AN ANALYSIS OF HISTORICAL EXTREME DISCHARGE SERIES WITH A VIEW TO FLOOD RISK MAPPING: A CASE STUDY

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Abstract: In the present study, the flood risk of the Sure river at the village of Steinheim (Grand Duchy of Luxembourg) was assessed with discharge data from the periods 1870-1920 and 1966-2003. To assess this flood risk, a seven step approach was used, which contains the assessment of urban development (1770-2003); rainfall runoff modelling (HBV model); peak discharge extraction; flood inundation modelling (HEC-RAS); flood extend mapping (GIS); combining flood frequency maps (GIS) and finally change detection and risk assessment. The comparison of the two comprehensive data sets, representing each a very distinct period in time, provides valuable information on the combined effect of vulnerability, land use change and climate change on flood risk. Despite a considerable amount of uncertainties, there is no doubt that the flood risk increased in the floodplain near the Steinheim village over the past 250 years. The observed change in flood risk could be attributed to some minor changes in flood frequency, but most of all to a very significant change in vulnerability. Furthermore, the findings of this study pointed out that flood risk maps should not be static tools, but should instead undergo continuous adaptation relative to possible changes in watershed hydrology due to a possible land use change or climate change. Flood prevention measures undertaken all along the river network should systematically be taken into account to measure their influence on the hazard maps and thus allow assessing the efficiency of cost-intensive flood protection measures. The study also revealed that vulnerability should be continuously monitored by using differentiated land cover maps and that most land management applications would benefit from the systematic updating of risk maps.

Keywords: hydrological modelling, extreme discharges, risk assessment

INTRODUCTION

In the last twelve years the Grand-Duchy of Luxembourg experienced its three largest flood events of the past five decades, causing considerable economic damage. From the layman's point of view this high frequency of floods seems unacceptable and keeps the hydrologist busy with the following important question: Did the frequency of extreme flood events change? The answer to this question regroups two main issues, which have become a major research priority over the last few years: climate and land use change. Regarding climate change, several studies have pointed out that there is a recent change in climate within the Rhine and Meuse basins. Climatological observations of the 19th and 20th century in the Grand-Duchy of Luxembourg show a clear trend towards higher rainfall totals as a consequence of changes in the dominating atmospheric circulation patterns (PFISTER *et al.* 2004a). Using continuous rainfall-runoff modelling and global change scenarios for the 2050 horizon, based on GCM projections from the KNMI and UKHI synoptic runs, DROGUE *et al.* (2004) demonstrate that in terms of micro- and mesoscale basins in the Grand-Duchy of Luxembourg the intra-annual contrast between high winter flow and low summer flow is amplified as a consequence of climate change and that mean winter flooding seems to be the most sensitive hydrological variable to climate change. Moreover, the observed climate change signal of the last 50 years has had very contrasting consequences on maximum stream flow, mainly due to the orientation of westerly fluxes and the influence of topography (PFISTER *et al.* 2004a). In the same study it is concluded that an increase in number of days with rainfall and/or in rainfall event duration could lead to a higher overall basin humidity, thus creating favourable conditions for high storm runoff rates. ENGEL (1997) also attributed an increase in average discharge rates and flood frequency in the Rhine during the last century to the increase in winter rainfall. During the last century, considerable changes in land use have occurred, commonly classified as urbanisation, change in forest cover and an increase in drained agricultural lands. Also, the geometry of the riverbed has changed due to erosion and sedimentation, re-naturalisation measures and the construction of hydraulic structures. The former changes have an impact on runoff generation, whereas the latter changes affect more the routing of a flood wave. However, no clear evidence exists of the impact of land use changes on flood frequency and magnitude in the main channels of the Rhine basin. Land use change may nevertheless have a significant impact on the hydrological behaviour in micro- or mesoscale river basins. Particularly urbanisation may have significant local effects in small basins with respect to flooding, especially during heavy local rainstorms (PFISTER *et al.* 2004b). Another cause of discharge regime change is the straightening of the river by reducing the floodplain with dykes and other structures. Re-naturalisation, which is applied in several locations in Luxembourg, restores the old floodplain and hence has the opposite effect on the discharge regime. For the Rhine and Meuse basins, EBEL & ENGEL (1994) have evaluated the loss in floodplain areas to as much as 70% of the initial 1400 km^2. The frequency of bank overtopping for the Geer (Belgium) increased 16 fold from 1965 to 1980 and was mainly attributed to river straightening (MABILLE & PETIT 1987).

The above-mentioned natural and/or anthropogenic changes in climate, land use and river morphology and their interaction make it difficult to predict changes in discharge regimes on every scale. This holds especially for extreme flood events, since they are very rare and their statistical properties are difficult to determine using existing observation periods. Also, major sources of uncertainty in flood risk assessment have to be expected in these same extreme value statistics (MERZ *et al.* 2002). Furthermore, identifying uncertainty sources is a difficult task, as in some cases a clear distinction between natural variability and lack-of-knowledge is unclear because of incomplete understanding of the system (APEL *et al.* 2004). However, since floodplains bring also certain gains to communities (SMITH & WARD 1998), the most realistic policy goal is to strive for the optimal use of floodplain land rather than to seek to eliminate the hazard through a total ban on development (MILLIMAN 1983). Hence, accurate quantification of flood risk is important for forecasting, planning and in many decision making processes. Not taking into account flood risk in flood prone areas during planning increases the potential socio-economic damage a flood event may have. Awareness of flood risk lessens the damage to infrastructure, public and private property including housing, commercial and industrial estates (PAPPENBERGER *et al.* 2007).

In this study, the flood risk of the Sure River is assessed at Steinheim (G.D. of Luxembourg) for the periods 1870-1920 and 1966-2003.

STUDY AREA, DATA AVAILABILITY AND METHODS

1. Study area

The study area comprises a stretch of the river Sure, its floodplain and the village of Steinheim, which is located in the eastern part of the Grand-Duchy of Luxembourg (Fig. 1). The river stretch on which the study focuses is 1.2 km long with an average slope of 0.001 m/m and has an average river width of 40 metres. The floodplain width varies between 110 and 320 metres. The village is located on the right side of the river looking downstream. The Sure River drains an area of 4,280 km^2 before reaching the village of Steinheim. Its confluence with the Mosel River is located in Wasserbillig, 22 km downstream of Steinheim.

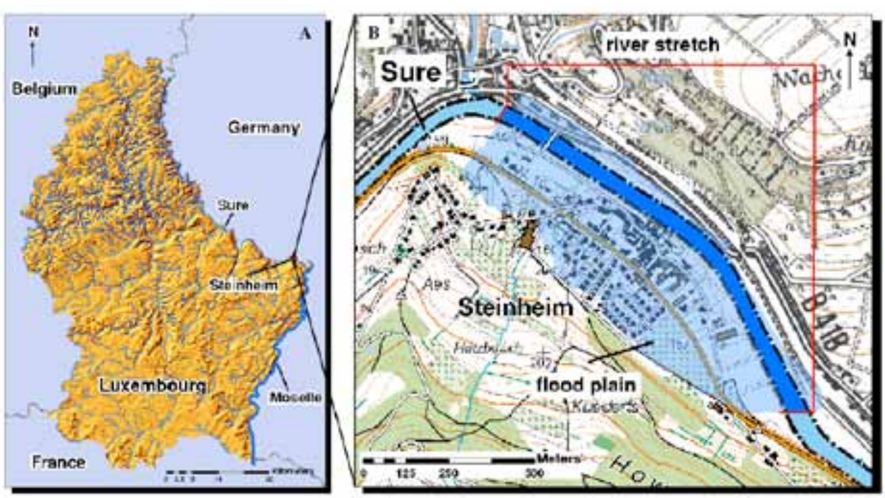

Fig. 1. Location of the village of Steinheim (G.D. of Luxembourg) (A) and a topographic map showing the study area, which includes the village, the river stretch and the natural floodplain (B).

2. Data availability

The comprehensive data set covers a period of 250 years and includes land use data, meteorological, hydrological and hydraulic as well as topographic data.

2.1. Land use data (Urban areas)

Six maps of varying detail, mapping and geo-referencing accuracy are used. Two historical maps dating back to as early as 1770 (Count of FERRARIS map, 1:50 000) and 1907 (HANSEN map, 1:50,000) are of lower mapping detail than the more recent maps of 1954, 1979, 1993, and 2003 (1:20,000) which are also used, and are difficult to process (e.g. scan, geo-rectify, digitise, etc.). Therefore, the most recent map of 2003 is taken as a reference to map urban change by removing or adding relevant structures with respect to the historical maps.

2.2. Meteorological data (rainfall and temperature)

Systematic rainfall recordings across the Sure river basins are available from 1966 to present. Temperature recordings used to estimate evaporation and transpiration (HAMON 1961) are available for the same time period. Since the meteorological data cover a longer time period than the discharge recordings, the rainfall and temperature records will be used as forcing data in a rainfall-runoff model, thereby providing the necessary input to generate a continuous discharge time series that covers the entire time period 1966-2003.

2.3. Hydrological data (discharge)

The discharge data represents the input to the flood inundation model. Water stages are continuously measured at the gauging station in Rosport from 1996 to present. Moreover, a set of historical discharge records dating back to as far as 1870 is kept at the archives of the Water Management Services. This data set is unique for Luxembourg and opens extraordinary possibilities in the sense that it allows the analysis of the combined effects of past land use changes and climate change on flood risk without having to undertake the uncertainty-laden task of modelling historical discharge series. For over 30 years, water stages were monitored in Steinheim. Using control measurements of flow velocity and assessing the river section, stage-discharge conversion was done using empirical rating curves. A data set including peak discharges of likely flood events for the time period 1870-1920 is available, thus surprisingly exceeding the measurement period of present day discharge. However, due to a lack of additional data, the accuracy of this historical data set cannot be assessed. Also, it is fairly unknown where and how historical flow velocity measurements were taken and, unfortunately, the rating curve used to compute the historical discharge series has not been archived. Hence, the metadata required for any thorough uncertainty analysis are missing.

2.4. Hydraulic data (flood depth and extent)

Measurements of maximum water level for a series of historical flood events are available within the study area. The flood inundation model is calibrated using a set of surveyed high water marks of the January 2003 event. Moreover, microwave remote sensing data (Advanced Synthetic Aperture Radar on board ENVISAT) has been processed in order to map the extent of the 2003 flood event. The SAR derived flood area is used to assess the model's ability to reproduce flood extent.

2.5. Topographic data

Topographic data are of paramount importance in any flood risk analysis. Riverbank overtopping is very much influenced by the geometry of river cross-sections and the accurate description of the micro-topography that influences river flow in the floodplain. The geometry of the study area is represented by 52 cross-sections that have been surveyed beforehand via a combination of field-based river channel surveying and aerial LiDAR scanning of the floodplain. Unfortunately, eventual changes of the channel and floodplain geometry over time cannot be assessed, since historical transects of channel geometry are not available or are incomplete. Therefore, the present day river geometry is used throughout. This means that river cross sections are kept unchanged over the years, although there is some field evidence that channel cross-sections have gradually been narrowing over time, probably due to erosion.

METHODOLOGY

As outlined in the schematic flow chart (Fig. 2), the flood risk assessment consists of 7 processing steps that are specified in detail hereafter.

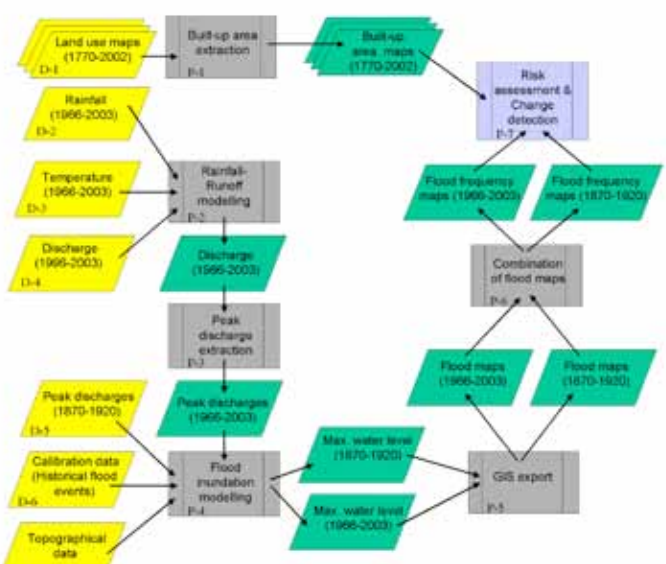

Fig. 2. Flow chart of the flood risk assessment methodology.

1. Assessing urban area development (P-1)

To map urban changes at the village of Steinheim from 1770 until 2003, the change in built-up area extracted from the six different land use maps is assessed. Due to the fact that the various maps contain a varying level of detail, no distinction was made between agricultural, commercial, residential and industrial buildings. Thus it is assumed that every single building is of equally weighted economic value. At a later stage, the urban area will be co-registered with the flood extension maps in order to assess how flood risk has changed over time.

2. Rainfall-runoff modelling (P-2)

Sufficiently long time series of river flow should be considered in any flood hazard assessment study. However, long discharge records are rarely available, whereas basic meteorological measurements of rainfall and temperature are rather frequent and reliable. As a matter of fact, discharge time series over representative time periods should be generated by rainfall-runoff modelling using historical meteorological data. In the present case study, recent discharge measurements at the gauging station of Rosport are only available from 1996 onwards, whereas meteorological data have been collected over the entire river basin ever since 1966.

Hence, processing step P-2 aims at using the historical data set of precipitation and temperature as input data to the rainfall-runoff model, thereby computing a continuous discharge record from 1966 up to 2003. The rainfall-runoff model used is an 11-parameter lumped conceptual model, which simulates discharge using basin-averaged rainfall and potential evaporation and transpiration as input data. The model is based on the widely used HBV model (LINDSTRÖM *et al.* 1997) and has been adapted to the particular environment of the Sure river basin. A detailed description of the model setup can be found in MATGEN *et al.* (2006). The rainfall-runoff model is calibrated using the recorded discharge data at Rosport from 1996 until 2003. Between 1996 and 2003 discharge data and meteorological data are synchronously available. The objective function that is used to calibrate the model is the NASH-SUTCLIFFE criterion. The SCE-UA algorithm (DUAN *et al.* 1992) is adopted to find the set of parameters that gives the highest performance measure for the time period 1996–2003 of hourly stream flow measurements. Once the model is calibrated, it can be used in simulation mode using any available meteorological data as forcing data. The simulated daily discharge values and the observed daily discharge series are assembled in one common data set, thereby creating a continuous time series of stream flow values over the period 1966-2003. Two reference time periods are now available, representing the historical (1870-1920) and the present day (1966-2003) hydrological regimes, respectively.

3. Peak discharge extraction (P-3)

The historical data set (1870-1920) only contains peak discharges of high events. Hence, in order to use similar data sets to estimate flood hazard for each time period, a preliminary task consists in extracting peak discharges from the simulated continuous discharge series (1996-2003). Preliminary tests with the calibrated flood inundation model reveal that no riverbank overtopping occurs within the modelled river reach below a discharge value of 450 m^3/s. Hence, the flood inundation model will only be run with peak discharges in each one of the two reference time periods that exceed 450 m^3/s.

4. Flood inundation modelling (P-4)

By sequentially defining observed and simulated peak discharges as the upstream boundary condition in a modelled river reach, flood inundation models allow the simulation of water levels at every cross section of the river floodplain for any flood prone event within the two reference time periods. The preliminary task consists in calibrating the hydraulic model by using observed water levels and extents of past flood events. The widely used Hydrologic Engineering Centre River Analysis System (HEC-RAS) is used for river flow computation. The HEC-RAS model has been developed by the U.S. Army Corps of Engineers and allows performing one-dimensional steady and unsteady flowing calculations. The two-dimensional flow field that is typically related to riverbank overtopping can be accurately approximated by a one-dimensional representation (i.e. velocity components in directions other than the direction of the river channel are not accounted for) because the direction of flow is mainly along channel in the case of the studied reach. The model is operated in a steady mode, because only peak discharges and not complete hydrographs of past flood events are available. Hydraulic resistance is based on the friction slope given by Manning's empirical equation. The model has been simplified and only two different roughness parameters are used to represent the channel and the floodplain. To solve the equations for the state variables stage and flow at specified points along the stream channel, HEC-RAS assumes that the water surface at each cross-section is horizontal and that the momentum exchange between the stream channel and the floodplain is negligible. On the Sure river reach, the channel and floodplain topography is represented by the geometry of 52 cross-sections perpendicularly placed to the direction of flow. The calibration consists in choosing the friction coefficients that are required to match the water levels and flood extent observed during both the January 2003 and January 1995 past flood events.

5. GIS export, flood extent mapping (P-5)

To compute flood extension maps, the HEC-RAS model outputs need to be exported into a GIS. The water level at each cross section is computed by the model, whereas between two adjacent cross-sections, the water elevation is interpolated linearly along the river reach. This allows the generation of a triangular irregular network (TIN) mesh of the water surface. The intersection of this water surface TIN and the terrain model TIN visualises event-specific flood depth and extent. The flooded zone(s) correspond to the area where the elevation of the water surface TIN exceeds that of the terrain TIN. The difference between the two gives the actual flood depth.

6. Combination of flood maps (P-6)

In order to estimate the flood hazard within the study area, flood probability maps need to be computed, thereby providing the data that are needed to estimate changes in flood frequency patterns. Therefore, for each reference time period, the flood maps are compiled and processed in order to estimate flood probability. Flood frequency is computed at the scale of hexagonal plots (area = 340 m^2) that cover the entire floodplain area. To quantify the spatially distributed changes in flood frequency and thereby enabling the assessment of eventual flood hazard changes between the two reference time periods, a flood frequency change map is derived. Flood frequency change corresponds to the difference in frequency with which cells were flooded from 1870 to 1920 and from 1966 to 2003, respectively.

In this study, hazard is thus defined as a natural phenomenon restricted to flooding. Moreover, a simplistic wet/dry classification characterises any given flood. Whilst such binary classifications are standard practice in many flood inundation studies (*e.g.* ARONICA *et al.* 2002) it may be argued that determining flood risk/hazard only based on the frequency of flooding may be of limited use. Indeed, the study of THIEKEN *et al.* (2005) demonstrates that water level, flood duration and contamination are the factors mostly responsible for serious damage to infrastructures. A simplistic binary classification is nevertheless adopted, because only peak discharges have been recorded (thus making it impossible to estimate flood duration) and because of the difficulty to estimate the geometry of the floodplain for past flood events (thus hampering the computation of accurate water levels at the scale of individual buildings). It is clear, however, that for a full hazard assessment, water stage and flow velocity should also be considered.

7. Change detection and risk assessment (P-7)

The term 'risk' is interpreted in many different ways in the context of natural hazards (KELMAN & SPENCE 2003). However, there is a general agreement that risk should be seen as a combination of both the probability of occurrence of a particular event and the impact that the event would cause if it occurred. In the present case study, the probability of flood events is determined through flood frequency maps that are established for each reference time period. The potential impact, often referred to as vulnerability, can be expressed in many ways. Vulnerability refers to a characteristic of society, which may be used as an indicator of the potential damage to occur as a result of hazard (KELMAN 2002). Due to the difficulty in associating a monetary value to each infrastructure from 1770 onwards, it is decided to express vulnerability simply as the area of urban settlements within the floodplain. In order to express vulnerability and risk at the scale of the same hexagonal plots that were used during the frequency analysis, the urban area within each grid cell is calculated. In these so-called value maps no differentiation is made between different types of infrastructure meaning that all buildings represent the same value. Next, the flood risk in each period is estimated by overlaying the corresponding flood frequency map with a representative value map and is thus expressed as the average built-up area being flooded each year. Intersecting the value map with the flood frequency map results in a so-called 'value at risk' map. Hence, in order to estimate present day flood risk, the value at risk is calculated by crossing the flood frequency map that is representative for the time frame 1966-2003 with the urban area of 2003. The historical flood risk is assessed by intersecting the flood frequency map computed for the time frame 1870-1920 with the value map of 1907. Defining risk in such a way may appear rather simplistic, as many factors influence flood damage. However, since many data sources of varying levels of detail and unknown accuracy have been processed in the present study, it can be argued that more complex methods would need to be based on a number of assumptions that cannot be justified with the data at hand.

RESULTS AND DISCUSSION

1. Urban area development

From 1770 to 2003, urbanisation at Steinheim took mostly place in the floodplain (Fig. 3): the core of the village was located in the floodplain in 1770 as well as most buildings are in 2003. From 1954 until 1993 the village of Steinheim expanded partly out of the floodplain; after 1993, this trend was reversed. The total urban area of Steinheim increased from 6,728 m^2 in 1770 to 44,613 m^2 in 2003: an increase of 663%.

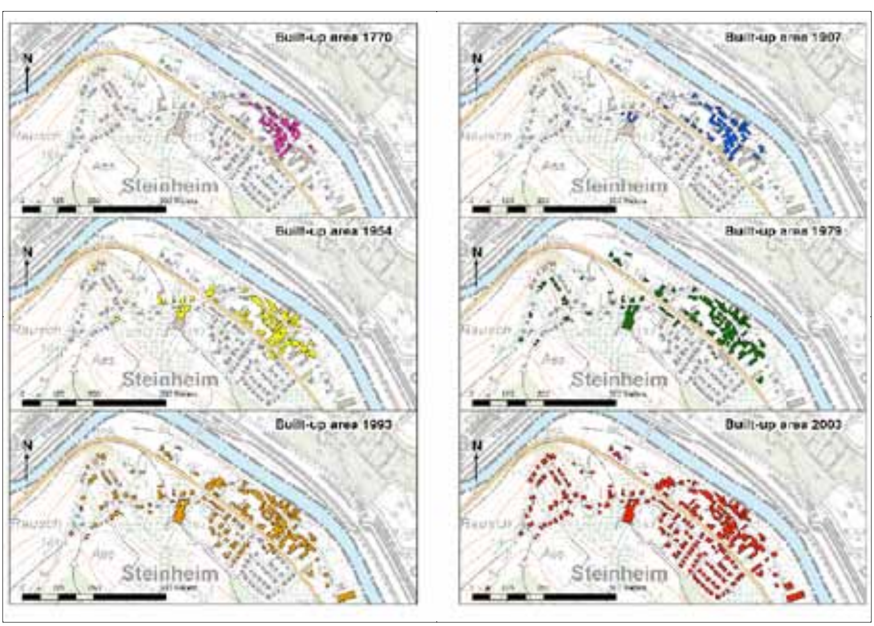

Fig. 3. Urbanization of the village of Steinheim from 1770 until 2002.

2. Rainfall-runoff modelling and peak discharge extraction

The NASH-SUTCLIFFE criterion of the best performing model is 0.90 with a volume error close to zero at the end of the calibration period. In simulation mode, a bias close to zero is particularly important in order to avoid the accumulation of volume errors that may cause significant over- and underestimations of discharge. Figure 4 shows the agreement of fit between simulated and observed peak discharges during calibration. Although some underestimations can be observed, it can be concluded that the model is capable of reproducing the peak discharges reasonably well.

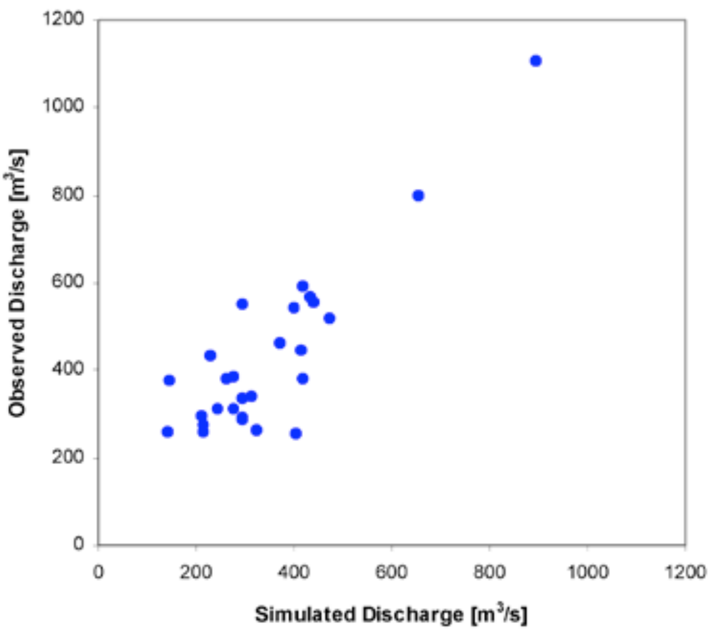

Fig. 4. Agreement of fit between simulated and observed peak discharges during calibration.

The analysis of the two continuous peak discharge series reveals some notable differences. On the one hand, within the time frame 1870-1920, 40 flood occurrences (i.e. discharge values above 450 m^3/s) were recorded, which corresponds to an annual flood probability of 78%. On the other hand, 25 flood events were extracted from the 1966-2003 time period, which corresponds to an annual flood probability of only 66%. Any runoff event that causes riverbank overtopping is considered a flood. Figure 5 summarizes the distribution of peak flood events in each sample of extracted discharge values and some additional differences become evident when considering the two cumulative distribution functions of peak discharges. Whilst the medium sized flood events (with peak discharges below 650 m³/s) were more frequent between 1870 and 1920, the major flood events appear to have been more frequent during the recent time period. However, the most extreme event ever recorded took place in 1918. Due to the laterally constrained nature of many floodplains, differences in water depth may not cause any notable difference in flood extent. Therefore, the next processing step, namely the computation of flood probability maps for each time period, intends to clarify the impact observed differences in discharge distributions may have on spatially distributed flood frequency. It is debatable whether flood boundary or water depth is the more influential factor for flood hazard assessment. There is no doubt, however, that accurate mapping of flood extent is important in most decision-making processes.

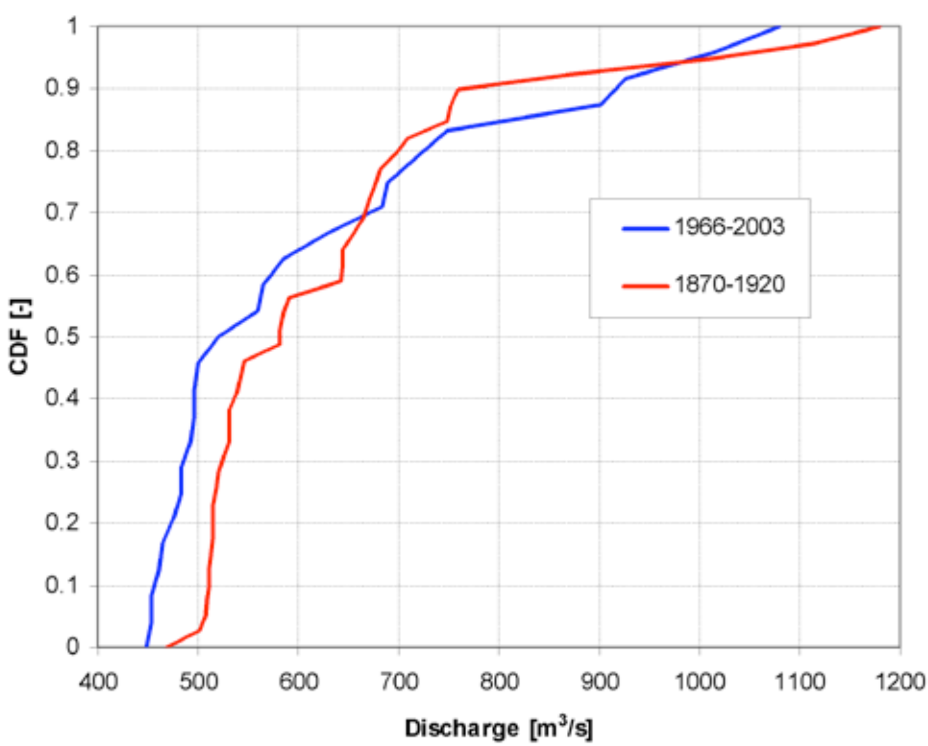

Fig. 5. Cumulative Density Functions (CDF) of the discharge for the two periods 1870-1920 and 1966-2003.

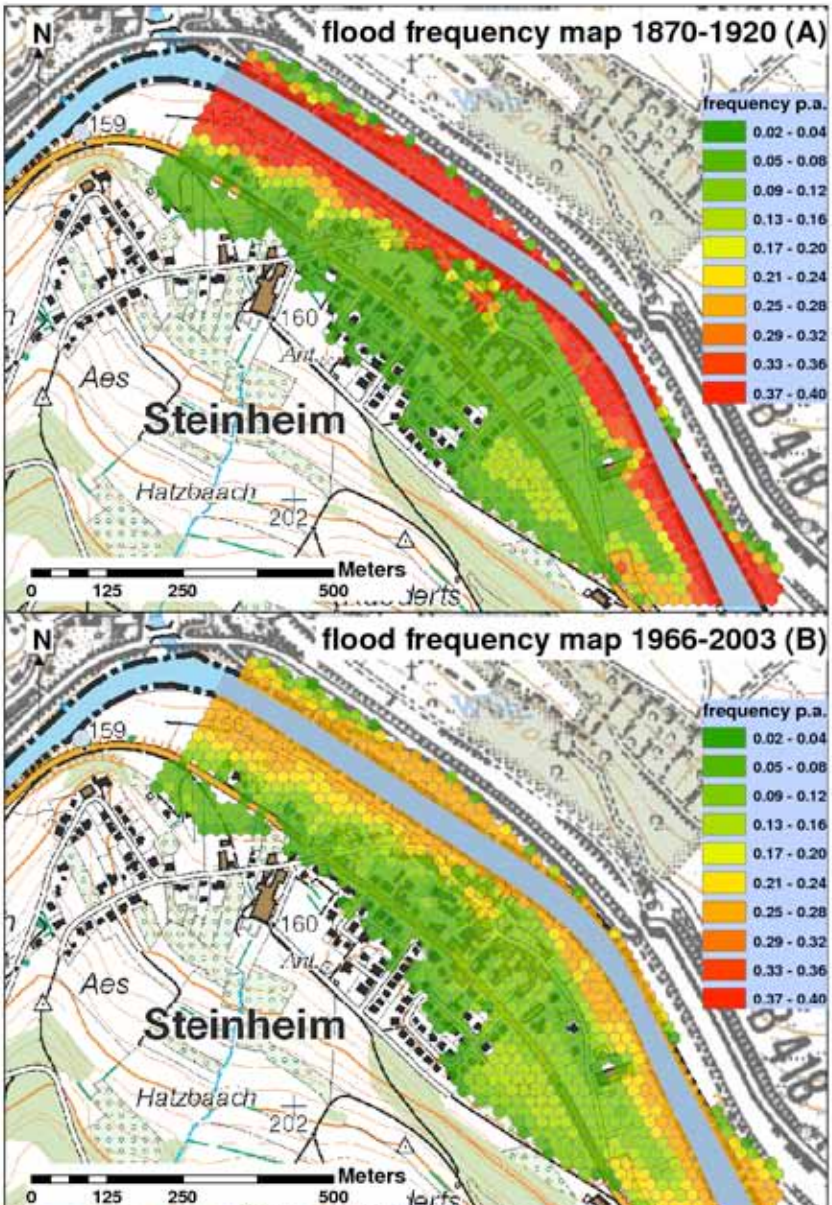

Fig. 6. Flood frequency for the periods 1870-1920 (A) and 1966-2003 (B) at Steinheim.

3. Flood frequency mapping

The flood inundation model is calibrated by choosing the channel and floodplain friction parameters that allow minimizing the difference between the computed water surface line and a series of surveyed high water marks. The mean squared error between the computed water levels and the "ground truth" is 3 cm and 4 cm for the flood events of January 1995 and January 2003 respectively. The subsequent comparison between the computed flood extent and the flood area derived from SAR imagery further demonstrates the ability of the flood inundation model to compute flood depth and extent satisfactory. Next, the flood frequency for each hexagonal grid cell of each particular period is calculated, which results in two flood frequency maps (Figs 6A-B). As can be seen in figures 6A and B, the maximum flood extension for the period 1870-1920 is slightly bigger than that for the period 1966-2003. This is due to the fact that in the former period the biggest ever recorded flood occurred (15 January 1918). The flood frequency in the vicinity of the river channel is also higher for the former period, indicating more frequent minor floods. However, the flood frequency within the urban area appears to be slightly higher for the period 1966-2003, which indicates a minor increase of floods of this larger magnitude. These observations are well in line with the observed differences in the CDFs of peak discharges.

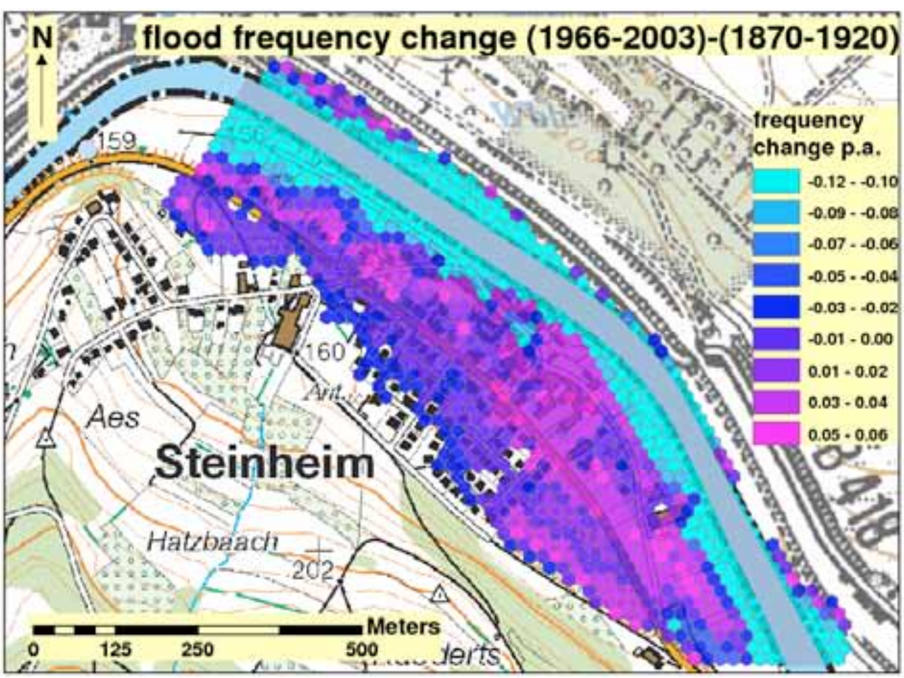

Fig. 7. Flood frequency change map.

The visual interpretation is further enhanced by subtracting the flood frequency of a cell of the period 1870-1920 from the frequency of flooding of the same cell during the period 1966-2003 (Fig. 7). The values of the grid cells in the map correspond thus to a change in the average number of floods per year. Again, it can be observed that the flood frequency decreased along the river stretch and increased into the floodplain.

4. Value mapping

The development of the total built-up area is given in figure 8.

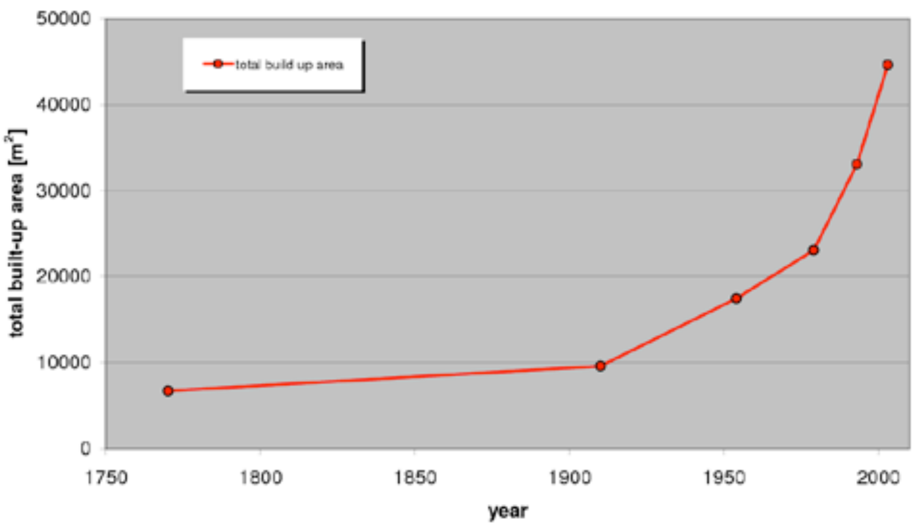

Fig. 8. The total built-up area from 1770 until 2003.

As can be seen in figure 8, the built-up area within the natural floodplain increased more than threefold in the last 250 years. For the two reference time periods, the value map that represents the area of urban settlements within each computational cell is given in figures 9A and 10A. The urban areas extracted from the Hansen map of 1907 and the topographic map of 2003 represent the floodplain vulnerability within the two time frames 1870-1920 and 1966-2003, respectively.

5. Risk mapping

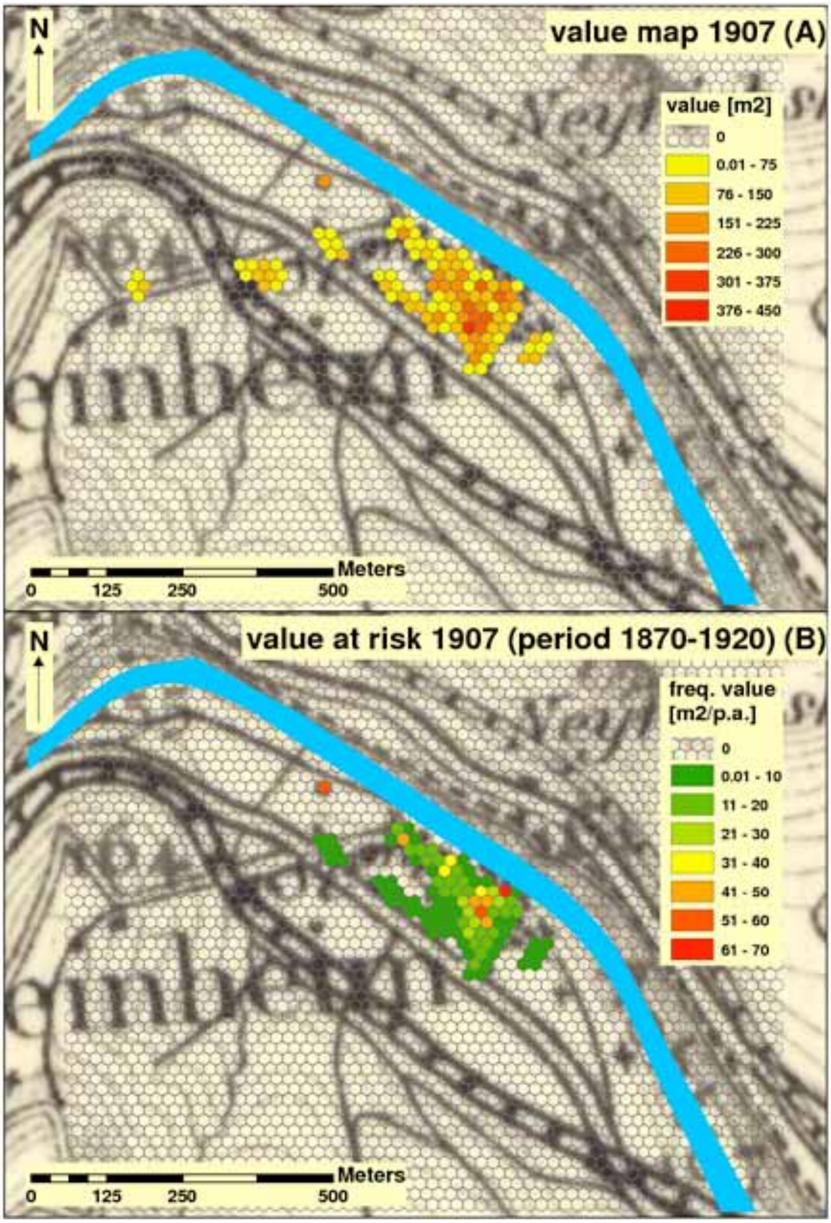

Fig. 9. The value map of the village of Steinheim for the year 1907 (A) and the value at risk map of the village of Steinheim for the period 1870-1920 (B).

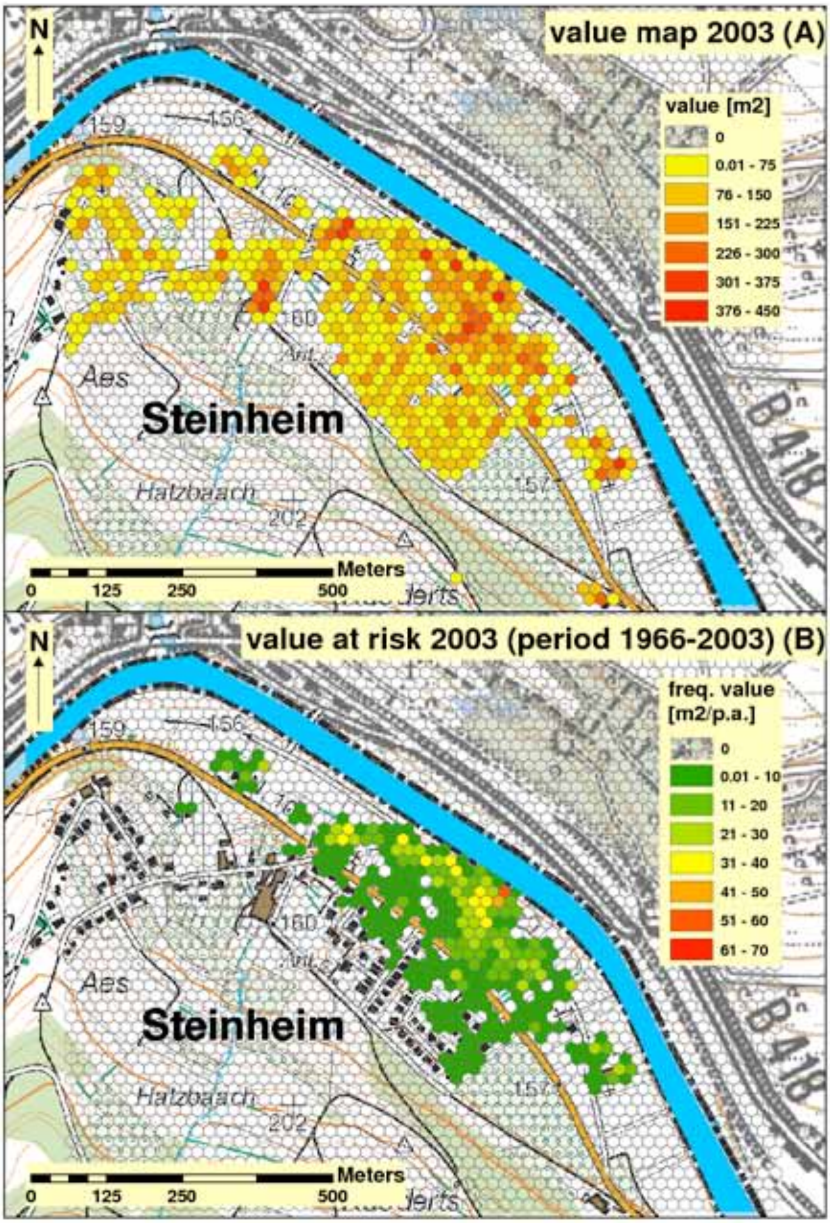

Fig. 10. The value map of the village of Steinheim for the year 2003 (A) and the value at risk map of the village of Steinheim for the period 1966-2003 (B).

As it can be expected to be the case in any floodplain, there appears to be a notable difference between areas that have a high flooding potential, but low value at risk (e.g. the most northern part of the floodplain) and areas that have a high value at risk, but a rather low flooding potential (e.g. the mid-southern part of the floodplain). The village centre located in the middle part of the floodplain represents both a high value and a high flood frequency, resulting in a high value at risk. This case study thus clearly indicates the necessity to consider both flood frequency and value in order to assess flood risk. For the two time periods, flood risk is depicted in figures 9B and 10B as the value at risk maps. According to our assessment, the flood risk for the period 1870-1920 can be expressed as 1064 m^2 of urban area being flooded in average per year. For the recent period from 1966 until 2003 flood risk was 2413 m^2 of urban area being flooded in average per year. This significant increase in flood risk (+ 127%) is mainly related to an increase in vulnerability. Although, most urbanisation took place at a certain distance from the river channel, the value located within the natural floodplain nevertheless significantly increased (+ 340%) over the past 96 years. Flood frequency with which the village of Steinheim was flooded in the period 1870-1920 only slightly differs from the flood frequency for the period 1966-2003 but shows some notable spatial and temporal variability. For the former period, medium sized floods (with peak discharges below 650 m^3/s) were more common than for the latter period. This notable decrease in the number of medium sized flood events can presumably be attributed to the construction of a dam in the upper Sure river basin during the 1950's, which mitigates impacts of such floods. However, only minor changes could be observed regarding the occurrence of major floods between the two periods 1870-1920 and 1966-2003, thereby proving that land use changes and climate change have not led to a significant increase in flood hazard within the study area. However, to the author's view, flood risk still substantially increased due to an increase of urban settlements within the flood prone area.

CONCLUSIONS

The comparison of two comprehensive data sets, representing each a very distinct period in time, provides valuable information on the combined effect of vulnerability, land use and climate change on flood risk. Despite a considerable amount of uncertainties related to hydrological and hydraulic modelling, the reliability of the historical discharge records and to the geometrical description of the river channel and floodplain, there is no doubt that flood risk increased in Steinheim's floodplain over the past 250 years. The observed change in flood risk is due to some minor changes in flood frequency but, most of all, to some very significant change in vulnerability. Hence, there is a clear discrepancy between the flood frequency maps and the value maps: whereas the flood probability did not change considerably over the past 100 years, the built-up area increased more than threefold within the natural floodplain over the same period. However, a high value does not automatically result in a high value at risk. Only the combined effect of a high flood frequency and a high value, as it is present most notably in the middle part of Steinheim's floodplain, provides a high flood risk and would reveal some notable security deficit.

The findings of the present study point out that flood risk maps should not be static tools but should, instead, undergo continuous adaptation relative to possible changes in watershed hydrology due to a possible climate or land use change. In the authors' view, flood prevention measures undertaken all along the river network (river bed enlargement, protection walls, dikes…etc.) should systematically be taken into account to measure their influence on the hazard maps and thus allow assessing the efficiency of cost-intensive flood protection measures. The study also reveals that vulnerability should be continuously monitored by using differentiated land cover maps. Most land management applications would benefit from the systematic updating of risk maps. Also, the resulting maps should be coupled with maps showing hazard related to other natural disasters and so could be useful tools for sustainable land planning in Luxembourg.

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