



Contribution of land use changes to future flood damage along the river Meuse in the Walloon region

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Abstract. Managing flood risk in Europe is a critical issue because climate change is expected to increase flood hazard in many European countries. Beside climate change, land use evolution is also a key factor influencing future flood risk. The core contribution of this paper is a new methodology to model residential land use evolution. Based on two climate scenarios (“dry” and “wet”), the method is applied to study the evolution of flood damage by 2100 along the river Meuse. Nine urbanization scenarios were developed: three of them assume a “current trend” land use evolution, leading to a significant urban sprawl, while six others assume a dense urban development, characterized by a higher density and a higher diversity of urban functions in the urbanized areas. Using damage curves, the damage estimation was performed by combining inundation maps for the present and future 100 yr flood with present and future land use maps and specific prices. According to the dry scenario, the flood discharge is expected not to increase. In this case, land use changes increase flood damages by 1–40 %, to € 334–462 million in 2100. In the wet scenario, the relative increase in flood damage is 540–630 %, corresponding to total damages of € 2.1–2.4 billion. In this extreme scenario, the influence of climate on the overall damage is 3–8 times higher than the effect of land use change. However, for seven municipalities along the river Meuse, these two factors have a comparable influence. Consequently, in the “wet” scenario and at the level of the whole Meuse valley in the Walloon region, careful spatial planning would reduce the increase in flood damage by no more than 11–23 %; but, at the level of several municipalities, more sustainable spatial planning would reduce future flood damage to a much greater degree.

1 Introduction

Climate change is expected to increase flood hazard across most of Europe, both in terms of peak discharge intensity and frequency (Dankers and Feyen, 2008; Kundzewicz, 2005). For instance, Milly et al. (2002) show an increase in extreme flood frequency as a result of a quadrupling of CO₂ concentrations. Consequently, managing flood risk will remain an issue of primary importance for decades to come (Ernst et al., 2010).

Flood risk can be defined as the combination of the probability of a flood event and its negative consequences (UNISDR, 2009). The latter are a function of the flood intensity, the exposure and the vulnerability. The exposure is defined here as the people, properties, systems, or other elements which are present in the flood-prone areas (UNISDR, 2009). As a consequence, exposure depends directly on land use, and, in this respect, not only climate change but also land use evolution is a key influencing factor for the assessment of future flood damage.

For some European rivers, these two factors were considered in flood damage assessments conducted for a relatively short term future (2030 in De Roo et al., 2003; te Linde et al., 2011 and Poussin et al., 2012; 2020 in Elmer et al., 2012). In contrast, very few studies have taken them into consideration for a longer term future (e.g. de Moel et al., 2011). The main purpose of this paper is to present a new methodological approach to model land use evolution for a long-term future and to evaluate the corresponding change in potential flood damage.

This new methodology was applied to a specific case study, for which the potential damage related to the 100 yr

flood was assessed for the present situation and for 2100, using nine land use evolution scenarios and two climate change scenarios. The study area is the river Meuse in the Walloon region (Belgium). The 100 yr flood was selected since it is the most frequently used return period to map flood risk in Europe (de Moel et al., 2009). Although the time horizon of 2100 is relatively distant, it was chosen here as it is usually used as a reference in studies on hydrological impacts of climate change (Leander et al., 2008; van pelt et al., 2009), including for the case study considered here (Drogue et al., 2010).

The assessment of future flood damage involves three steps (Fig. 1): (1) future flood hazard assessment, (2) future exposure assessment, and (3) future flood damage assessment. Since climatic, hydrological, and hydraulic modelling (step 1) were described in previous studies (Drogue et al., 2010; Detrembleur et al., 2011), this paper focuses on the exposure and damage assessments, considering two different residential urbanization models and several scenarios. Here, rainfall–runoff modelling was not coupled with land use evolution, which is obviously an essential work to be performed in the future.

Section 2 of the paper provides some background on land use modelling. Section 3 details the data and methods, including the main hydrological characteristics of the river Meuse and the spatial planning policy in the Walloon region (Sect. 3.1, step 1 in Fig. 1), as well as the methodology for land use evolution modelling (Sect. 3.2, step 2) and for damage assessment (Sect. 3.3, step 3). Section 4 presents the results of land use evolution and flood damage, which then are discussed in Sect. 5. Conclusions are drawn in Sect. 6.

2 Land use modelling

Numerous studies using land use evolution models have been carried out in western Europe (Verburg et al., 2002, 2004, 2007; Barredo et al., 2003; Antrop, 2004; Antoni, 2006; Overmars et al., 2007; Hoymann, 2010, 2011). Land use evolution models simulate complex interactions between bio-physical and socio-economic factors. Verburg et al. (2004) reviewed different categories of models and identified six main features to classify the existing models: the level of analysis, the cross-scale dynamics, the level of integration, the considered driving forces, and the spatial interactions and neighbourhood effects, as well as the temporal dynamics.

Verburg et al. (2004) distinguish first between micro- and macro-levels. The former is mainly used in social sciences and consists in studying the behaviour of individuals, either qualitatively or quantitatively. In contrast, geographers and ecologists usually analyse land use and societies characteristics at a macro-scale.

The second main feature of land use evolution modelling is the cross-scale dynamics. Geographic processes often result from interactions between processes taking place at different

scales (Gregory et al., 2011). In the present case, these processes include residential choices of citizens (local level), spatial planning (regional or national level), and the evolution of the price of oil (global level).

The consideration of these cross-scale dynamics in the modelling approach is a third main feature, called the level of integration. Land use systems are characterized by strong interactions between their constitutive parts (subsystems). A high level of integration consists in reflecting in the model these interactions between levels or subsystems (Verburg, 2006). In contrast, each subsystem can be modelled separately provided that feedbacks between the different components remain insignificant.

Another main feature pointed out by Verburg et al. (2004) is the reproduction in the model of the driving forces responsible for land use changes (Bürgi et al., 2004). They are generally classified in four groups: socio-economic drivers (population growth, standard of living, culture), bio-physical drivers (altitude, slope, soil type), land use policies (such as land use management plan), and neighbourhood effects.

This last group of driving forces is particularly important because land use patterns often exhibit positive spatial autocorrelations. For example, urban expansion is often situated close to existing urban areas. Conversely, a nuclear power plant tends to hinder the development of residential areas around it. These attraction or repulsion effects within the same land use category (e.g. residential areas) or between different land use categories need to be accounted for.

The last feature is temporal dynamics. Future land use evolution is not necessarily the continuation of past trends. Therefore, rather than applying simple extrapolations of past trends, a scenario-based approach should be developed, in which each scenario corresponds to a combination of consistent assumptions concerning the future evolution of societies, climate, price of oil, etc.

In practical terms, land use evolution modelling at the macro-level usually consists of two main steps: non-spatial and spatial analyses (Verburg et al., 2002). The goal of the former is to quantify the future demand for each land use category (e.g. forest, cropland, residential area). This may be carried out either using complex macro-economic and climatic models (Verburg et al., 2007), or by extrapolation of recent trends (Antoni, 2006). In the framework of a raster analysis, the non-spatial analysis determines the number of cells in which land use will change at each time step. Next, the location of the changing cells is defined by the spatial analysis. It consists in identifying the driving forces for the location of land use changes (e.g. distance to the nearest city, mean slope of the cell, land use of the neighbouring cells, land use policy) as well as in deriving transition rules. Finally, the combination of land use demand (non-spatial analysis) and transition rules (spatial analysis) enables determining in which cells land use will change at each time step.

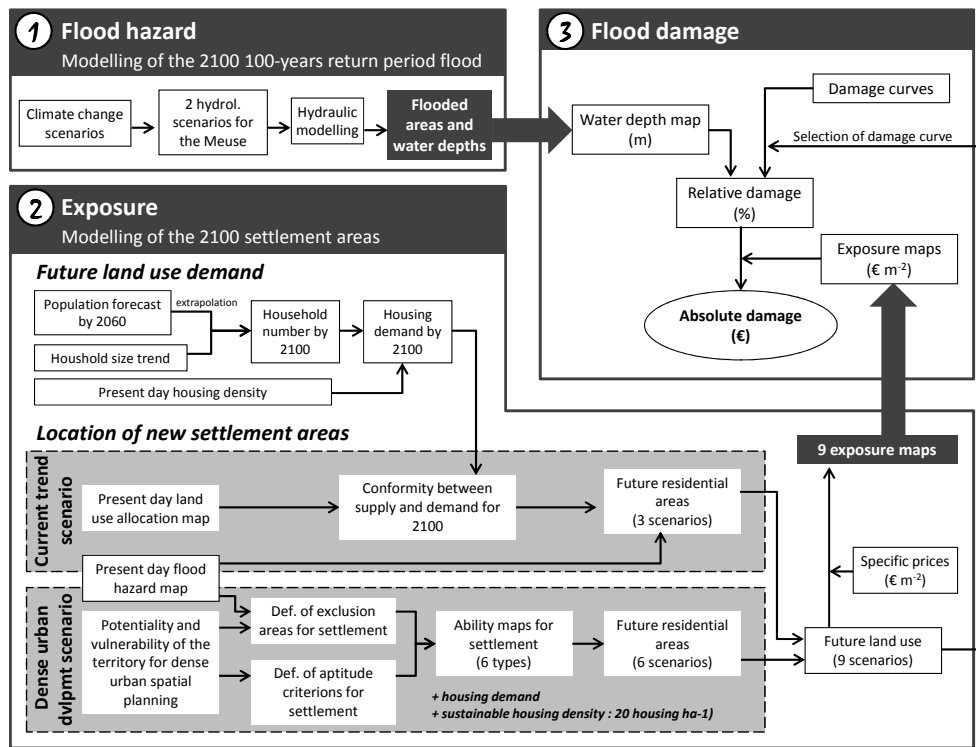


Fig. 1. Flow chart of the methodology used to assess future flood damage. In this paper, the focus is set on steps 2 and 3.

3 Data and methods

3.1 Case study

3.1.1 Hydrology and future discharges

The river Meuse is a 905 km long river crossing three western European countries. It originates in the Langres Plateau in France (384 m a.s.l.), crosses the Ardennes Massif in the Walloon region of Belgium and flows into the North Sea in the Netherlands. Of the total length, 185 km are in Belgium (152 km in the Walloon region, between Hastière and Lixhe; see Fig. 2), where it crosses 19 municipalities. These municipalities define the area of analysis. The whole watershed of the river Meuse covers $\sim 34\,000\text{ km}^2$, among which about $13\,900\text{ km}^2$ are in Belgium ($12\,300\text{ km}^2$ in the Walloon region) (Institut de conseil et d'études en développement durable, 2005; Commission internationale de la Meuse, 2009).

Improving flood risk management in the Meuse Basin is one of the goals of the Interreg IV-b AMICE project (<http://www.amice-project.eu>). In this framework, several regional hydrological models were run based on projections of rainfall and temperature changes (Drogue et al., 2010). Future estimates of the 100 yr flood were derived for the time horizons 2021–2050 and 2071–2100 (step 1 in Fig. 1). Considering a “wet climate” scenario, the results show a mean increase in the peak discharge by 15% for the

time horizon 2021–2050 and by 30% for the time horizon 2071–2100 (Drogue et al., 2010). In Liège, these future discharges correspond to $3660\text{ m}^3\text{ s}^{-1}$ and $4140\text{ m}^3\text{ s}^{-1}$, respectively. A “dry climate” scenario was also considered in the hydrological modelling, and it leads to a slight decrease in the peak discharge. Here, to provide a possible range of the impact of climate change, the present value of Q_{100} was used as a proxy for the 100 yr flood in 2100 according to the dry climate scenario. This is supported by the results of the hydrological modelling of Drogue et al. (2010), which reveal only a limited decrease of the 100 yr flood peak discharge in 2100 for the dry climate scenario.

Land use evolution was not taken into account in the hydrological modelling, contrary to some other studies (e.g. Dorner et al., 2008, or, including the Meuse Basin, Ward et al., 2011b). The latter study showed that, for the periods 1950–2000 and 2000–2050, the effects of land use change on the flood discharges in the river Meuse are small compared to the larger increase induced by the considered climate change scenarios. For the last century, this issue was also studied by Tu et al. (2005) and Ashagrie et al. (2006), who showed that the evolution of observed discharges of the river Meuse result mainly from climate variability, and not from land use change. These findings support our decision not to consider land use change in hydrological modelling.

In the Walloon region, the inundation extents and water depths corresponding to the present climate and to the

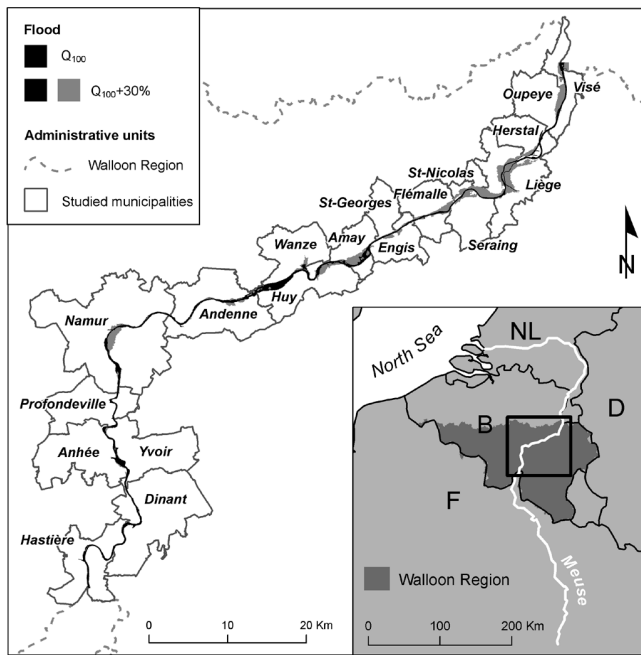


Fig. 2. Study area. Situation of the 19 studied municipalities in the river Meuse Basin and flooded area corresponding to two studied discharges (Q_{100} and $Q_{100} + 30\%$).

AMICE wet scenario were computed with the hydraulic model WOLF 2D, which is two dimensional and based on the complete shallow-water equations (Detrembleur et al., 2011; see Erpicum et al., 2010, for detailed methodology and validation). The inundation extents corresponding to Q_{100} and $Q_{100} + 30\%$ are shown in Fig. 2.

3.1.2 Spatial planning

Spatial planning is the main driving force of land use evolution in the Walloon region. Indeed, land allocation is strictly controlled by several regulations, including the regional development plan (called *plan de secteur*). For each land plot, it defines the legally authorized land allocation. Dating back to the 1980s, the development plan tends to foster urban sprawl (Fig. 3), which leads to increasingly challenging difficulties such as a dramatic increase in the length of supply networks and in the use of individual cars (Newman and Kenworthy, 1996; Halleux, 2008). This prompts the Walloon policymakers to initiate the preparation of an update of this *plan de secteur* (Delforge and Géron, 2008; CPDT, 2010).

3.1.3 Flood risk management

Official flood hazard maps are available in the Walloon region. They identify flood-prone areas based on three levels: low, medium, or high flood hazard. Depending on the type of river, three complementary methods were combined

to prepare these maps (Groupe Transversal Inondations, 2006). First, for all river sections where hydrological data were available, high-resolution 2-D hydraulic modelling was performed for the 25-, 50- and 100 yr floods. The typical grid resolution was 2–5 m. Using the matrix shown in Fig. 4, the water depth computed in each grid cell was combined with the corresponding flood frequency to obtain the level of flood hazard. When hydrological data were missing (ungauged catchments), the extent of flood-prone areas was estimated from field investigations (Peeters et al., 2006) and by analysing the extent of Holocene alluvial deposits (Dautrebande et al., 2006). The resulting flood hazard maps were approved by the Walloon government in 2006 and are now available online (<http://cartopro3.wallonie.be/CIGALE/viewer.htm>). They are routinely used by the authorities in their assessments of applications for building permits.

3.2 Exposure assessment

Exposure is a function of the type and characteristics of land use categories (e.g. specific value), and is therefore directly influenced by land use change. We focus here on the future evolution of residential areas because this land use category represents more than 50% of the total recorded damage for past flood events in the Meuse Basin (Giron et al., 2009). This high share of damage in the residential sector has also been observed for other basins, such as in Germany (te Linde et al., 2011). For 2100, nine future land use scenarios were developed and compared to the present situation (2009 data).

Information on the present land use in the Walloon region was obtained by combining two regional databases: the PLI database and the land registry (Région Wallonne, 2012; SPF Finances, 2012). The PLI database (*plan de localisation informatique*) contains the location and geometry of land plots and buildings at the scale 1 : 10000. For each land plot, the land registry provides the corresponding land use category, out of a total of 222 categories. These were sampled down into 10 classes, for which specific prices can be derived for the damage assessment (see the classification Table A1 in the Appendix A). As the PLI database and the land registry are used for fiscal purpose, they are regularly updated and provide reliable data.

The evolution of urbanization was not modelled dynamically, based on numerous transition rules. In contrast, we built our analysis upon the definition of residential areas with the ability to provide housing for the expected population in 2100. This approach is in line with the Standing Conference for Territorial Development (CPDT) working on an update of the regional development plan (CPDT, 2010), and is justified by the overwhelming influence of spatial planning among the driving forces for future developments. Two families of urbanization scenarios were developed: the “current trend” scenario and the “dense urban development” scenarios. They are defined in detail in the following two sections.

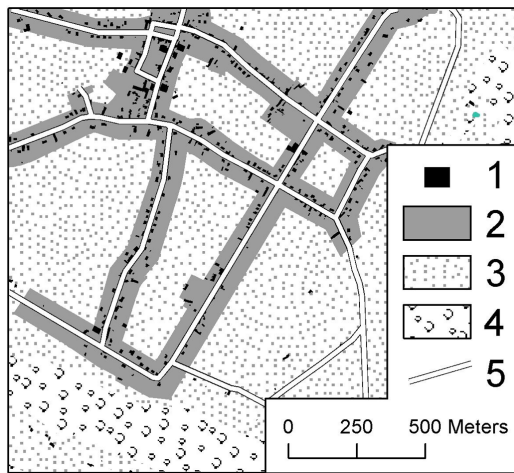


Fig. 3. Example of urban sprawl fostered by the *plan de secteur* in Profondeville: 1 – buildings; 2 – settlement areas of the land use allocation map (LUAM); 3 – agriculture (LUAM); 4 – forest (LUAM); 5 – roads.

For each family of scenarios, three levels of building restrictions based on the flood hazard maps were tested. The first one stops the construction of new residential buildings in the “high” flood hazard areas, which is in line with the present regulations in the Walloon region. The second level bans new developments not only in the “high” but also in the “medium” flood hazard areas. This enables the influence on flood damage of a tightening of existing spatial planning laws to be appreciated. To test the efficiency of the present regulation in mitigating flood damage, the third level constitutes a baseline scenario in which no building restrictions based on flood hazard maps are taken into account.

3.2.1 Current trend scenario

In the first considered scenario, the present trend in urbanization is assumed to continue in the future. It consists mainly in urban sprawl, resulting in new residential areas with a relatively low density and large land plots. By 2100, this scenario implies the urbanization of all land plots legally allocated as “residential” according to the *plan de secteur*.

To show that this scenario is reasonable, the past urbanization rate of each municipality was linearly extrapolated in order to assess the time needed to urbanize the whole municipality area (where urbanization is allowed by the *plan de secteur*). For this assessment, the 1997–2007 mean urbanization rates were obtained from the CAPRU database (<http://www.gembloux.ulg.ac.be/eg/capru/communes-wallonnes-en-chiffres>) and the available surface in each municipality was derived by combining the PLI database and the development plan. In the CAPRU database, the urbanized area is the sum of the areas of all land plots containing a building, whatever its function (residential,

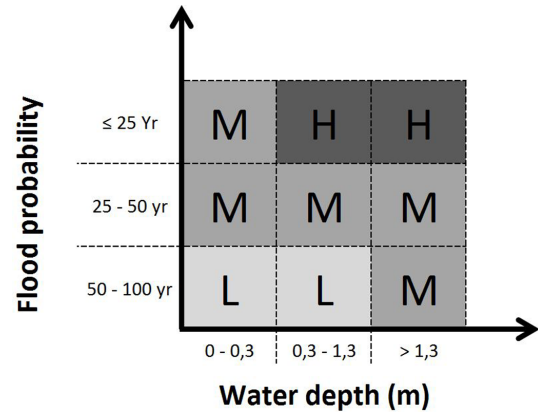


Fig. 4. Levels of hazard used for the official flood hazard maps of the Walloon region. They are defined based on a combination of the water depth (horizontal axis) and the range of return period (vertical axis). H represents high flood hazard; M, medium flood hazard; L, low flood hazard. Adapted from Groupe Transversal Inondations (2006).

industrial, etc.). It was also assumed that no transfer occurs between the 19 municipalities in the considered study area. This means that when a municipality is fully urbanized, its urbanization rate is not allocated to another municipality, resulting in a possible overestimation of the time needed for full urbanization of all municipalities.

Figure 5 shows the past evolution of urbanization in the 19 municipalities. The mean year of full urbanization is 2102 (standard deviation = 48 yr). The most quickly urbanized municipality is Profondeville (2052) and the slowest one is Amay (2241). According to these results, and considering the probable overestimation of the time required for complete urbanization, the assumption of a complete urbanization by 2100 of the residential areas defined by the *plan de secteur* is considered as realistic for the 19 studied municipalities.

Besides corresponding to the current trend in terms of urbanization rate, this scenario is also consistent with the expected population growth until 2100. Indeed, using 2004 land use data, Lepers and Morelle (2008) estimated that the available residential areas of the *plan de secteur* can provide housing for ~ 1.5 million inhabitants in the case of a current trend scenario. This value is similar to the forecast for the 2100 population in the Walloon region. Indeed, extrapolating linearly the Belgian average projected rate of population growth between 2007 and 2060 or 2040 and 2060 (Bureau fédéral du Plan, 2008) results in an increase of in between 1.43 and 1.61 million inhabitants between 2004 and 2100, which matches with Lepers and Morelle’s assessment (Fig. 6).

3.2.2 Dense urban development scenarios

Future spatial planning in the Walloon region is likely to be guided by a revised version of the *plan de secteur*, which has been fostering urban sprawl for three decades. To

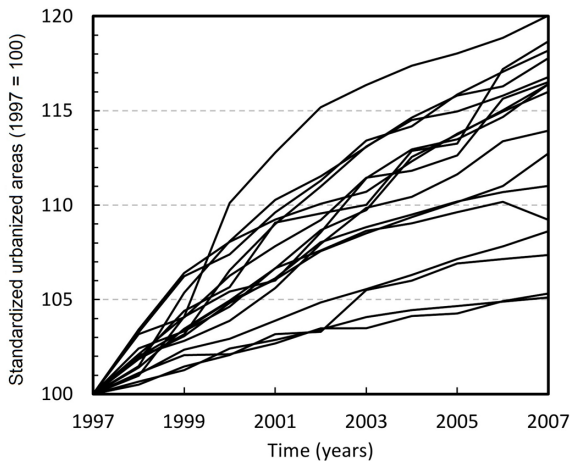


Fig. 5. Growth in urbanization of the 19 studied municipalities between 1997 and 2007. Urbanized area in 1997 for each municipality is 100.

take into account this possible evolution, a second family of scenarios was developed, involving drivers which tend to promote a higher density in the future residential areas. The overarching objective underlying these “dense urban development” (DUD) scenarios is a reduction in the use of individual cars. Therefore, three main spatial planning rules were assumed: (1) more compact settlements to stop urban sprawl, (2) a higher settlement density to accommodate more people in urban centres, and (3) the preferred location of new housing in places where the diversity of urban functions is already high (schools, shops, public transports, etc.) in order to reduce the demand for transportation.

In line with an ongoing work of the Walloon authorities (Delforge and Géron, 2008; Charlier et al., 2011), new residential areas called “settlement cores” were defined. In these settlement cores, the housing density in 2100 should not be less than 20 households ha^{-1} (objective of density), and no new housing may be built outside these settlement cores (objective of compactness). Moreover, the total area of settlement cores should accommodate housing for the expected population in 2100.

The spatial delimitation of settlement cores was performed in four main steps: (1) build potential maps combining indicators reflecting the spatial planning rules; (2) identify so-called exclusion areas, where new developments are either not possible or not allowed; (3) define the thresholds to be applied to the potential maps to obtain the settlement cores corresponding to a given scenario; and (4) disregard too small settlement cores. The analysis was conducted for the entire Walloon region, which corresponds to the administrative level at which spatial planning policy is managed. A raster with a resolution of 100 m \times 100 m was used. This is consistent with the resolution of the available housing density data. The obtained settlement cores may include both already-built and non-built land plots.

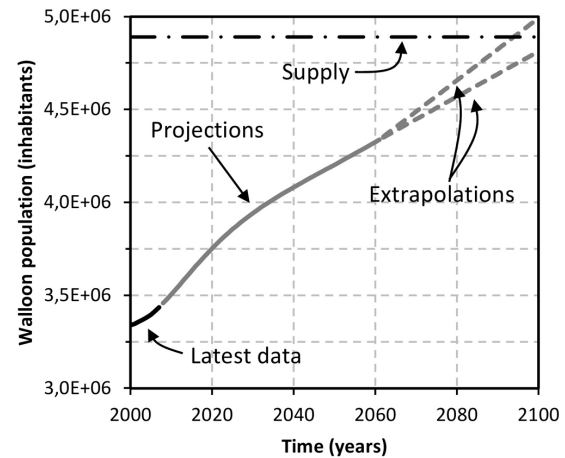


Fig. 6. Population forecast for the Walloon region. Latest data come from <http://statbel.fgov.be>, and projections from Bureau fédéral du Plan (2008). Linear extrapolations until 2100 use the mean increase rate between 2007–2060 (upper dashed line) and 2040–2060 (lower dashed line). Housing supply until 2100 corresponds to the assessment of Lepers and Morelle (2008).

The potential maps were built using three variables: (1) the present housing density, (2) the present land use diversity, and (3) an employment-related potential. The variable representing the present housing density (D) was evaluated as the mean housing density in a 700 m radius circle around each raster cell. This variable was used to foster future developments near existing residential areas with a higher density. Land use diversity (F) was defined as the weighted sum of land use categories located in a 500 m radius circle around each cell (Dujardin et al., 2010). The land use categories are listed in Table 1. The weights vary from 1 to 5 depending on the distance within the 500 m radius circle. Locating new housing where land use diversity is high enables new residents to decrease their need for an individual car.

The employment-related potential P_e is used to reflect a preference for locating new housing at a lower distance from the main employment centres, and thus to decrease the demand for transportation. Ten employment centres were considered: Brussels, the six main cities of the Walloon region (Liège, Charleroi, Namur, Mons, Verviers, Tournai) according to the urban hierarchy (Van Hecke et al., 2009), and the three main border cities (Luxembourg, Lille, and Aachen). As a result, the variable P_e is defined as

$$P_e = \log \left(\sum_{i=1}^{10} e_i / d_i^{0.25} \right), \quad (1)$$

where e_i is the number of jobs in the employment centre i and d_i is the Euclidian distance between the cell and the employment centre i . This equation is derived from Huff's (1963) model, which enables human behaviours to be described by mimicking gravitational interactions. Due to the

Table 1. Land use categories considered for the assessment of land use diversity.

Land use categories
Housing
Industry and craft industry
Administrative services
Social and health services
Scholar equipment
Social and cultural equipment
Indoor sport and recreational equipment
Trade
Offices and services

high density of highway and railway networks in Belgium, the Euclidian distance is an acceptable approximation for the real travelled distance.

Potential maps were derived by combining these three variables using the logical operator OR. Two different combinations were tested. The first one combines the housing density *D* with the land use diversity *F*:

$$P_{LD} = 1 - (1 - D) \cdot (1 - F). \tag{2}$$

The scenario obtained from this potential P_{LD} is referred to as the “local development scenario”. For the second one, the employment-related potential P_e was also included in the formula:

$$P_{RD} = 1 - (1 - D) \cdot (1 - F) \cdot (1 - P_e). \tag{3}$$

The resulting scenario is called the “regional development scenario”, and is in line with a regional policy providing incentives to commuters for living closer to their job. By combining these two potential maps with the three different levels for considering flood hazard in spatial planning (Sect. 3.1.3), a family of six DUD scenarios was obtained. Altogether, nine different urbanization scenarios for 2100 were built (Fig. 7).

In a second step, exclusion areas were identified to reflect the impossibility of accommodating residential developments on different land plots, due to bio-physical factors (steep slope, landslide hazard, karst hazard), legal reasons (nature conservation areas and other protected areas), or because the area is already occupied by other functions such as schools, transportation network, industry, etc. These exclusion areas were defined based on the list provided in Table 2. These exclusion areas were deleted from the potential maps corresponding to each of the six DUD scenarios.

The spatial delimitation of the settlement cores requires the definition, for each potential map, of a threshold above which a cell is considered as belonging to a settlement core. This threshold was selected so as to enable the amount of new housing to match the expected growth in the number

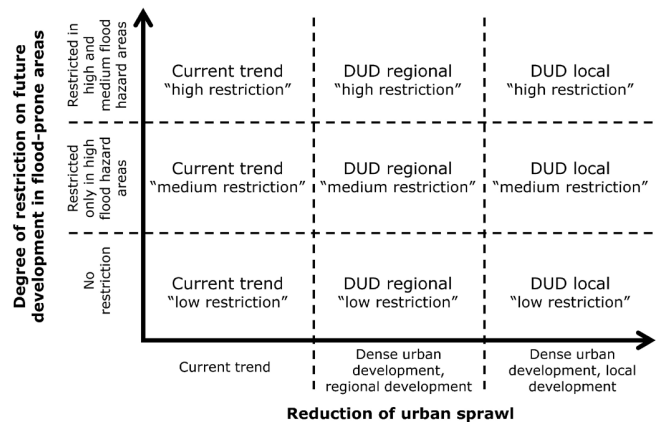


Fig. 7. Summary of the nine urbanization scenarios characteristics according to two criteria.

Table 2. Exclusion areas, defined based on the PLI and land registry database, as well as on additional data for non-registered land use categories (hydrography, road network, etc.).

Class	Source
Natura 2000 areas	Walloon auth.
Rockslide hazard	Walloon auth.
Karst hazard	Walloon auth.
Lakes and wet areas	COSW*
Planned “green areas” and parks	Plan de secteur
Slope > 35°	20 m resolution DEM
Industry and craft industry	COSW*
Aerodromes	COSW*
Airports	COSW*
Quarry	COSW*
Cemetery	COSW*
Urban parks	COSW*
Rail way and linked areas	COSW*
Road and linked areas	COSW*
Port	COSW*
Worship facilities	COSW*
Scholar facilities	COSW*
Social and cultural facilities	COSW*
Technical facilities	COSW*
Indoor sport and recreational facilities	COSW*
Administrative facilities	COSW*
Health facilities	COSW*

*COSW is a land use map developed by the Walloon authorities (see http://cartographie.wallonie.be/NewPortailCarto/PDF/legende_COSW.pdf for land use classifications).

of households by 2100. The population growth for 2100 in the Walloon region was estimated at 1.43–1.61 M people (Sect. 3.2.1). Since the mean number of inhabitants per household in 2100 will presumably lie in-between 2.00 and 2.29 (2008 value), the number of new households in the Walloon region between 2008 and 2100 could be reasonably estimated at 700 000.

For a given threshold, a raster of the settlement cores distribution (SC) could be created by reclassifying the corresponding potential map (1 – core settlement; 0 – other) and a raster of the future housing density (FHD) could be obtained using

$$\text{FHD} = \text{SC} \cdot (20 - \text{HD}), \quad (4)$$

where HD is the raster of the present housing density, as elaborated by Dujardin et al. (2010), in which values above 20 housing ha⁻¹ were reclassified to 20 housing ha⁻¹. The best threshold value was obtained, for each potential map, using the false position method and Eq. (4) to link the thresholds values to the total amount of new housing.

Previous studies on the definition of settlement cores in the Walloon region considered that actual settlement cores should have a minimum size. This threshold was usually set at 150 inhabitants (Van der Haegen et al., 1981; Van Hecke et al., 2009). Since one cell of a settlement core contains 20 or more residential units, each of them accommodating a household of 2.00–2.29 inhabitants, a threshold of 4 ha (4 cells) was selected as the most reasonable for our purpose. As a result, each settlement core made of less than four cells was removed. The neighbourhood used is eight cells.

3.2.3 2100 land use databases

For each of the nine urbanization scenarios for 2100, the future residential areas (defined based on the *plan de secteur* or on the settlement cores) were integrated into the present PLI and land registry database. Land plots were first divided to fit with the boundaries of the 2100 residential areas. Next, the land use category of each non-built land plot situated in a future residential area was modified by substituting “residential area” to the past land use category.

3.2.4 Specific prices

Finally, for each scenario, a specific price was assigned to each land plot depending on its land use category. Specific prices (given in year 2009 euros) were derived from ATKIS (the official topographic-cartographic information system of Germany (Muller, 2000; Sinaba and Peter Huber, 2011)) data, and adapted to correspond to the mean specific price of residential areas in the Walloon region (Table 3). Residential area is the only land use category for which price data are available in the studied area. To estimate the adaptation factor, a specific price for the residential areas in the 19 studied municipalities was first assessed by dividing the average price of a house (€ 129 427, from real-estate transactions in 2009) by the mean size of residential land plots in the maximum flooded area (332 m²). The specific price obtained for settlement in the studied area is € 389 m⁻², i.e. 31 % more than the ATKIS value. Consequently, ATKIS specific prices for the land use categories potentially influenced by the real-estate market

Table 3. Specific prices used for the damage assessment.

ATKIS damage category	ATKIS values		Walloon Meuse values	
	Immobile [€ m ⁻²]	Mobile [€ m ⁻²]	Immobile [€ m ⁻²]	Mobile [€ m ⁻²]
Miscellaneous (wood, lake)	0.00	0.00	0.00	0.00
Residential area	295	119	389	119
Industry and business area	260	90.0	343	90.0
Mixed used	496	99.5	496	99.5
Governmental utilization	281	1.32	370	1.32
Leisure and recreation area	10.5	0.00	10.5	0.00
Infrastructure	106	280	106	280
Grassland and cultivated area	2.61	0.00	2.61	0.00
Supply buildings	297	2.17	297	2.17
Forestry	0.99	0.00	0.99	0.00

(residential, industrial and business, governmental use areas) were multiplied by 1.31. Only specific prices for buildings were adapted, whereas ATKIS values were used for mobile assets, as proposed by Sinaba and Peter Huber (2011).

3.3 Flood damage assessment

The objective of this step (no. 3 in Fig. 1) is to combine inundation depths with exposure to obtain flood damage for each municipality. Stage–damage functions were used to assess the relative damage for each land plot (Fig. 8). The Flood Loss Estimation Model (FLEMO) was used for the residential, industrial, and commercial land plots (Kreibich et al., 2010; Thielen et al., 2008). For forestry, agriculture, and infrastructure we used stage–damage functions from the Rhine Atlas (IKSR, 2001). The same curve was used for mobile and immobile assets, except for industrial and commercial assets, for which separate damage curves are available (FLEMOcs, Kreibich et al., 2010). The spatial resolutions of the inundation depth data (5 m × 5 m raster) and the land use data (land plots geometry) are consistent.

The computed relative damage was multiplied by the specific price and by the area of the processed land plot in order to obtain absolute damage. Finally, absolute damages of each land plot were summed up to deduce the amount of damage in each municipality.

The damage assessment was carried out for the Q_{100} and $Q_{100} + 30\%$ discharges, combined with the present urbanization and the nine future land use scenarios.

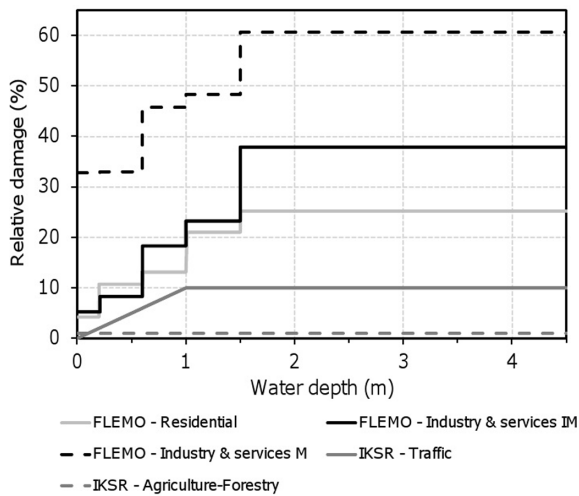


Fig. 8. FLEMO and IKSR damage curves. Black: industrial and commercial areas (dotted line represents mobile assets; continuous line, immobile assets); light grey: residential areas; dark grey: infrastructure; dark grey, dotted line: forestry and agriculture.

4 Results

4.1 Future urbanization

4.1.1 Dense urban development scenarios

Before describing the location of new residential areas according to the DUD scenarios, the following intermediate results are successively presented: the employment-related potential, and the potential maps for the two DUD scenarios, as well as an example of exclusion areas.

As shown in Fig. 9, the employment-related potential is highly influenced by the capital city Brussels, where the highest number of jobs in Belgium are concentrated. The regional city Charleroi is also characterized by a high potential, partly due to its relative proximity to Brussels. In contrast, the potential is much lower in the southeastern part of the Walloon region (the Ardennes Massif), particularly along the French and German borders. It slightly increases near the Grand Duchy of Luxembourg because of the high number of jobs in this country.

The potential maps for new residential areas are shown in Fig. 10 for the two subsets of DUD scenarios: regional vs. local development (Sect. 3.2.2). In the first case, the maps reflect the influence of the employment-related potential, while in both cases the spatial distribution of high values of the potential is determined by existing household density and land use diversity.

As an example, the exclusion areas in the centre of Liège are illustrated in Fig. 11. 21.6% of the Walloon territory (i.e. 3640 km²) fall in such exclusion areas, considered as inappropriate for housing. Natura 2000 areas represent 60.4% of the whole exclusion area.

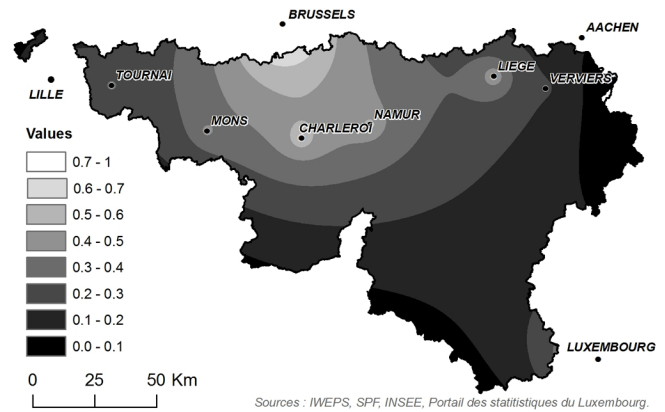


Fig. 9. Employment-related potential in the Walloon region, used to define the core settlements according to the dense urban development scenario (regional development). Values were standardized and are consequently non-dimensional.

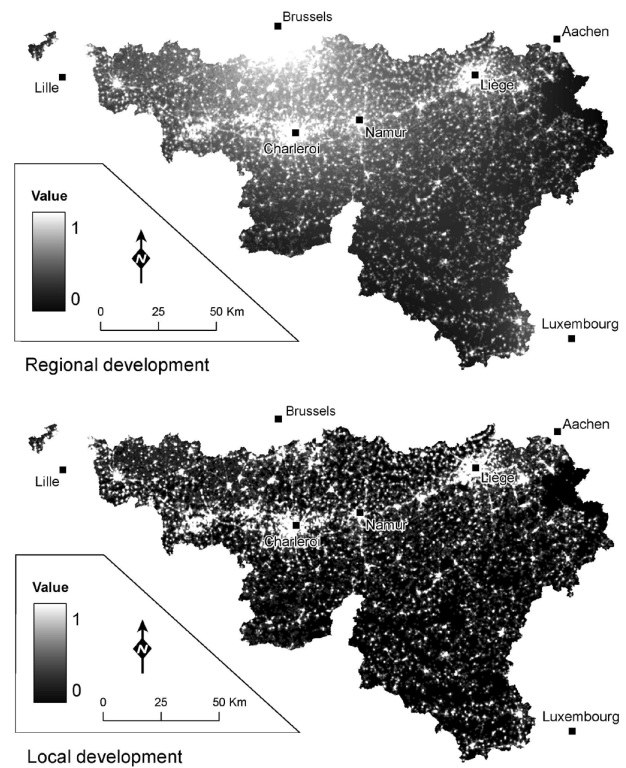


Fig. 10. Potential maps for new residential areas in the Walloon region in the two subsets of dense urban development scenarios.

Six operational potential maps were obtained by combining the two potential maps presented in Fig. 10 with the three different levels of restriction on development based on the flood hazard maps. After subtracting exclusion areas, thresholds were applied to these maps to define six spatial distributions of settlement cores, as shown in Fig. 12 for the scenarios “regional development, high flood hazard” (Fig. 12a) and “local development, high flood hazard”

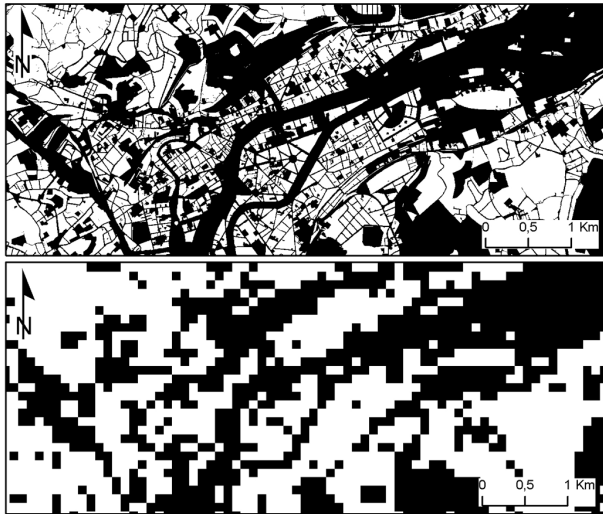


Fig. 11. Exclusion areas in the centre of Liège: vector representation of raw data (top) and raster representation used in the analysis (bottom).

(Fig. 12b). In these figures, flood hazard and exclusion areas were not subtracted from the settlement cores, in order to improve the map readability. Comparing the six DUD scenarios reveals that the different levels of consideration of the flood hazard maps do not significantly change the overall pattern of the settlement cores distribution. In the regional development scenario (Fig. 12a), three large settlement cores are defined: Charleroi, Liège, and the southern suburb of Brussels. These correspond to the main employment areas. Settlement cores are scarce and small within the Ardennes (southeast). In the case of the local development scenario (Fig. 12b), settlement cores show a more scattered distribution. No large settlement core exists in the suburb of Brussels, and the Ardennes settlement cores are more numerous and larger than in the regional development scenario.

4.1.2 Comparison of scenarios

As an example, the spatial distributions of future residential areas near the city Namur is shown in Fig. 13 for the different scenarios (current trend, DUD regional development, and DUD local development). In the same way as the level of restriction on development in flood-prone areas does not significantly change the pattern of settlement cores at the scale of the whole Walloon region, its influence on the overall regional distribution of future residential areas remains also insignificant: within each family of scenarios, changing the level of restriction on development in flood-prone areas does not change the total surface area of new residential areas by more than 1%. In Fig. 14, the evolution of urbanization for each family of scenarios is detailed for each of the 19 studied municipalities.

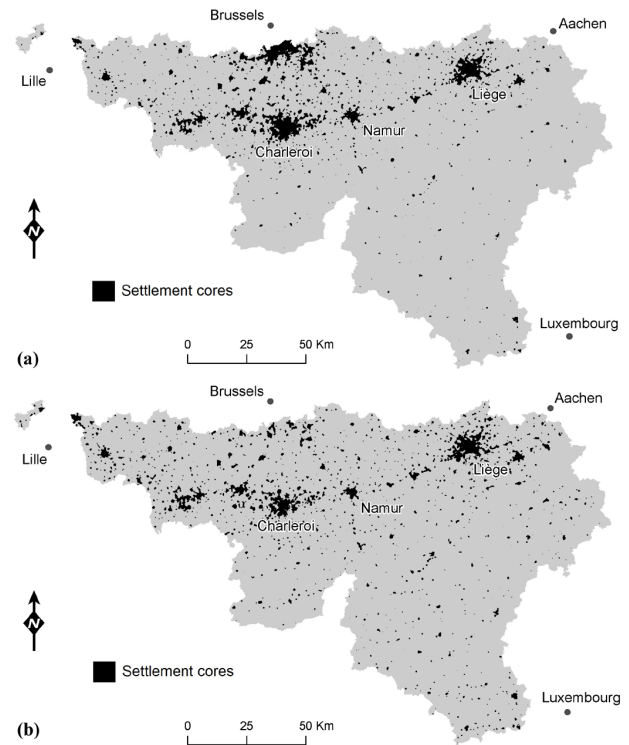


Fig. 12. Delimitation of the settlement cores in the two subsets of dense urban development scenarios: regional (a) and local (b) development scenarios. At this stage, neither the exclusion areas nor the high or moderate flood hazard areas were subtracted from the settlement cores in order to improve map readability.

In the current trend scenario (Fig. 13a), future residential areas are more widespread in comparison to the two other scenarios (Fig. 13b and c). Section 3.1.2 already highlighted this effect of dispersion of the future residential areas when the *plan de secteur* is used. In this scenario, future urbanized areas have a larger extent in every municipality than they have in the DUD scenarios (Fig. 14a). This difference reaches between -69% and -74% on average in the 19 municipalities (Fig. 14b). Differences between the two DUD scenarios are smaller. New residential areas are larger in the local development scenario in 15 municipalities, similar between both scenarios in two municipalities and larger in the regional development scenario for two others (Namur and Liège), which correspond to a high employment-related potential.

4.2 Flood damage

4.2.1 Damage evolution between 2009 and 2100

Computed damages for all scenarios are shown in Table 4. In the present situation (2009), the damage induced in the Walloon region by a 100 yr flood of the river Meuse is estimated at € 331 million. Most of the damages take place in municipalities upstream of Engis, since flood protections

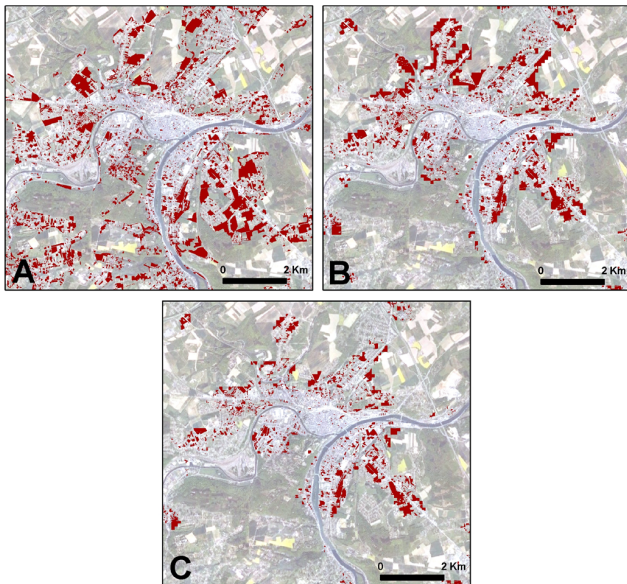


Fig. 13. New residential areas in Namur, year 2100. (A) Current trend scenario; (B) dense urban development, regional development scenario; and (C) dense urban development, local development scenario. A high level of restriction on development in flood-prone areas was considered here.

further downstream were designed for the 100 yr flood (Figs. 2 and 15). In the dry climate scenario, the damage in 2100 reaches between € 334 and 462 million, depending on the urbanization scenario. This corresponds to an increase of 1–40 %.

In the wet climate scenario, the damage in 2100 reaches between €2124 and 2408 million, which corresponds to an increase of 540–630 % (Fig. 16). The increase in damage varies strongly between municipalities. In the south, the municipalities of Hastière, Dinant, Anhée, Yvoir, and Philippeville undergo relatively moderate damage increases, partly because the inundation extent does not change a lot between the discharges Q_{100} and $Q_{100} + 30\%$ (Fig. 2). This results from the topography of the valley in this part of the river Meuse. The river crosses there the Ardennes Massif composed of resistant Palaeozoic rocks. Consequently, the floodplain is relatively narrow (250–350 m wide) with steep lateral slopes, and is completely flooded for the Q_{100} discharge. However, water depth increases by 125 % on average in this area compared to the Q_{100} discharge, reaching 3 m in some places. This induces a doubling of the damage in these municipalities when considering the most pessimistic urbanization scenario. Downstream of Philippeville the increase in damage is larger, varying between a factor 1.9 for Andenne to more than 5000 for the municipalities downstream of Wanze which are almost not flooded for a Q_{100} flood in the present situation. In terms of absolute damage, the largest increases in the wet scenario are observed in Liège (+€ 430–450 million), Seraing (+€ 275

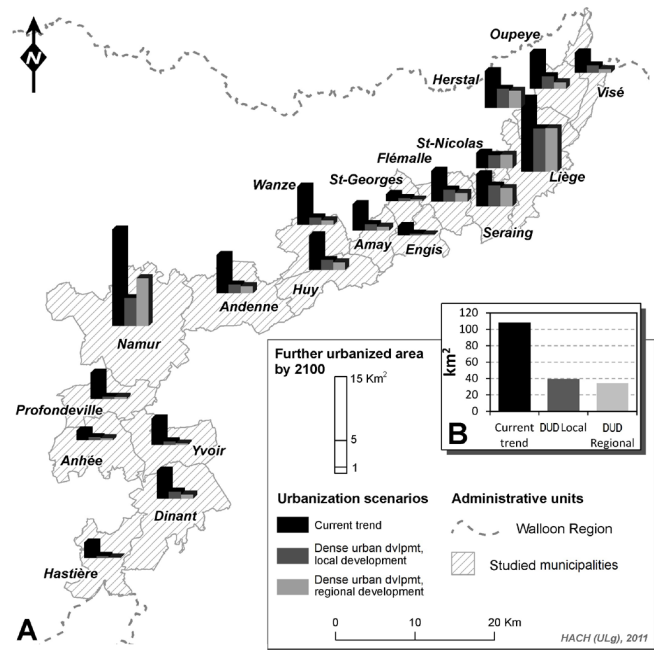


Fig. 14. Increase in residential areas between 2009 and 2100 within the 19 municipalities studied. (A) Detail by municipality, and (B) sum over the 19 municipalities.

Table 4. Expected damages for a 100 yr flood of the river Meuse in the Walloon region in 2009 (reference) and in 2100 (values in million euros). Building restrictions for 2100 are based on the available flood hazard map: high means no building in the high and medium flood hazard areas; medium, no building in the high flood hazard areas; low, no restriction.

Discharges	2009	Urbanization scenarios for 2100			
		Level of building restriction	DUD Regional	DUD Local	Current trend
Q_{100}	331	high	334	334	351
		medium	342	345	378
		low	364	377	462
$Q_{100} + 30\%$	1935	high	2124	2138	2246
		medium	2149	2169	2304
		low	2186	2213	2408

million) and Namur (+€ 220–240 million). These three municipalities are characterized by large urbanized areas along with a large increase in flooded area between 2009 and 2100 (Fig. 2).

4.2.2 Relative contribution of climate change and urbanization

In the dry scenario, the relative contribution of climate change to the increase in flood damage between 2009 and 2100 remains zero. This results simply from the definition

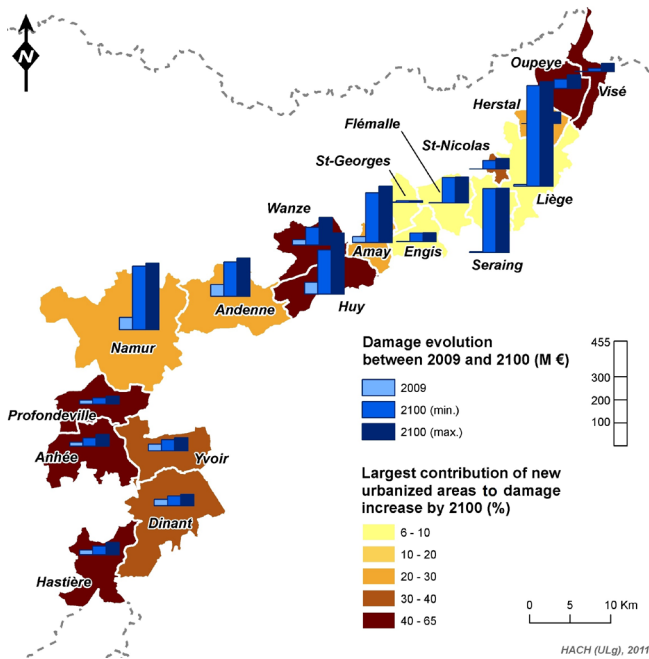


Fig. 15. Flood damage evolution between 2009 and 2100 for the 100yr flood according to the wet climate scenario, and relative contribution of future urbanization to damage by municipality.

of the dry climate scenario considered here (Sect. 3.1.1). The corresponding relative contribution for the wet scenario is given by the difference between the damage in the present situation and the damage induced by the $Q_{100} + 30\%$ flood combined with the present land use. The remaining part of the additional damage is due to urbanization. This is shown in light grey in Fig. 16. For the whole study area, the contribution of climate change is considerably larger than that of land use change, reaching 77–89% depending on the land use evolution scenario. However, the relative influences of both effects varies between the municipalities. This is illustrated in Fig. 15, where the colour of the municipalities represents the relative contribution of urbanization in the increase of damage. In the upstream part, Hastière, Dinant, Yvoir, Anihée, and Profondeville show a maximum contribution of urbanization to the increase of damage between 32% (Yvoir) and 54% (Anihée). In this case, the contribution of urbanization in the current trend land use evolution scenario is significantly larger than that of climate change. In Namur and Andenne, the contribution of urbanization to the additional damage is limited (22–27% and 7–21%, respectively). For the current trend scenario in Huy and Wanze, it reaches 42% and 46%, respectively. This is due to the vast amount of land plots remaining available for building development in the 2100 flood-prone area in these two municipalities. The influence of future urbanization significantly decreases from Engis to Liège, due to the limited availability in non-built land plots in

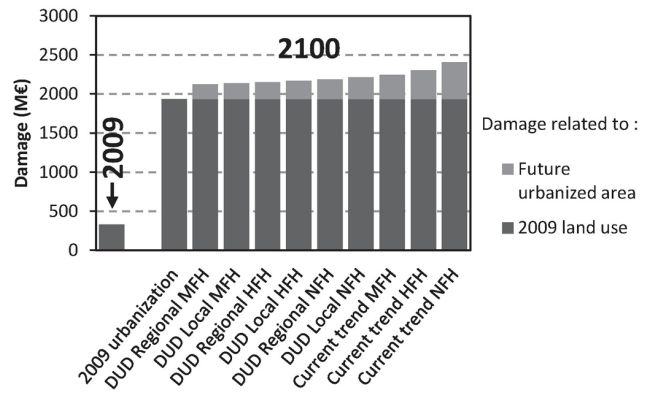


Fig. 16. Evolution of flood damage between 2009 and 2100 for a 100yr flood of the river Meuse and according to a wet climate scenario. DUD is dense urban development; MFH, no new residential areas in the medium and high flood hazard areas; HFH, no new residential areas in the high flood hazard areas; and NFH, the flood hazard map is not considered for spatial planning.

the flood hazard areas in these municipalities. Finally, the relative contribution of urbanization to the additional damage is higher in Oupeye and Visé, which are two essentially rural municipalities. The maximum value is reached in Visé (65% in the current trend scenario) for the same reason as in Huy and Wanze.

5 Discussion

We successively discuss the land use evolution models and the computed estimates for future flood damage.

5.1 Future urbanization

Since the *plan de secteur* remains one of the main driving forces of urbanization in the Walloon region, it is of particularly high relevance to take it into account in the analysis of future land use evolution. This supports the use of our “current trend” family of land use scenarios.

The development of original DUD scenarios may be analysed in the light of the six main characteristics of land use evolution models according to Verburg et al. (2004). Since characteristics of the territory, and not of individuals, were used in the model, the level of analysis is the macro-scale. Nonetheless, cross-scale dynamics were considered: the regional level was used to assess the future land use demand, while the definition of settlement cores and exclusion areas were based on data at the local level. No feedback was considered between the different levels. Driving forces were considered here, not to explain past land use evolution, but to identify spatial opportunities for a future spatial planning enabling the ongoing urban sprawl to be better controlled and mitigated. This is in line with the

methodology developed by CPDT (2010) in a similar study focused on the region of Huy. The three identified driving forces are related to spatial interactions (employment-related potential) and neighbourhood effects (function diversity, housing density). Finally, temporal dynamics were also considered by multiplying the future scenarios.

Results of our models show significant differences in terms of additional urbanized areas between 2009 and 2100. More significant and spatially more uniform is the difference between the two main families of scenarios: current trend vs. DUD scenario (Fig. 14). The reason for this is twofold. First, in the DUD scenarios, the density of households in settlement cores may be increased even if no more land plots are available for building. Consequently, to accommodate a given number of inhabitants, less area is needed in the DUD scenarios than in the current trend scenarios. Second, the DUD scenarios were developed in a way which land use supply corresponds to land use demand in 2100 at the level of the Walloon region. However, the future demand may show spatial variations (e.g. linked to the uneven distribution of population growth) so that the balance between supply and demand is not met everywhere. Consequently, assuming a spatial homogeneity of land demand may cause local over- or underestimations of both the number and the size of core settlements. This in turn may lead to over- or underestimations of flood damage.

Only the development of future residential areas is reproduced in the land use evolution models. In reality, all other land use categories will also evolve and influence future flood damage. Nevertheless, damage assessments in the current situation have shown that the residential sector represents over 54 % of the total damage at the level of the 19 municipalities. Moreover, the residential sector is the land use category in which the most important changes will occur in the flood-prone areas of the river Meuse for $Q_{100} + 30\%$. Therefore, neglecting the other land use categories in the land use evolution models leads to a limited underestimation of the additional damage due to future land use changes in the floodplains of the river Meuse.

5.2 Flood damage

5.2.1 Relative contribution of climate change and urbanization

The relative contribution of climate change and urbanization to future flood damage is highly dependent on the considered climate scenario. In the dry scenario, urbanization is the only factor influencing the evolution of flood damage, while in the wet scenario the effect of climate change largely exceeds the contribution of urbanization. The results of the wet climate scenario are discussed here in comparison with previous studies carried out in northwest Europe. Despite differences in the studied areas, the methodology and the formulation of the results, our results in the wet climate scenario are

consistent with those of te Linde et al. (2011). Based on the analysis of the evolution of flood risk along the Rhine river between 2000 and 2030, te Linde et al. (2011) obtained basin-wide flood risk increases by 43–160 % due to climate change, whereas land use change resulted in increases of only 6.5–27 %. The computed flood risk/damage increases are higher in the case of the present study (542–628 %), compared to the Rhine study (43–230 %), since the time horizon considered here is also far more distant (2100 vs. 2030). However, the relative contributions of both factors are similar. Elmer et al. (2012) obtained opposite results in a German catchment. Based on the study of the drivers of flood risk change in residential areas between 1990 and 2020, they concluded that the expansion of residential areas would be the main driver of flood risk evolution in this region. Poussin et al. (2012) studied the same issue for a section of the river Meuse in the southeast of the Netherlands between 2000 and 2030. Unlike in the present study, Poussin et al. (2012) assumed that flood protections may be upgraded in the future to preserve their current nominal protection standards. Without this upgrade, the relative contribution of land use change exceeds the effect of climate change, whereas, with upgraded flood protections, both effects are similar in a “low” scenario and, in a “high” scenario, climate change impacts exceed those of land use change. The “low” scenario refers here to a “low” climate scenario combined with a “low” land use scenario, as defined by Poussin et al. (2012), and conversely for “high” scenario. Three main elements can explain these differences. First, the wet climate scenario considered here is relatively extreme, and the time horizon (2100) is more distant than those used in the two previous studies. As emphasized by Elmer et al. (2012), the climate influence could be more decisive in the long term. Second, the land use characteristics of the three studied areas are very different: the study area in the present study is much more urbanized than those analysed by Elmer et al. (2012) and Poussin et al. (2012). Consequently, less space is available for new residential areas in the river Meuse valley in the Walloon region, and the relative influence of new urbanization on flood damage evolution is therefore reduced. Finally, no legal constraints force water authorities in the Walloon region to systematically upgrade flood defence systems to maintain protection against a given design flood, and, as a result, flood protection projects are evaluated on a case-by-case basis. Therefore, our modelling did not include upgrades in the flood protections until 2100. This simplification may partly explain the contrast between our results and some findings of Poussin et al. (2012).

Based on our results for the wet climate scenario, more sustainable spatial planning, limiting urban sprawl, would not be sufficient to substantially reduce the future rise in the overall flood damage induced by a 100 yr flood of the river Meuse in the Walloon region. Additional flood protection measures should therefore be planned. Nonetheless, in seven

of the studied municipalities, specifically considering flood hazard areas for spatial planning would reduce future flood damage by over 40 %.

5.2.2 Flood damage and urbanization scenarios

The results demonstrate that the type of land use evolution scenario influences the future value of flood damage, as shown in Fig. 16 for the wet climate scenario. The current trend scenarios lead to the highest increase in damage. These differences may result from the combined effect of differences in the extents of the new residential areas and in the location of these areas with respect to the flood hazard zone. As shown in Sect. 4.1.2, the current trend scenarios lead to the largest increase in the surface of new residential areas. In contrast, using the concept of settlement cores, in the DUD scenarios, promotes the concentration of new residential areas near the centre of urban agglomerations, which are generally closer to the main riverbed. Moreover, the spatial distribution of new residential areas is more dispersed in the current trend scenarios (see for instance Fig. 13). Consequently, the results demonstrate that the wider expansion of new residential areas in the current trend scenarios has a more detrimental effect on damage than the concentration of new residential areas in the DUD scenarios.

For the case of the wet climate scenario, Table 5 shows the effect of different levels of restriction on development in flood hazard areas. Prohibiting residential buildings within the high-hazard zone only, which is the current practice in the Walloon region, enables the future flood damage in the river Meuse valley to decrease by 1.7–2.0 % (DUD scenarios) to 4.3 % (current trend scenario). If new developments are prohibited both in the high and in the medium hazard zones, the decrease in damage reaches 2.8–3.4 % to 6.7 %. Although relatively small, these effects remain significant. This highlights the importance of accounting for the available knowledge on flood hazard in spatial planning along the river Meuse. A next step could be to control future developments also in the low-hazard areas of the present flood maps, but a more sensible solution would consist in preparing updated flood hazard maps taking into account the effects of climate change on future flood discharges.

5.3 Limitations

Uncertainties on absolute flood damage values are high and difficult to quantify (de Moel and Aerts, 2011). As discussed below, this results from the numerous sources of uncertainties affecting flood damage assessment, as well as from the underlying assumptions.

Particularly high uncertainties arise from the climate change projections. Their influence on flood hazard was appreciated here by considering just two climate change scenarios (“wet” vs. “dry”). The extreme value statistics

Table 5. Influence of the degree of restriction on future development in flood-prone areas using the present-day flood hazard map on the decrease in flood damage in the 19 municipalities for the wet climate scenario. Values are the damage decrease (%) compared to the non-consideration of the flood hazard map.

	High flood hazard	Moderate and high flood hazard
Current trend	4.29	6.72
Dense urban development, regional development	1.68	2.83
Dense urban development, local development	1.99	3.41

used for flood frequency analysis introduce additional uncertainties into the estimations of the present and future 100 yr flood discharges. This was emphasized by Apel et al. (2008), who quantified this effect in the case of the Rhine river. Assuming no evolution in the flood defence system is obviously a simplifying assumption.

The main limitations in the assessment of future exposure result from the following three simplifications: (i) a single population growth scenario was considered, (ii) only residential areas were modelled, and (iii) they were lumped into one single class because our land use evolution models do not handle different trends depending on the type of residential areas. Moreover, the age of the buildings was not taken into account in the estimation of the specific prices, which were assumed constant in time. Adapting our modelling approach for the residential sector to other land use categories, such as trade and industry, would highly improve the future exposure assessment.

The absolute values of present and future flood damage should be considered with care since, as it is generally the case, absolute damage estimates differ significantly between different damage models (Bubeck et al., 2011; Jongman et al., 2012). The value of the elements at risk and the damage curves constitute the main sources of uncertainties (de Moel and Aerts, 2011; Jongman et al., 2012). So far, no damage curve has been specifically developed for the Walloon region. Filling this gap would significantly improve the accuracy of the results. A better quantification of uncertainties would be obtained if the exposure and vulnerability models could be validated based on observed flood damage data in the Walloon region. This type of information is recorded by the Belgian Disaster Fund, but available data so far significantly underestimate exposure and damage, and are therefore difficult to use (Ernst et al., 2010). Collecting more reliable damage data in the river Meuse valley is an essential work to be conducted in the future. However, we focus here on relative changes in damage, and these are considered as relatively well detected by current

damage models, despite inaccuracies in the absolute damage estimates (Bubeck et al., 2011).

Finally, different return periods should be considered to derive the annual expected damage and perform a genuine risk assessment. The EU Floods Directive (2007/60/EC) recommends using three return periods. Several studies suggest that more return periods are needed to derive a reliable estimate of the risk (e.g. Messner et al., 2007; Ernst et al., 2010; Penning-Rowsell et al., 2010; Ward et al., 2011a).

6 Conclusions

Damages induced by a 100 yr flood of the river Meuse in the Walloon region (Belgium) were assessed at the level of individual land plots. Two time horizons were considered: present (2009) and 2100. To account for the evolution of exposure between 2009 and 2100, a new methodology has been developed to model future developments in the residential sector. Nine different spatial planning scenarios were considered, together with two climate scenarios (“dry” and “wet”). Results show that, between 2009 and 2100, flood damage could be multiplied by 1.01–1.4 in the dry scenario and by 5.4–6.3 in the wet one. In the dry scenario, urbanization is the only influencing factor because 100 yr flood discharge is assumed not to increase. In contrast, in the wet scenario, the effect of climate change is 3–8 times more influential than the effect of urbanization. These results must be considered in the light of the particularly wet hydrological scenario used as well as the assumption of no evolution of protection measures.

As shown by the results, a distinctive spatial pattern can be identified between the different municipalities along the river Meuse in the Walloon region. In the case of the wet climate scenario, careful spatial planning for new residential areas has a limited effect on the the total damage increase by 2100, whereas, in 2 out of the 19 studied municipalities, the influence of future urbanization even exceeds the effect of climate change. Consequently, careful spatial planning, considering specifically future flood hazard, definitely needs to be promoted to reduce the future increase in flood damage in several municipalities. This should be complemented by additional flood protection measures in other municipalities, in which the Meuse valley is already densely urbanized.

Appendix A

Table A1. Correspondence between the land use categories of the land registry of the Walloon region and the classes of specific price used in the damage assessment.

Classes in the Land Registry (in French)	Classes of specific prices
Habitations et dependances	Residential area
Immeubles a appartements – Habitations superposees	Residential area
Agriculture – Horticulture – Elevage	Industry and business area
Artisanat – Petites entreprises	Industry and business area
Industrie: production de produits alimentaires	Industry and business area
Industrie: habillement et articles usuels	Industry and business area
Industrie: materiaux de construction	Industry and business area
Industrie: autres secteurs de production que 5 a 7	Industry and business area
Industrie: batiments divers et constructions diverses, qui ne peuvent etre classes dans un secteur de production bien determine, vise sous 5 a 8	Industry and business area
Commerce – Services – Entreprises “horeca”	Industry and business area
Batiments publics – Batiments d’utilite publique	Governmental utilization
Bienfaisance – Hospitalisation – Soins	Governmental utilization
Enseignement	Governmental utilization
Cultes	Governmental utilization
Vancances – Sports – Récreation – Culture	Leisure and recreation area
Batiments speciaux	Supply buildings
Agriculture et Horticulture	Grassland and cultivated area
Arbres	Forestry
Recreation	Leisure and recreation area
Eaux	–
Chemins cadastres	Infrastructure
Terres vaines et vagues	–
Industrie	Industry and business area
Destination speciale	–
Materiel et outillage non bati	Infrastructure

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References

- Antoni, J.-P.: Calibrer un modèle d'évolution de l'occupation du sol urbain: L'exemple de Belfort, *Cybergeo: European Journal of Geography, Systèmes, Modélisation, Géostatistiques*, 347, 19 pp. doi:10.4000/cybergeo.2436, 2006 (in French).
- Antrop, M.: Landscape change and the urbanization process in Europe, *Landscape Urban Plan.*, 67, 9–26, 2004.
- Apel, H., Merz, B., and Thielen, A. H.: Quantification of uncertainties in flood risk assessments, *International Journal of River Basin Management*, 6, 149–162, 2008.
- Ashagrie, A. G., de Laat, P. J. M., de Wit, M. J. M., Tu, M., and Uhlenbrook, S.: Detecting the influence of land use changes on Floods in the Meuse River Basin – the predictive power of a ninety-year rainfall-runoff relation, *Hydrol. Earth Syst. Sci. Discuss.*, 3, 529–559, doi:10.5194/hessd-3-529-2006, 2006.
- Barredo, J. I., Lavalle, C., Demicheli, L., Kasanko, M., and McCormick, N.: Sustainable urban and regional planning: the MOLAND activities on urban scenario modelling and forecast, *Tech. rep.*, 55 pp., European Commission Joint Research Center, available at: <http://publications.jrc.ec.europa.eu/repository/handle/111111111/7836>, last access: 30 June 2012, 2003.
- Bubeck, P., de Moel, H., Bouwer, L. M., and Aerts, J. C. J. H.: How reliable are projections of future flood damage?, *Nat. Hazards Earth Syst. Sci.*, 11, 3293–3306, doi:10.5194/nhess-11-3293-2011, 2011.
- Bureau fédéral du Plan: Planning paper 105 – Perspectives de population 2007–2060, *Tech. rep.*, 136 pp., Bureau fédéral du Plan, available at: http://www.plan.be/publications/Publication_det.php?lang=fr&TM=30&KeyPub=650, last access: 30 June 2012, 2008.
- Bürgi, M., Hersperger, A. M., and Schneeberger, N.: Driving forces of landscape change – current and new directions, *Landscape Ecol.*, 19, 857–868, 2004.
- Charlier, J., Reginster, I., and Juprelle, J.: Construction d'indicateurs de développement territorial: étude de la localisation résidentielle récente et analyse au regard de critères de développement territorial durable, *Tech. rep.*, 60 pp., Institut wallon de l'évaluation, de la prospective et de la statistique, available at: <http://www.iweps.be/working-paper-de-liweps-ndeg2>, last access: 30 June 2012, 2011 (in French).
- Commission internationale de la Meuse: Plan de gestion du district hydrographique international de la Meuse – Partie faitière, *Tech. rep.*, 87 pp., Commission internationale de la Meuse, available at: <http://www.meuse-maas.be>, last access: 15 December 2012, 2009 (in French).
- CPDT: Expertise veille –état du territoire wallon, annexes, *Tech. rep.*, 75 pp., Conférence permanente du développement territorial de la Wallonie, available at: http://cpdt.wallonie.be/old/Data/recherches/finalisees/subv_09-10/V3/Rapport.pdf, last access: 15 December 2012, 2010 (in French).
- Dankers, R. and Feyen, L.: Climate change impact on flood hazard in Europe: An assessment based on high-resolution climate simulations, *J. Geophys. Res.*, 113, D19105, doi:10.1029/2007JD009719, 2008.
- Dautrebande, S., Colard, F., Dagnelies, J., Gaspar, S., and Vandendael, L.: Détermination de la “courbe enveloppe” des zones d'inondation de cours d'eau en Région wallonne par une méthode hydropédologique, in: *Les risques majeurs en Région wallonne: prévenir en aménageant*, edited by: Direction générale de l'Aménagement du territoire du Logement et du Patrimoine, Ministère de la Région wallonne, Namur, 90–97, 2006 (in French).
- Delforge, Y. and Géron, G.: Les noyaux d'habitat en Wallonie: je t'aime, moi non plus!, *Les cahiers de l'urbanisme*, 67, 16–20, 2008 (in French).
- de Moel, H. and Aerts, J. C. J. H.: Effect of uncertainty in land use, damage models and inundation depth on flood damage estimates, *Nat. Hazard*, 58, 407–425, 2011.
- de Moel, H., van Alphen, J., and Aerts, J. C. J. H.: Flood maps in Europe – methods, availability and use, *Nat. Hazards Earth Syst. Sci.*, 9, 289–301, doi:10.5194/nhess-9-289-2009, 2009.
- de Moel, H., Aerts, J. C. J. H., and Koomen, E.: Development of flood exposure in the Netherlands during the 20th and 21st century, *Global Environ. Chang.*, 21, 620–627, 2011.
- De Roo, A., Schmuck, G., Perdiago, V., and Thielen, J.: The influence of historic land use changes and future planned land use scenarios on floods in the Oder catchment, *Phys. Chem. Earth*, 28, 1291–1300, 2003.
- Detrembleur, S., Dewals, B., Fournier, M., Becker, B., Guilmin, E., Moeskops, S., Kufeld, M., Archangeau, P., de Keizer, O., Pontegnée, D., Huber, N., Vanneuville, W., Buiteveld, H., Schüttrumpf, H., and Pirotton, M.: Hydraulic modelling of the Meuse: WP1 report – Action 6, *Tech. rep.*, 12 pp., Interreg IVb AMICE project, 2011.
- Dorner, W., Porter, M., and Metzka, R.: Are floods in part a form of land use externality?, *Nat. Hazards Earth Syst. Sci.*, 8, 523–532, doi:10.5194/nhess-8-523-2008, 2008.
- Drogue, G., Fournier, M., Bauwens, A., Commeaux, F., De Keizer, O., François, D., Guilmin, E., Degré, A., Detrembleur, S., Dewals, B., Pirotton, M., Pontegnée, D., Sohier, C., and Vanneuville, W.: Analysis of climate change, high-flows and low-flows scenarios on the Meuse basin, *Tech. rep.*, 69 pp., Interreg IV-b AMICE project, available at: <http://orbi.ulg.ac.be/handle/2268/66197>, last access: 30 June 2012, 2010.
- Dujardin, S., Labeeuw, F.-L., Melin, E., Pirart, F., and Teller, J.: Structuration du territoire pour répondre aux objectifs de réduction des émissions des gaz à effets de serre, *Territoire(s) wallon(s)*, 6, 43–57, 2010 (in French).
- Elmer, F., Hoymann, J., Dütthmann, D., Vorogushyn, S., and Kreibich, H.: Drivers of flood risk change in residential areas, *Nat. Hazards Earth Syst. Sci.*, 12, 1641–1657, doi:10.5194/nhess-12-1641-2012, 2012.
- Ernst, J., Dewals, B. J., Detrembleur, S., Archangeau, P., Erpicum, S., and Pirotton, M.: Micro-scale flood risk analysis based on detailed 2D hydraulic modelling and high resolution geographic data, *Nat. Hazards*, 55, 181–209, 2010.
- Erpicum, S., Dewals, B. J., Archangeau, P., Detrembleur, S., and Pirotton, M.: Detailed inundation modelling using high resolution DEMs, *Engineering Applications of Computational Fluid Mechanics*, 2, 196–208, 2010.
- Giron, E., Coninx, I., Dewals, B. J., El Kahloun, M., De Smet, L., Sacre, D., Detrembleur, S., Bachus, K., Pirotton, M., Meire, P., De Sutter, R., and Hecq, W.: Towards an integrated decision tool for adaptation measures – case study: floods, ADAPT final report phase 1., *Tech. rep.*, Belgian Science Policy, 2009.

- Gregory, D., Johnston, R., Pratt, G., Watts, M., and Whatmore, S.: The Dictionary of Human Geography, John Wiley & Sons, Chichester, UK, 2011.
- Groupe Transversal Inondations: La cartographie des zones d'inondation dans le cadre du Plan "PLUIES", in: Les risques majeurs en Région wallonne: prévenir en aménageant, edited by Direction générale de l'Aménagement du territoire du Logement et du Patrimoine, Ministère de la Région wallonne, Namur, 34–40, 2006 (in French).
- Halleux, J.-M.: Une ville compacte, qualitative ... dans les limbes, *Politique*, 55, 12–14, 2008 (in French).
- Hoymann, J.: Spatial allocation of future residential land use in the Elbe River Basin, *Environ. Plann. B*, 37, 911–928, 2010.
- Hoymann, J.: Modelling Future Residential Development: A Scenario Analysis for the Elbe River Basin, Ph.D. thesis, Techn. Univ. of Berlin, Germany, 2011.
- Huff, D.: A Probabilistic Analysis of Shopping Center Trade Areas, *Land Econ.*, 39, 81–90, 1963.
- IKSR: Atlas der Überschwemmungsgefährdung und möglichen Schäden bei Extremhochwasser am Rhein, Koblenz, Tech. rep., Internationale Kommission zum Schutz des Rheins (IKSR), 2001 (in German).
- Institut de conseil et d'études en développement durable: Atlas de Wallonie, Ministère de la Région Wallonne, Direction générale de l'Aménagement du territoire, du Logement et du Patrimoine (DGATLP), 2005 (in German).
- Jongman, B., Kreibich, H., Apel, H., Barredo, J. I., Bates, P. D., Feyen, L., Gericke, A., Neal, J., Aerts, J. C. J. H., and Ward, P. J.: Comparative flood damage model assessment: towards a European approach, *Nat. Hazards Earth Syst. Sci.*, 12, 3733–3752, doi:10.5194/nhess-12-3733-2012, 2012.
- Kreibich, H., Seifert, I., Merz, B., and Thielen, A.: Development of FLEMOcs – a new model for the estimation of flood losses in the commercial sector, *Hydrolog. Sci. J.*, 55, 1302–1314, 2010.
- Kundzewicz, Z. W.: Is the Frequency and Intensity of Flooding Changing in Europe?, in: Extreme Weather events and Public Health Responses, Chapter 1, 25–32, doi:10.1007/3-540-28862-7_3, 2005.
- Leander, R., Adri Buishand, T., van den Hurk, B., and de Wit, M.: Estimated changes in flood quantiles of the river Meuse from resampling of regional climate model output, *J. Hydrol.*, 351, 331–343, 2008.
- Lepers, M. and Morelle, D.: Occupation et affectation du sol, empreintes de la structure du territoire?, *Territoire wallon*, 2, 44–58, available at: [http://cpdt.wallonie.be/old/Data/publications/territoire\(s\)wallon\(s\)/TW2/5.occupation%20sol%20corr.pdf](http://cpdt.wallonie.be/old/Data/publications/territoire(s)wallon(s)/TW2/5.occupation%20sol%20corr.pdf), last access: 30 June 2012, 2008 (in French).
- Messner, F., Penning-Rowsell, E. C., Green, C., Meyer, V., Tunstall, S. M., and Van der Veen, A.: Evaluating flood damages: guidance and recommendations on principles and methods, Tech. rep., FLOODsite Report Number T09-06-01, 2007.
- Milly, P. C. D., Wetherald, R., Dunne, K., and Delworth, T.: Increasing risk of great floods in a changing climate, *Nature*, 415, 514–517, 2002.
- Muller, W.: ATKIS® data base revision and generation of digital topographic base maps, *International Archives of Photogrammetry and Remote Sensing*, 33, 710–717, 2000.
- Newman, P. and Kenworthy, J.: The land use – transport connexion, *Land Use Policy*, 13, 1–22, 1996.
- Overmars, K. P., Verburg, P. H., and Veldkamp, T. A.: Comparison of a deductive and an inductive approach to specify land suitability in a spatially explicit land use model, *Land Use Policy*, 24, 584–599, 2007.
- Peeters, A., Van Campenhout, J., Donnay, F., Mols, J., Snijders, J.-P., and Petit, F.: La cartographie des zones inondées: approche géomorphologique et enquêtes de terrain, in: Les risques majeurs en Région wallonne: prévenir en aménageant, edited by: Direction générale de l'Aménagement du territoire du Logement et du Patrimoine, Ministère de la Région wallonne, Namur, 44–59, 2006 (in French).
- Penning-Rowsell, E., Viavattene, C., Pardoe, J., Chatterton, J., Parker, D., and Morris, J.: The benefits of flood and coastal risk management: a handbook of assessment techniques, Flood Hazard Research Centre, London, 2010.
- Poussin, J. K., Bubeck, P., Aerts, J. C. J. H., and Ward, P. J.: Potential of semi-structural and non-structural adaptation strategies to reduce future flood risk: case study for the Meuse, *Nat. Hazards Earth Syst. Sci.*, 12, 3455–3471, doi:10.5194/nhess-12-3455-2012, 2012.
- Région Wallonne: PLI – Plan de Localisation Informatique VO6, available at: <http://dgo4.spw.wallonie.be/dgatlp/dgatlp/default.asp>, last access: 9 April 2012, 2012 (in French).
- Sinaba, B. and Peter Huber, N.: Quantification of the impacts of future floods on the economy in the transnational Meuse basin – Flood Risk Assessment Methodology – Action 7, Tech. rep., Interreg IV-b AMICE project, 2011.
- SPF Finances: SPF Finances – Documentation Patrimoniaire, Informatisation du plan cadastral: le projet CADMAP, available at: <http://minfin.fgov.be/portail2/fr/current/spokesperson-12-07-03.htm>, last access: 30 June 2012, 2012.
- te Linde, A. H., Bubeck, P., Dekkers, J. E. C., de Moel, H., and Aerts, J. C. J. H.: Future flood risk estimates along the river Rhine, *Nat. Hazards Earth Syst. Sci.*, 11, 459–473, doi:10.5194/nhess-11-459-2011, 2011.
- Thielen, A., Ackermann, V., Elmer, F., Kreibich, H., Kuhlmann, B., Kunert, U., Maiwald, H., Merz, B., Müller, M., Piroth, K., Schwarz, J., Schwarze, R., Seifert, I., and Seifert, J.: Methods for the evaluation of direct and indirect flood losses, in: 4th International Symposium on Flood Defence: Managing Flood Risk, Reliability and Vulnerability, 6–8 May 2008, Toronto, Ontario, Canada, 2008.
- Tu, M., Hall, M. J., De Laat, P., and De Wit, M.: Extreme floods in the Meuse river over the past century: aggravated by land-use changes?, *Phys. Chem. Earth Pt. C*, 30, 267–276, doi:10.1016/j.pce.2004.10.001, 2005.
- UNISDR: 2009 UNISDR Terminology on Disaster Risk Reduction, United Nations International Strategy for Disaster Reduction, Tech. rep., 30 pp., 2009.
- Van der Haegen, H., Pattyn, M., and Rousseau, S.: Dispersion et relations de niveau élémentaire des noyaux d'habitat en Belgique – Situation en 1980, *Bulletin de Statistique*, 5–6, 265–284, 1981 (in French).
- Van Hecke, E., Halleux, J., Decroly, J., and Mérenne-Schoumaker, B.: Noyaux d'habitat et régions urbaines dans une Belgique urbanisée, in: Monographie urbanisation de l'Enquête socio-économique 2001, SPF Economie, PME, Classes moyennes et Energie, Brussels, 2009 (in French).

- van Pelt, S. C., Kabat, P., ter Maat, H. W., van den Hurk, B. J. J. M., and Weerts, A. H.: Discharge simulations performed with a hydrological model using bias corrected regional climate model input, *Hydrol. Earth Syst. Sci.*, 13, 2387–2397, doi:10.5194/hess-13-2387-2009, 2009.
- Verburg, P. H.: Simulating feedbacks in land use and land cover change models, *Landscape Ecol.*, 21, 1171–1183, 2006.
- Verburg, P. H., Veldkamp, A., Espaldon, V., and Mastura, S. A.: Modelling the Spatial Dynamics of Regional LandUse: The CLUE-S Model, *Environ. Manage.*, 30, 391–405, 2002.
- Verburg, P. H., Schot, P. P., Dijst, M. J., and Veldkamp, A.: Land use change modelling: current practice and research priorities, *Geojournal*, 61, 309–324, 2004.
- Verburg, P. H., Eickout, B., and VanMeijl, H.: A multi-scale, multi-model approach for analyzing the future dynamics of European land use, *Ann. Regional Sci.*, 42, 57–77, 2007.
- Ward, P. J., de Moel, H., and Aerts, J. C. J. H.: How are flood risk estimates affected by the choice of return-periods?, *Nat. Hazards Earth Syst. Sci.*, 11, 3181–3195, doi:10.5194/nhess-11-3181-2011, 2011a.
- Ward, P. J., Renssen, H., Aerts, J. C. J. H., and Verburg, P. H.: Sensitivity of discharge and flood frequency to 21st Century and late Holocene changes in climate and land use (River Meuse, northwest Europe), *Climatic Change*, 106, 179–202, doi:10.1007/s10584-010-9926-2, 2011b.