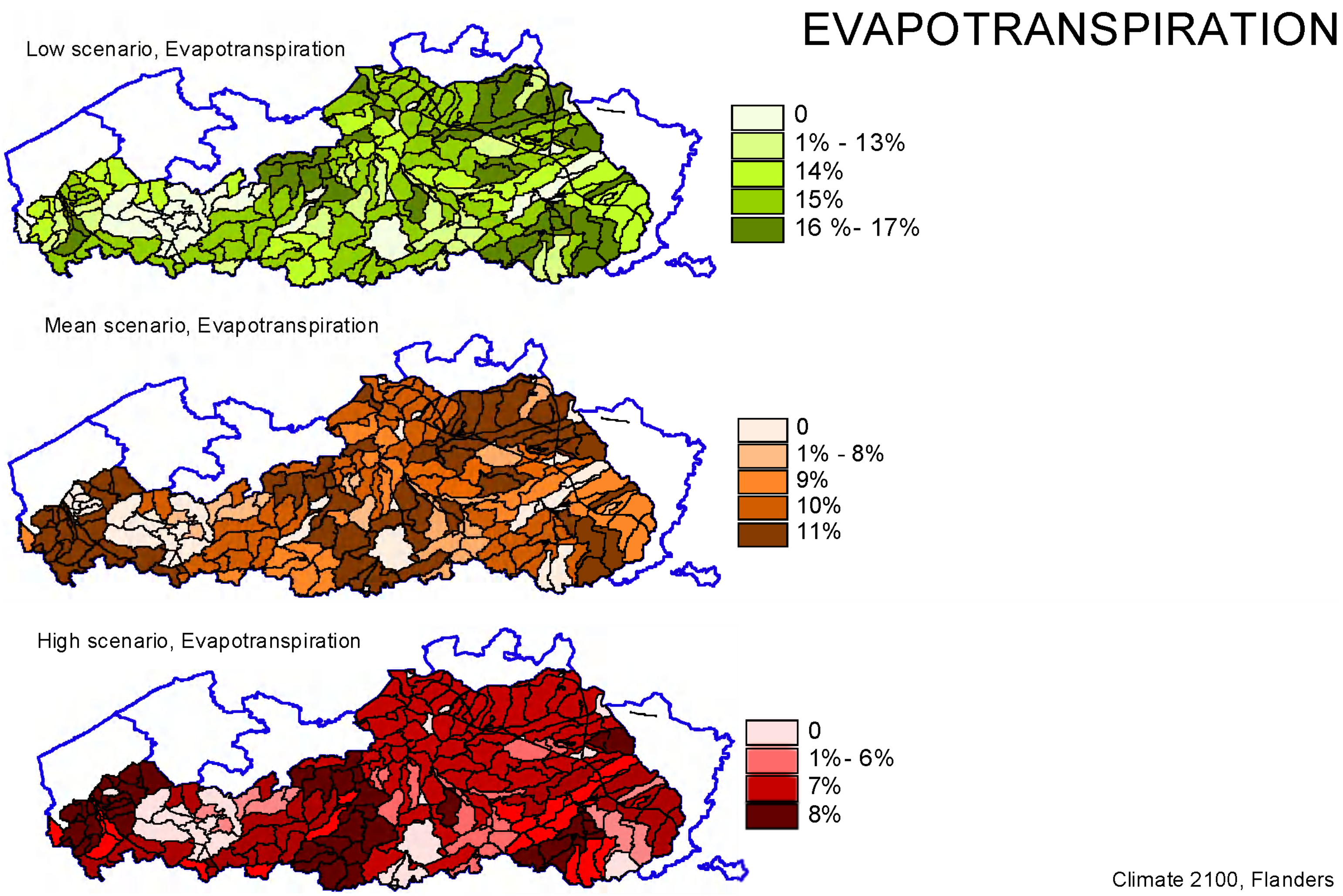


Figure 18. Percentage of variation of evapo(transpi)ration volume for the low, mean and high scenarios for the Flanders, regional differences.

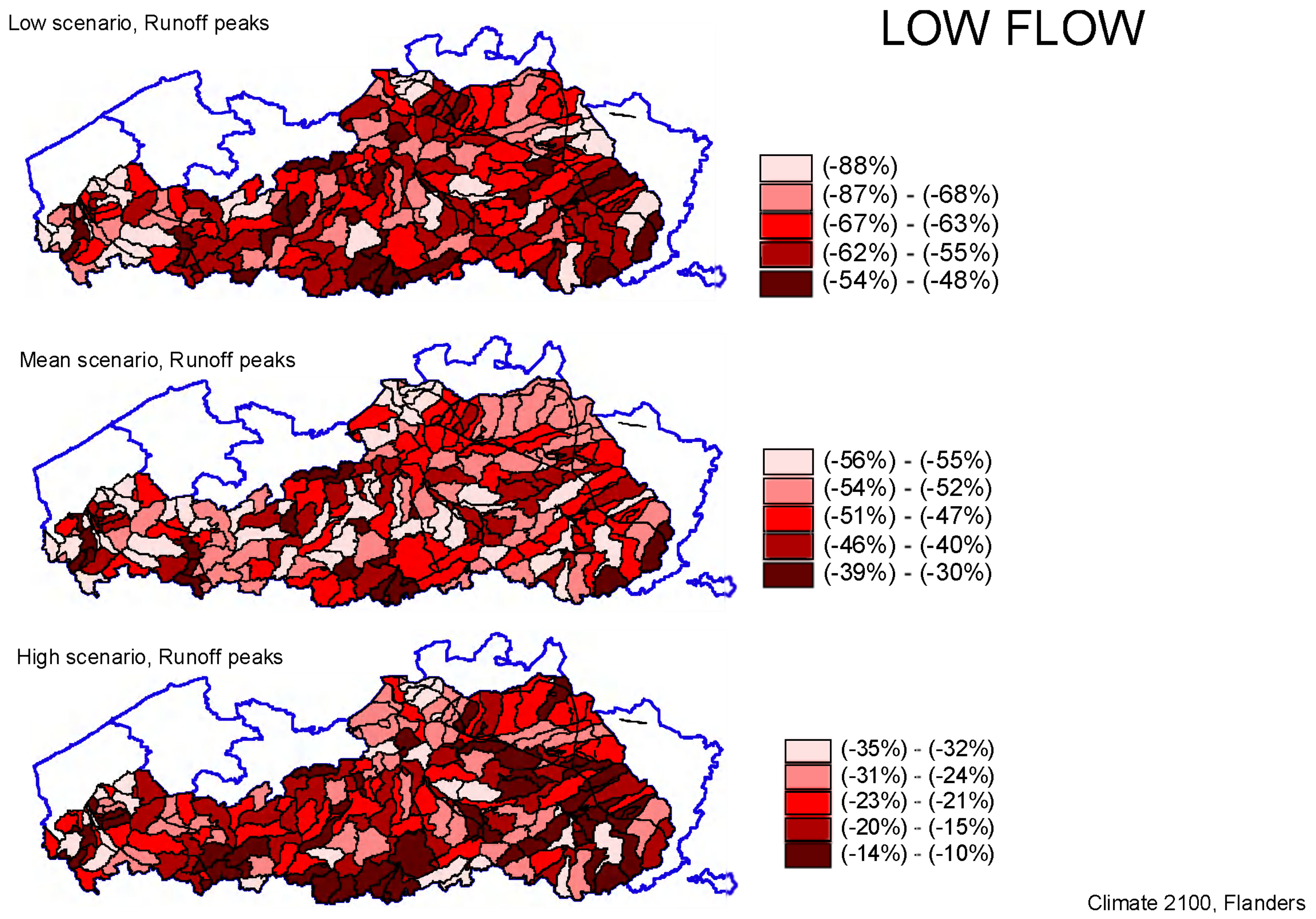


Figure 19. Percentage of variation of low flow minima for the low, mean and high scenarios for the Flanders, regional differences.

5.2 Correlation results and discussion

In a previous WL study, Willems and Rombauts (2004) derived catchment characteristics (percentage of slope, percentage of land use and percentage of soil type) for NAM model calibration needs. The work has been done primary for the Dender catchment, then extended to all of the Flanders catchments.

While being based on a DTM (Digital Terrain Model) with a grid resolution of 50m * 50m, the slope property has been derived by comparing the percentage of grid cells with slope higher than 4 degrees in comparison with the neighbor cells.

As for the land use property, the percentages of agricultural parcels, forest parcels and urban areas have been derived based on the land use map for Flanders and Brussels of 1995 with spatial resolution of 20m.

The digitized version map of the soil association map of Belgium 1970 with a scale of 1:50000 has been used to extract the soil type properties by fraction of parcels with sandy soil, loamy soil and impermeable soil types (Willems and Rombauts, 2004).

Throughout the results panel for every catchment of the Scheldt River Basin District (see panels below), in most cases, the signature of the physico-morphological characteristics does not provide efficient explanation to the spatial hydrological heterogeneity. Indeed, there, are no real strong correlations, although some tendencies can be detected.

While loamy soils would contribute to the increase of runoff peaks due to their fine texture and low permeability coefficient, sandy soils would behave totally in the opposite way. This can be seen clearly for all the basins although the uncertainties are high and no strong correlation can be concluded. The best correlation coefficient is found for the Zenne basin with a value of R^2= 0.16 between the percentage of variation of runoff peaks and the percentage of loamy soils.

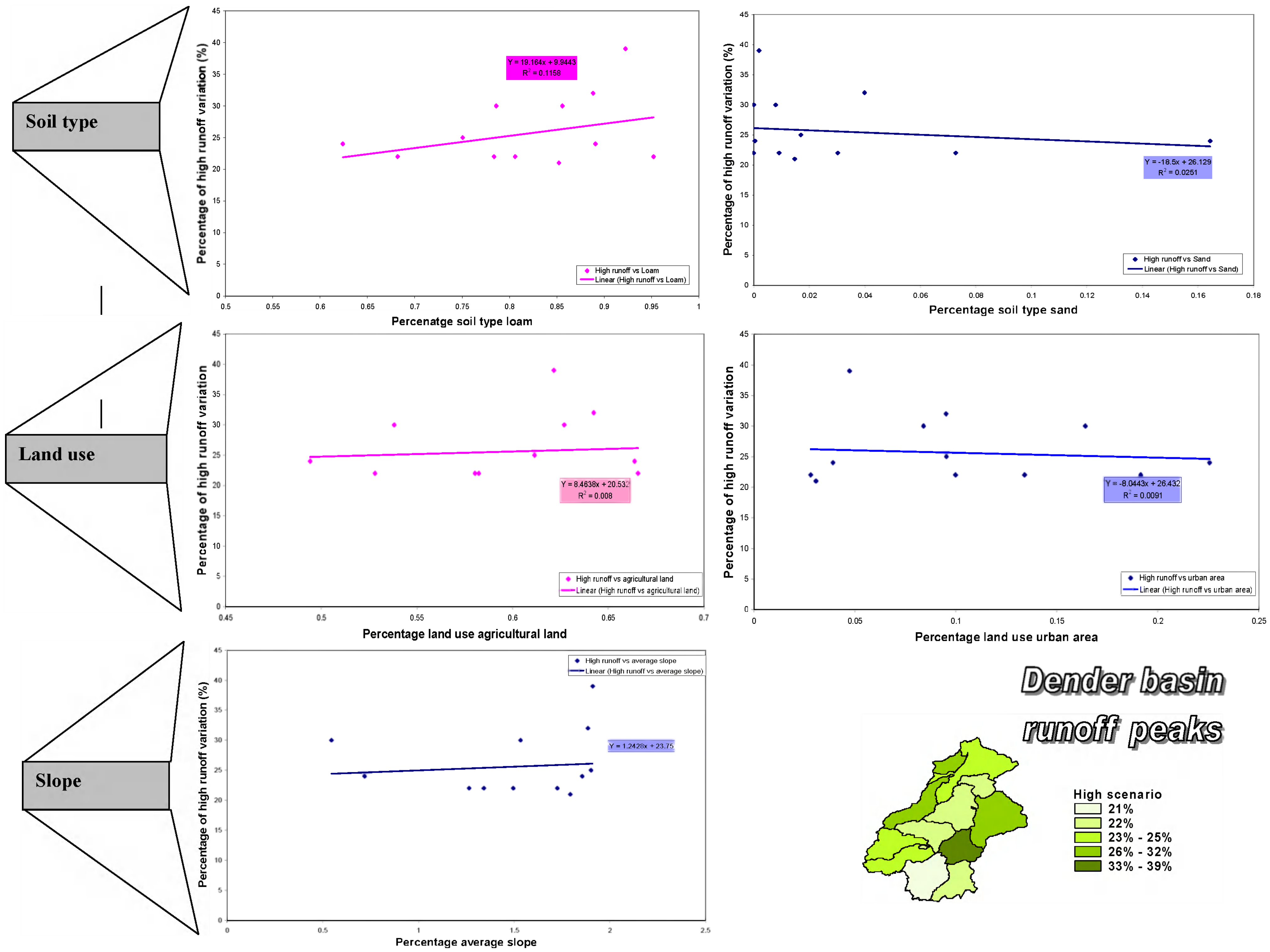
From the other side, and being totally unexpected, there is almost no correlation between the percentage of variation of runoff peaks and land use in Flanders. In all catchments, the degree of urbanization does not seem to contribute into the hydrological response although it is commonly known that hydrological responses of catchments to urbanization are increased runoff volumes and increased peak flows due to vegetation clearing and soil compaction.

As for topographical slope, for all the basins, the correlation shows a weak to moderate impact of topography on the hydrological response heterogeneity. No strong correlations are found for all the basins indicating large model uncertainty, but general tendencies are seen where with increasing topographical slope, runoff peaks increase which is very logic. This indicates that topographical slope explains part of the hydrological response heterogeneity.

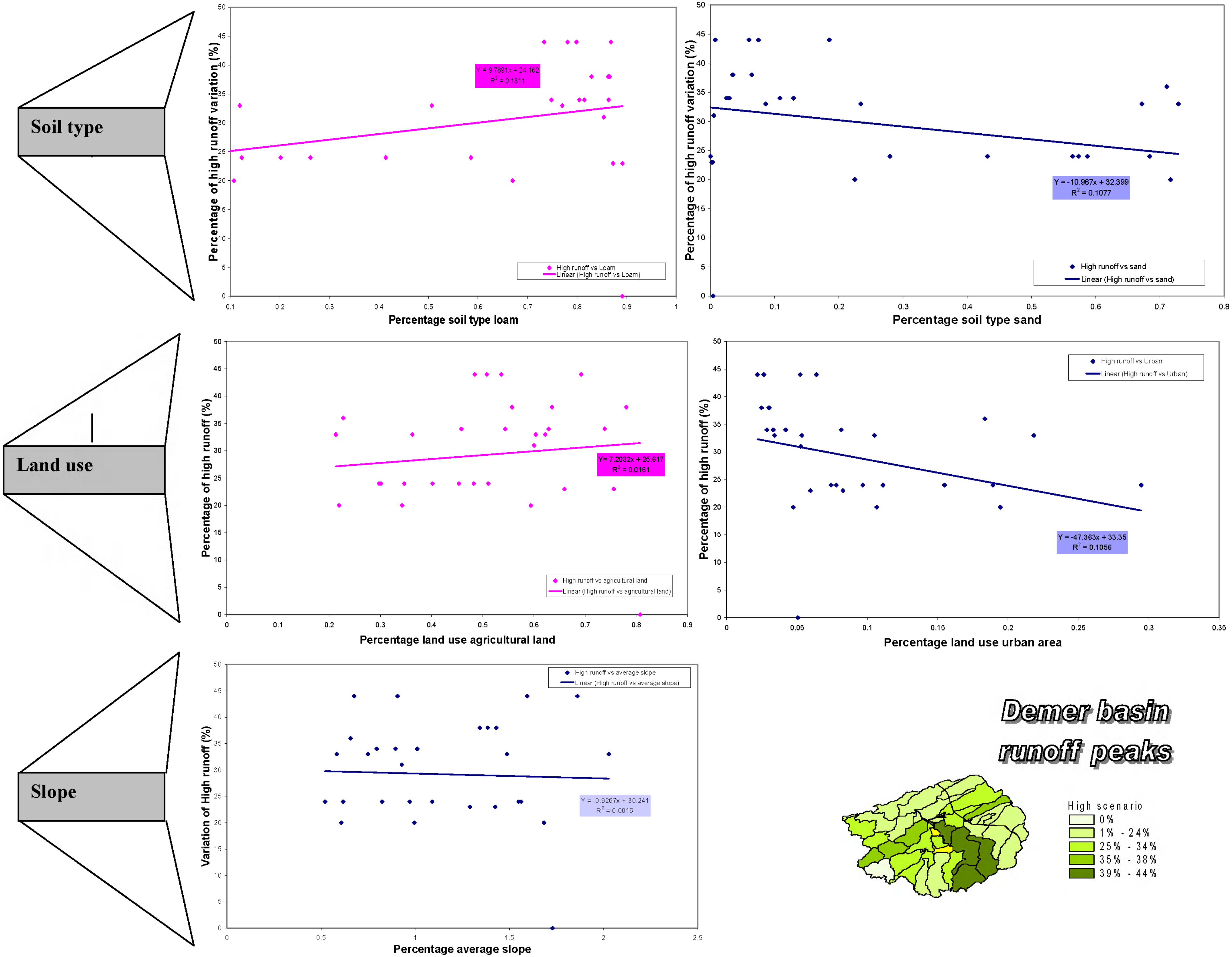
The overall results show that the difference in the hydrological response to climate change scenarios only in part can be explained by soil type and topographical slope. However, the uncertainty remains very high. Possible explanation of the additional heterogeneity in hydrological response is related to the hydrological model uncertainty. Although reaching acceptable accuracy, the hydrological models for every basin are still providing considerable uncertainty. The calibration of hydrological models furthermore is subject to inconsistencies and subjectivities due to calibrations done by different people.

It moreover should be mentioned that the generated climate scenarios were based on the PRUDENCE project data extraction to the closest grid point to the Uccle station, making the assumption that this station is the most representative of the Belgian area. This assumption might bring additional uncertainty as, for instance, precipitation shows considerable spatial distribution variation between the coast and the eastern part of Flanders. Thus, upon processing other PRUDENCE grid points covering Flanders, new climate scenarios can be generated for each specific region. This work is currently under progress in the CCI-HYDR project.

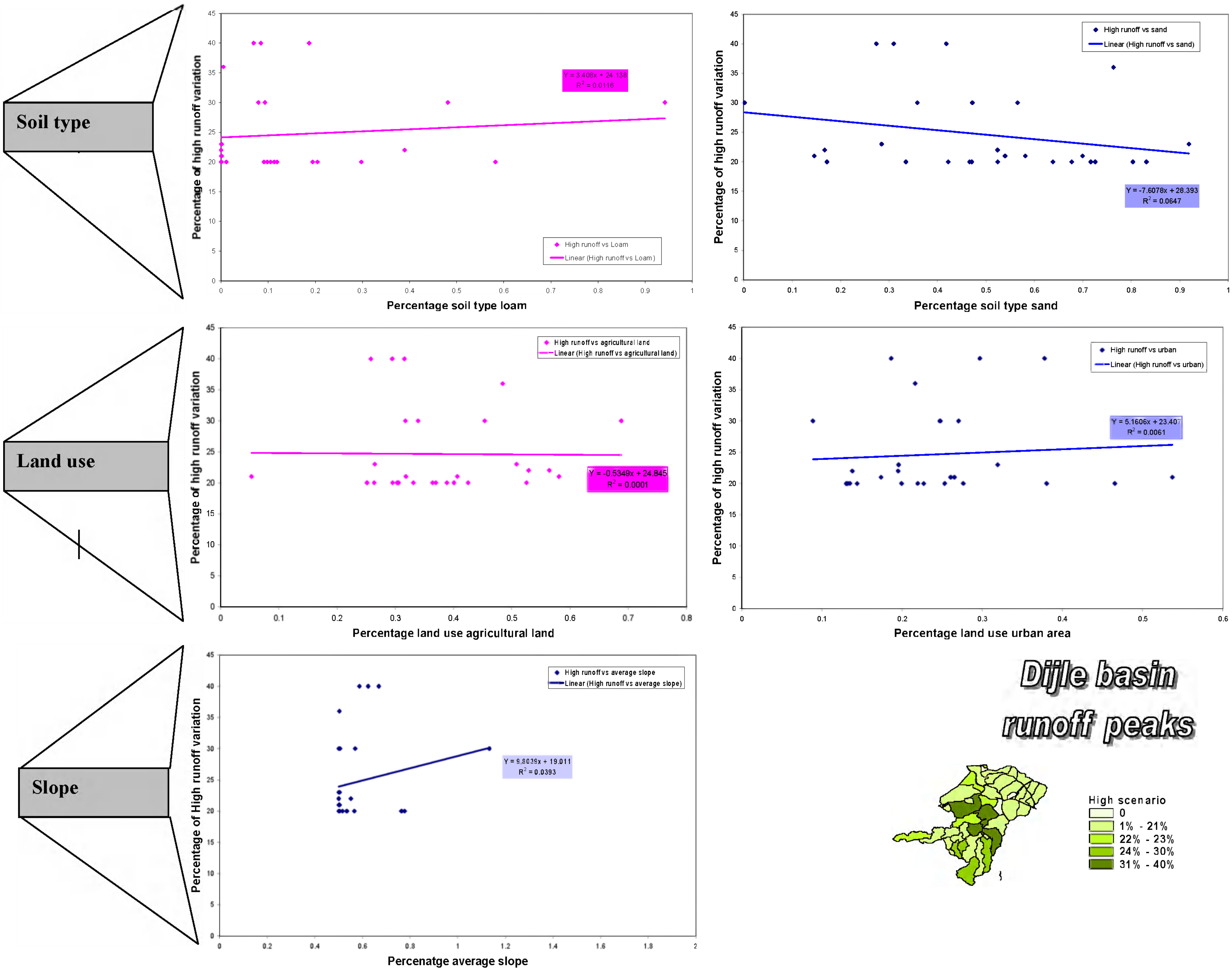
The un-expected result of absence of contribution of the land use into the hydrological responses differences should be taken with high caution as land use is continuously changing and is predicted to show high fluctuations in the shadow of the long term climate change.



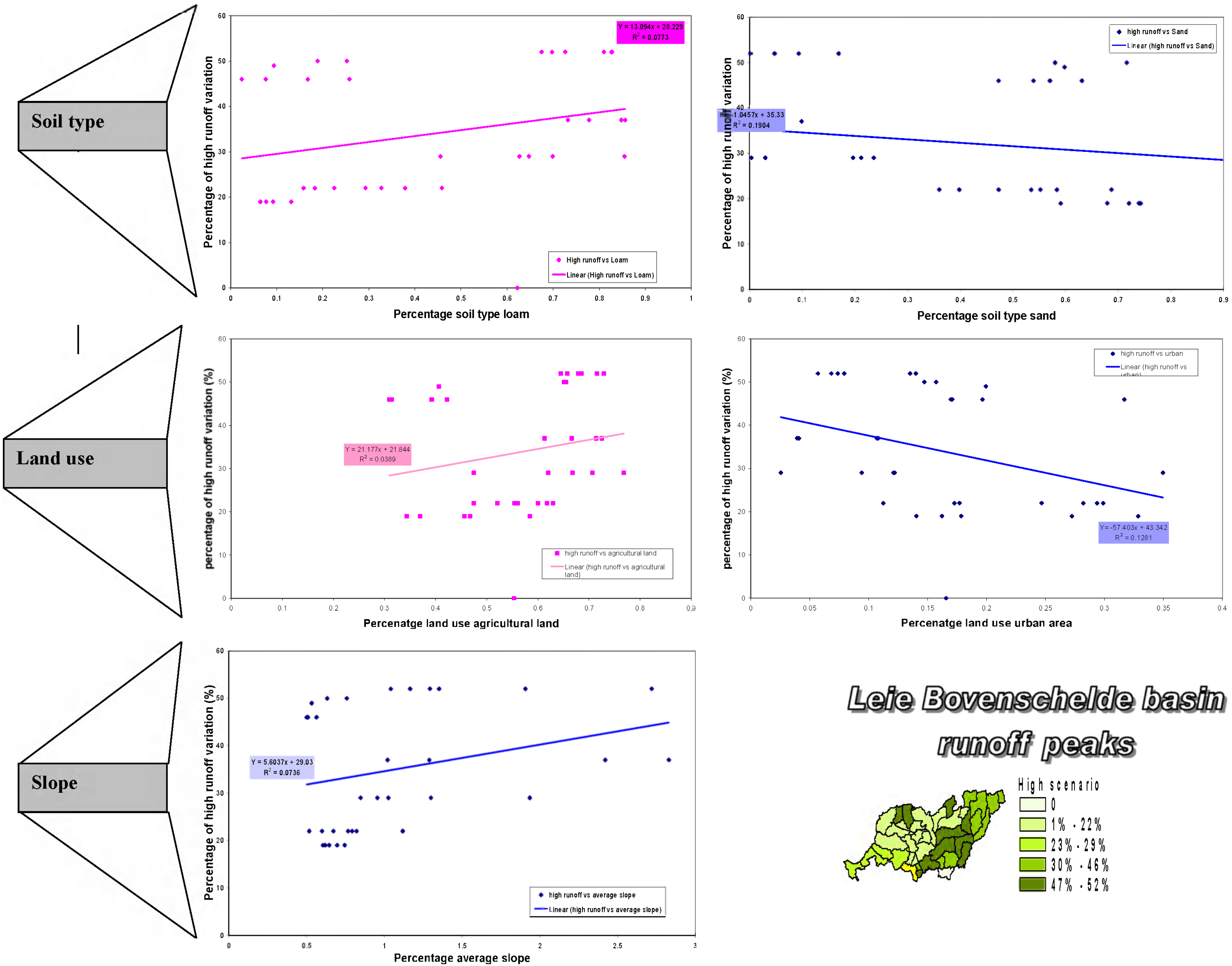
Soil type
Land use
Slope
Percentage of high runoff variation (%)
Y = 19.164x + 9.9443
R² = 0.1158
High runoff vs Loam
Linear (High runoff vs Loam)
Percenatge soil type loam
Y = -18.5x + 26.129
R² = 0.0251
High runoff vs Sand
Linear (High runoff vs Sand)
Percentage soil type sand
Percentage of high runoff variation
Y = 8.4638x + 20.532
R² = 0.008
High runoff vs agricultural land
Linear (High runoff vs agricultural land)
Percentage land use agricultural land
Y = -8.0443x + 26.432
R² = 0.0091
High runoff vs urban area
Linear (High runoff vs urban area)
Percentage land use urban area
High runoff vs average slope
Linear (High runoff vs average slope)
Y = 1.2428x + 23.75
Percentage average slope
Dender basin
runoff peaks
High scenario
21%
22%
23% - 25%
26% - 32%
33% - 39%



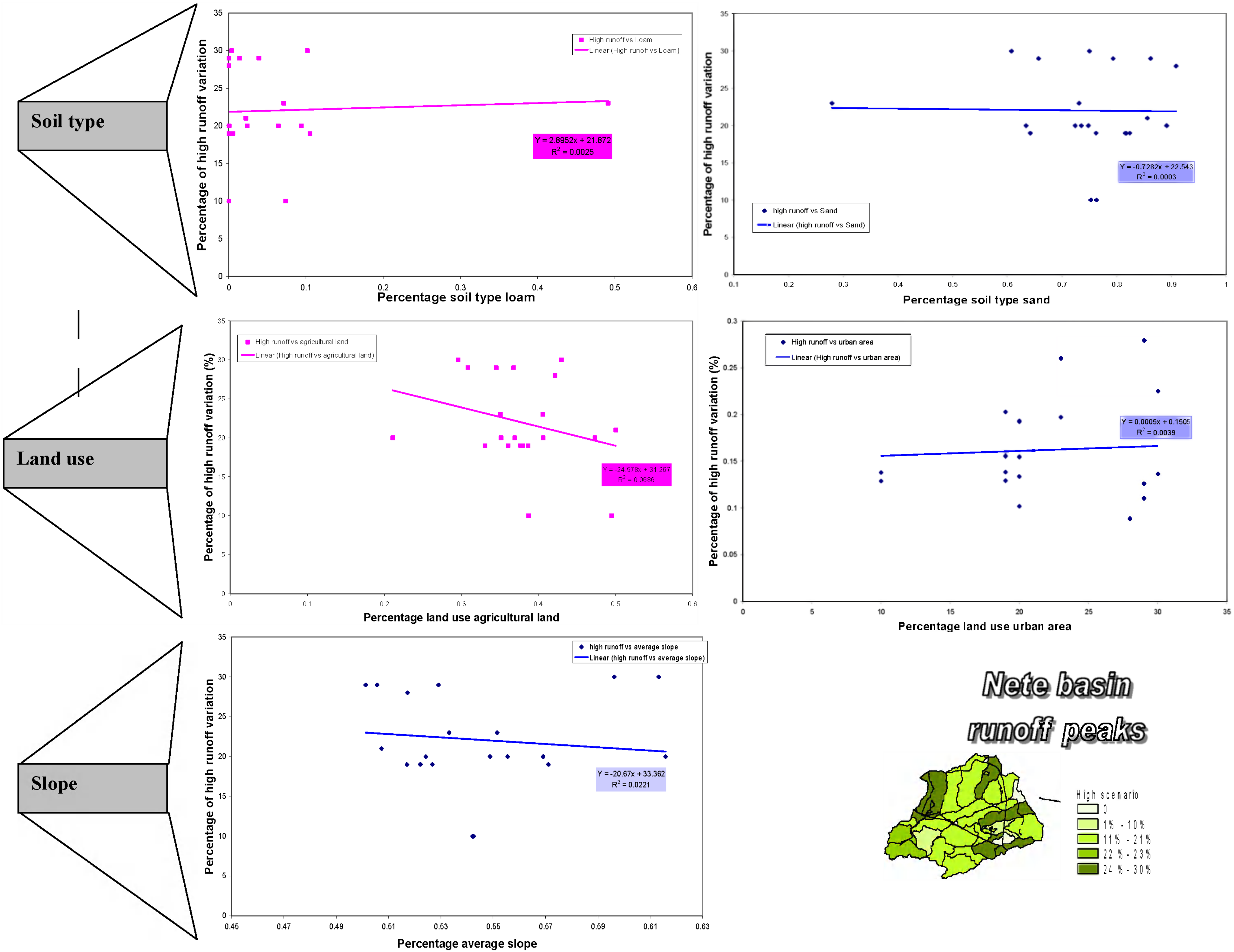
Soil type
Land use
Slope
Percentage of high runoff variation (%)
Percentage soil type loam
High runoff vs Loam
Linear (High runoff vs Loam)
Y = 9.7891x + 24.162
R² = 0.1311
Percentage soil type sand
High runoff vs sand
Linear (High runoff vs sand)
Y = -10.967x + 32.399
R² = 0.1077
Percentage of high runoff (%)
Percentage land use agricultural land
High runoff vs agricultural land
Linear (High runoff vs agricultural land)
Y= 7.2032x + 25.617
R² = 0.0161
Percentage land use urban area
High runoff vs Urban
Linear (High runoff vs Urban)
Y = -47.363x + 33.35
R² = 0.1056
Variation of High runoff (%)
Percentage average slope
High runoff vs average slope
Linear (High runoff vs average slope)
Y = -0.9267x + 30.241
R² = 0.0016
Demer basin
runoff peaks
High scenario
0%
1% - 24%
25% - 34%
35% - 38%
39% - 44%



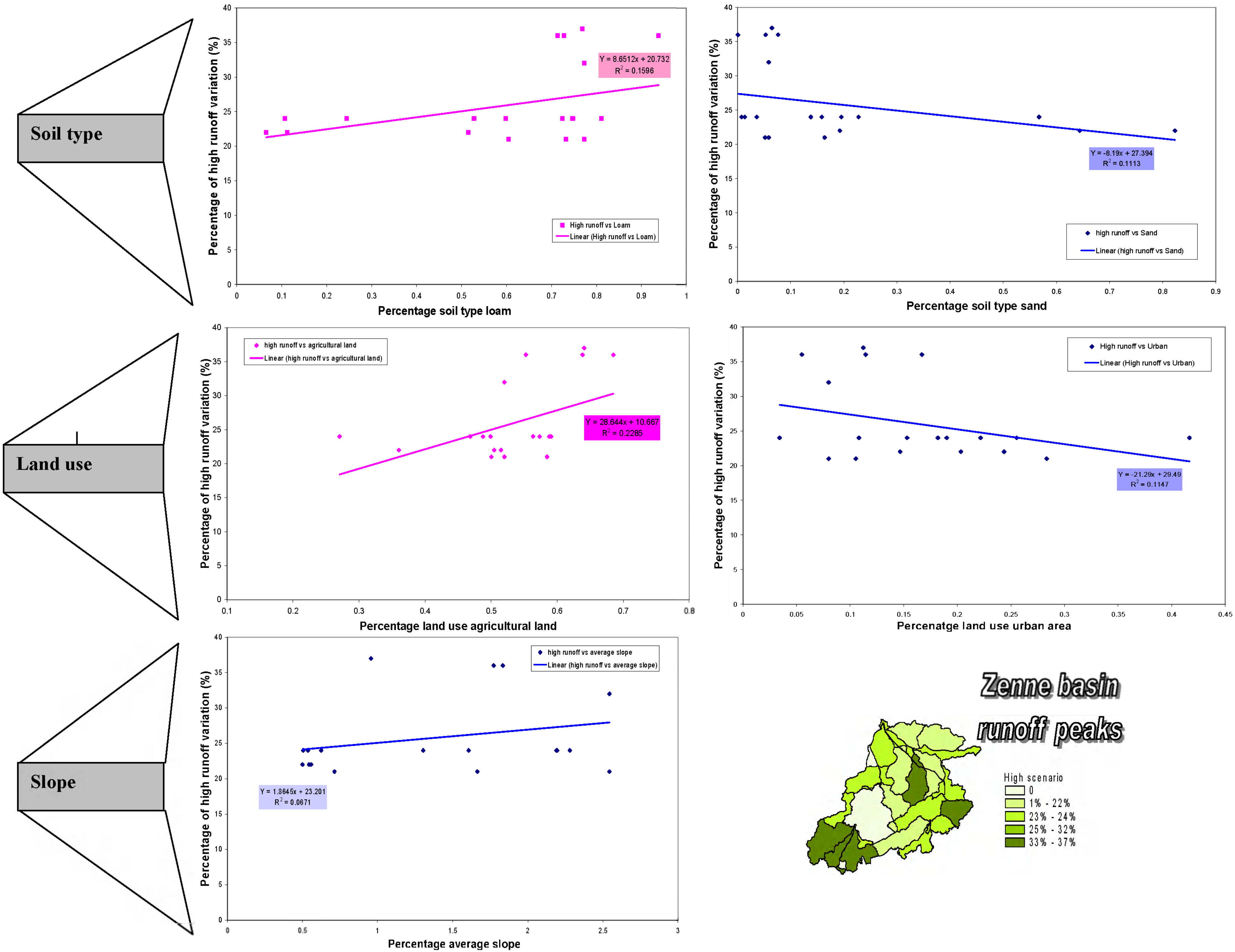
Soil type
Land use
Slope
Percentage of high runoff variation
Percentage soil type loam
High runoff vs Loam
Linear (High runoff vs Loam)
Y = 3.408x + 24.138
R² = 0.0116
Percentage soil type sand
High runoff vs sand
Linear (High runoff vs sand)
Y = -7.6078x + 28.393
R² = 0.0647
Percentage land use agricultural land
High runoff vs agricultural land
Linear (High runoff vs agricultural land)
Y = -0.5349x + 24.845
R² = 0.0001
Percentage land use urban area
High runoff vs urban
Linear (High runoff vs urban)
Y = 5.1606x + 23.407
R² = 0.0061
Percentage of High runoff variation
Percenatge average slope
High runoff vs average slope
Linear (High runoff vs average slope)
Y = 9.8039x + 19.011
R² = 0.0393
Dijle basin
runoff peaks
High scenario
0
1% - 21%
22% - 23%
24% - 30%
31% - 40%



Soil type
Land use
Slope
Percentage of high runoff variation
Percentage soil type loam
Y = 13.094x + 28.229
R² = 0.0773
High runoff vs Loam
Linear (High runoff vs Loam)
Percentage soil type sand
-1.0457x + 35.33
R² = 0.1904
high runoff vs Sand
Linear (high runoff vs Sand)
percentage of high runoff variation (%)
Percenatge land use agricultural land
Y = 21.177x + 21.844
R² = 0.0389
high runoff vs agricultural land
Linear (high runoff vs agricultural land)
Percenatge land use urban area
Y = -57.403x + 43.342
R² = 0.1281
high runoff vs urban
Linear (high runoff vs urban)
Percentage of high runoff variation (%)
Percentage average slope
Y = 5.6037x + 29.03
R² = 0.0736
high runoff vs average slope
Linear (high runoff vs average slope)
Leie Bovenschelde basin runoff peaks
High scenario
0
1% - 22%
23% - 29%
30% - 46%
47% - 52%



Soil type
Land use
Slope
High runoff vs Loam
Linear (High runoff vs Loam)
Y = 2.8952x + 21.872
R2 = 0.0025
Percentage of high runoff variation
Percentage soil type loam
high runoff vs Sand
Linear (high runoff vs Sand)
Y = -0.7282x + 22.543
R2 = 0.0003
Percentage soil type sand
High runoff vs agricultural land
Linear (High runoff vs agricultural land)
Y = -24.578x + 31.287
R2 = 0.0686
Percentage of high runoff variation (%)
Percentage land use agricultural land
High runoff vs urban area
Linear (High runoff vs urban area)
Y = 0.0005x + 0.1505
R2 = 0.0039
Percentage land use urban area
high runoff vs average slope
Linear (high runoff vs average slope)
Y = -20.67x + 33.362
R2 = 0.0221
Percentage average slope
Nete basin
runoff peaks
High scenario
0
1% - 10%
11% - 21%
22 % - 23%
24 % - 30%



Soil type
Land use
Slope
Percentage of high runoff variation (%)
Percentage soil type loam
High runoff vs Loam
Linear (High runoff vs Loam)
Y = 8.6512x + 20.732
R2 = 0.1596
Percentage soil type sand
high runoff vs Sand
Linear (high runoff vs Sand)
Y = -8.19x + 27.394
R2 = 0.1113
Percentage land use agricultural land
high runoff vs agricultural land
Linear (high runoff vs agricultural land)
Y = 28.644x + 10.667
R2 = 0.2285
Percenatge land use urban area
High runoff vs Urban
Linear (High runoff vs Urban)
Y = -21.29x + 29.49
R2 = 0.1147
Percentage average slope
high runoff vs average slope
Linear (high runoff vs average slope)
Y = 1.8645x + 23.201
R2 = 0.0671
Zenne basin
runoff peaks
High scenario
0
1% - 22%
23% - 24%
25% - 32%
33% - 37%

5.3 Conclusion: Regional climate change impact on hydrological extremes in Flanders

While Flanders is concerned about climate change and the possible impacts of the predicted wetter winters and drier summers, the hydrological response appears similar throughout the entire area. The findings show that the intensity of the impacts is only slightly dependent on the location.

Facing three generated climate scenarios representing from one side extreme future conditions for precipitation and potential evapo(transpi)ration with the high and low scenarios, and from the other side an average scenario, the Scheldt River Basin District reacts very sensitively. The runoff volumes and overland flow volumes systematically increase and decrease depending on the scenario. Runoff peak changes (flood risk) show high uncertainty and can reach increases up to +35%. Actual evapo(transpi)ration remains increasing for all the scenarios as a result of temperature increase.

The local physico-morphological characteristics seem to weakly influence the differences in hydrological responses due to climate change scenarios forcing leaving their place to natural variability and to uncertainty brought through hydrological models.

Regardless the high uncertainty within climate and hydrological simulations the direct economic impact of climate change due to possible “water-related” damage might be significant and should be taken into account in future water management activities.

6. General conclusions

This study addresses climate change impact assessment on the hydrological extremes in Flanders. It aims to ensure that the needs of the Flemish climate impacts community for scenarios of hydrological extremes as floods and low flows along rivers are taken into account and that outputs from the most recent climate model simulations are available for use.

Changes in the frequency and intensity of extreme events are surely having more impacts on environment and human activities than changes in the mean climate. Losses of life and very high economic damages have been experienced during recent flooding events in the last decade in Belgium. A vital question for Belgium is, therefore, whether such events will occur more strong and more frequently in the future.

The CCI-HYDR project titled “Climate change impact on hydrological extremes along rivers and sewer systems in Belgium” set a methodology for assessing climate induced impacts based on the European project PRUDENCE that provided large database with 24 regional climate model simulations highly resolute produced with different time scales, including estimates of precipitation and potential evapo(transpi)ration till 2100 and covering the studied area.

The hydrological and hydraulic simulations show that water balance variations are very sensitive depending on the balance between the summer perturbation effect (less rainfall) versus the winter perturbation effect (more rainfall), and on the balance between the rainfall perturbation effect versus the evapo(transpi)ration perturbation effect.

The high flow peaks and flood risk have potential tendency to increase up to 35%, or decrease to -70% depending on the scenario while low flows show systematically reduction, indicating that low flow problems become more severe in the future and are probably more important than the increase in flood risk.

The other important results consist in the regional differences, where it was clearly shown that climate change does not impact lonely, but in combination with the local conditions (up to some extents), while models uncertainty still count considerably.

It is to be mentioned that new developments and results are taking place within the CCI-HYDR project (i.e., low flows analysis) and therefore the results of this study should be re-assessed on the light of the new developments.

This study made clear that encouraging more research on this topic in order to increase awareness and to help improve further investigations and predictions is very important. However, due to uncertainty, taking potential climate change into account for future hydrological studies is important rather than focusing on the guarantee that climate change will cause more floods.

7. References

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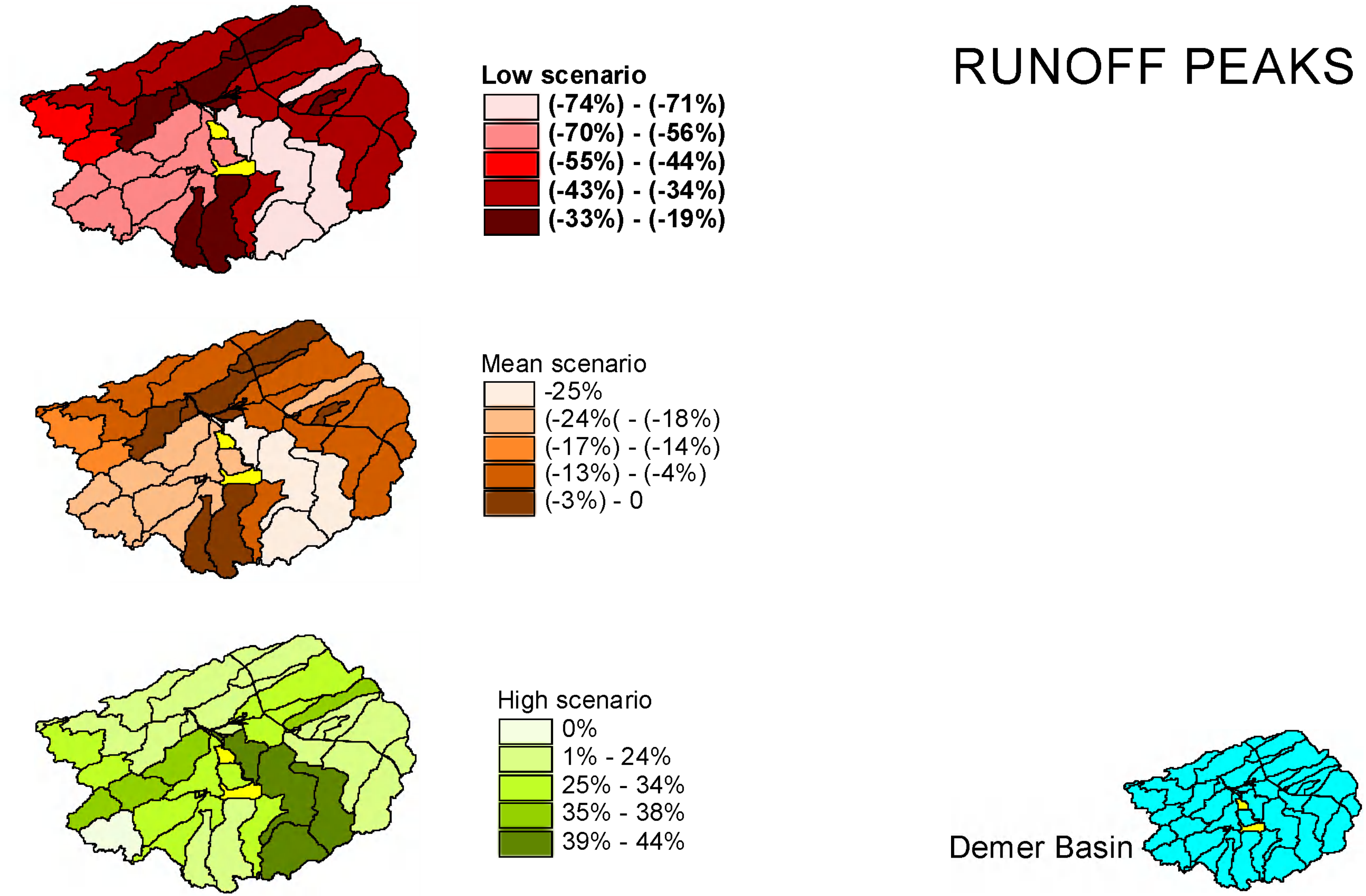
Appendix: Climate change impact on the hydrological extremes for the different Flemish catchments

The Demer basin

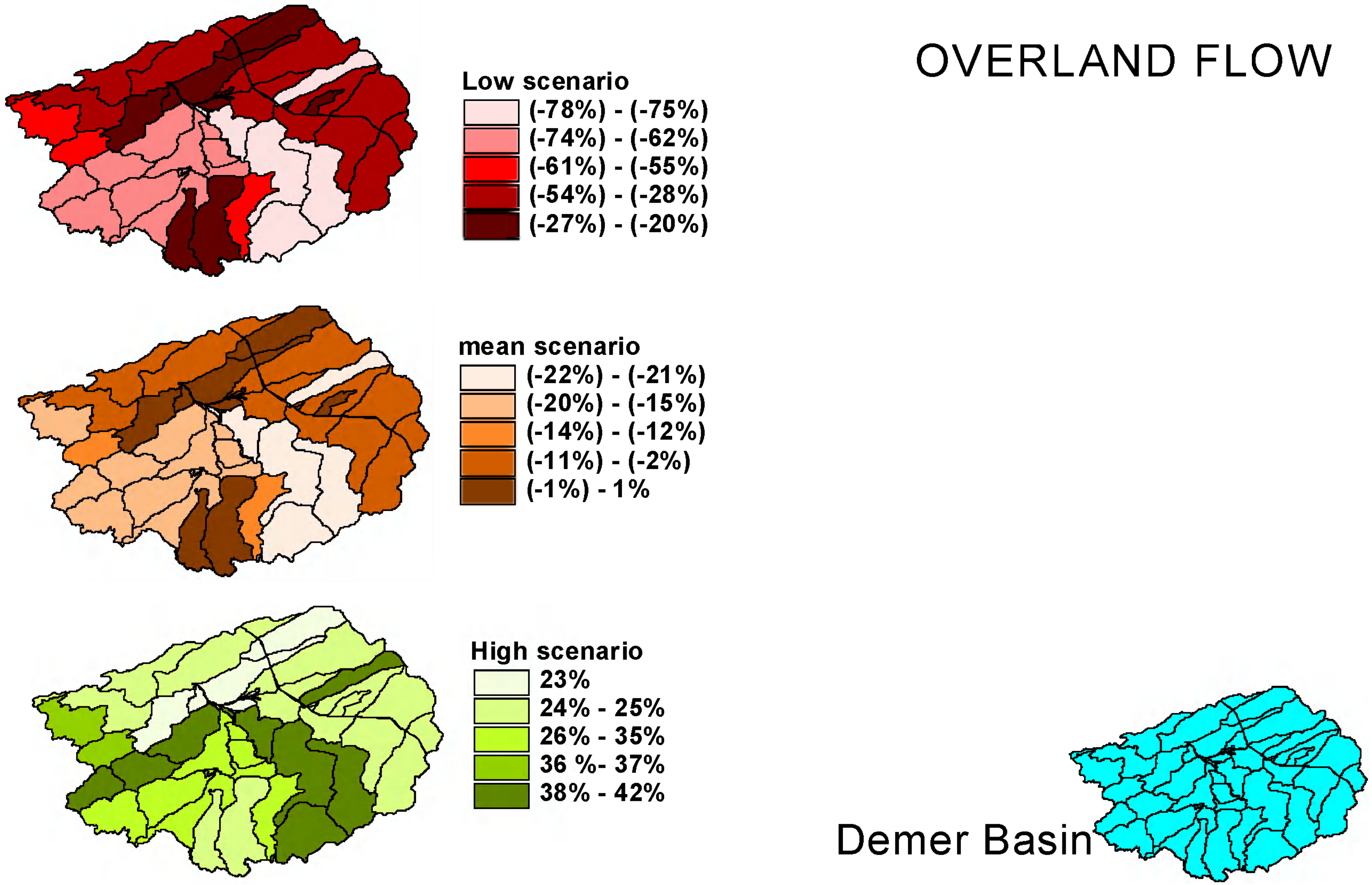
As for the Dender, the same procedure has been applied for the Demer basin to extract the composite hydrographs factors. The results are shown in the table below.

Sub-basins	Low scenario	Mean scenario	High scenario
093_Dijle	-74.01	-19.23	36.02
136_Demer	-34.10	-5.04	22.01
141_Winge	-44.50	-14.61	33.02
143_Losting	-32.42	-5.20	29.60
144_Motte	-21.82	-0.83	23.50
145_Velpe	-53.60	-17.88	37.22
147_Hulpe	-21.54	-6.63	17.19
148_Zwartebeek	-18.89	1.70	20.37
152_Gete	-63.90	-21.11	33.24
161_Mangelbeek	-38.32	-5.26	32.60
163_Herk	-70.58	-25.06	41.21

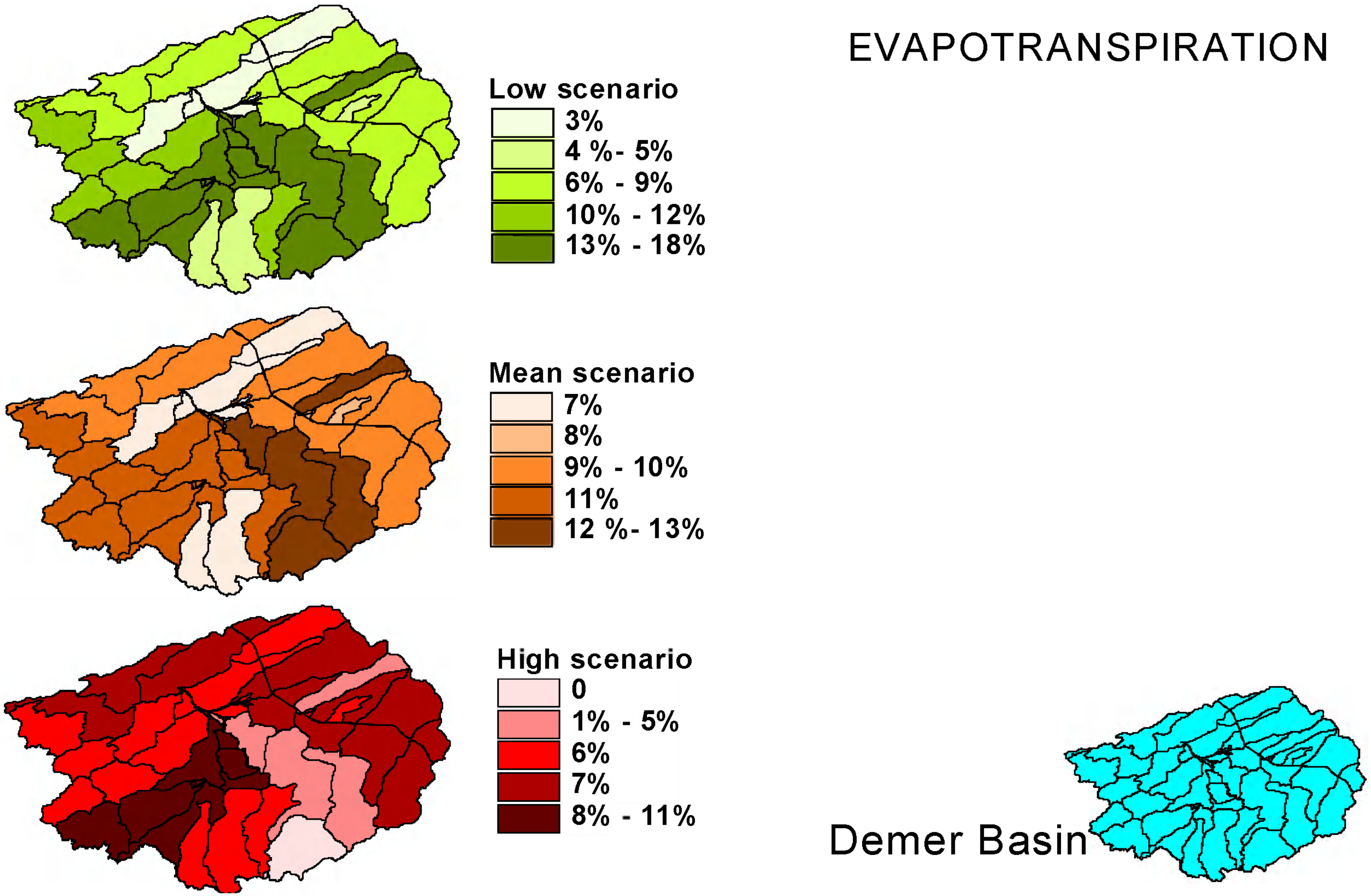
Percentages of variations of the composite hydrographs for the Demer basin for the different climate scenarios.



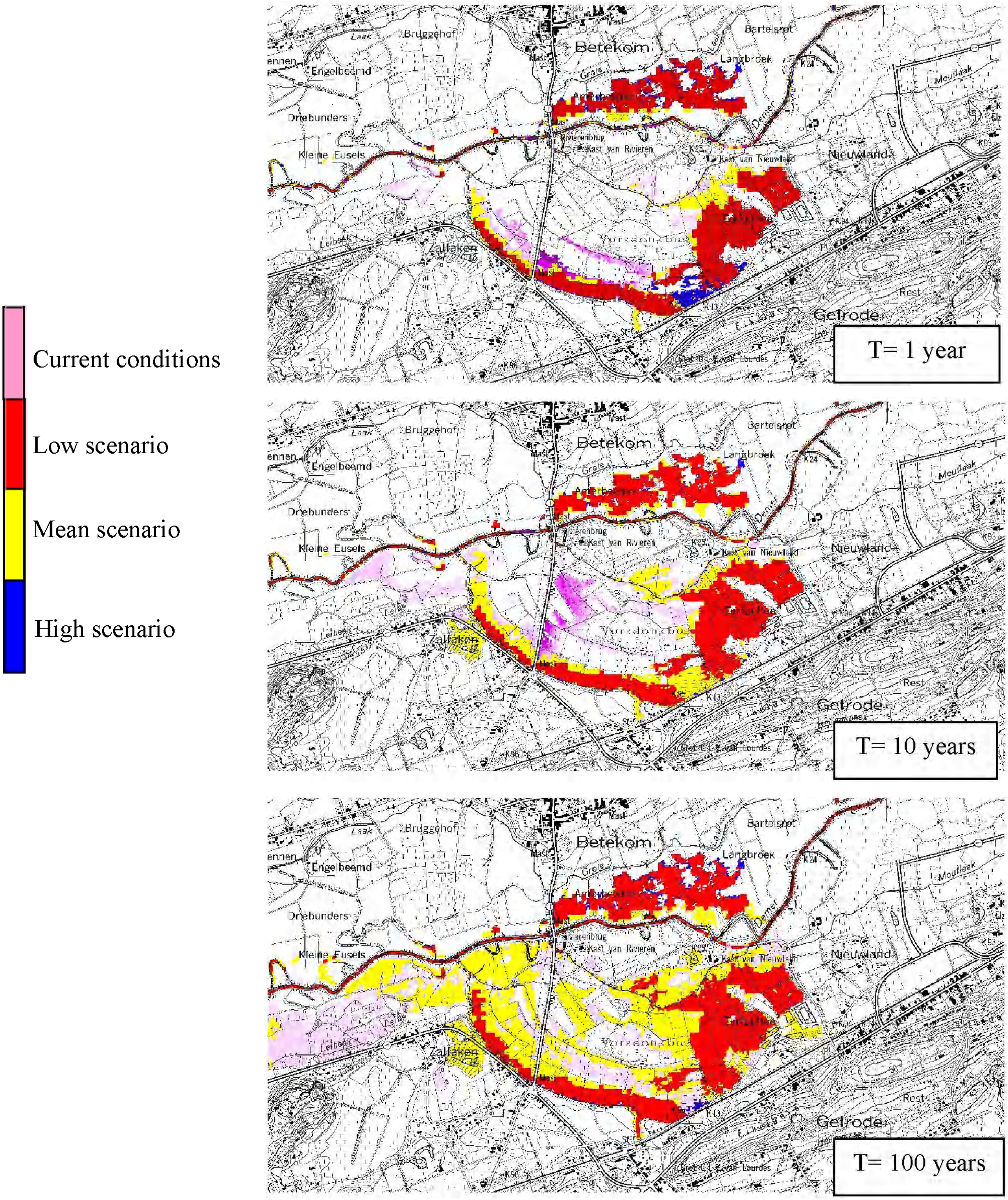
Percentage of variation of runoff peaks for the low, mean and high scenarios for the Demer basin, regional differences.



Percentage of variation of overland flow for the low, mean and high scenarios for the Demer basin, regional differences.



Percentage of variation of evapo(transpi)ration for the low, mean and high scenarios for the Demer basin, regional differences.

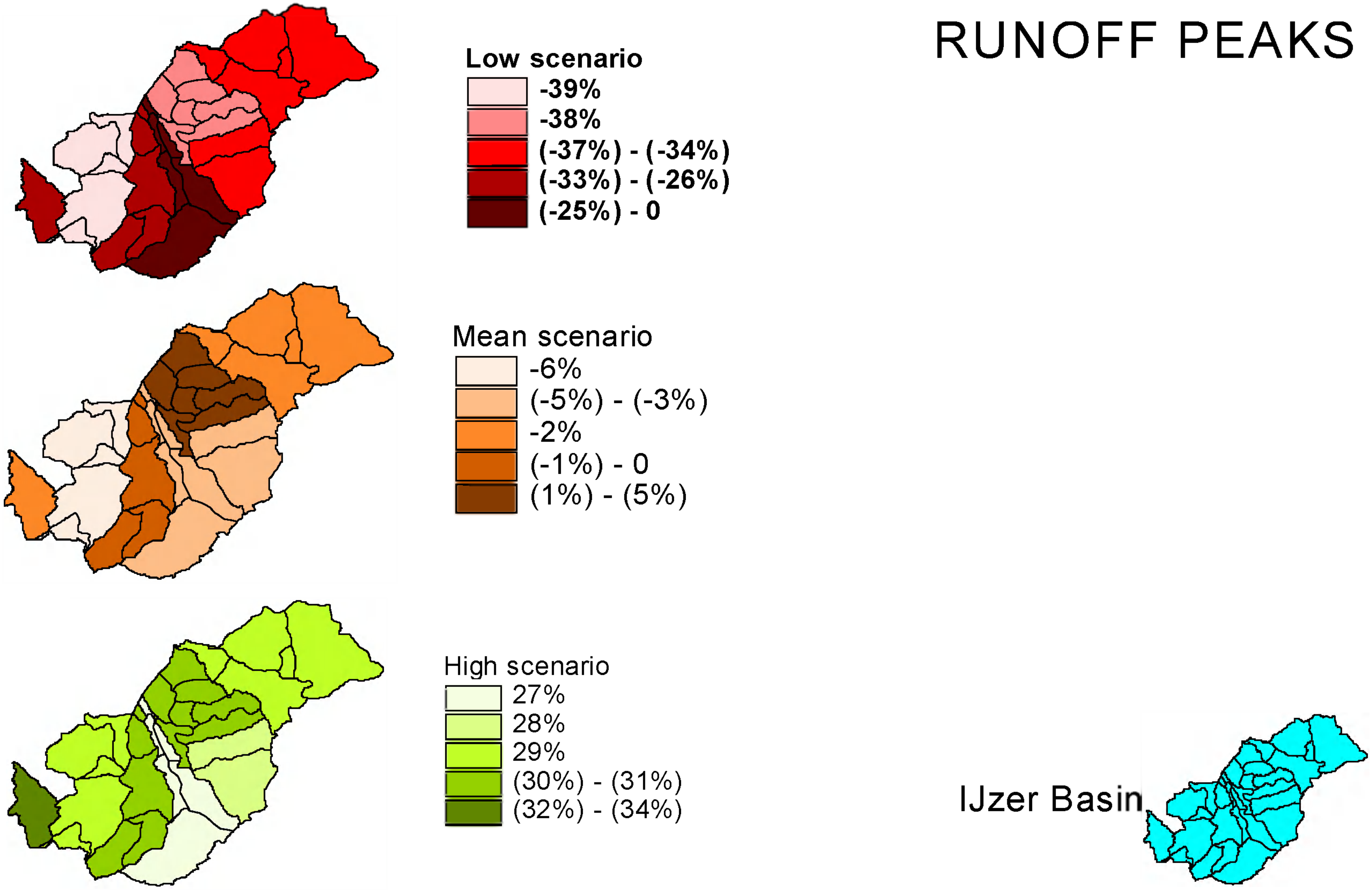


Example of flood maps for the Demer basin.

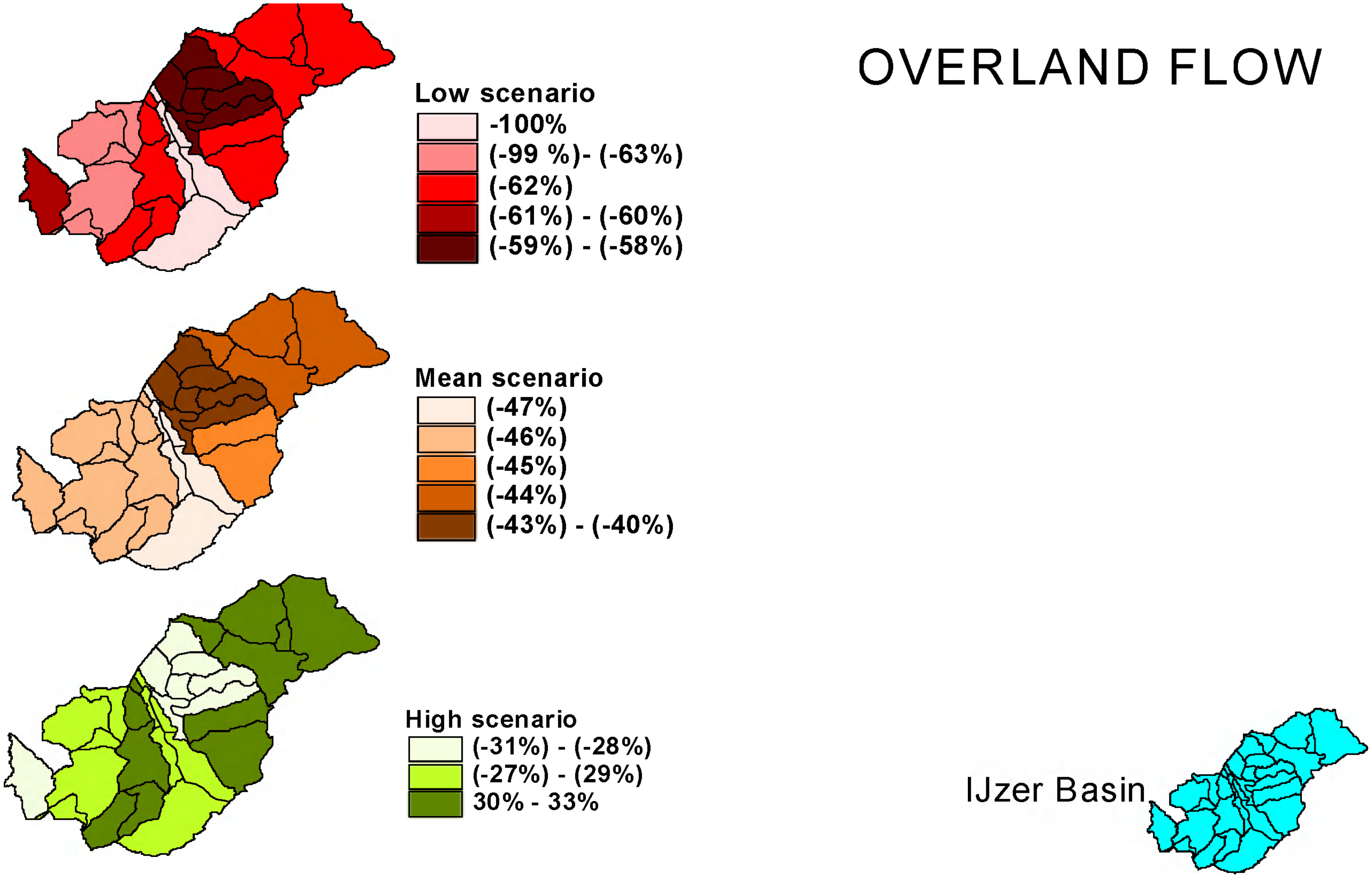
The IJzer basin

Sub-basins	Low scenario	Mean scenario	High scenario
Handzamevaart 488	-35.08	-1.63	29.79
Ieperlee 495	-85.46	-2.09	27.79
Ijzer Roesbrugge 468	-28.69	-1.918	34.23
Kemmelbeek 492	-26.35	-0.39	29.29
Martjesvaart	-33.89	-4.02	28.46
Poperingevaart 491	-39.35	-5.08	29.31
Poperingevaart 499 (SSV)	-38.83	4.87	31.47

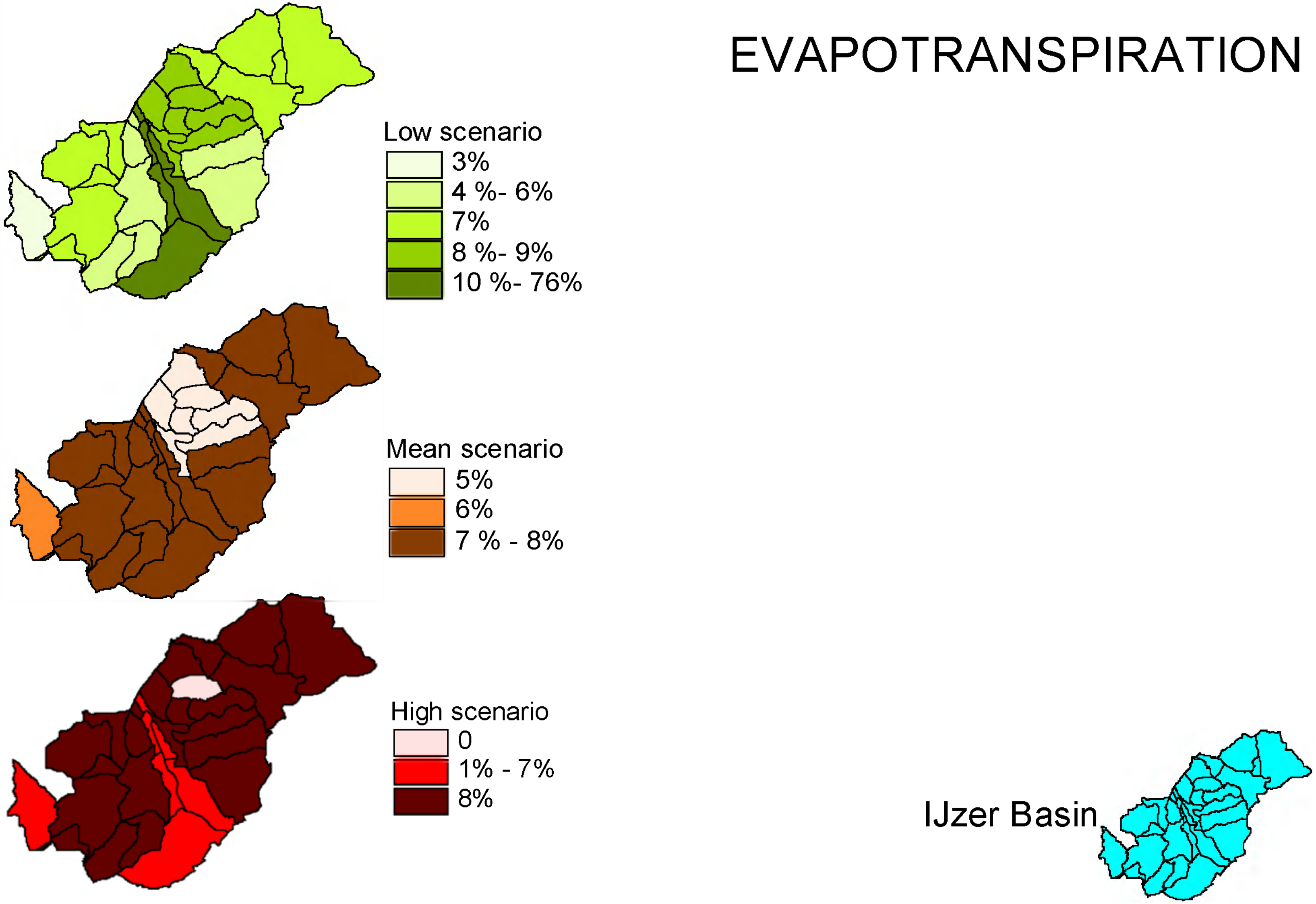
Percentages of variations of the composite hydrographs for the IJzer basin for the different climate scenarios



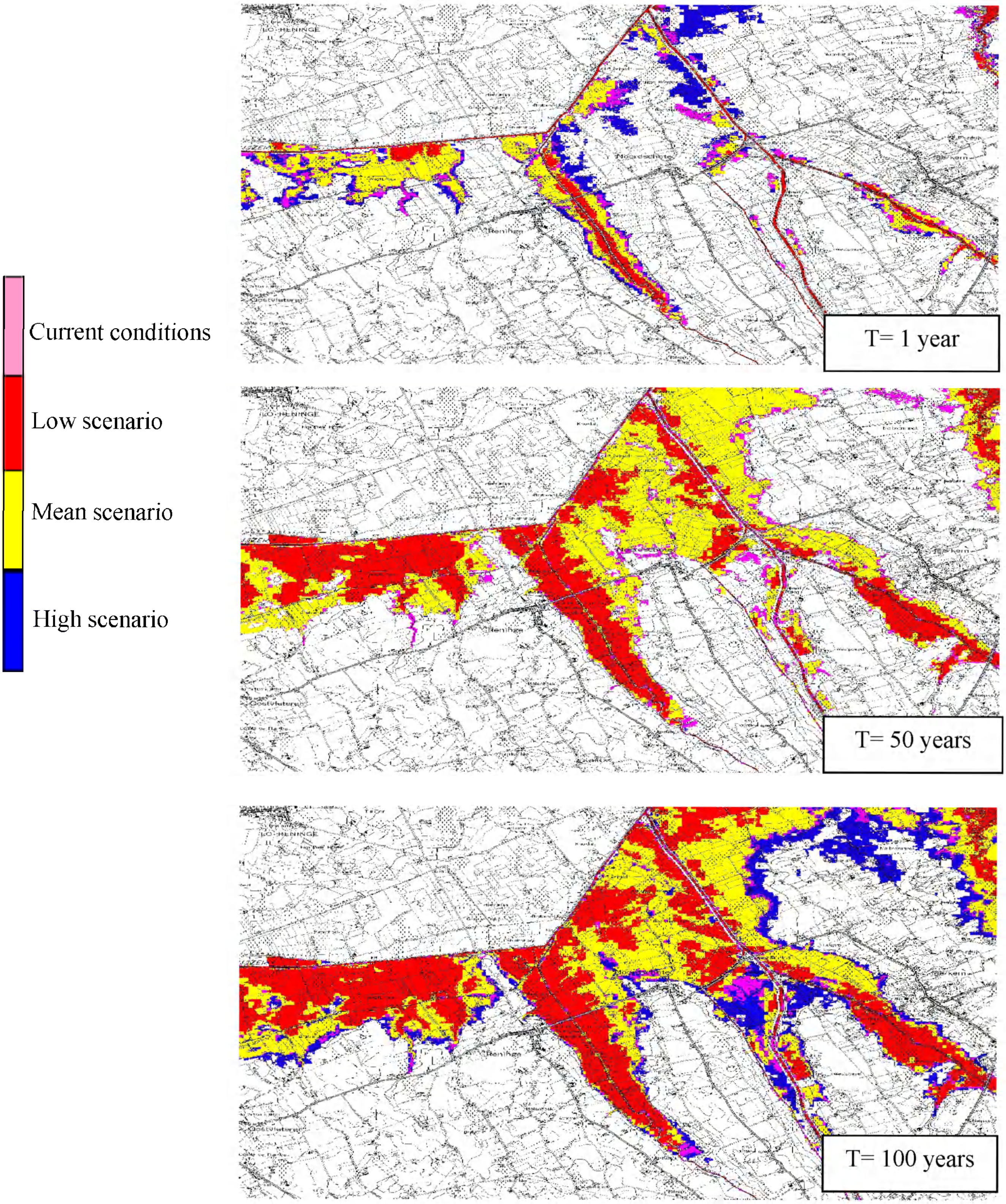
Percentage of variation of runoff peaks for the low, mean and high scenarios for the Ijzer basin, regional differences.



Percentage of variation of overland flow for the low, mean and high scenarios for the Ijzer basin, regional differences.



Percentage of variation of evapo(transpi)ration for the low, mean and high scenarios for the Ijzer basin, regional differences.

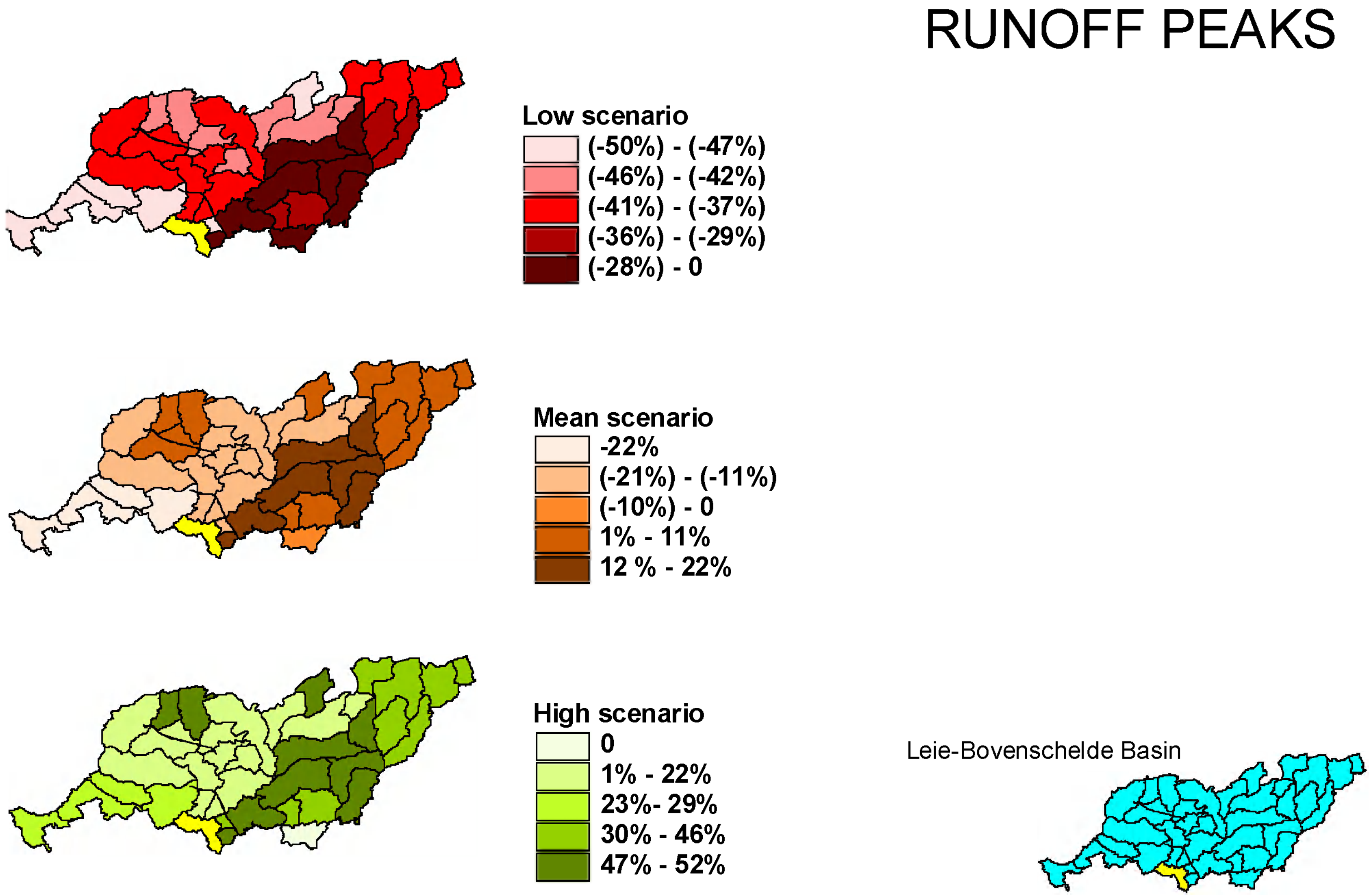


Example of flood maps for the IJzer basin.

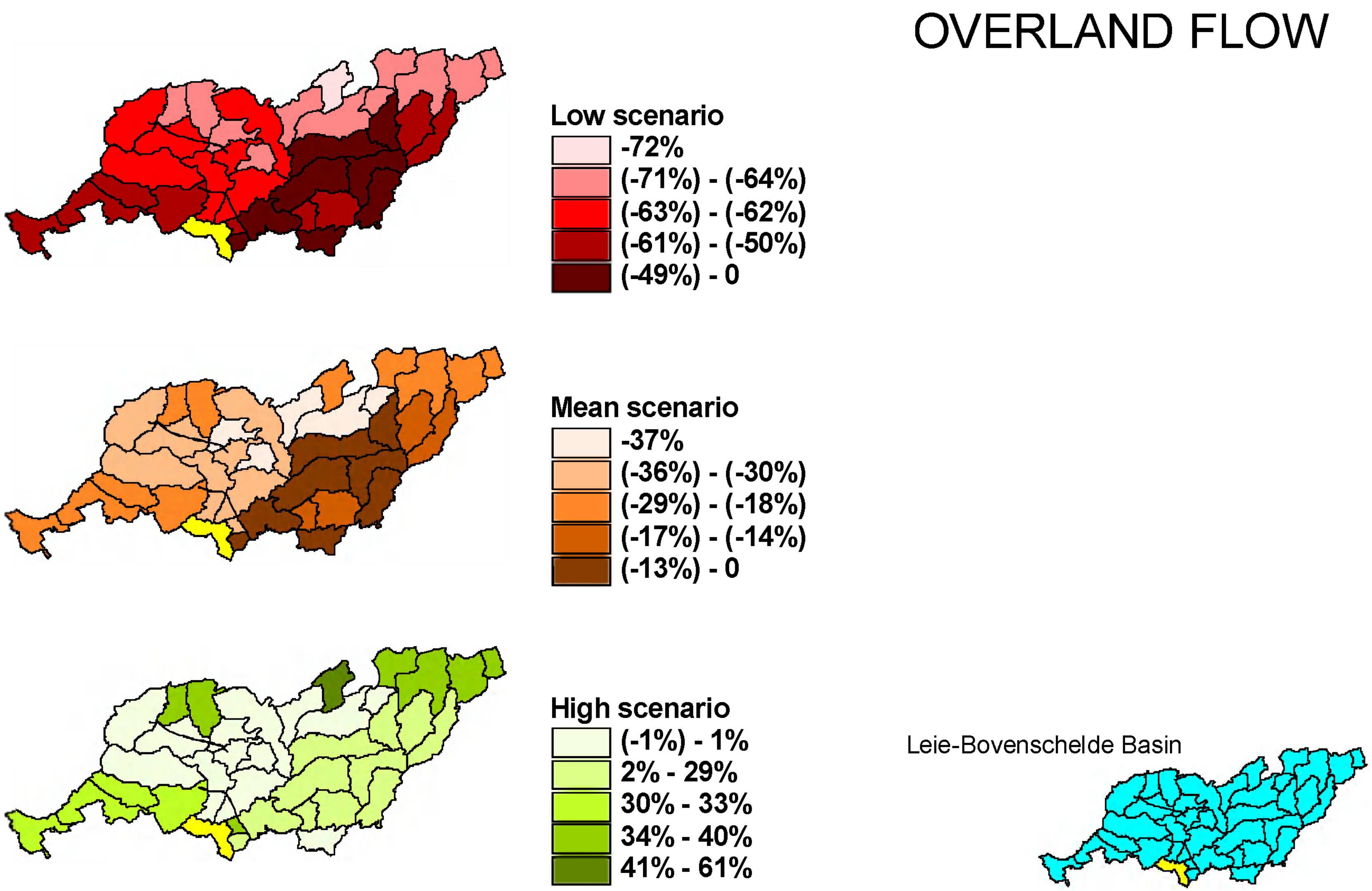
The Leie-Bovenschelde basin

Sub-basin	Low scenario	Mean scenario	High scenario
Bossuit	-85.42	-17.19	42.97
Hertsbergebeek	-45.97	3.603	65.43
Kerkebeek	-54.25	2.95	54.22
Markebeek	-29.26	3.12	33.54
Mandel1	-38.89	-15.54	23.86
Mandel2	-42.64	-13.30	18.94
Moervaart	-38.03	4.44	43.45
Riverbeek	-44.76	4.94	49.46
Zwalm	-2.07	20.71	45.93
Menen	-82.75	-22.17	29.68

Percentages of variations of the composite hydrographs for the Leie-Bovenschelde basin for the different climate scenarios.

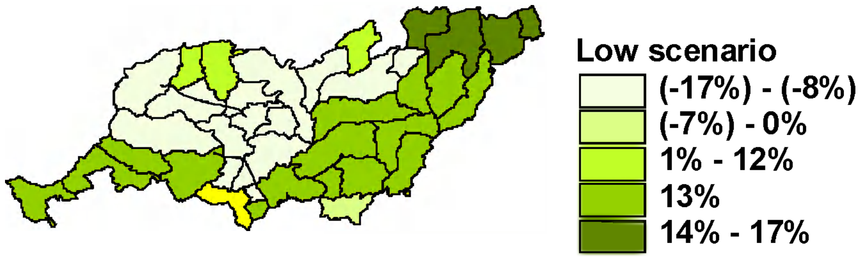


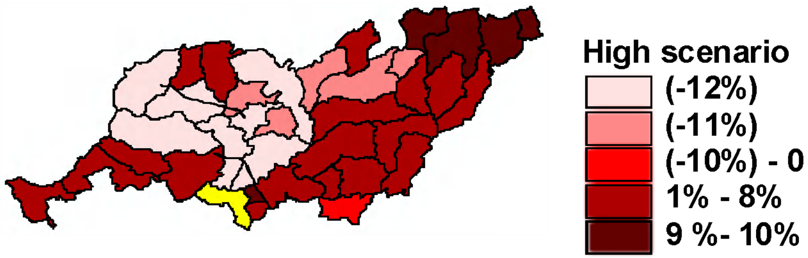
Percentage of variation of runoff peaks for the low, mean and high scenarios for the Leie-Bovenschelde basin, regional differences.

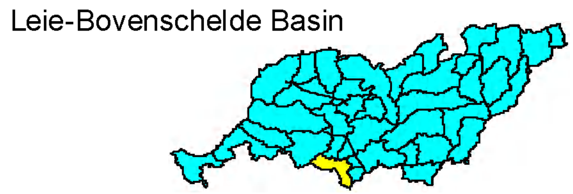


Percentage of variation of overland flow for the low, mean and high scenarios for the Leie-Bovenschelde basin, regional differences.

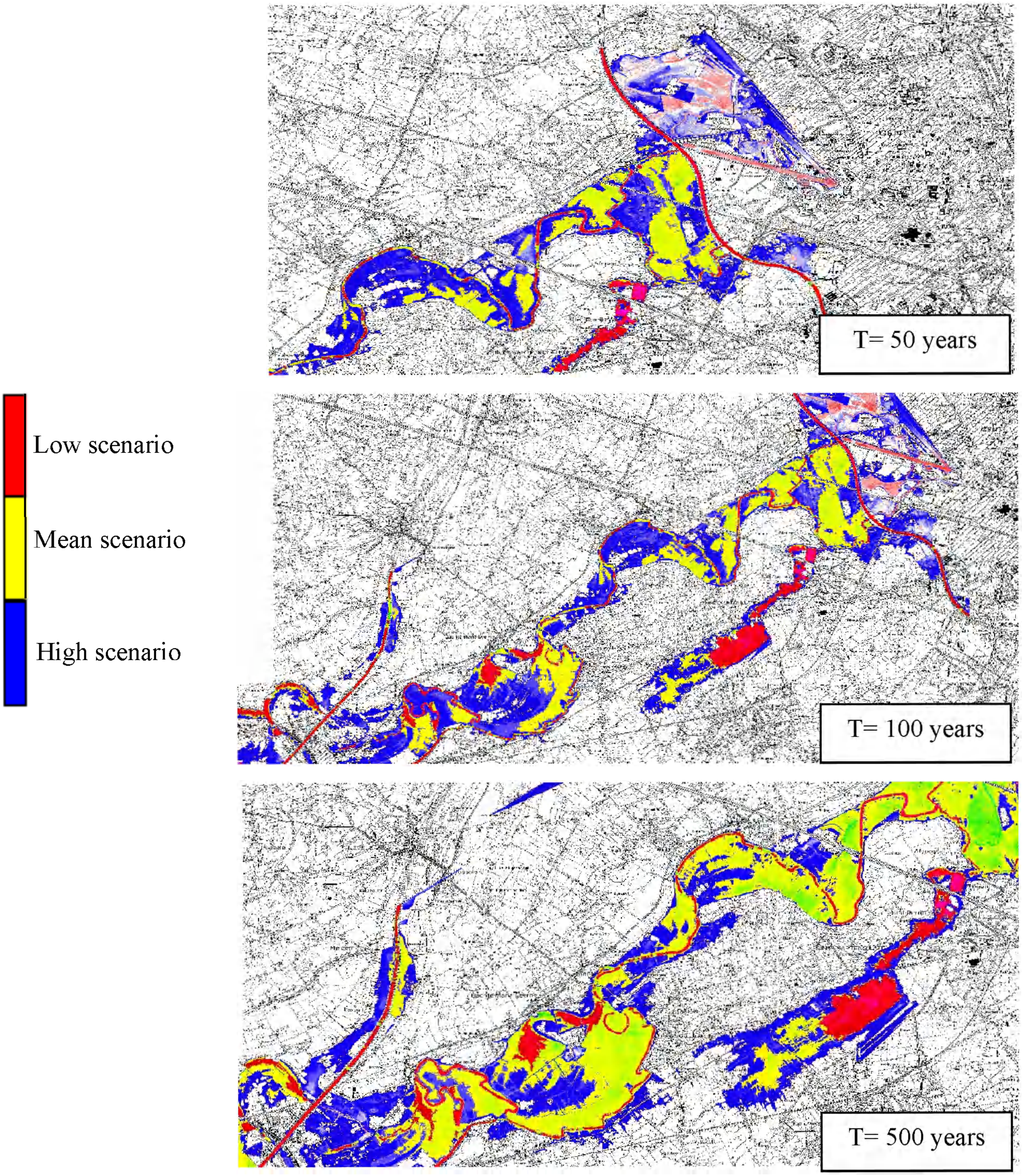
EVAPOTRANSPIRATION







Percentage of variation of evapo(transpi)ration for the low, mean and high scenarios for the Leie-Bovenschelde basin, regional differences.

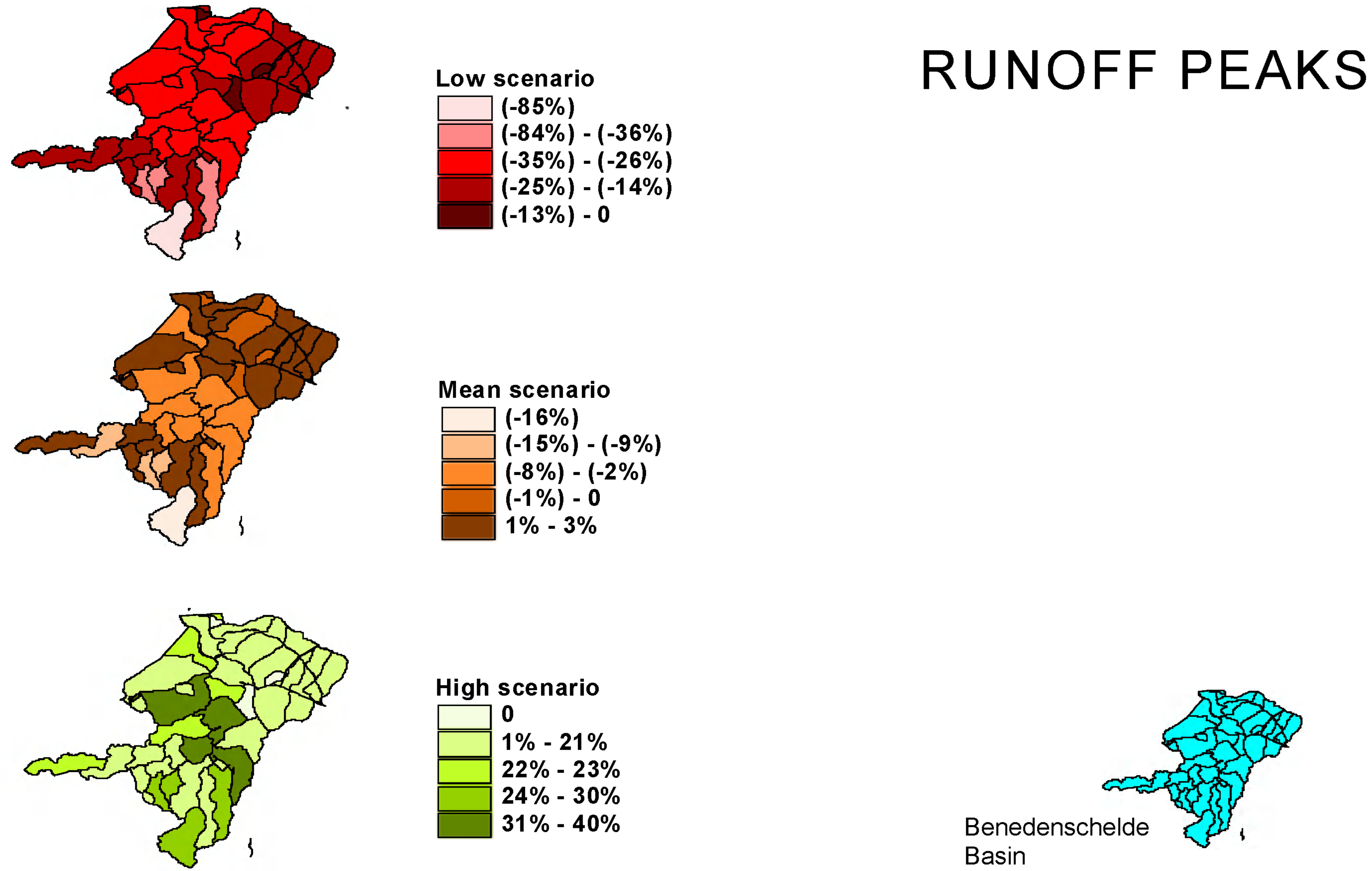


Example of flood maps for the Leie-Bovenschelde basin.

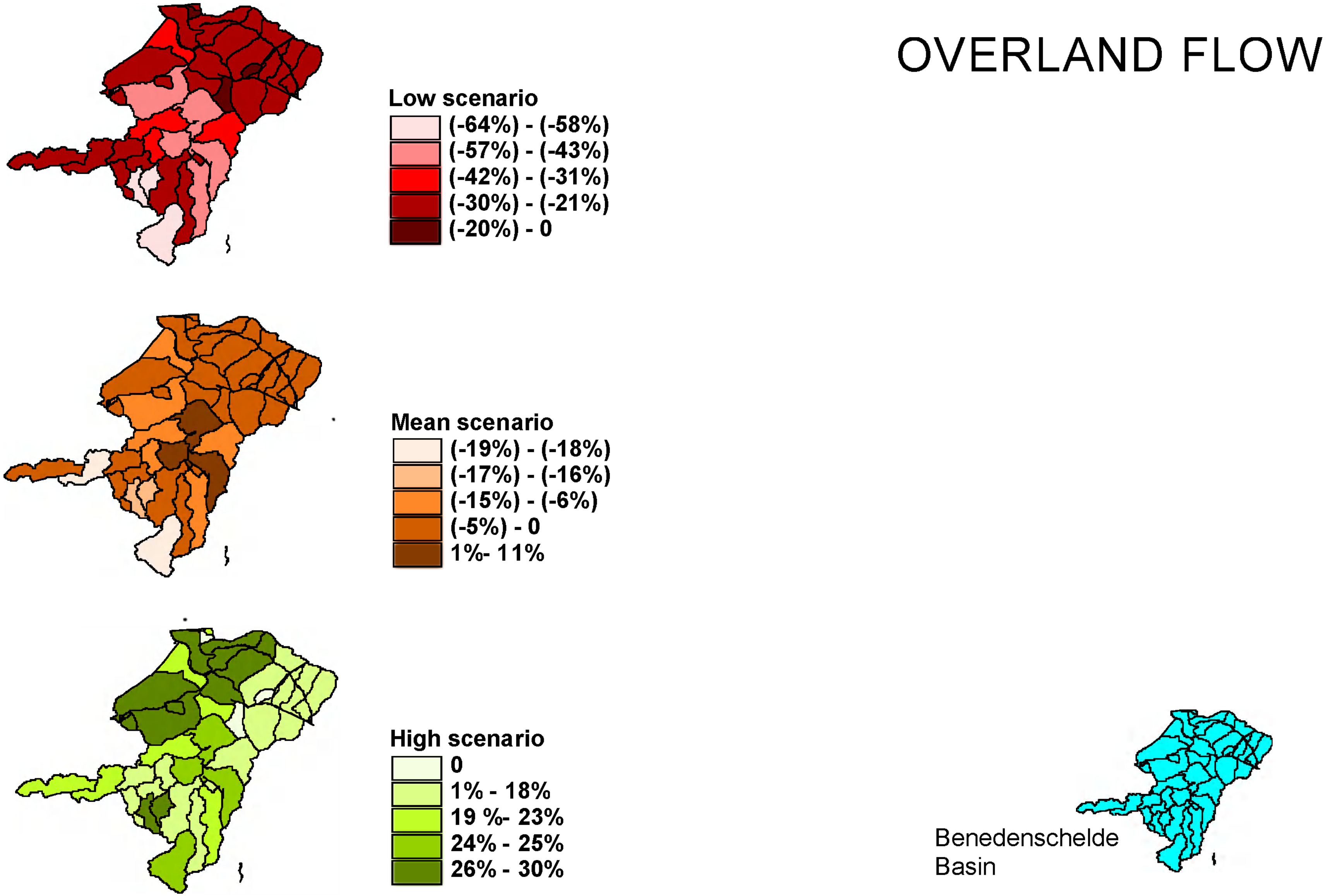
The Benedenschelde basin

Sub-basins	Low scenario	Mean scenario	High scenario
Kleinebeek	-14.5	2	20
Ledebeek	-14	3	23
Molenbeek	-15	2	20
Rodebeek	-26	2.5	21
Rupel	-28	-2.5	40
Vrouvwliet	-28	-4.5	20
Zielbeek	-36	-6	30
Barbierbeek	-27	-3.43	22.5

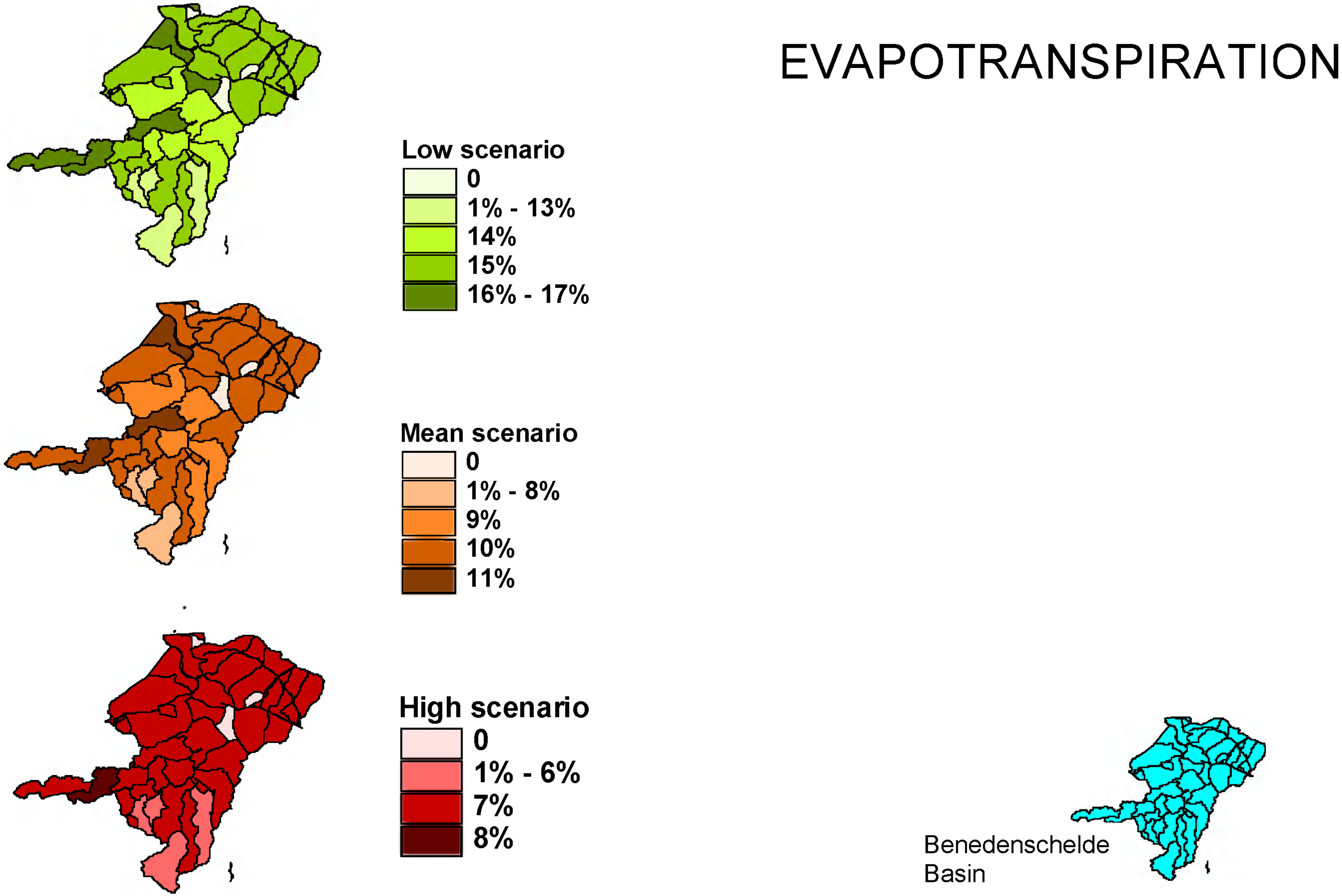
Percentages of variations of the composite hydrographs for the Benedenschelde basin for the different climate scenarios.



Percentage of variation of runoff peaks for the low, mean and high scenarios for the Benedenschelde basin, regional differences.



Percentage of variation of overland flow for the low, mean and high scenarios for the Benedenschelde basin, regional differences.



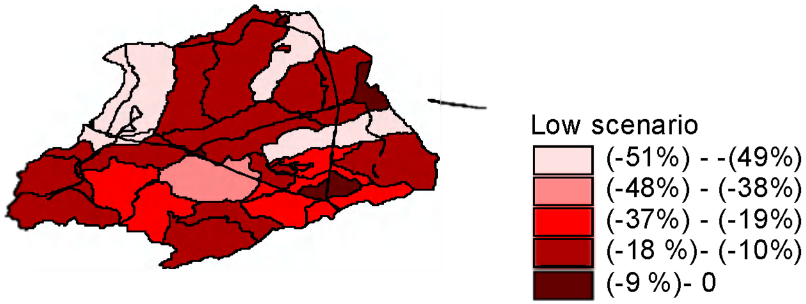
Percentage of variation of evapo(transpi)ration for the low, mean and high scenarios for the Benedenschelde basin, regional differences.

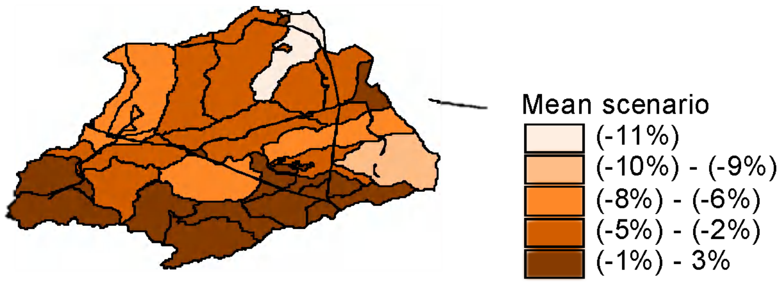
The Nete basin

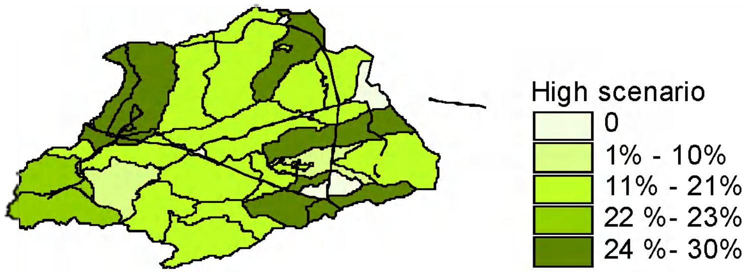
Sub-basins	Low scenario	Mean scenario	High scenario
Assbeek	-15	-9	20
Broekloop	-14	3	20
Grote Laak	-19	0	20
Kleine Nete	-10	-2	19
Luisbeek	-23	0	30
Molenbeek	-51	-6	29
Itterbeek	-14	3	23
Rupel	-28	-3	40
Steenkensbeek	-14	2	20
Wamp	-49	-11	28
Wimp	-38	-7.5	21.5

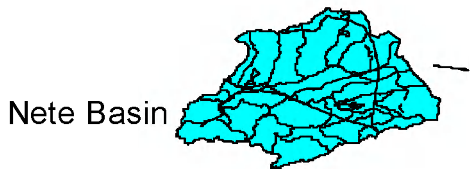
Percentages of variations of the composite hydrographs for the Nete basin for the different climate scenarios.

RUNOFF PEAKS



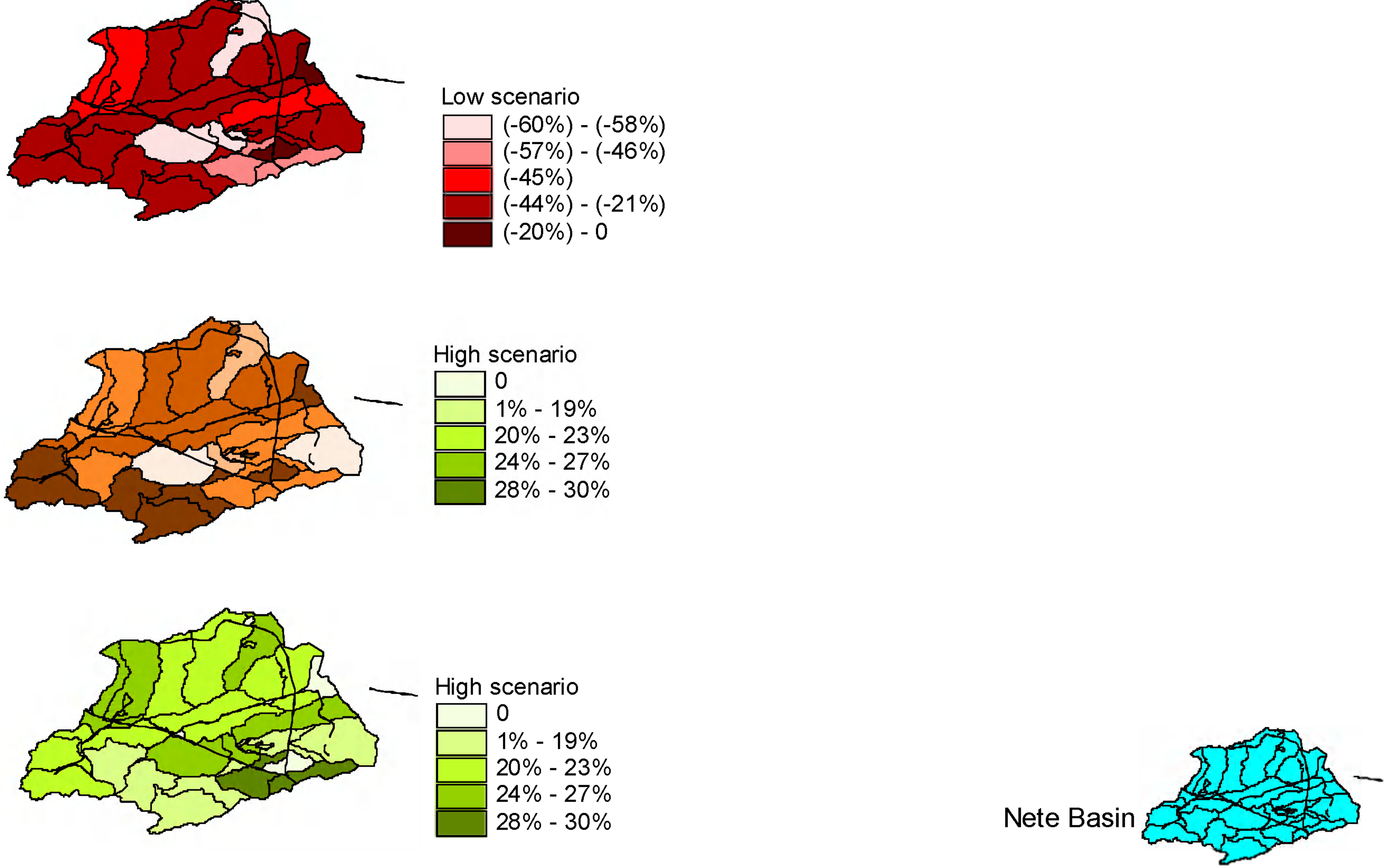






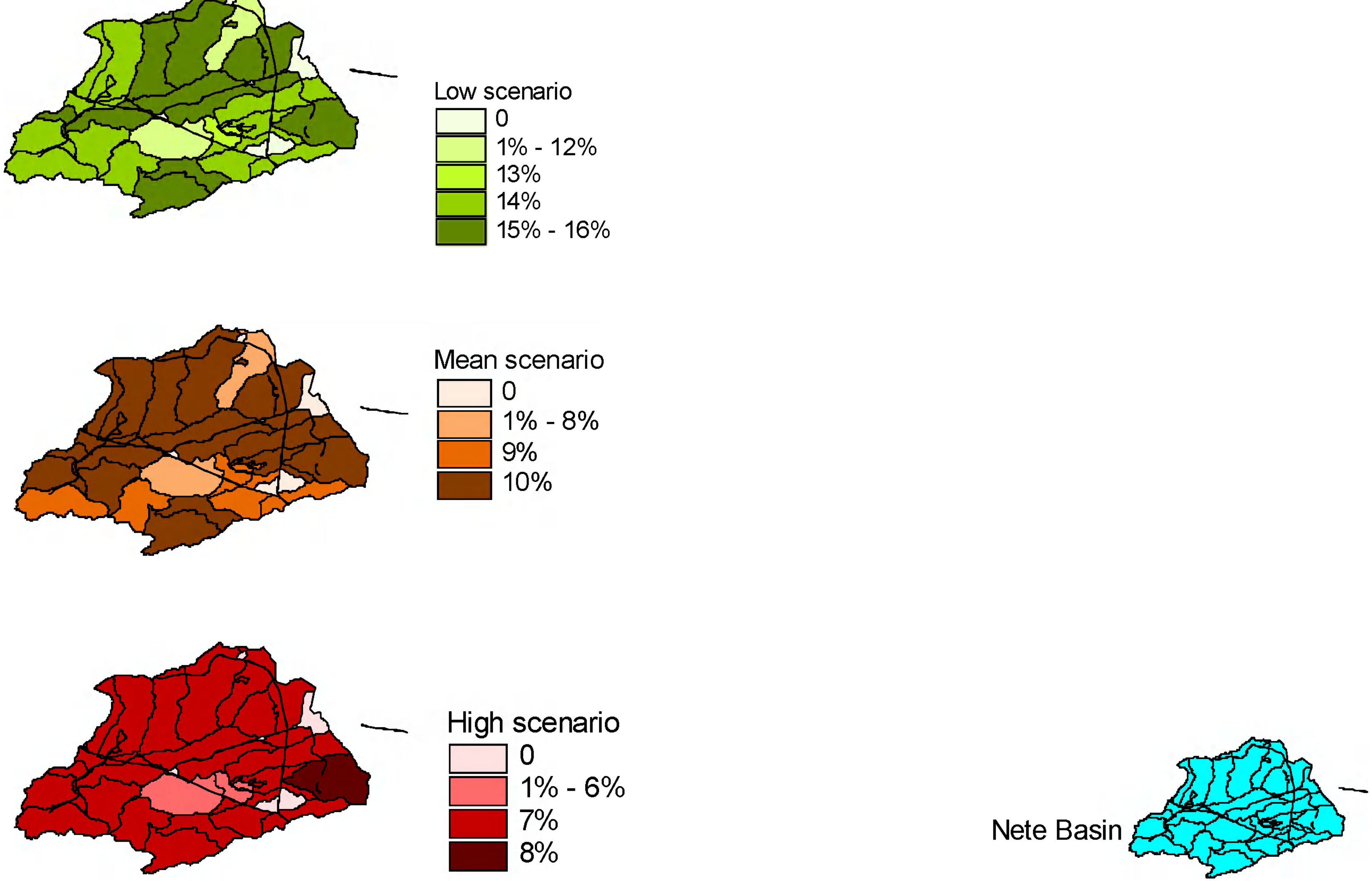
Percentage of variation of runoff peaks for the low, mean and high scenarios for the Nete basin, regional differences.

OVERLAND FLOW



Percentage of variation of overland flow for the low, mean and high scenarios for the Nete basin, regional differences.

EVAPOTRANSPIRATION

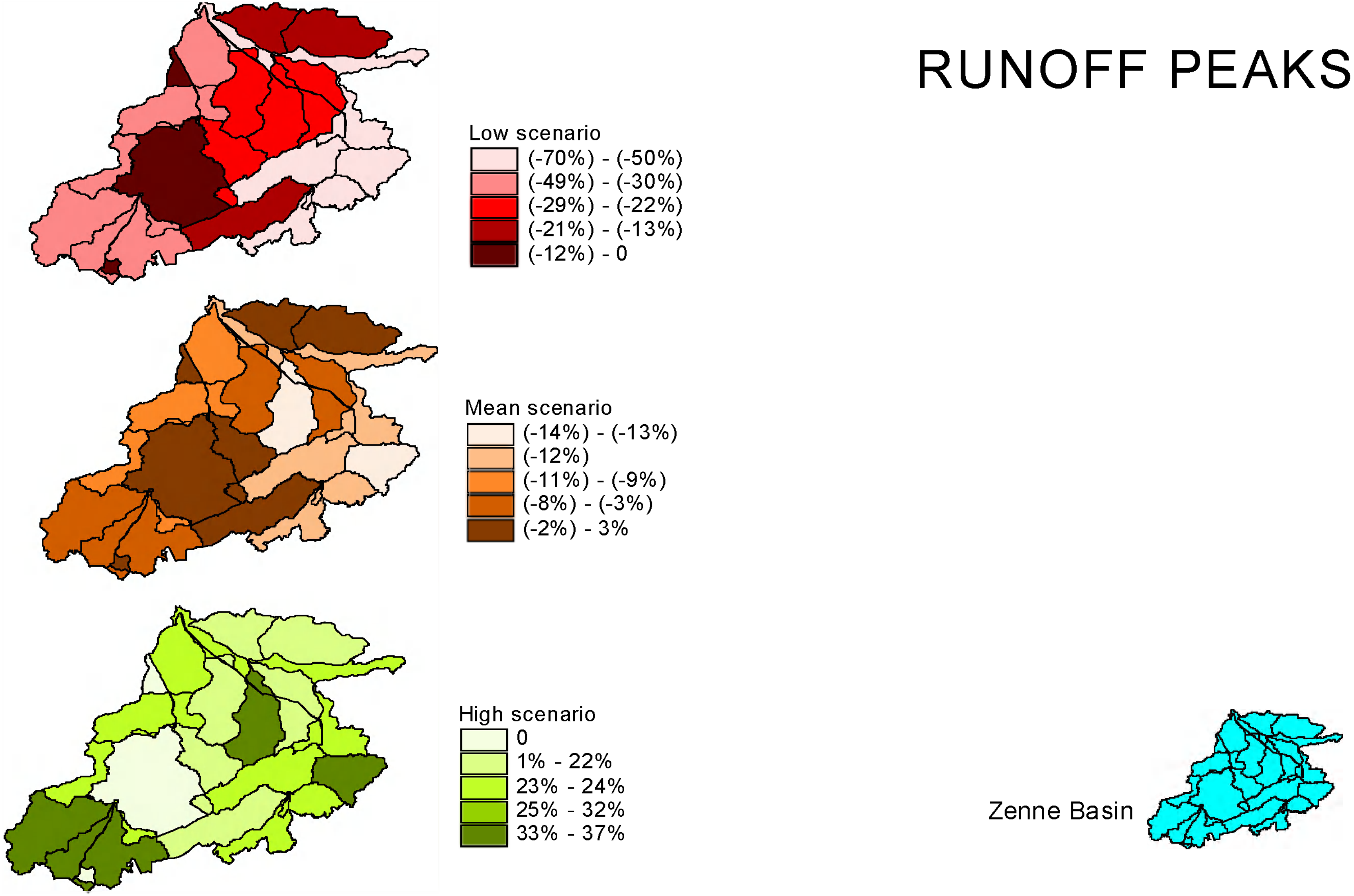


Percentage of variation of evapo(transpi)ration for the low, mean and high scenarios for the Nete basin, regional differences.

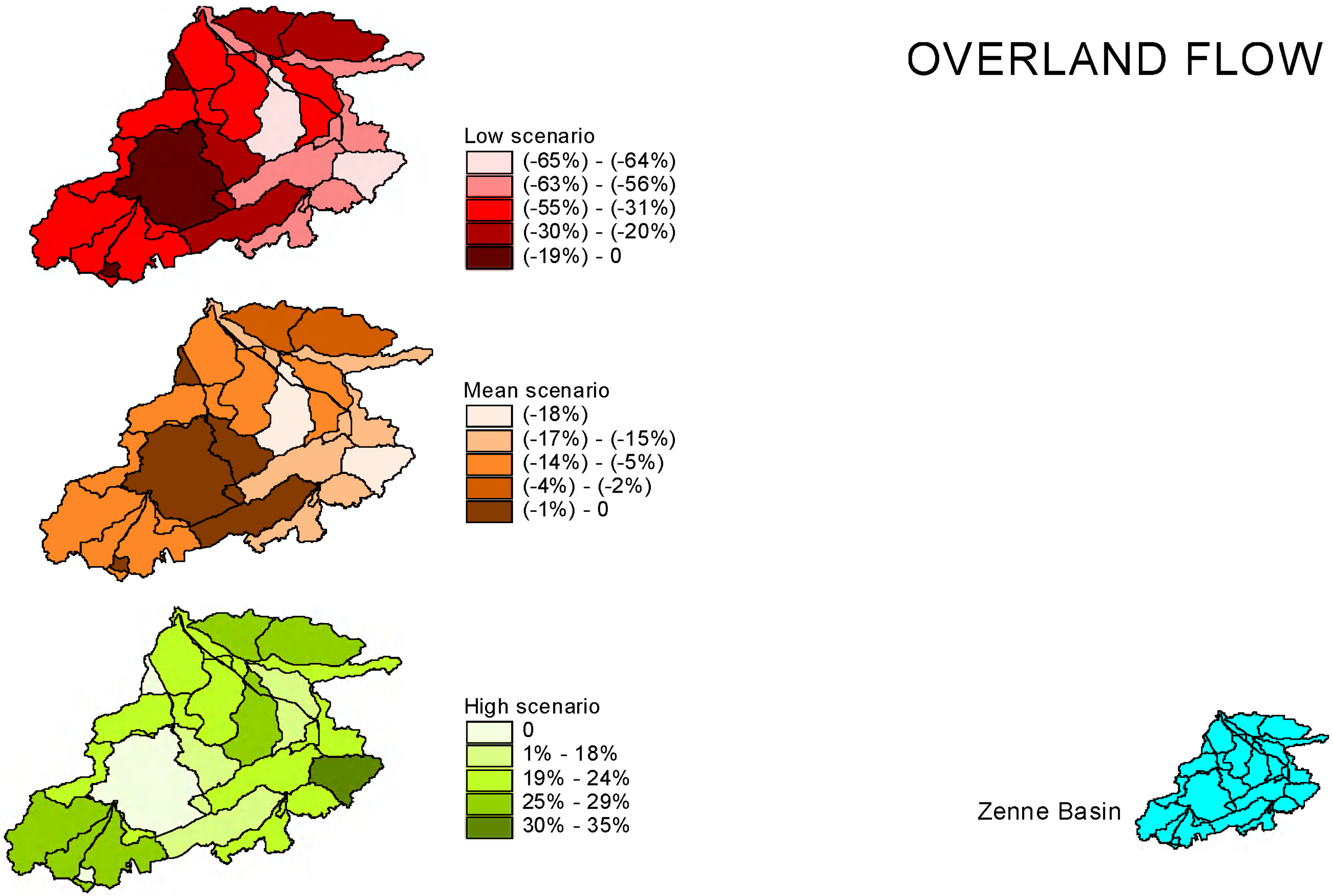
The Dijle-Zenne basin

Sub-basins	Low scenario	Mean scenario	High scenario
Barebeek	-27	-3	22
Dijle	-50	-12	24
Liebeek	-27	-4	21
Molenbeek	-70	-13	36
Krekelbeek	-13	3	22
Weesbeek	-28	-14	37
Zenne	-32	-9	24
Zuunbeek	-30	-3	36

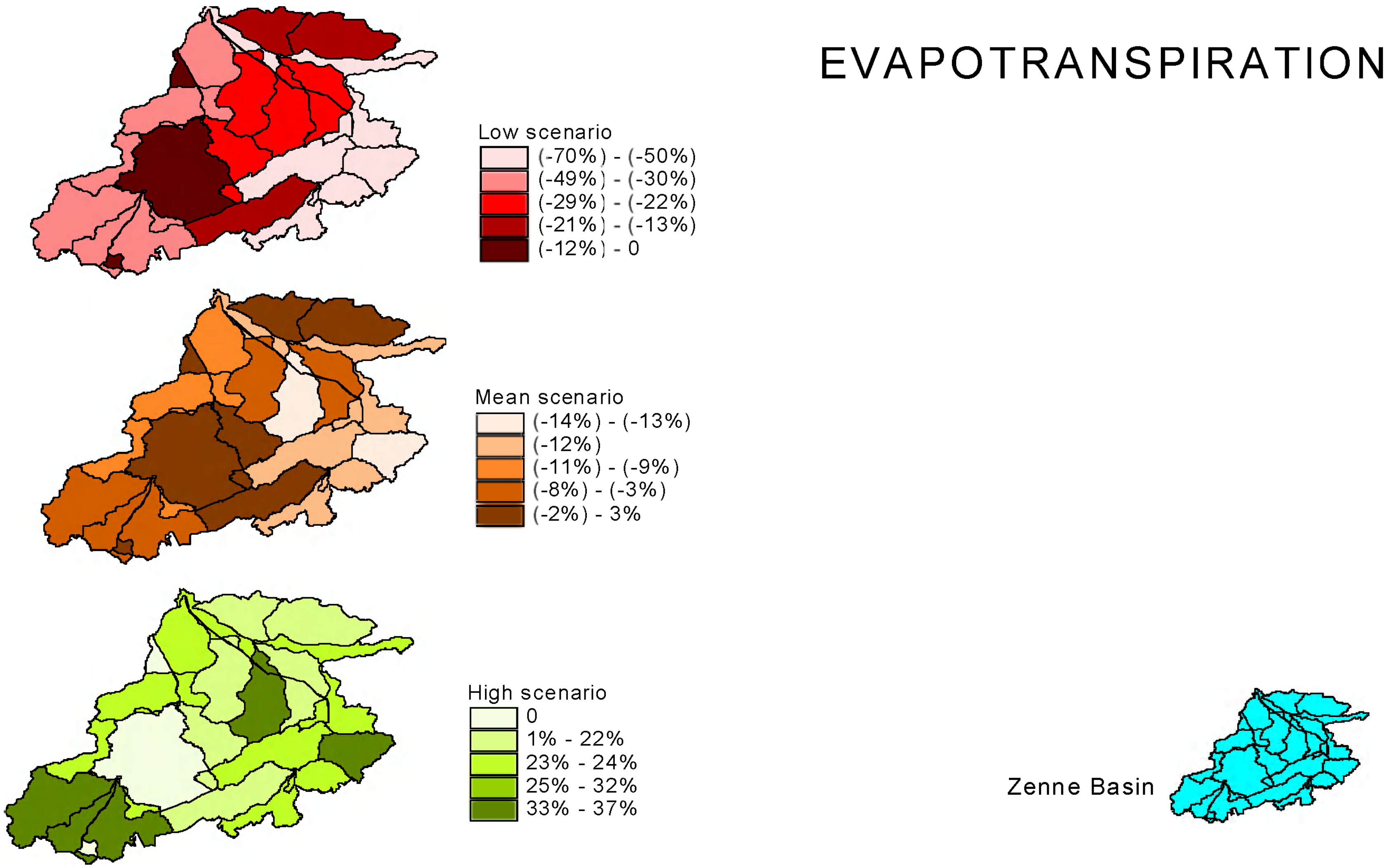
Percentages of variations of the composite hydrographs for the Dijle-Zenne basin for the different climate scenarios.



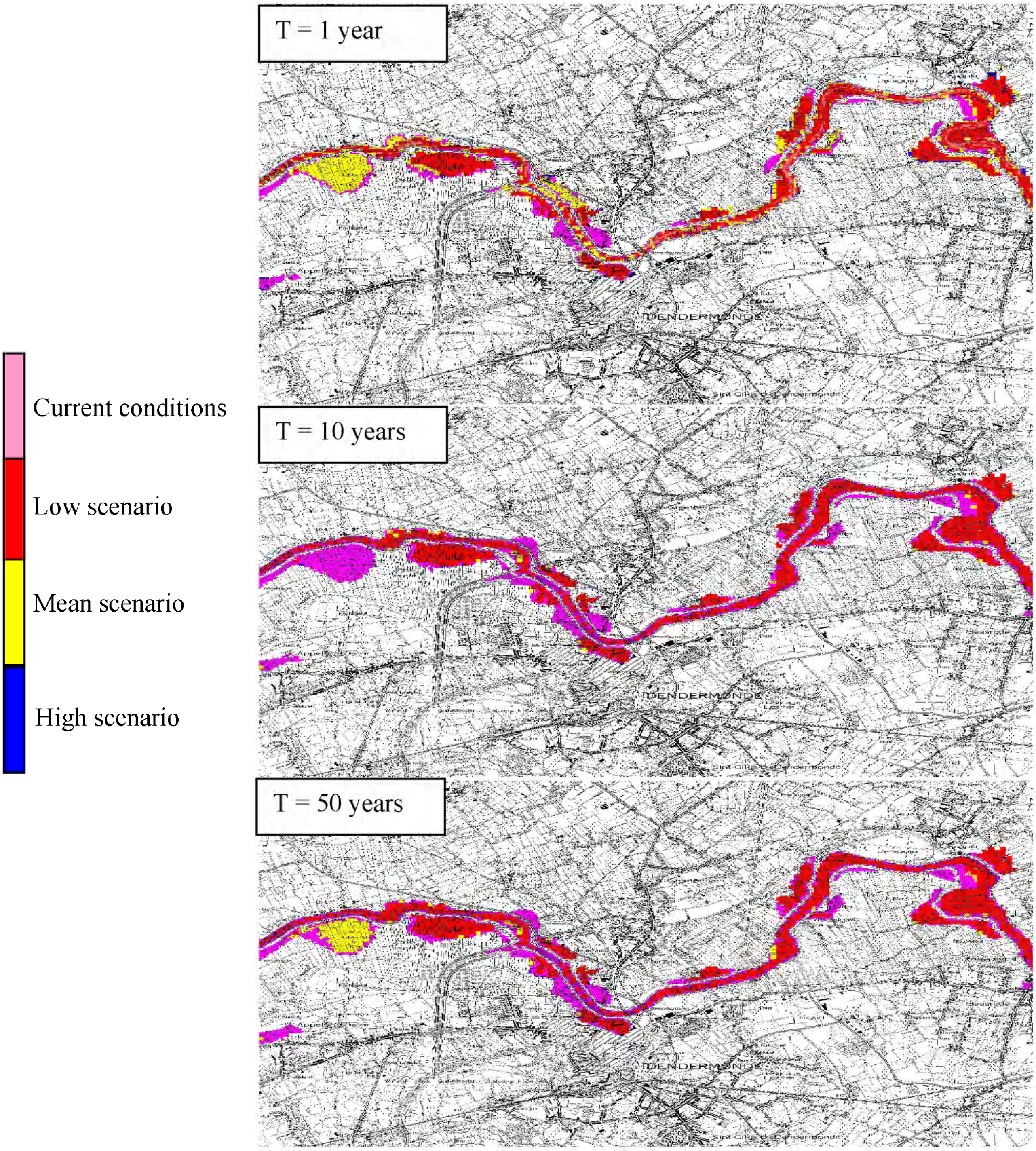
Percentage of variation of runoff peaks for the low, mean and high scenarios for the Dijle-Zenne basin, regional differences.



Percentage of variation of overland flow for the low, mean and high scenarios for the Dijle-Zenne basin, regional differences.



Percentage of variation of evapo(transpi)ration for the low, mean and high scenarios for the Dijle-Zenne basin, regional differences.



Example of flood maps for the Sigma model area (Nete, Dijle and Zenne basins).

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