The KULTURisk Regional Risk Assessment methodology for water-related natural hazards -Part 2: Application to the Zurich case study

P. Ronco[1-2], M. Bullo[1], S. Torresan[2], A. Critto[1-2], R. Olschewski[3], M. Zappa[4], A. Marcomini[1-2]

[1] {Dept. of Environmental Sciences, Informatics and Statistics, University Ca' Foscari of Venice, Venice, Italy}
[2] {Euro-Mediterranean Centre on Climate Change (CMCC), Impacts on Soil and Coast Division, Lecce, Italy}
[3] {Swiss Federal Research Institute WSL, Economics and Social Sciences, Birmensdorf, Switzerland}
[4] {Swiss Federal Research Institute WSL, Mountain Hydrology and Mass Movements, Birmensdorf, Switzerland}
Correspondence to: A. Marcomini (marcom@unive.it)

Abstract

The main objective of the paper is the application of the KULTURisk Regional Risk Assessment (KR-RRA) methodology, presented in the companion paper (Part 1, Ronco et al., 2014), to the Sihl river valley, in Switzerland. Flood related risks have been assessed for different receptors lying on the Sihl river valley including the city of Zurich, which represents a typical case of river flooding in urban area, by means of a tuning process of the methodology to the site-specific context and features. Risk maps have been developed under a 300 years return period scenario for six identified relevant targets, exposed to flood risk in the Sihl valley, namely: people, economic activities (including buildings, infrastructure and agriculture), natural and semi-natural systems and cultural heritage. Finally, the total risk index map has been produced to visualize the spatial pattern of flood risk within the area of study and, therefore, to identify and rank areas and hotspots at risk by means of multi criteria decision analysis (MCDA) tools. Through of a tailored participative approach, the total risk maps supplement the consideration of technical experts with the (essential) point of view of the relevant stakeholders for the appraisal of the specific scores and weights related to the receptor-relative risks. The total risk maps obtained for the Sihl river case study are associated with the lower classes of risk. In general, higher relative

risks are concentrated in the deeply urbanized area within and around the Zurich city centre and areas that rely just behind to the river course. Here, forecasted injuries and potential fatalities are mainly due to high population density and high presence of vulnerable people; inundated buildings are mainly classified as continuous and discontinuous urban fabric; flooded roads, pathways and railways, the majority of them referring to the Zurich main train station (Hauptbahnhof), are at high risk of inundation, causing huge indirect damages. Moreover, the analysis of flood risk to agriculture, natural and semi-natural systems and cultural heritage have pointed out that these receptors could be relatively less impacted by the selected flood scenario mainly because their scattered presence. Finally, the application of the KR-RRA methodology to the Sihl river case study, as well as to several other sites across Europe (not presented here), has demonstrated its flexibility and possible adaptation to different geographical and socio-economic contexts, depending on data availability and peculiarities of the sites, as well as for other (hazard) scenarios.

1. Introduction

Nowadays, one of the major environmental issues which is asserting more and more at global scale is the increasing threat related to natural disasters. Among the variety of such disasters, flooding has significant impacts on human activities as it can threaten people's lives, property, assets, services as well as the environment. Assets at risk can include housing, transport and public service infrastructure, as well as commercial, industrial and agricultural enterprises. The health, social, economic and environmental impacts of flooding can be dramatic and have a wide community impact (Mazzorana et al., 2012). In this sense, the so called not-sustainable development can exacerbate the problems of flooding by accelerating and increasing surface water run-off, altering watercourses and removing floodplain storage (OPW, 2009). In the meantime, frequency and magnitude of floods events are currently being intensified by changes in temperature, precipitation, glaciers and snow cover, triggered by climate change dynamics. Projected changes in precipitation regimes will also contribute to altering the intensity and frequency of rain-fed floods and possibly also of flash floods (IPCC, 2012). In Europe, floods account for the biggest share of damage inflicted by natural disasters, both on economic terms and life threat (see: Statistics about natural disasters losses and frequency in Europe for the period 1980-2008. Source: EM-DAT, 2009.).

Particularly, in Switzerland severe flood events have occurred in many catchments in the last decade: frequent floods alternated with quieter periods have occurred during the last 150 years (Bründl et al., 2009). In northern Switzerland, indeed, numerous floods were recorded between 1874 and 1881 and from 1968 onwards, while few floods have occurred in-between. Since around 1900, three massive flood events in northern Switzerland have occurred (1999, 2005 and 2007, Schmocker-Fackel and Naef, 2010). Recent researches conducted by Hilker et al. (2009) and Badoux et al. (2014) has estimated an approximate 8 billion Euros of total monetary loss due to floods, debris flows, landslides and rockfall, where 56% of this damage caused by six single flood events from 1978 to 2005, and (up to) 37% due to sediment transport.

On these basis, the pro-active and effective engagement of scientists, stakeholders, policy and decision makers towards the challenging objective of reducing and possibly mitigating the impact of floods, is dramatically needed. In fact, only over the last few years the science of these events, their impacts, and options for dealing with them has become robust enough to support and develop comprehensive and mature assessment strategies (IPCC, 2012). Several methodologies to assess the risk posed by water-related natural hazards have been proposed within the scientific community, but very few of them can be adopted to fully implement the last European Flood Directive (FD). Through a tailored Regional Risk Assessment (RRA) approach, the recently phased out FP7-KULTURisk Project (Knowledge-based approach to develop a cULTUre of Risk prevention-KR), developed a state-of-the-art risk assessment methodology to assess the risk posed by a variety of water-related hazards. The KR-RRA methodology has been widely presented by Ronco et al. (2014) in the companion paper, part 1. The Regional Risk Assessment approach, in general, is aimed at providing a quantitative and systematic way to estimate and compare the impacts of environmental problems that affect large geographic areas (Hunsaker et al., 1990). By means of different, more or less sophisticated algorithms, the main objectives of Regional Scale Assessment are the evaluation of broader scale problems, their contribution and influence on local scale problems as well as the cumulative effects of local scale issues on regional endpoints in order to prioritize the risks present in the region of interest in order to prioritise and evaluate intervention and mitigation measures. Accordingly, RRA becomes important when policymakers are called to face problems caused by a multiplicity of sources of hazards, widely spread over a large area, which impact a multiplicity of endpoint of regional interest . The proposed KR-RRA methodology follows the theoretical approach proposed by Landis and Weigers (1997) and used in a wide range of cases (Pasini et al., 2012, Torresan et al., 2012), that suggested the following implementation steps: i) identification of the different sources, habitats and impacts; ii) ranking the (relative) importance of the different components of the risk assessment; iii) spatial visualisation of the different components of the risk assessment; iv) relative risk estimation.

Finally, through the integration of the three pillars of risk concept defined by UNISDR (2005) and IPCC (2012) as hazard, exposure, and vulnerability, the proposed KR-RRA methodology represents a benchmark for the implementation of the Floods Directive at the European level.

This innovative, effective and integrated approach has been used for assessing the risk of flood posed by the Sihl river and tributaries to the city of Zurich and surrounding, by considering different flood impacts on multiple receptors (i.e. people, economic activities, natural and semi-natural systems, cultural heritage) at the meso-scale level.

2. The Sihl river valley

The Sihl is a 68 km long alpine river located in the foothills of the Alps of Switzerland. The sources of the river (total basin coverage: 336 km^2) are located at Drusberg in the Canton of Schwyz (SZ) in the central part of Switzerland. Downstream it flows through the artificial Sihl lake regulated by a concrete dam (upstream basin: 156 km^2) entering the Canton of Zurich (ZH) through the Sihl valley and flowing parallel with Zurich lake, separated by a chain of hills. Finally, the Sihl river joins the Limmat river at Platzspitz in the Zurich city centre (downstream basin: 180 km^2). As many of the alpine rivers, the Sihl preserves most of its natural morphological pattern of a meandering river and it is not navigable.

The Sihl river valley is extensively wooded and, in particular, the forest lying on the hills is classified as coniferous and mixed forest. Since the year 2000, the Sihl forest has been declared as (protected) Natural Reserve and several areas along the river have become attractive for recreation purposes as well as important ecological habitats. The river valley is also cultivated as arable land and with pastures. The upstream part of the Sihl consist of several small torrential rivers, able to mobilize high quantities of bedload (Rickenmann et al., 2012) and drift-wood (Turowski et al., 2013). While bedload just causes the typical brown color of the water of the Sihl (Fig.2) that join the clear waters of the Limmat, drift wood represent a serious treat along the whole channel of the Sihl, since it can cause obstruction of the river section below bridges and, most important, below Zürich central station.

As far as the administrative characterization is concerned, the Sihl river valley includes parts of the districts of Einsiedeln (SZ) (upper Sihl valley), Horgen (ZH) and Zurich (lower Sihl valley). The studied area (77.97 km^2) covers only the lower part of the valley and in particular the city of Zurich with its 21 districts (Albisrieden, Alt-Wiedikon, Altstetten, City, Enge, Escher Wyss, Friesenberg, Gewerbeschule, Hard, Hochschule, Höngg, Langstrasse, Leimbach, Lindenhof, Oberstrass, Rathaus, Sihlfeld, Unterstrass, Werd, Wipkingen, Wollishofen) and 5 municipalities (Adliswil, Kilchberg, Langnau am Albis, Rüschlikon and Thalwil) (see Fig.1).

Figure 1

The area of reference is densely populated, in particular on its lower part close to the city of Zurich, which is located north and north-west of Zurich lake. According to CORINE Land Cover (CLC) classification (EEA, 2007), the residential area covers 41.28 km^2 (more than half of the case study area) and the total population is 289'029 (Statistical Office of Canton of Zurich, 2011), while 20.19 km^2 are covered by forest and just 7.67 km^2 are devoted to agriculture. Several cultural heritage hotspots are present in the valley and especially in Zurich city centre, among the others are the Swiss National Museum, the Kaspar Escher House, the Fraumünster and the Church of Bühl.

3. Hydrological pattern and regime

The Sihl river basin is located in the middle of Swiss Alps and it is particularly prone to flash floods: during wintertime snow accumulates in the headwaters and snow melt governs runoff generation in late spring and early summer. Flash-floods as triggered by intense thunderstorms might be responsible for high damages in the upstream areas (e.g. the region of Einsiedeln), but rarely lead to critical peak-runoff in the downstream part of the river. Critical runoff for the environs of Zürich are triggered by long-lasting rainfall events that lead to the overspill of the Sihl lake (Scherrer et al., 2013) This process is generally slow but severe floods can occur whenever the rate of water input exceeds the ability of the soil to absorb it or when the amount of water exceeds natural storage capacities in soil, rivers, lakes and reservoirs. In fact, Sihl river represents the largest flood threat for the city of Zurich, Switzerland's most populated city(Addor et al., 2011): just before joining the Limmat river, the Sihl flows beneath the main railway station of Zurich (Zürich Hauptbahnhof HB) located in the city centre, as showed in Fig.2.

Figure 2

Pro Sihltal (2008) reported the most important floods that have occurred in the Sihl river valley during the last three centuries. In 1910, in particular, a massive event flooded Zurich main train station with more than 40 cm of water, some railway tracks were badly damaged and the service was interrupted, Leimbach and Adliswil districts were under 1 m of water and some buildings of the Swiss National Museum at Platzplitz were completely flooded. In 1937, the artificial multipurpose Sihl lake was realized for both hydropower and as retention (over-flow) basin to reduce the frequency of flooding downstream (Schwanbeck et al., 2010). Until 1999 no more floods have been registered in the area but in 2005 and in 2007 severe inundations have demonstrated that the buffer capacity of Sihl lake retention basin is not enough to mitigate the impacts of extreme flood events during heavy rainfalls seasons. In fact, even if the discharge of the Sihl is relatively modest and most of the waters from the catchment area upstream of the dam are usually diverged into the lake of Zurich, in case of heavy precipitations dam overflow might occur and, according to the dam emergency regulations procedures, discharges as high as 470 m^3/s can be released into the Sihl river, with dramatic consequences downstream (Addor, 2009). The extreme rainfall of August 2005, extensively described in Bezzola and Hegg, 2007; Jaun et al., 2008, triggered a (preliminary) flood risk assessment for the entire catchment (Schwanbeck et al., 2007) and, finally, the planning of few immediate, intermediate and long-term prevention measures. However, out of the planned ones, only the early warning system (EWS) model to forecast extreme events and mitigate their impact has been implemented so far, while intermediate and long-term prevention measures are still under analysis and discussion by the different stakeholders and institutions/authorities of the area. The complexity of hydrological pattern of the Sihl river valley and the need for a planned strategy of prevention measures severely asks for a broader integrated approach in order to assess the risk of flood to multiple receptors and a suite of effective tools to identify and prioritize areas and targets at risk to finally evaluate the benefits of different prevention scenarios.

4. Dataset characterization and processing

The dataset required for the application of the KR-RRA methodology includes: i) characterization of the intensity and the frequency of the flood event, to be framed into specific hazard scenario (e.g. hazard metrics such as flow velocity, water depth, flood extension, return period); ii) spatial pattern and distribution of the investigated receptors (e.g. people, economic activities, natural and semi-natural systems, cultural heritage) in order to perform the exposure assessment; iii) relevant indicators (e.g. percentage of disable people, slope, soil type etc.) to perform the vulnerability assessment, that is the degree to which the different receptors could be affected by the (flood) hazard. The dataset has been mainly provided by the GIS Centre of Canton of Zurich, the Swiss Federal Office of Topography, the Statistical Office of Canton of Zurich, the Swiss Federal Statistical Office (BFS, Bundesamt für Statistik) and the Swiss Federal Office for Agriculture (FOAG), (Bundesamt für Landwirtschaft, BLW) in raster, vector graphic or numerical format, as specified in Table 1.

For the risk assessment to agriculture and natural & semi-natural systems, the CLC dataset (EEA, 2007, with spatial resolution of 1:100’000) has been used to spatially characterize the targets at the regional level; while for buildings, infrastructures and cultural heritage, data with a finer resolution (spatial resolution of 1:5’000) has been used. Finally, to characterize the receptor people, the residential census data provided has been used to compute the number of people within residential cells of 25 m^2. The work load (in terms of man/days) required to process the dataset and produce the maps related to the four assessment steps is also presented in Table 1.

Table1

4.1 Hazard data processing

As explained by Ronco et al. (2014) in Part I, the hazard assessment is aimed at identifying the relevant physical metrics (water depth, velocity and flood extension) obtained from hydrodynamics models for the different scenarios to be investigated (baseline or alternative). The methodology makes different use of the various hazard metrics depending on the analysed receptors in order to assess the relative risk, as depicted in Table 2.

Table 2

Water depths and velocities are normally computed (and mapped) by commercial, more or less sophisticated, hydraulics models. Moreover, the debris factor, that ranges between 0 and 1 respectively low and high probability that debris would lead to a significant hazard, can be easily assigned according to different ranges of water depth and velocity, as per Table 3.

Table 3

However, while existing flood hazard maps can be easily used to estimate flood depth, they do provide information on flow velocity very rarely (DEFRA, 2006). This is the case of the Sihl river valley, where patterns of velocities were not available. In fact, only patterns of water depths and intensities (namely: the combination between water depths and velocities) calssified in range of values (classes) have been provided by the local authorities, without any explicit specification about the particular (hydraulic) models that have been used (see Table 4 and 5).

Table 4

Table 5

The pattern of water velocity has been calculated as follow. Based on a precautionary principle (highest values of depth d and velocity v are associated to the highest level of hazard) the highest values for depth d and $v \cdot d$ product have been selected for each class (e.g: d = 0,5 m for the class 2 of Table 4, and $v \cdot d$ = 0,5 m^2/s for class 1 of Table 5). Moreover, due to the specific range of values refereed to the case study, classes 2 and 3 of intensity have been merged as well as classes 6 and 7 of depth. Now, provided that the $v \cdot d$ product and d are known as single values, and not as a range of values as it was before, it was easy to derive the pattern of velocities (see Table 6).

Table 6

5. Baseline and alternative hazard scenarios

The KULTURisk methodological framework requires the preliminary setting and analysis of different flood scenarios (baseline and alternative) where structural and/or non-structural solutions to mitigate, and possibly reduce, the risk are planned.

As request by the European Flood Directive (2007/60/EC), the baseline scenarios should be based on deterministic flood hazard maps, where flood-prone areas are classified according to different classes of frequency of the event (high, medium and low). In particular, the probability depends on the concept of return period of the hazardous event and the classification is based on the following thresholds:

- Frequent event TR < 30 years – High probability of floods
- Average event 30 years < TR < 100 years – Medium probability of floods
- Rare event 100 years < TR < 300 years – Low probability of floods.

Spatially distributed flood hazard maps are normally used by property owners, local authorities and land planners to characterize the hazard in the area, prepare for floods and properly manage the events (EEA, 2009). As far as the Zurich case study is concerned, the available flood hazard maps referring to three classes of hazards (30, 100 and 300 years of return period) have been provided by the GIS Centre of Canton of Zurich. The low probability – high intensity 300 years return period scenario has been considered the most relevant for the purpose of this study (see Fig.3) since the other two scenarios (30 and 100 years) only marginally affect the typical prone area of the Sihl valley and, in particular, do not affect the main railway station of Zurich that, according to local stakeholders, experts and forensic analysis of past flood events, has been considered the hottest spot of analysis. Moreover, relative risk maps for these (marginal) hazard scenarios have not been presented as not relevant to the overall objective of the study: to test the degree of applicability of an innovative methodological approach in an (emblematic) case study, and not to assess the complete suite of risk patterns according to the different (and not bounded) plausible scenarios that could characterize the hazard for that particular case study, in order to support that (case-specific) decision making process. Finally, by assessing the most catastrophic configuration, the selected (baseline) scenario gives the opportunity to plan the mitigation, adaptive, response and preparedness actions in a (very) precautionary framework.

Figure 3

In 2008 an Early Warning System (EWS IFKIS Hydro Sihl) has been installed along the Sihl river valley (Romang et al., 2011; Bruen et al. 2010). The EWS IFKIS is a hydro-meteorological ensemble prediction system based on atmospheric forecasts provided by the (deterministic) model COSMO-7 and the (probabilistic) model COSMO-LEPS. It propagates the atmospheric uncertainty by ingesting atmospheric ensembles from COSMO-LEPS, leading a probability of errors . Coupled with a flood retention system by extending the reservoir buffering capacity of the Sihl lake, the EWS contributes to a consistent reduction of flood risk magnitude of the Sihl river. However, in this study the baseline scenario considers the situation before the establishment of this mitigation measure since the reduction of the flood risk for the EWS cannot be assessed to a reliable degree because data referring to larger flood events are not (yet) available (Addor et al., 2011).

The Canton of Zurich is currently discussing further prevention measures such as bypass tunnel (close to Langnau am Albis, Fig. 1) diverging flood peaks along the Sihl valley into the Lake of Zürich, or a larger pipe between the Sihl lake and the lake of Zürich to both allow for increased hydropower production and accelerated drawdown of the lake to increase the buffering capacity of the Sihl lake during critical flood events. Furthermore a reservoir for drift wood is thought of to be realized in Langnau am Albis(Fig. 1). In case of being established, these prevention measures could reduce the flood risk of the Sihl to a lower level but details on the expected impact under different prevention measures have not yet been estimated. Due to this, alternative scenarios have not been considered in this study.

6. Results of the KR-RRA application to the selected receptors

The KR-RRA methodology presented in the companion paper (Part 1) has been applied to the Zurich case study by considering the whole suite of receptors at risk, namely: people; economic activities, including buildings, infrastructure and agriculture; natural and semi-natural systems and cultural heritage. Through the sub-sequential implementation of the hazard, exposure, susceptibility and risk assessments, GIS based maps and related statistics of total and receptor-related risks have been produced and presented below.

6.1 Risk to People

6.1.1 Assessment

According to the KR-RRA procedure (see the Part 1, Eq.(1)) and following the (hazard) data processing presented above, the hazard scores for Sihl river case study have been calculated and reported in Table 7. The hazard scores range from 0.9 to 6, where increasing values mean an increasing hazard for people.

Table7

As far as the exposure assessment is concerned, the total population living in residential areas is of 289’029. The largest district is Altstetten (7.48 km^2 with 30’148 habitants), while Sihlfeld and Gewerbeschule are the most densely populated ones (11'759 habitants/km^2 and 13,163 habitants/km^2 respectively). Most of the upper part of the Sihl Valley has a lower density, with a range between 826 and 5’981 habitants/km^2. Moreover, the Statistical Office of Canton of Zurich has provided demographic data of people to characterize the susceptibility factors (people aged more than 75 and residents with disabilities). The same value (5%) has been considered for each district, assuming that for each municipalities the number of disable people is equally distributed. Therefore, differences among the SF score actually depend only on the percentage of elderlyresidents. andranges from 7.6% to 32.3%. Finally, the presence of people within each district has been used to estimate the number of people within cells of 25 m resolution in the residential areas. The normalization phase has been performed according the KR-RRA procedure, so the number of injured/killed people has been divided by the number of people relative to the district with highest population.

6.1.2 Results

People related risk maps (Figs.4 and 5, Tables 8 and 9) provide the number of injuries (R_1) and fatalities (R_2) spatially distributed along the Sihl river valley. As for the other receptors, the classificationis obtained through the equal-interval methods. The forecasted number of total injuries is estimated in 1000, while the number of total (potential) fatalities is estimated in 29. Among the affected areas, Albisrieden and Altstetten districts, that are densely populated with medium scores for susceptibility, are subject of higher values of casualties with 223 and 155 injuries and 5 fatalities each, respectively. It should be underlined that these two districts are normally flooded by the Limmat river, a tributary of the Sihl. Considering only the Sihl prone-area, the districts that suffer from the higher numbers of casualties are Adliswill, Alt-Wiedikon, Langstrasse and Sihlfeld with a range of injuries between 55 to 96 and 2 to 3 fatalities. The percentage of injured people considering the total population of the study area is 0.35% and the percentage of dead people is 0.01%. These rates suggest that risk to people is generally low, despite not negligible, if we consider the high density of population that actually rely on the residential area.

As already mentioned, in fact, the KR-RRA methodology considers people living in residential areas only, and does not include people eventually present in other zones, such as commercial, industrial and agricultural areas. Moreover, the methodology doesn't discriminate between day/night times. During the daytime, in fact, people are usually located in their working places and/or in restaurants, bars, shopping centres, facilities (as the main station of Zurich) and along the streets. Therefore the methodology is somehow underestimating the number of injuries and fatalities in these areas while overestimating injuries and fatalities in the residential areas. Finally, it is worth to notice that the RRA methodology only partially consider people's coping and adaptive capacity since these aspects are fully enclosed in the social-economic clusters (SERRA) of the (complete) KR methodology (see Giupponi et al., 2014).

Figure 4

Table 8

Figure 5

Table 9

6.2 Risk to Economic activities: Buildings

6.2.1 Assessment

Floods have a potential massive impact on buildings infrastructures (e.g. partial or total damage to the structures, damage to the indoor goods), particularly in densely populated area as it is for most of the Sihl river valley. The analysis makes considerable use of the Building footprint GIS shapefile (GIS Centre of Canton of Zurich TLM3D Building footprint) for the spatial localization of the buildings at risk (total number of buildings: 19'430; total surface covered by buildings: 10.67 km^2). Moreover, coupling these data with the hazard maps, it is possible to discriminate flooded building belonging to different uses (i.e. residential, commercial and industrial areas). Table 10 shows the statistics related to the presence and coverage of buildings which can potentially be flooded, according to the different CLC classes.

Table 10

As already reported by the companion paper (Part 1), the vulnerability assessment assumes that, at the meso-scale level, the buildings are characterized by the same structure. Therefore, the susceptibility of buildings is assumed as a constant value. Finally, the risk assessment to buildings estimates the number, surface and percentage of flooded buildings referring to different uses; the related normalization phase for buildings has been developed by considering normalized scores where values from 0 (no risk) to 1 (maximum risk) are assigned according to the different classes of risk.

6.2.2 Results

The GIS-based risk map (Fig.6) points out the spatial distribution of the risk to building across the studied area. Being the intensity of considered scenario lower than the fixed threshold, all the buildings affected by the flood event would be only inundated and would not suffer from dramatic structural damages. Despite this, the flooding can still have dramatic consequences on the infrastructure because many assets of primary importance, such as electricity and water services, heating, are normally located at the lower ground level. The total number of buildings at risk is 3,267 and the related surface area at risk is 2.2 km^2. The percentage of flooded buildings is around 17% while the percentage of flooded areas is almost 20% over the total surface actually covered by buildings.

As already mentioned, the studied area is mostly classified as residential one and almost 95% of flooded buildings belong to class 1.1.1 and 1.1.2 of CLC (Continuous and discontinuous urban fabric) while just less than 6% of inundated buildings belong to classes 1.2.1, 1.2.2, 1.4.1 and 1.4.2 (Industrial or commercial units, Road and rail networks and associated land, Green urban areas and Sport leisure facilities). In particular, only 17 items are classified as infrastructure related to the supply of services (road, rail networks and associated land class) so the risk for this category is very relevant (most of them are linked to the strategic transportation network of the main railway station of Zurich city, Zurich Hauptbahnhof). Box A of Fig. 6 focuses on the districts with higher number of inundated buildings around the Zurich city centre. Several small residential areas would be flooded also in the southern part of the city, namely Leimbach, Adliswil, Thalwil and Langnau am Albis. Table 12 presents the relevant data for the analysed receptor, considering the different use of buildings.

Figure 6

Table 11

Table 12

6.3 Risk to Economic activities: Infrastructure

6.3.1 Assessment

The strategic network of infrastructures have been identified using the Roads and Railways shapefiles, provided by the GIS Centre of Canton of Zurich. The information includes the characterization of roads, pathways and railway lines within the study area. Zurich main train station represents an important and strategic hub for the Cantonal railway network system as well as for the Swiss and European railways network systems: more than 1900 trains daily pass-by the Hauptbahnhof main train station. In fact, urban commuter rail networks are focused on the country's major cities: Zurich, Geneva, Basel, Bern, Lausanne and Neuchatel. Strategic highways and roads also run in and out Zurich city.

The flood hazard assessment to infrastructures considers the flood extension as relevant flood metric; no other flood metrics (e.g. flow velocity) have been considered because the analysis is not oriented to the evaluation of direct structural damages for infrastructure, but rather to the characterization of the loss of service. The exposure assessment step focuses on the spatial localization and distribution of the roads, railways and pathways. All these objects could be geometrically characterized by their linear extension (length) and by their extension (area). In particular, pathway routes have been considered relevant since many of them are normally used by pedestrian to connect rural area to the city centre, running along the flood prone area of the Sihl river.

6.3.2 Results

The infrastructuresrelated risk map (Fig. 7) identifies the assets potentially affected by a flood event of 300 years return period. The total extent of road, railways and pathways at risk is around 209 km out of 1,540 km of infrastructure that currently rely on the study area (less than 14% of items are at risk). In particular, around 54 km refers to railways network and 155 km to roads and pathways.

As far as the spatial distribution of the (relative) risk is concerned, the Langstrasse and Albisrieden districts are the most affected by the flood event, belonging to the very high class and high class of risk. The extent of inundated infrastructure has been computed in 32 km and 26 km, respectively. Moreover, the roads/railway network of Escher Wyss, Unterstrass, Hard and Rathaus districts do not experience any loss of services do to flood.

The infrastructure receptor is very relevant for the city of Zurich if we consider that the Sihl river flows underneath the main station and many railways lines are located just beside of the river course. For example, the Sihltal road (Sihltalstrasse) that runs along the Sihl river for around 16 km connecting the city of Zurich with the southern area of the Sihl river valley where the Sihlwald (Sihl forest natural area) ends reaching the Sihlbrugg small village. Again, within the district of Langnau am Albis (with almost 17 km of flooded items) the railway lines could be completely flooded, as well as most of the ones belonging to the main station of Zurich city in Langstrasse district. Moreover, several pathways along the Sihl river could be affected. Of course, the flooding of pathways is less relevant than the one of highway and railways, especially by considering the economic impact. Therefore it is particularly important to discriminate and to rank the different level of service that the different categories of infrastructure could provide.

Considering the pattern of the urban mobility within the studied area, the following items could be considered the most critical hotspots points:

- Part of Zurich main train station Hauptbahnhof (HB), see Fig.8.
- Zurich City centre area with its pedestrian and urban road in Langstrasse and City districts including Bahnhofbrücke and Walchebrücke (two bridges next to Zurich main train station), see Fig.8
- Pathways at Platzspitz green area, see Fig.8.
- Railway lines at Langnau-Gattikon train station in Langnau am Albis district
- Sihltalstrasse in some spots where the roads runs next to the Sihl river, in particular in Adliswil, Leimbach and Langnau am Albis districts.

Figure 7

Table 13

Figure 8

6.4 Risk to Economic activities: Agriculture

6.4.1 Assessment

The flood hazard assessment step requires the identification of water depth and flow velocity as relevant flood metrics, while the exposure assessment to agriculture allows to identify the agricultural typologies present in the Sihl river valley according to the different classes of the CLC dataset (class 2.1.1 as Non irrigated arable land and class 2.3.1 as Pastures). The total area devoted to agriculture is 7.67 km^2, most of it classified as arable land. Since none of the agricultural typologies mentioned in the companion paper (Part 1) are actually present in the Sihl valley (namely: vegetables, vineyards, fruit trees and olive groves), it has been assumed that arable lands and pastures should be classified as vegetables, with similar thresholds.

As a sake of simplification and according to the overall scope of the analysis, namely a risk assessment at regional scale, it has been assumed that the agricultural typologies in the Sihl river valley have similar growing pattern (low growing plants) and, therefore, the same susceptibility score. According to Torresan et al. (2012) and to the technical evaluation of the authors, the two CLC classes of agricultural typologies have been considered similar to the class of poor vegetation and meadow (more susceptible to flood) with a score equal to 1.

6.4.2 Results

The agriculture related risk map (Fig.9) has been elaborated according to the procedure and features of analysis introduced above. It is worth to notice that despite the pattern of flow velocity is above the minimum threshold of 0.25 m/s, the risk for the agricultural cluster is very limited: the flooded agricultural area only amounts to 0.59 km^2 (around 8% of the total agricultural area). Out of this, 0.53 km^2 belongs to the non-irrigated arable land class (class 2.1.1) and 0.07 km^2 to the pastures class (class 2.3.1) (Table 15). The districts more stricken are Albisrieden and Leimbach.

The total surface at risk is probably underestimated because the exposure classification have been performed according to the CLC resolution that could have missed out some small agricultural areas that might be important for cash crop cultivation.

However, the area of the Sihl river valley is mainly devoted to residential and commercial purposes, therefore the agriculture can be considered less important than other receptors such as people, buildings and infrastructure.

Figure9

Table 14

Table 15

6.5 Risk to Natural and Semi-Natural Systems

6.5.1 Assessment

Flood extension has been used to characterize the hazard for the natural and semi-natural systems. As for the other receptors, the CLC classification dataset has been used to identify and characterize the natural and semi-natural systems exposed to the risk of flood along the Sihl river valley, that account for more than 20 km^2. The valley is characterized by two different kind of forest systems: coniferous forest (0.21 km^2, CLC class 3.1.2) which covers the area only for very small part, and mixed forest (19.98 km^2, CLC class 3.1.3) which occupied most of the natural environment in the case study area. The intrinsic characteristics of the territory, namely the (susceptibility) factors that influence the degree of impact of the flood to the receptor, have been assessed according to the scores suggested by the companion paper (Part 1) contribution.

6.5.2 Results

The natural and semi-natural systems related risk map (Fig. 10) allows to identify the area potentially affected by loss of ecosystem service caused by a 300 years return period flood event. As a result, only a limited portion of forest is at risk of inundation (0.29 km^2, 1.4 % of total forest areas) and two classes of risk have been identified: a very small part (625 m^2) belongs to the high class of risk while the rest (around 289,000 m^2) belongs to the very high class of risk.

Even if the inundated land belongs mostly to the very high class of risk, due to the different susceptibility factors and in particular to the impermeable ground characteristics of the area and degrees of slope, the risk related to this receptor can be considered as not relevant. In fact, forests are generally stable and resilient ecosystems, whiles growing along rivers they are very well adapted to occasional and seasonal flooding. In addition, in the Sihl valley most of the forests are located along the hilly part of the area and this reduces their susceptibility.

In this sense, the ecological, recreational and economic functionalities of the Sihl valley forest ecosystem is not compromised by a flood event of such magnitude.

Figure 10

6.6 Risk to Cultural Heritage

6.6.1 Assessment

The hazard assessment step consists in the spatial characterization (extent) of the flooded area. Moreover, the exposure assessment requires the localization of the cultural heritage assets in the case study area. In Sihl river valley, 416 cultural assets are present, mainly classified as ancient buildings. They include different confessional buildings such as Fraumuster, Grossmunster and the Synagogue in Zurich city centre, the Swiss National Museum, the central library of Zurich, the Rathaus (the municipal building), the Opernhaus, several ancient residential buildings and villas in the centre as well as along the Zurich lake etc.

6.6.2 Results

The cultural heritage related risk map is shown in Fig. 11: it identifies the number of cultural assets which are supposed to be flooded in the framework of the investigated scenario. As a result, 40 items could be inundated, corresponding to the 9.13% of the total number within the area (416 items). These assets belongs to different cultural protection level (regional and cantonal). As already reported, the Swiss national museum is at risk of inundation while the districts belonging to higher class of risk (number of inundated objects between 10 and 15) are Langstrasse (close to city centre of Zurich city) and Langnau am Albis (along the lower Sihl valley).

Figure 11

7. Total Risk Index

7.1 Weighing process

The total risk index is calculated by aggregating different receptor-related risks by means of MCDA methods that allow identifying and ranking areas and hotspots at risk, within the studied area. Prior to this, a normalization process for each of the analysed receptor is performed to rescale the receptor-related risk scores into a numerical scale between 0 and 1 and, therefore, to allow comparison among (relative) risks expressed by different unit of measurement (Zabeo et al., 2011). Within this study, for people, infrastructure and cultural heritage the normalisation has been implemented at CLC polygon size level. For buildings, agriculture and natural and semi-natural systems the normalization has been performed according to the relative tables and scores, as follow: flooded buildings: 0.2, destroyed agricultural: 1; natural and semi-natural systems: 1 for the very high class of risk and 0.8 for the high class of risk. Normalised risks has been assigned to raster cells of 25 m resolution that allow a better and more detailed visualization of the spatial variability of the total risk.

The proposed MCDA method of aggregation is the weighted average which considers overlapping receptors' risk to be linearly additive. The ranking process is supposed to give numerical priority to those events whose damaging consequences are considered as burdensome. In this sense, weighting is a typical political decision making process and the involvement of relevant stakeholders and experts is seen as a fundamental prerequisite for its effectiveness (Yosie and Herbst, 1998). In order to lower the level of arbitrariness derived from expert based weight selection (Santoro et.al., 2013), , the weighting process has been implemented during a roundtable-meeting organized with several local experts involved in the project. They were aware of some preliminary results and this could have influenced their opinion during the weights assignation. The assigned weights are as per the Table 16.

Table16

The lowest weights have been assigned to relatively less important receptors: natural and semi-natural systems have scored 0 (zero) because, as stated above, they are considered as stable and very resilient ecosystems without consistent impact from flood events. A weight of 0.1 has been assigned to cultural heritage because these assets have been already considered in the buildings analysis, and therefore just an additional, cultural, value has been added to the particular building under protection. A weight of 0.2 has been assigned to agriculture because this sector is not considered to be relevant for the socio-economic context of the valley: the flooded agricultural areas are not of particular quality and do not have any valuable cash crops relying on it.

The people receptor has scored 0.4, less than the one assigned to buildings and to infrastructure, and this choice has raised a not-bounded discussion. The main argument that has been used to support this assignation is the fact that the selected baseline scenario does not consider the role played by the EWS in mitigating the (flood) impact to the population living in the studied area. Moreover, it has been argued that the methodology only focuses on the citizens actually living in the residential area, and do to consider the number of people normally present, for example, at the main station or at the main shopping area, which exceeds by far the number of actual residents in that district, particularly during the day time and the weekend evenings. In this sense, they argued that the methodology overestimated the risk to people in residential area and, in the meantime, underestimated the risk to others area, therefore there should be a kind of "compensation" in the computation of the total risk index. Higher weights have been assigned to buildings (0.6) and infrastructures (0.8) which have been considered the most relevant receptors for the socio-economic context of the Zurich city. Considering the specific characteristics of the study area, damages related to flooded infrastructures and buildings result also in very high (indirect) costs for the loss of services they provide. In particular, the inundation of the Zurich main train station entails wide loss of services since it represents a very important and nodal location both for public transport connections for the whole Canton and for commercial reasons (a big shopping centre area is located in and around the train station, frequented by a lot of residents and tourists).

7.2 Results and discussion

The total risk map shows the spatial pattern of flood risk within the analysed area within the Sihl river valley (Fig.12). The total surface at risk is 7.98 km^2 and the total risk index ranges between 0 and 0.24, that represents the lower class of risk considering the classification scores presented in Part 1. In order to better visualize the relative distribution of risk belonging to these classes, the green to red colour classification, normally tuned within the 0-1 range, has been re-tuned according to the calculated range. The map specifically identifies the hotspots and the areas at risk along the Sihl river valley. Langstrasse district and part of the city of Zurich present the relative highest values of risk; areas within the districts of Werd, Sihlfeld, Alt-Wiedikon and Friesenberg that rely next to the Sihl river course also present relative higher risk levels. Areas within Albisrieden district are characterized by relative high risk as well. Results are very much plausible because they demonstrate that the overall risk for the study area, considering the receptor of importance, is higher in area close to the main station of Zurich, where lot of infrastructures and railway lines and buildings would be possibly flooded, and on the left side area of the Sihl river before it join the Limmat river, notably at risk.

The total risk index represents a useful indicator which allows the ranking of “area more at risk” than others, but it is, of course, highly dependent from receptor related risk analysis and weighting process.

In fact, the choice of a weight for risk of people to be lower than the one for infrastructure might seem inappropriate, as already stated in Sect. 7.1., but within the expert judgement their own experience during recent events plays a major role. This is what makes KR-RRA approach appealing and valuable. When putting on the table different factors it was agreed that infrastructure might be a major source of risk than human life. Background information from several stakeholders and local experts triggered this choice, starting from forensic analysis of past events. In fact, since the 1970’s Switzerland experienced several major floods that exceeded a return period of 300 years (e.g. Rössler et al., 2014), but despite this, only 3 fatalities per year can be attributed to water related disasters (floods, landslides and debris flows) (Hilker et al., 2009). Moreover, Swiss legislation allows having closed settlements only in areas where the buildings are protected by additional measures against floods with return period between 100 and 300 years. This is not the case for infrastructure and according to the latest estimation (pre- KR-RRA) a damage of Zürich main station may trigger damages of over 4 billion Euros. The local authorities are aware of this and are improving their flood management system with additional structural and non-structural measures. It is an advantage of this novel approach to allow stakeholders and experts to come up with a site-specific configuration of weights and thereby improving the adaptation to the local situation. For instance, local authorities reported that after using some standard risk assessment procedure (pre- KR-RRA) a map was created where the risk "hot-spot" was a tennis resort in the north-western part of the city of Zürich. After including expert knowledge and adapting the weighting accordingly, the areas around central station prompted to be the one with highest risk.

Moreover, it is worth to notice that the final risk index aggregates scores coming from multiple heterogeneous parameters. The final decision-making process should therefore consider not only the final values of the index, but also the factors that contributed in determining that value (i.e. susceptibility indicators, hazard metrics). A correct interpretation of these factors is particularly relevant for the analysis of the potential prevention measures that could be suitable for reducing the risk for current hot spot areas (Torresan et al., 2012).

It is important to underline that the application of the KULTURisk methodology at the meso-scale provides a screening analysis that allows the assessment and prioritization of targets and areas at risks in the considered region. However, a more detailed analysis (at the micro-scale) could be required in the areas considered at risk or where more specific information are available.

Figure12

Table 17

8. Conclusions

The study addressed the application of a state-of-the-art Regional Risk Assessment (RRA) methodology for flood risk assessment to a very site-specific case, namely the Sihl river valley around the city of Zurich, in Switzerland. The complete KR-RRA methodology, developed within the KULTURisk-FP7 (KR) Project for flood risks and introduced in the companion paper Part 1, followed four subsequent levels of analysis, namely the hazards, exposure, vulnerability and risk assessments. In particular, the paper described the tuning process as well as the implementation procedure that has been applied in order to assess the risk of flood for the river valley represented by a 300 years return period hazard scenario, the be considered the most cautelative one. Relative risk maps (GIS based) and related statistics, specifically referring to the impact of flood hazard to selected receptors, have been developed. By means of MCDA, with a tailored participative approach of relevant local experts that suggested the weights to be applied for each receptor, the total risk maps have been produced allowing the identification of hot spots and area at risk as well as the spatial characterization of the risk pattern. The total risk maps obtained for the Sihl river case study are associated with the lower classes of risk, while the relative risk is higher in Zurich city centre districts, in the urban area around the city centre and areas that rely just behind to the Sihl river course.

Together with the presented one, the KR-RRA methodology has been successfully applied to a wide range of cases studies across Europe (not presented in this work) which have contributed in demonstrating its flexibility and possible adaptation to different geographical and socio-economic contexts, depending on data availability and peculiarities of the site, as well as for other hazard scenarios (i.e. other relevant return period scenarios). In this sense, the methodology can be easily up-scaled in order to evaluate river flood impacts at a broader region/national/sub national scale (i.e. national level including more than one river basin) or can be detailed on a smaller area by focusing on impacts on a very local scale by using more detailed datasets for the characterization of exposure and vulnerability (i.e. finer Digital Elevation Model, finer data about land cover).

The receptor-related risk maps, as main outputs of the KR-RRA methodology, have proven to be a very useful (and relatively easy) tool for the risk evaluation in the studied area as well as for the support of the decision making process for appropriate risk management practices (when based on prevention, protection and preparedness concepts). Despite being arguable for the methodology that has been followed for the assignation of weights, the involvement of relevant local experts improved the consistency and relevance of the application exercise. Finally, the paper demonstrated the relevance of the KR-RRA methodology, which has proven to be a comprehensive and integrated risk assessment tool able to coordinate information coming from deterministic as well as probabilistic flood forecasting and to integrate the multi-faceted physical/environmental aspects of exposure and vulnerability, in order to evaluate flood risks for different elements at risk, as required by the European Floods Directive.

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Table 1. Summary of the dataset used for the application of the KULTURisk RRA methodology within the Sihl river valley.

Step of assessment		**People**	**Buildings**	**Infrastructures**	**Agriculture**	**Natural and Semi-Natural Systems**	**Cultural Heritage**
Hazard	Dataset	- Flood hazard map (*, 2013, 1: 5000) for water depth, velocity, flood coverage - Switzerland CORINE Land Cover map (***, GIS WSL, 2006, 1: 100000) for debris factor					
	Work load [man/days]	3	1	1	1	1	0,5
Exposure	Dataset	- People in residential areas (**, 2011) - Switzerland CORINE Land Cover map (***, GIS WSL, 2006, 1: 100’000)	- Building footprint map (* TLM3D, 2013, 1: 5000) - Switzerland CORINE Land Cover map (***, GIS WSL, 2006, 1: 100’000)	- Roads (Strasse_CH_line) and Railways (Eisenbahn_CH_line) maps (* TLM3D, 2012, 1: 5000) - Switzerland CORINE Land Cover map (***, GIS WSL, 2006, 1: 100’000)	- Switzerland CORINE Land Cover map (***, GIS WSL, 2006, 1: 100000)	- Switzerland CORINE Land Cover map (***, GIS WSL, 2006, 1: 100000)	- Protected objects of historical interest map (Denkmalschutz objekte, *, 2013, 1: 5000)
	Work load [man/days]	3	2	2	2	2	1
Vulnerability	Dataset	- Percentage of disable in Zurich city and data census (*****,	-	-	- Digital map of soil coverage of Switzerland (****, 2012, 1: 200’000)	- 25 m DEM (***, GIS WSL, 1994) - Digital map of soil coverage of Switzerland	-

		2010)				(****, 2012, 1: 200’000)	
	Work load [man/days]	1	-	-	1	2	-
Risk	Work load [man/days]	0,5	0,5	0,5	0,5	0,5	0,5

**GIS Centre of Canton of Zurich*

***Statistical Office of Canton of Zurich*

****Swiss Federal Office of Topography*

*****Swiss Federal Office for Agriculture*

******Swiss Federal Statistical Office*

Table 2. Flood metrics selected to assess hazard for different receptors.

HAZARD ASSEMENT	Selected flood metric	Receptor
Flood hazard	Water depth (m)	People, Buildings
	Flow velocity (m/s)	People, Buildings, Agriculture
	Flood extension (Km^2)	Infrastructures, Natural and Semi-Natural Systems, Cultural Heritage
	Debris Factor	People

Table 3. Guidance for the definition of debris factor (DF) for different pattern of water depths and velocities in urban areas (DEFRA, 2006).

Flood depth (d)	Debris factor (DF) for urban areas
$d \leq 0.25$ m	0
0.25 m $< d < 0.75$ m	1
$d \geq 0.75$ or $v > 2$ m/s	1

Table 4. Classification of water depths as provided by the GIS Centre of Canton of Zurich through flood hazard maps

Depth Classes	[m]
1	< 0.25
2	0.25 – 0.50
3	0.50 – 0.75
4	0.75 – 1.00
5	1.00 – 1.50
6	1.50 – 2.00
7	>2.00

Table 5. Classification of intensity parameter (function of water depth – d, and velocity - v) as provided by the GIS Centre of Canton of Zurich through flood hazard maps

Intensity Classes	Description	Condition
1	Low	$d < 0.5$ m or $v \cdot d < 0.5\ m^2/s$
2	Medium	$0.5 < d < 2.0$ m or $0.5\ m^2/s < v \cdot d < 2.0\ m^2/s$
3	High	$d > 2$ m or $v \cdot d > 2\ m^2/s$

Table 6. Computation of (single) values of velocity (v) from available data (water depths –d, debris factor – DF, and intensity - I).

Depth classes	Depth of reference (d) [m]	DF	**Velocity v = I / d** Intensity class 1 (d · v = 0.5) [m/s]	Intensity classes 2 and 3 (d · v = 2) [m/s]
1	0.25	0	**2.00**	**8.00**
2	0.5	1	**1.00**	**4.00**
3	0.75	1	**0.67**	**2.67**
4	1	1	**0.50**	**2.00**
5	1.5	1	**0.33**	**1.33**
6 and 7	2	1	**0.25**	**1.00**

Table 7. Hazard scores to people computed from available data (water depths –d, velocity – v, debris factor – DF, and intensity - I).

			$H_{people} = d \cdot v + d \cdot 1.5 + DF$	
Depth classes	Depth of reference (d) [m]	DF	Intensity (I) class 1 ($d \cdot v = 0.5$)	Intensity (I) classes 2 and 3 ($d \cdot v = 2$)
1	0.25	0	**0.875**	**2.375**
2	0.5	1	**2.25**	**3.75**
3	0.75	1	**2.625**	**4.125**
4	1	1	**3**	**4.5**
5	1.5	1	**3.75**	**5.25**
6 and 7	2	1	**4.5**	**6**

Table 8. Relative risk classes and range of values for injured people.

Risk Classes (R1)	Number of injuries
Very low	1 - 50
Low	50 - 100
Medium	100 - 150
High	150- 200
Very high	>200

Table 9. Relative risk classes and range of values for fatalities.

Risk Classes (R2)	Number of fatalities
Very low	1
Low	2
Medium	3
High	4
Very high	>5

Table 10. Statistics about the buildings coverage along the Sihl river valley.

Buildings: CLC class	Total [#]	%	coverage [Km^2]	% of coverage
111-112: Continuous urban fabric - Discontinuous urban fabric	18,255	94.0	8.9	83.4
121: Industrial or commercial units	780	4.0	1.4	12.9
122: Road and rail networks and associated land	100	0.5	0.3	3.1
141-142: Green urban areas - Sport leisure facilities	295	1.5	0.1	0.6
Total	19,430	100.0	10.7	100.0

Table 11. Relative risk classes and range of values for buildings.

Risk Classes (R3)	Description	# of inundated buildings
Not at risk	Not inundated	16,163
Low	Inundation	3267
Medium	Partial damage	0
High	Total destruction	0

Table 12. Statistics related to the Risk for buildings for different CLC classes.

Risk for buildings (CLC classes)	Flooded [#]	Flooded [%]	Flooded area [km^2]	Flooded area [%]
1.1.1-1.1.2: Continuous urban fabric - Discontinuous urban fabric	3,075	94.1	1.8	83.4
1.2.1: Industrial or commercial units	154	4.7	0.3	12.4
1.2.2: Road and rail networks and associated land	17	0.5	0.1	4.1
1.4.1-1.4.2: Green urban areas - Sport leisure facilities	21	0.6	0.004	0.2
Total	3,267	100.0	2.2	100.0

Table 13. Relative risk classes and range of values for infrastructures.

Risk Classes (R4)	Length of infrastructures at risk within each district [km]
Very low	0.01 - 7
Low	7 - 14
Medium	14 - 21
High	21 - 28
Very high	28 - 32

Table 14. Relative risk classes and range of values for agriculture.

Risk Classes (R5)	Description	Agricultural areas [km^2]
Not at risk	Not inundated	7.08
Low	Inundated	0
High	Destructed	0.59

Table 15. Statistics related to the Risk for agriculture for different CLC classes.

Agricultural typology *(CLC classes)*	Description	Total Area [km^2]	Flooded agricultural area [km^2]
CLC class 2.1.1	Non-irrigated arable land	7.35	0.53
CLC class 2.3.1	Pastures	0.31	0.07
Total		7.67	0.59

Table 16. Weight assigned to different receptors by local relevant experts.

Receptor	Weights
Infrastructures	0.8
Buildings	0.6
People	0.4
Agriculture	0.2
Cultural Heritage	0.1
Natural and semi-natural systems	0

Table 17. Total risk index classification and range of values.

Total Risk Classes	Score
Very low	0– 0.048
Low	0.048 – 0.96
Medium	0.096 – 0.14
High	0.14 – 0.19
Very high	0.19 – 0.24

Figure 1. The case study area: a) its location in Switzerland and b) its main characteristics.

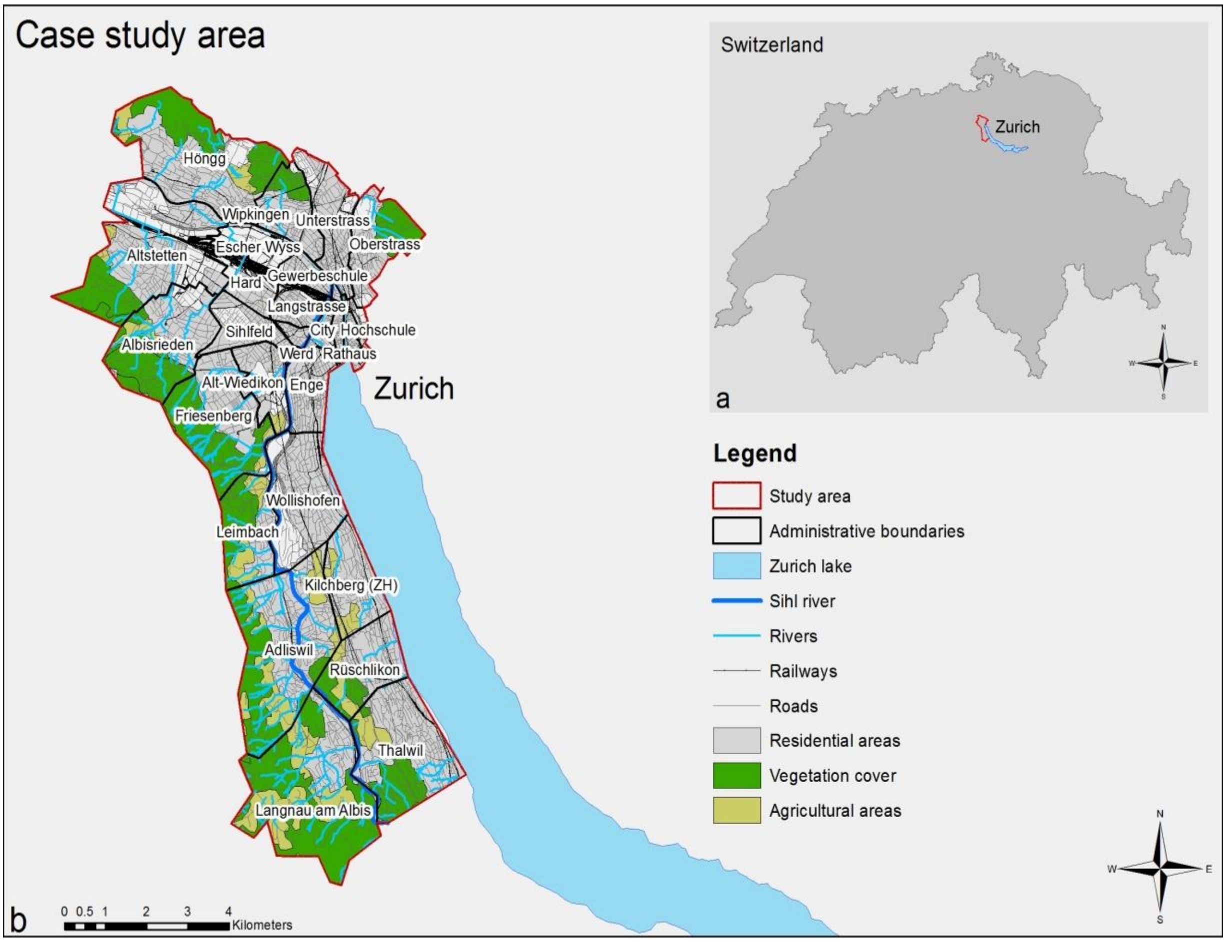

Figure 2. Sihl river flowing beneath Zurich main train station before it joins the Limmat river: (A) image adapted from Google map; the box at the bottom shows the critical Sihl river section in August 2005 during a flood even, source: A. Senn (WSL).

(B) Sihl river flowing underneath Zurich main train station in August 2005 (discharge: 280 m^3/s), source: Office of Waste, Water, Energy and Air, Zürich (M. Oplatka).

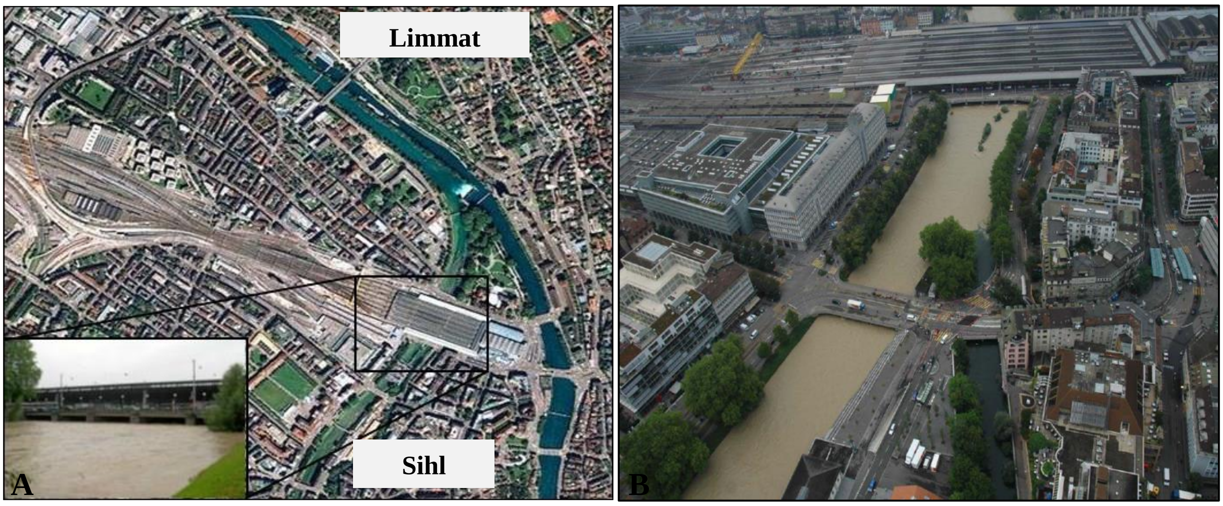

Figure 3. Baseline scenario for Sihl case study related to a flood event of 300 years return period, in box A the zoom on the Zurich main station, in box B the zoom on the upstream river valley area.

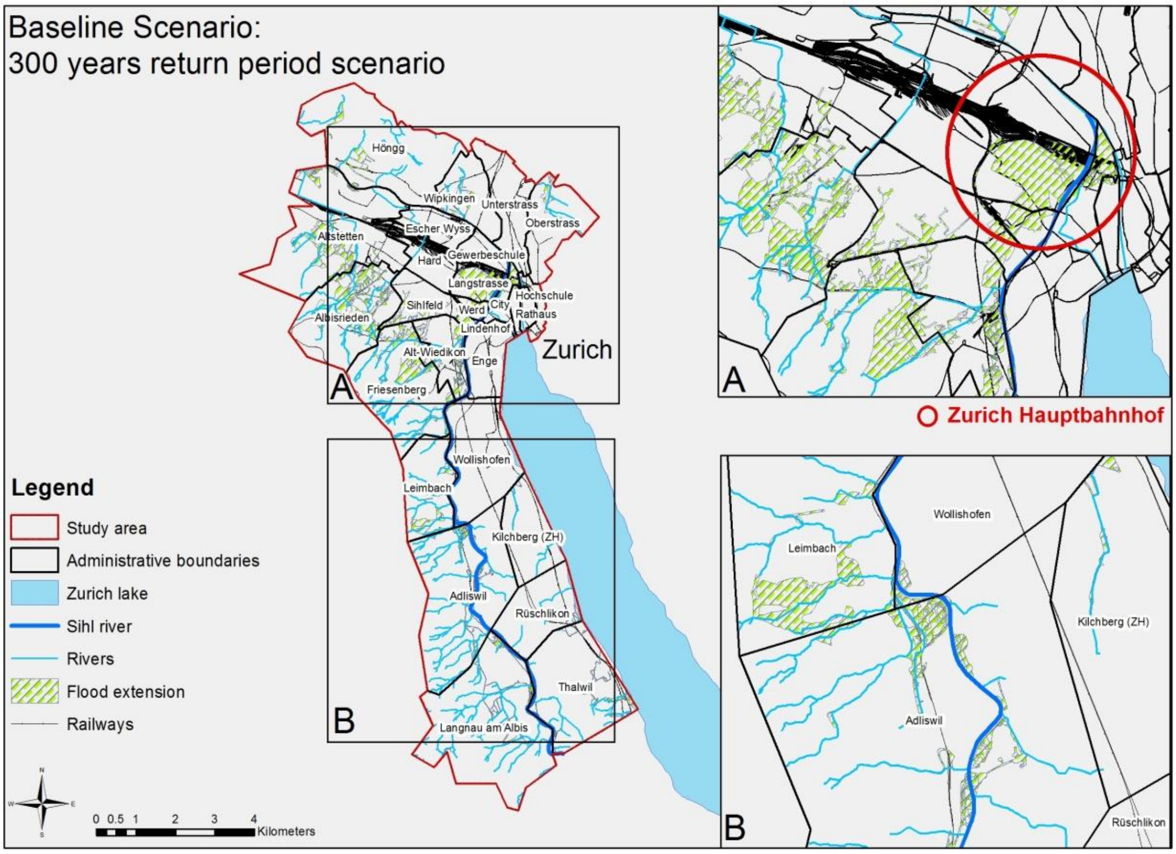

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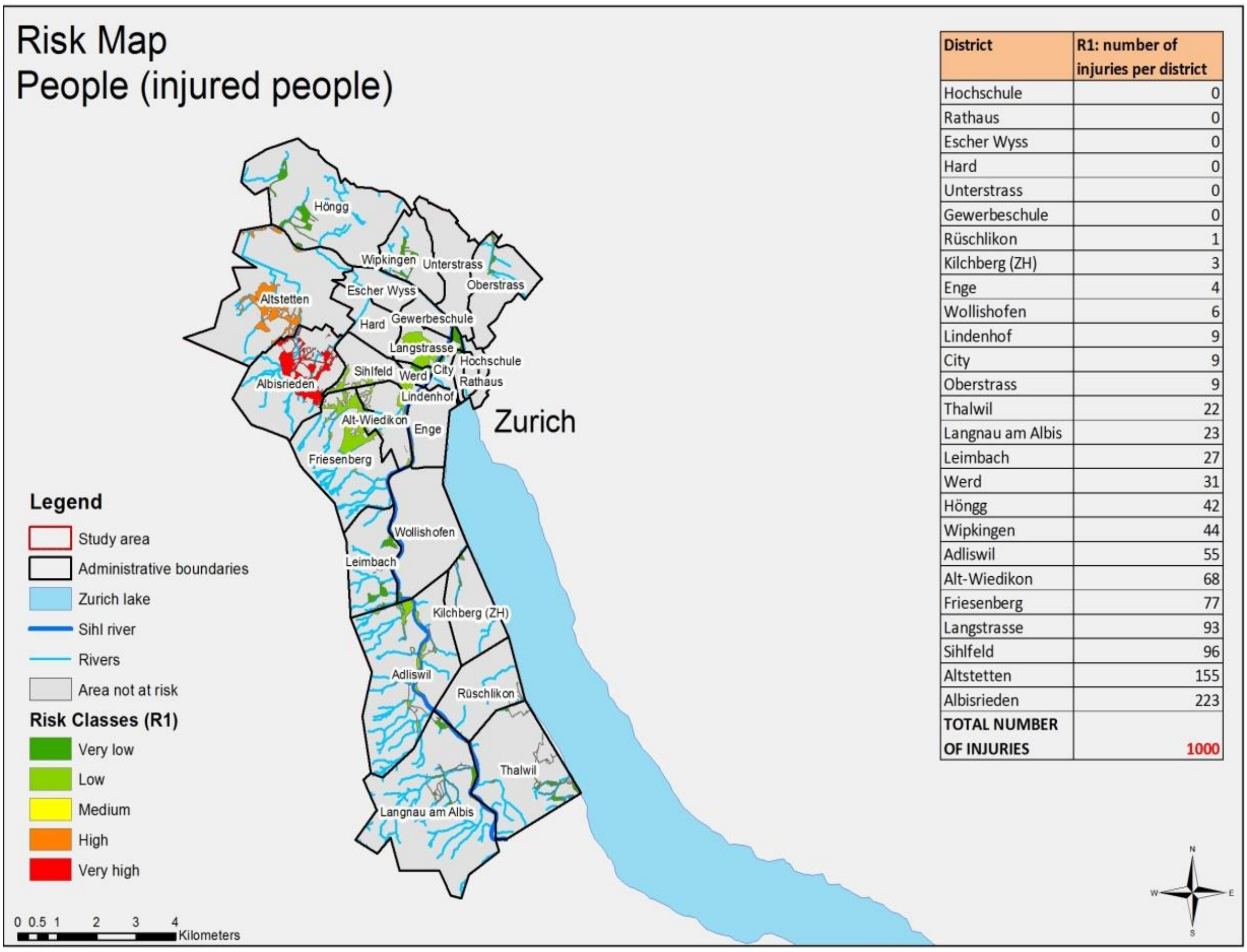
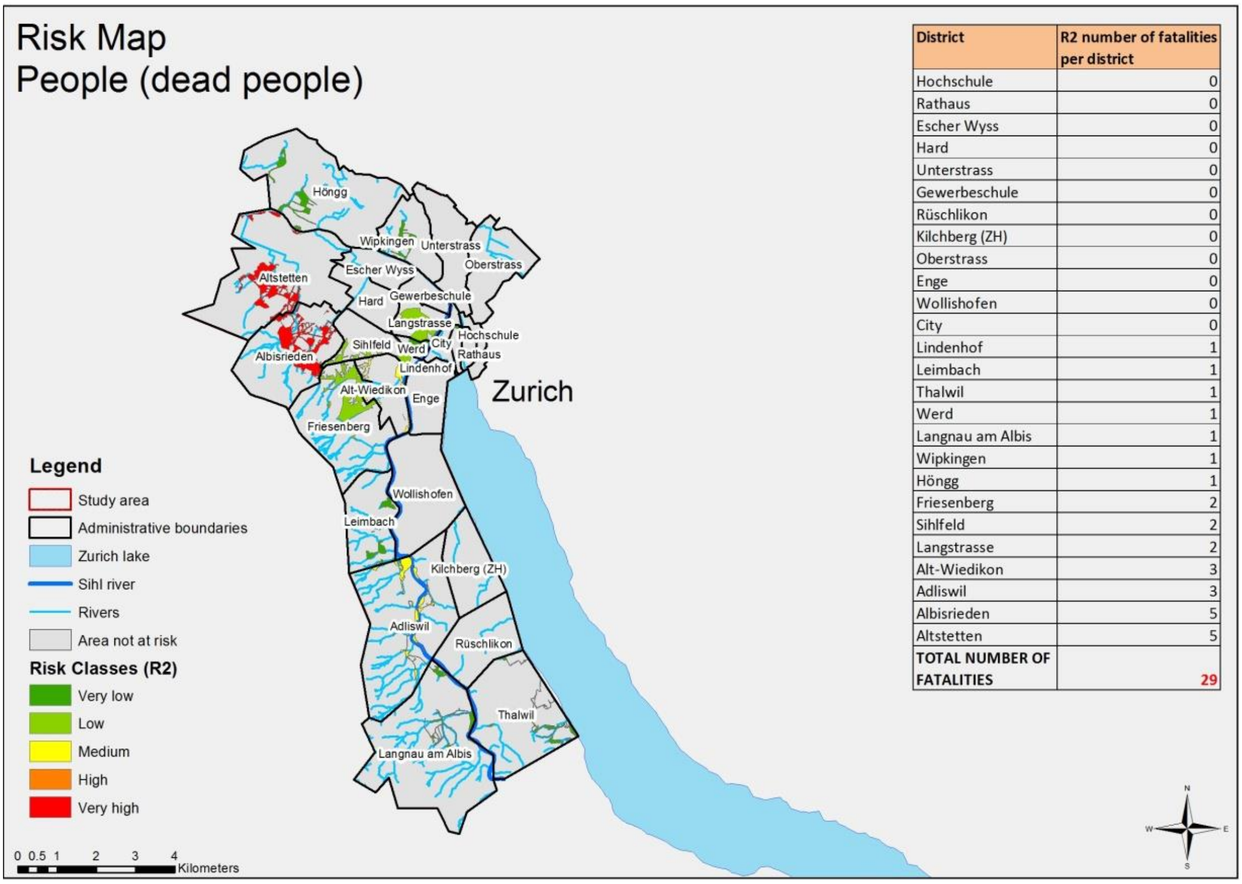
Figure 4. Relative risk map for injured people with statistics at District level.



District	R1: number of injuries per district
Hochschule	0
Rathaus	0
Escher Wyss	0
Hard	0
Unterstrass	0
Gewerbeschule	0
Rüschlikon	1
Kilchberg (ZH)	3
Enge	4
Wollishofen	6
Lindenhof	9
City	9
Oberstrass	9
Thalwil	22
Langnau am Albis	23
Leimbach	27
Werd	31
Höngg	42
Wipkingen	44
Adliswil	55
Alt-Wiedikon	68
Friesenberg	77
Langstrasse	93
Sihlfeld	96
Altstetten	155
Albisrieden	223
TOTAL NUMBER OF INJURIES	**1000**

Figure 5. Relative risk map for fatalities with statistics at District level.



District	R2 number of fatalities per district
Hochschule	0
Rathaus	0
Escher Wyss	0
Hard	0
Unterstrass	0
Gewerbeschule	0
Rüschlikon	0
Kilchberg (ZH)	0
Oberstrass	0
Enge	0
Wollishofen	0
City	0
Lindenhof	1
Leimbach	1
Thalwil	1
Werd	1
Langnau am Albis	1
Wipkingen	1
Höngg	1
Friesenberg	2
Sihlfeld	2
Langstrasse	2
Alt-Wiedikon	3
Adliswil	3
Albisrieden	5
Altstetten	5
TOTAL NUMBER OF FATALITIES	29

Figure 6. Relative risk map of buildings (left) and a zoom on the city centre (right).

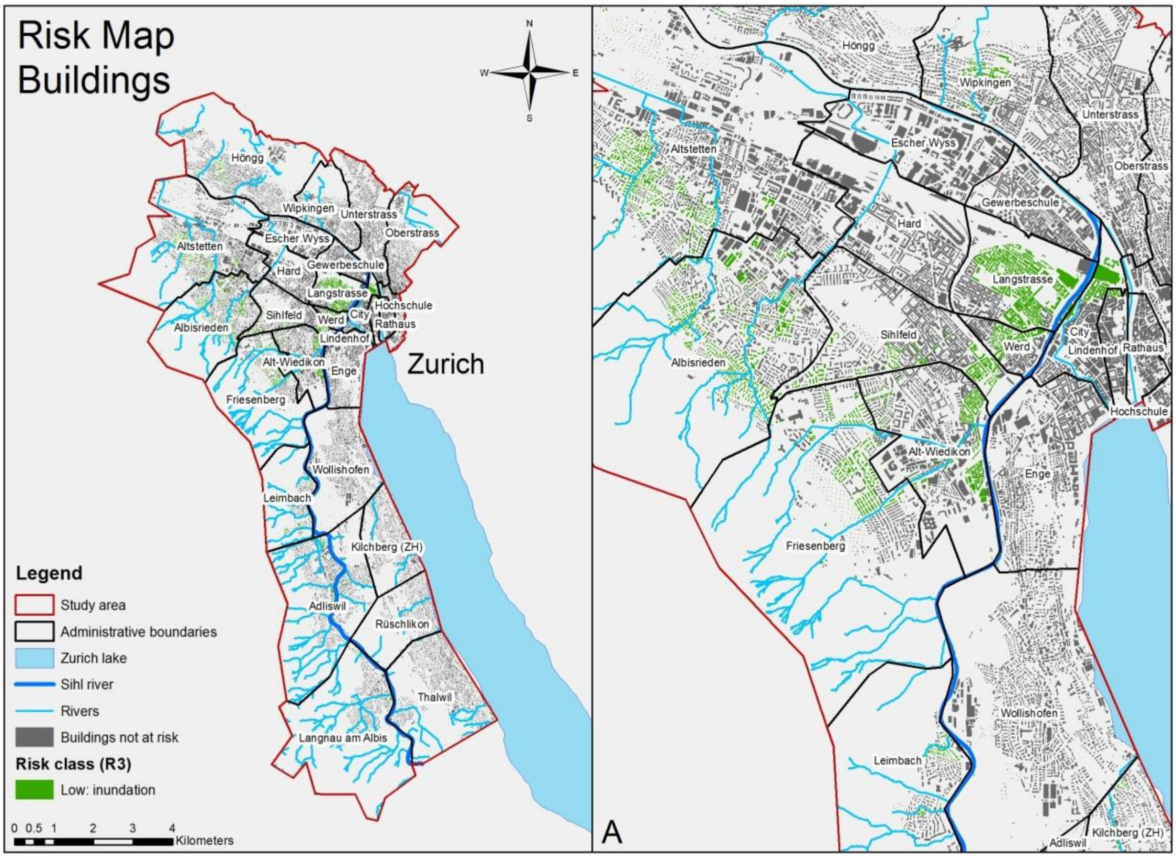


Figure 7. Exposure (left) and relative risk (right) map for infrastructures (roads, railways, pathways).

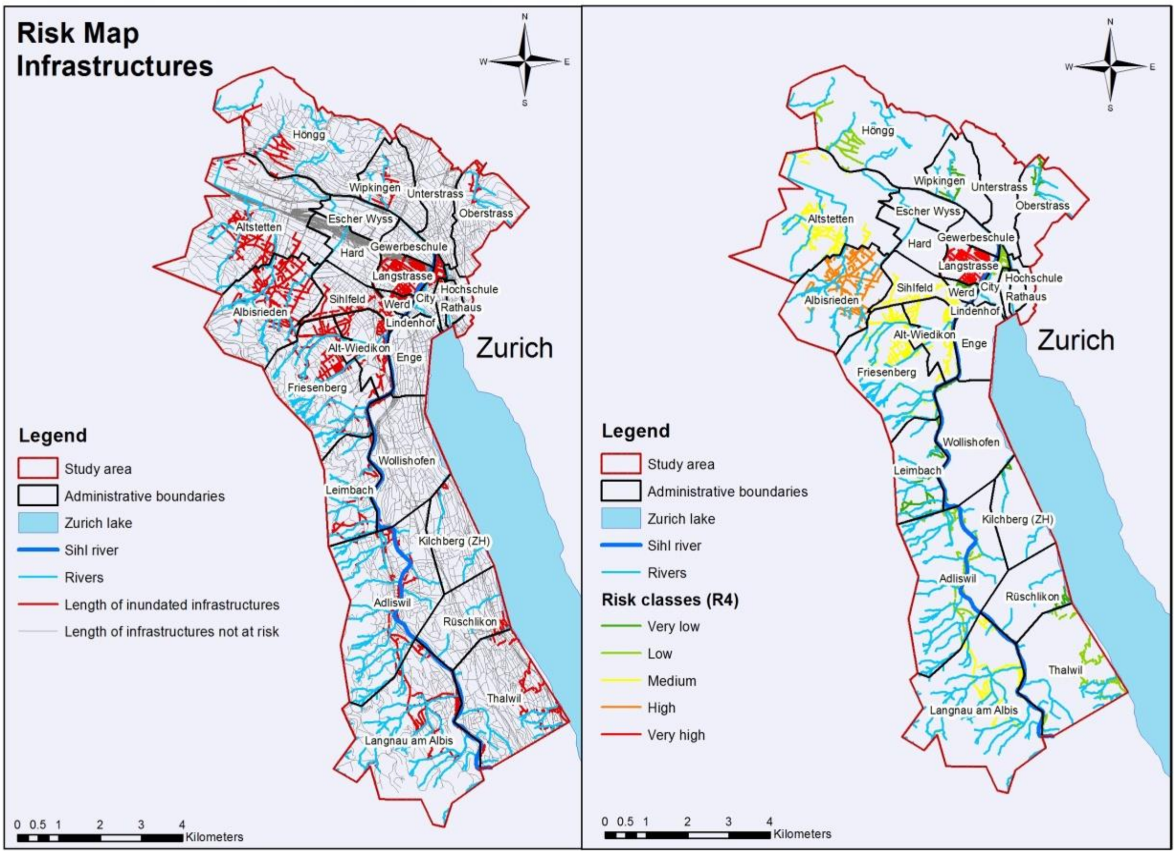


Figure 8. Some relevant infrastructures (hotspots) at risk (Langstrasse and City areas with their roads, Zurich main train station Hauptbahnhof (HB), Platzspitz, Bahnhofbrücke and Walchebrücke bridges). Source: Google maps modified.

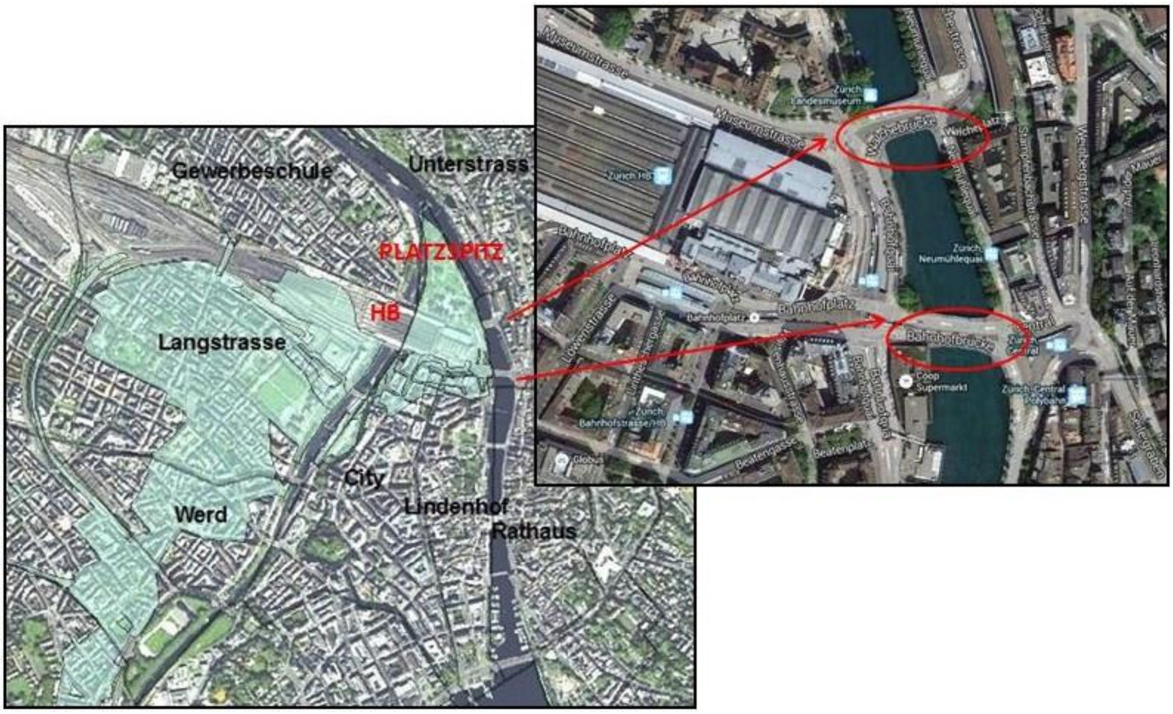


Figure 9. Relative risk map for agriculture showing flooded and destructed agricultural areas. A zoom on the most affected area is reported.

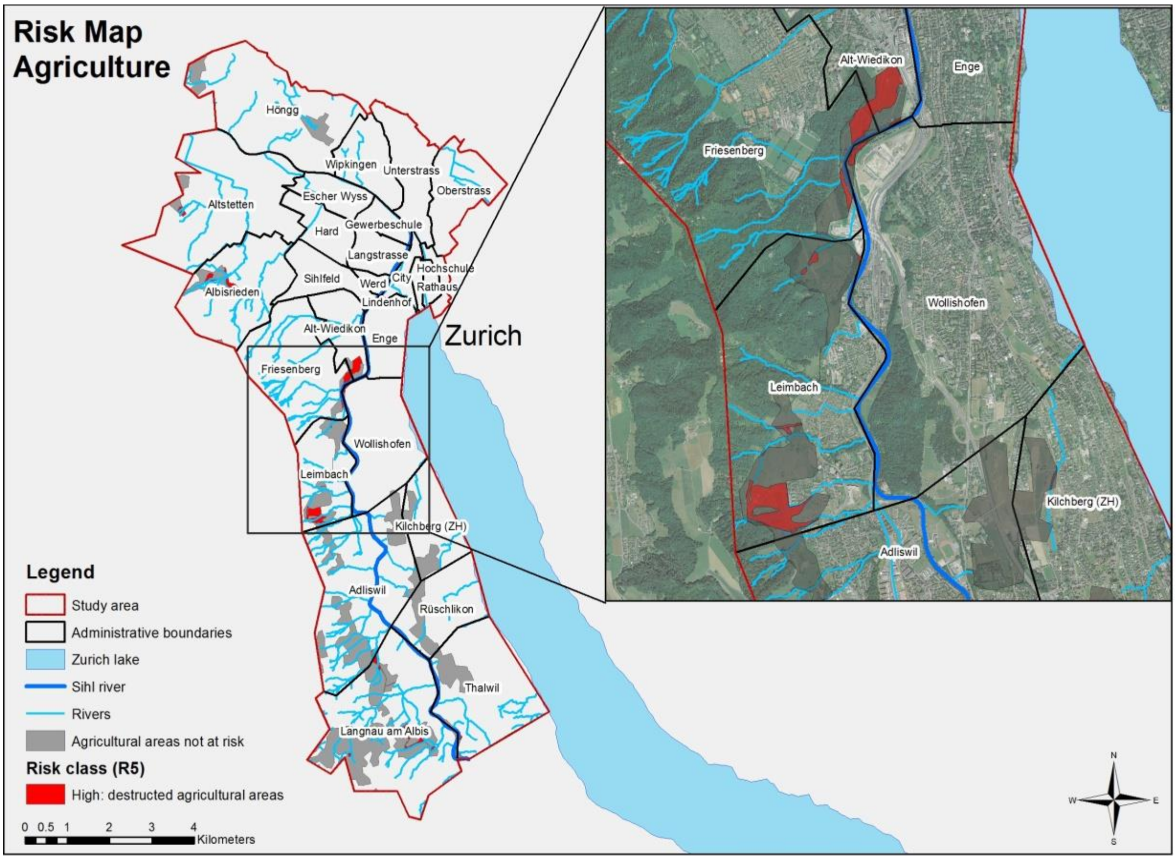


Figure 10. Relative risk map for natural and semi-natural systems (left) with two zooms showing the most affected area (right).

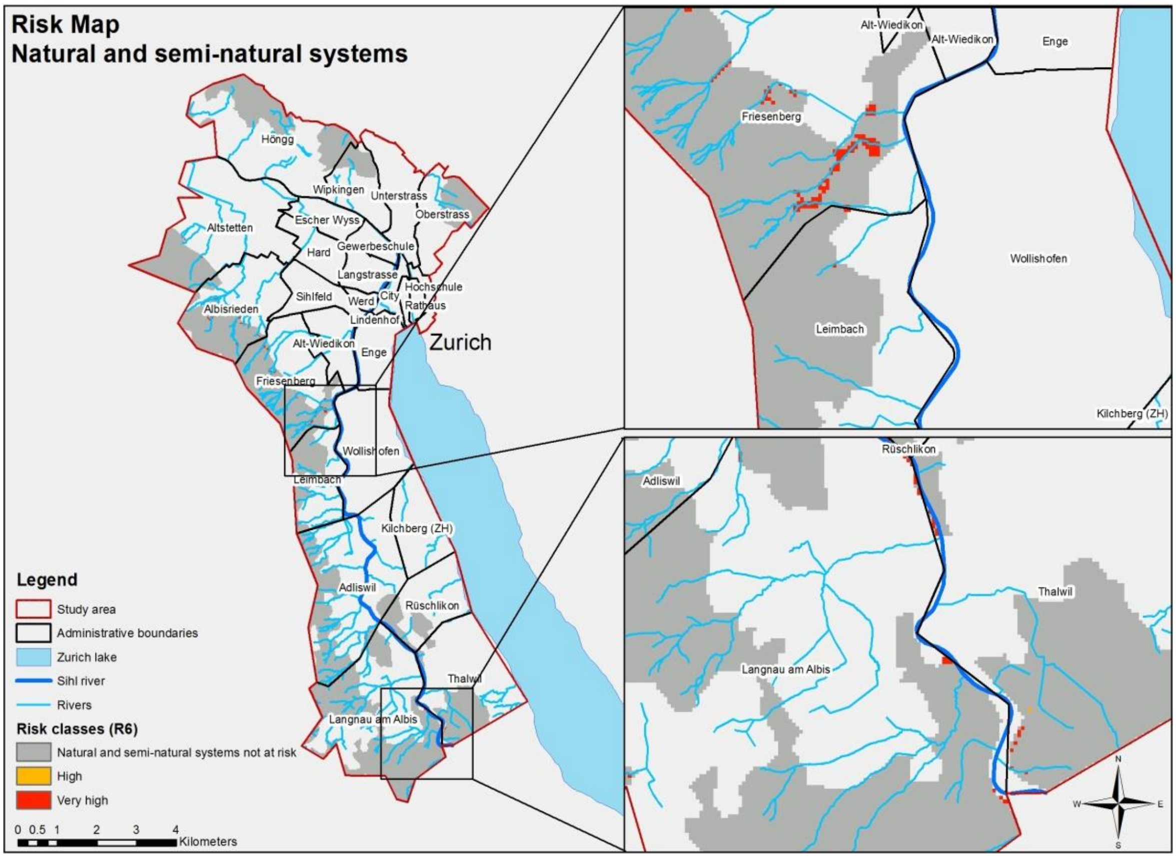


Figure 11. Relative risk map for cultural heritage (left) with two zooms (right).

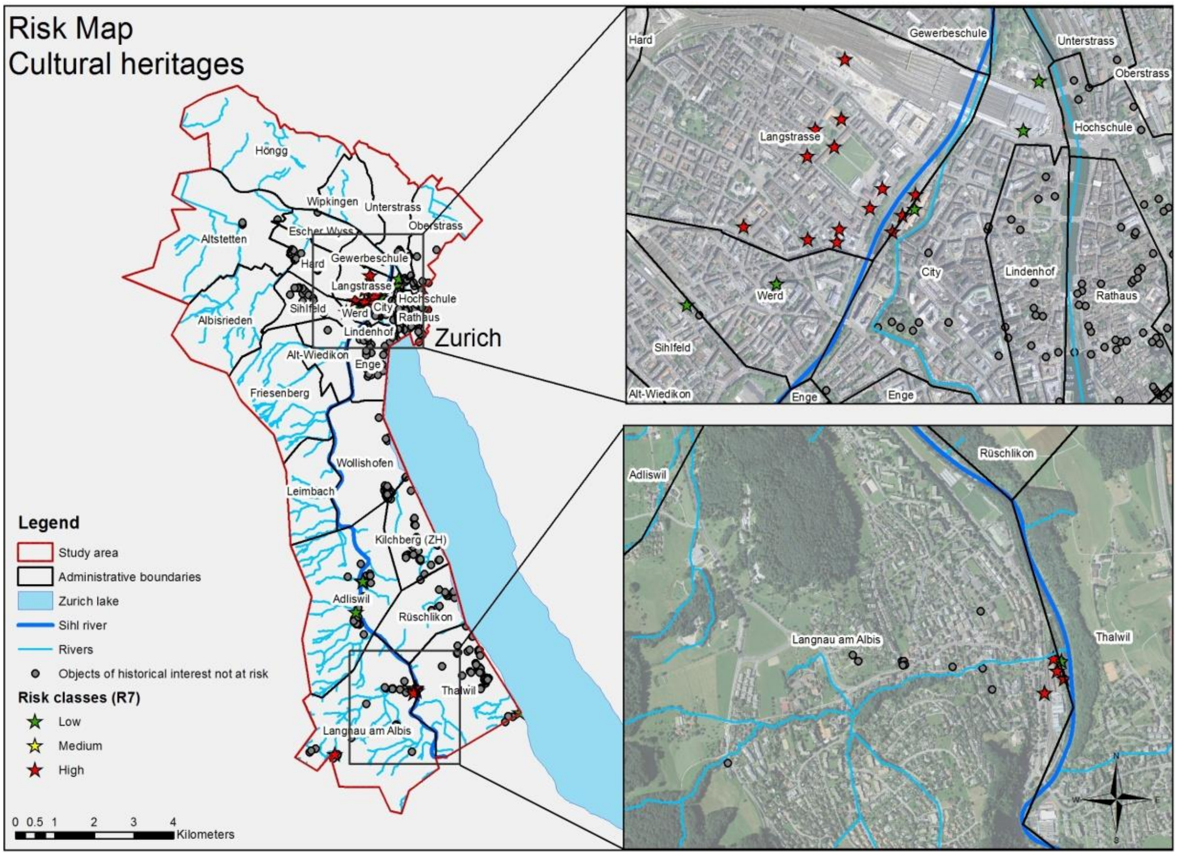


Figure 12. Total risk map for the Sihl river valley considering the 300 years return period scenario.