Floods in the Ölfusá basin, Iceland: A geographic contribution to the assessment of flood hazard and management of flood risk

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Thesis submitted for the degree of *Philosophiæ Doctor* in Geography

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Contents

Abstract

This research is a geographic exploration of the physical and societal components of flood risk in the Ölfusá basin, Southern Iceland. Two specific aspects were investigated:

- Impact of ice jams on the extent, boundaries, and depth of historical floods;
- Public perception of flood hazard and flood risk and public preferences in the management of flood risk in the town of Selfoss.

The research on historical floods indicates that discharge at gauging sites is not a reliable parameter for flood hazard mapping, as the extent and boundaries of ice-jam floods depend essentially on the location and nature of ice jams that form at specific sections of the Hvítá-Ölfusá river complex. Accurate delineation of flood hazard zones is accessible without monitoring of ice-jamming sites, based on reconstructions at high resolution of past ice-jam floods, which provide robust information on the extent and depth of extreme flooding events.

The research on flood risk perception indicates that public awareness of flood hazard is insufficient and shows the need for improved information sharing on the outcome of inundations induced by ice jams, whose genesis and boundaries are unknown to an important part of the population. The study on public preferences in the management of flood risk suggests that the population surveyed favours polycentric governance, restrictions in land use planning, and actions centred on the people: passive measures, which are individual solutions applicable at the home level.

Ágrip

Flóð á vatnasviði Ölfusár eru mismunandi og hafa margvíslegar afleiðingar í för með sér. Í rannsókninni er beitt landræðilegum aðferðum við mat á náttúrufarslegum og samfélagslegum þáttum flóðahættu á vatnasviði Ölfusár. Þeir þættir sem sérstaklega voru rannsakaðir eru:

- Áhrif jakastíflna á umfang, mörk og dýpi flóða;
- Viðhorf almennings til flóða og flóðahættu og jafnframt hvaða kosti almenningur teldi vænlegasta varðandi skipulag flóðamála á Selfossi.

Niðurstöður rannsóknarinnar sýna að rennsli á vatnshæðarmælistað nýtist ekki vel við kortlagningu á flóðahættu því umfang og mörk flóða sem verða af jakastíflum er einkum háð staðsetningu og eðli þeirra þar sem þær myndast á ákveðnum svæðum á vatnasviði Hvítár-Ölfusár. Kortlagning á flóðahættusvæðum er nákvæmust þegar unnið er ítarlegt hermilíkan af stærstu jakastífluflóðum fyrri tíma, en þau veita góðar upplýsingar um umfang og dýpt stærstu flóða.

Rannsókn á viðhorfi íbúa bendir til þess að skilningi á flóðahættu sé ábótavant og sýnir þörf á betri upplýsingamiðlun á afleiðingum flóða sem verða af völdum jakastíflna, en stór hluti fólks áttar sig hvorki á uppruna flóðanna né umfangi.

Könnun á því hvaða kosti almenningur teldi heppilegasta varðandi stjórnun flóðamála leiðir í ljós að fólk kýs að stjórnsýsluákvarðanir séu teknar heima í héraði, kvaðir megi ákveða í skipulagsáætlunum og aðgerðir taki mið af þörfum einstaklinga.

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I would like to thank my many colleagues at the Hydrological Service and at the Icelandic Meteorological Office for having made my life as a research scientist easier over the last three years. I am especially grateful to Jórunn Harðardóttir, director of the Research and Process Department, and to Sigrún Karlsdóttir, Director of Natural Hazards, for their continuous trust and support. I am also grateful to Bogi B. Björnsson, for his expertise on GIS issues and for the good share of fieldwork out in the Icelandic „wilderness“; we have managed to survive together quick sands, collapsing banks, glacial bursts, volcanic ash, and frenzy horses looking for entertainment. I am also thankful to the multitalented Oddur Sigurðsson, to Tómas Jóhannesson and Matthew J. Roberts for their comments on the research papers, to Professor Gunnar Stefánsson at the University of Iceland for his comments and advices on statistical issues, and to Theodór Theodórsson at Landsvirkjun Power for allowing me using their one-meter DTM covering the western bank of the Þjórsá River.

Regarding the survey on flood hazard perception and preferences in flood risk management in the urban area of Selfoss, I would like to thank Friðþór Sófus Sigurmundsson, M.Sc. in geography, for his contribution to visiting residents. I would also like to thank Katrín Georgsdóttir, advisor for the environment at the Árborg municipality at the time of survey, Oddur Árnason, Chief of Police in Selfoss, and Örlygur Karlsson and Þórarinn Ingólfsson, respectively principal and vice-principal at South Iceland College in Selfoss, who all welcomed the survey and provided precious help in arranging interviews. Eventually, I would like to thank all the visited residents in Árborg who accepted to give their time and take part in the survey.

I would like to pay tribute to departed farmers Páll Lýðsson (1936-2008) from Litla-Sandvík and Jón Eiriksson from Vorsabær (1921-2010), who patiently collected the history of their respective home districts, saving precious information on decades of floods in the lower reach of the Hvítá-Ölfusá complex. Their contribution provides an essential background for the development of a sustainable culture of living with floods in the Ölfusá basin. Many thanks to Lýður Pálsson, curator of the House Museum in Eyrarbakki, to historian Guðmundur Kristinsson, and to photographers Ragnar Axelsson and Gunnar Sigurgeirsson. Thanks to all the dwellers who have delivered photographs and shared knowledge with us.

Thanks to fellow graduate students of the Department of Geography and Tourism and of the Institute of Earth Sciences at the University of Iceland for their friendship.

I will thank, finally, my family and friends in France, Iceland, and abroad. I am particularly indebted to my wife, Aldís, and our two daughters, Anna and Ellen, for their daily patience and support.

1 Introduction

1.1 Background

The Icelandic national authorities are making preparations for implementing the European Directive on the assessment and management of flood risks (European Parliament & European Council, 2007). In countries where the directive applies, authorities are required to produce flood hazard maps and flood risk maps for discharge scenarios of low, medium, and high probabilities. The flood hazards maps produced should include information on the inundation extent, depth of flooding and/or water levels, and flow velocity. In turn, the flood risk maps should emphasise on the adverse consequences of the floods. The directive also commands to develop flood risk management plans “focusing on prevention, protection, preparedness”, and promotion of “sustainable land use practices, improvement of water retention” and “controlled flooding of certain areas in the case of a flood event”. The effective implementation of the directive would represent a significant step forward for Iceland in the management of flood risk:

- Iceland has little experience in flood mapping;
- Inclusion of flood risk in the existing planning legislation and regulation is incomplete;
- Little is known of the psychological and social dimensions of flood risk in Iceland.

Iceland has 60 years of experience in monitoring water levels and discharge in rivers but, in turn, little experience in flood mapping. Following the large river floods which struck several catchments of Iceland in December 2006, the Hydrological Service received a three-year governmental funding to map the extent of the inundations (Snorrason et al., 2007), to develop a database on historical floods, and to implement flood warning gauges. Prior to this, only the extent of the volcanogenic glacial burst which flooded the Skeiðarársandur outwash plain in 1996 had been mapped (Snorrason et al., 1997). The development of flood hazard maps and flood risk maps corresponding to specific discharge scenarios (European Parliament & European Council, 2007) has not started yet.

Inclusion of flood risk in the existing planning legislation and regulation is incomplete. Besides the legal requirements regarding the identification of flood hazard zones (Ministry of Justice and Ecclesiastical Affairs, 1998; Parliament of Iceland, 2010), binding documents and guidelines applicable to the designation of flood risk zones and to the enforcement of building codes do not exist for flooding from rivers. Unlike the countries of North America (Environment Canada, 1993; NARA, 2009) and of Europe (MATE/METL, 1999; DEFRA, 2006; EXIMAP, 2007; de Moel et al. 2009), Iceland does not provide a classification of flood hazard from which flood risk zoning could be derived.

Little is known about the psychological and social dimensions of flood risk in Iceland. The flood risk-related investigations led so far focused exclusively on communities under the threat of subglacial eruptions of Katla volcano. They put a light on the impact of the local cultural framework on how dwellers perceive flood risk and react to emergency and evacuation plans (Bird et al., 2010; Jóhannesdóttir and Gísladóttir, 2010). Views of the general public on strategies that should prevail in the mitigation of floods remain unknown.

1.2 Aims of the research

Led in an Icelandic watershed prone to ice-jam floods, the present research is a geographic contribution to methods and approaches to be used in the assessment of flood hazard and in the management of flood risk in Iceland. It relies on the fundamental assumption that geography, as a field concerned with space but also with places and emplacement (Casey, 1993), is an interdisciplinary science that is effective in comprehending the physical and societal components of natural disasters. As Icelandic authorities are moving towards the implementation of the European Directive on the assessment and management of flood risks (European Parliament, Council, 2007), it is of particular interest to investigate some challenges posed by ice jams in rivers and to bring, eventually, some insight and results that would serve, in Iceland, the development of a holistic strategy in the management of flood risk. Two specific aspects of flood hazard and flood risk were examined:

- Impact of ice jams on the extent, boundaries, and depth of historical floods (Papers I-II);
- Public perception of flood hazard and flood risk, and public preferences in the management of flood risk in areas prone to ice-jam floods (Papers III-IV).

Shared knowledge and mutual understanding among stakeholders have become one of the main goals of risk communication (Renn, 2004) and form one of the key principles of the adaptive and integrated management paradigm (Aven and Kristensen, 2005; Huntjens et al., 2010). Production of cooperative discourse is, nevertheless, difficult to achieve as hydrologists, authorities, planners, and the general public have their own perception of flood risk (Patt &Schröter, 2008; Harries and Penning-Rowsell, 2011). Perception of the public is of particular importance. Lay people are prone to form intuitive judgments of probability that are biased. For instance, the probability of events is often evaluated by the ease with which relevant instances come to mind (Tversky and Kahneman, 1973). The public also tends to perceive a flood having a one-percent chance of occurring in any given year and a 100-year flood as two different realities (Bell and Tobin, 2007), although both expressions refer to the same predicted flood which hydrologists, in fact, phrase in two different manners. Public understanding of flood hazard and flood risk also reflects the complexity of a lifeworld under the influence of psychometric factors, such as worry and fear (Fischhoff et al. 1978; Slovic et al., 1984; Slovic, 1987), and of world views and values such as individualism (Wildavsky and Dake, 1990; Dake, 1991; Schwartz, 1996; Penning-Rowsell et al., 2006). The way the general public understands flood risk is not the sole issue when it comes to consider the importance of perceptions. How hydrologists may perceive flood risk is also of concern as “epistemic” uncertainties (Refsgaard et al, 2007) are not always identified and acknowledged in the assessment of flood hazard. For instance, the methodology in which flood hazard maps and flood risk maps are obtained from scenarios of discharge exceedance (European Parliament, Council, 2007) is particularly questionable, as this approach relies on the fundamental assumption that the extent and boundaries of flooding events are reflected in the water levels observed at gauging sites. Unfortunately, the relation between gauge observations and the extent and boundaries of flooding events is not self-evident in the case of ice-jam floods (Beltaos, 1995).

1.3 Regional settings

The research was carried out in the Ölfusá basin, Southern Iceland. The Ölfusá basin drains an area of 6.190 km^2 that extends from the Langjökull and Hofsjökull highland ice-caps down to the Atlantic Ocean (Figure 1.1). The oblong shape of the basin and its orientation result from the NE-SW rifting of the Eurasian and American tectonic plates (Sigmundsson, 2006; Thordarson & Höskuldsson, 2008). The presence of a natural barrier of fissural and central volcanoes ensures an important orographic forcing on the circulation of oceanic air masses above Iceland (Crochet et al., 2007), which causes important precipitation above the basin, from 1.350 mm by the Atlantic coast up to 3.800 mm above the two ice caps (Jóhannesson et al., 2007). Because of harsh climatic conditions, only the fraction of the basin below 240 meters a.s.l. is permanently settled and cultivated. South from Mount Vörðufell lays the Great Þjórsá lava field (Figure 1.2), which separated 8.700 years ago the River Hvítá and the River Þjórsá, as a result of the volcanic activity of the Veiðivötn fissure swarm (Hjartarson, 1994). The lava field is mostly a flat and smooth interface of wetlands that have been repeatedly flooded over the past 200 years because of rain and melt floods (Rist, 1983; Paper I), but also because of ice jams (Rist, 1983; Imsland, 2005; Paper I) that caused water encroachment and submersion of large inhabited areas that are safe from inundation under open-water conditions (Paper I; Paper II; Figure 1.3; Figure 1.4). How an ice-jam flood was initiated in the Hvítá River in 1623, by Mount Hestfjall (Figure 1.2), is preserved in a contemporary document which depicts quite correctly the spatial grip of ice-jam floods in the area but also reflects well the importance of perceptions:

« Þremur vikum fyrir jól 1623 sást hinn voðalegi ormur í Hvítá tvo daga samfleytt hjá bænum Árhrauni eftir að rökkvað var. Fyrra kvöldið sprengdi hann ísinn, svo að áin fór að flóa út yfir bakkana ; sást hann þá um þvera ána í tveimur hlykkjum. Seinna kvöldið var hann í einum hlykk, og bar svo hátt, að hann náði upp í mitt Hestfjall ».

Gísli Biskup Oddson (1593-1638)

"Three weeks before Christmas 1623, at dusk, two days in a row, the dwellers at Árhraun farm saw a terrifying worm in the Hvítá River. The first evening, the worm blew the ice away so the river overtopped its banks. The worm was obvious as two curves emerging from the river. On the second evening, the worm emerged standing as a one tall curve that reached mid-height of Mount Hestfjall."

Gísli Oddson, Bishop of Skálholt (1593-1638)

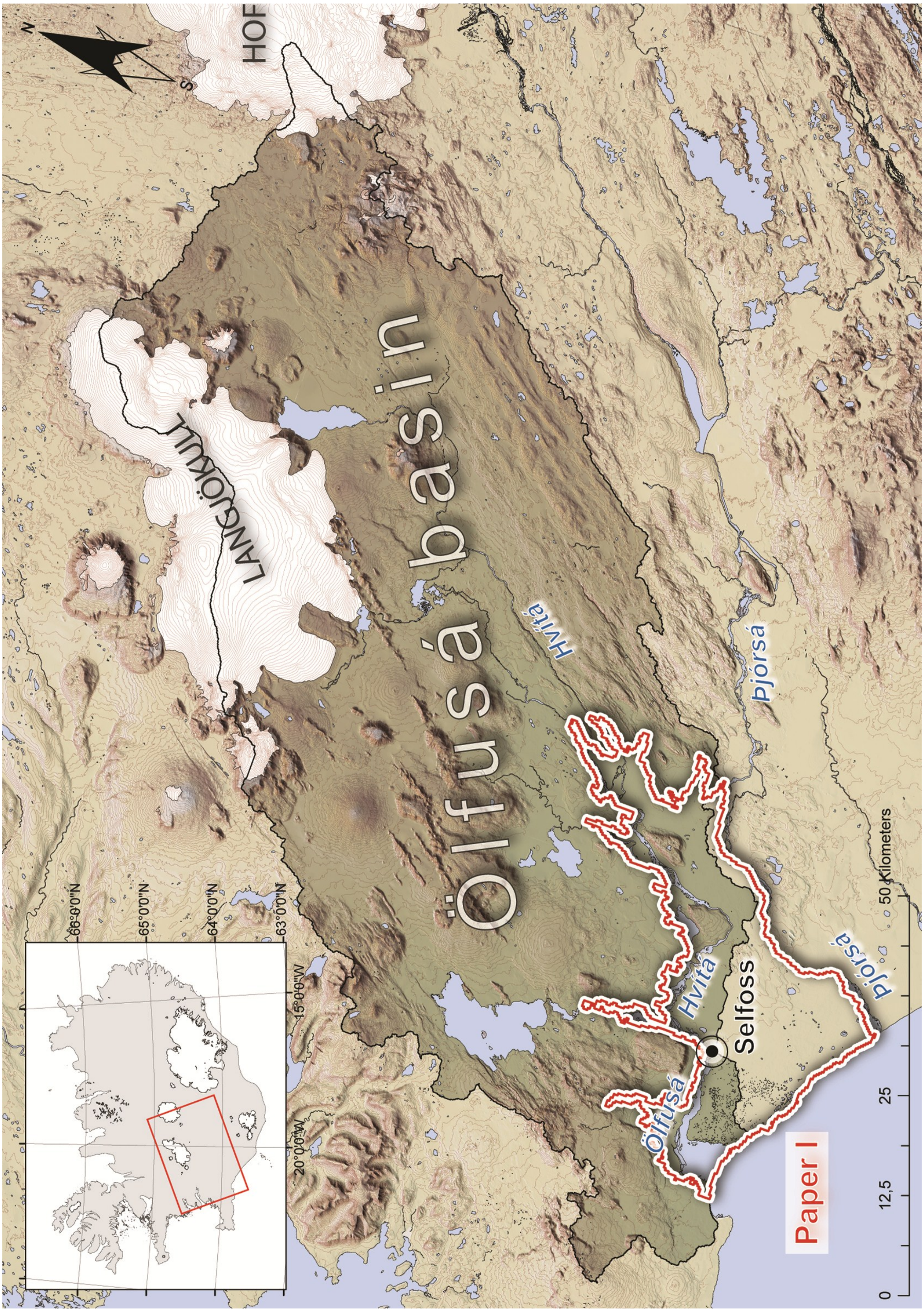

Figure 1.1 Overview on the Ölfusá catchment. Boundaries of the study area in Paper I are shown.

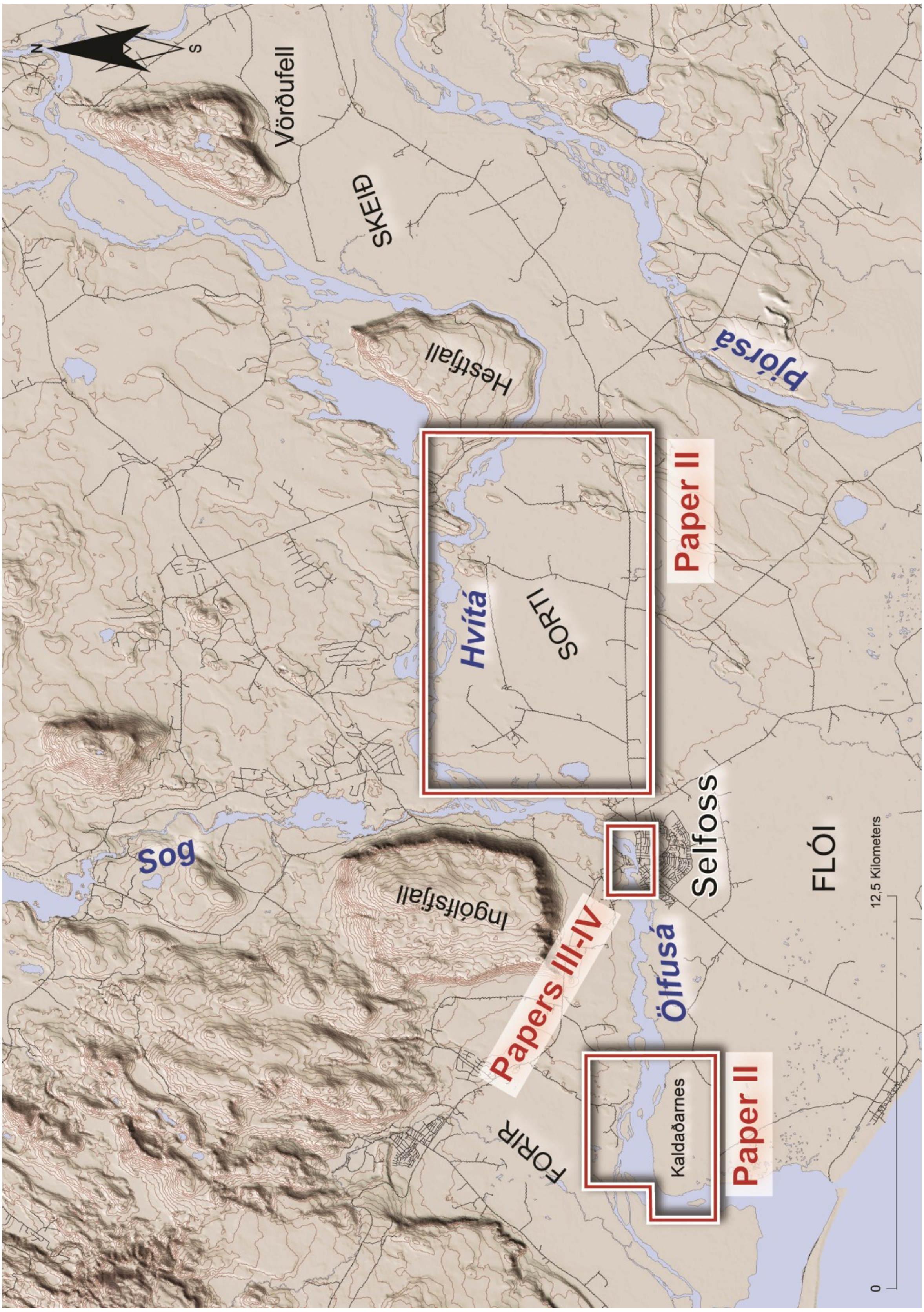

Figure 1.2 Lower reach of the Hvítá/Ölfusá hydrological complex. Boundaries of the studied areas from papers II, III, and IV are shown.

Figure 1.3 Remnants of an ice run by Flugunes, downstream from Selfoss, after a jam release wave in the Ölfusá River on January 23 1983. Kids from Litla-Sandvík Estate are making fun of the river ice blocks transported on land during the onset of the ice-jam flood. Photographer: Lýður Pálsson.

Figure 1.4 Hraungerði Estate on January 12 2001, during the onset of an ice-jam flood initiated by Kiðjaberg, in the Hvítá River. Buildings obvious on the photographs are located on lava outcrops admittedly safe from inundation. Photographer: Jón Eiríksson.

1.4 Methods and results

Methods and results of the research are fully described in four papers included in the thesis as subsequent chapters and summarised below.

1.4.1 Paper I

Pagneux, E., Gísladóttir, G., Snorrason, Á. (2010). Inundation extent as a key parameter for assessing the magnitude and return period of flooding events in South Iceland. *Hydrol. Sci. J.* 55(5), 704-716, DOI: 10.1080/02626667.2010.489281

The first paper describes two centuries of flooding events in the lower reach of the Hvítá/Ölfusá hydrological complex and in the adjacent catchments west from the Þjórsá River (Figure 1.1). The study carried out should be seen as a preliminary assessment of flood hazard with a geographic focus. The first task was to make a census of the flooding events that occurred from 1825 to 2006, emphasising on their triggering parameters and seasonality. The second objective was to provide consistent information on the conveyance routes of flood waters and a macro-scale estimation of the extent and boundaries of the floodplain over the period, including spatial information on the return period of flooding events that would include ice-jam floods and coastal flooding. A regulated grid of 250x250m cells was designed to take full advantage of all historical sources, including photographic material and the toponymic references appearing in the newspapers articles and dwellers diaries.

The results indicate that most of the flooding events substantiated over the past 200 years were winter polygenic inundations. Interestingly enough, 40% of the inundations related to river floods did involve ice jams at specific river sections, which caused water encroachment and submersion of areas that are safe from inundation under open water conditions. The boundaries and extent of inundations caused by ice jams were shown to depend essentially on the location of the jams, irrespective of the discharge estimated from the water levels recorded at the gauging sites.

Spatial aggregation of known flooding events emanates from a fundamental translation of key concepts in which extent and boundaries replace discharge in the calculation of return periods. Although not predictive, the results provide a better insight on the likelihood of inundations than estimated from a probabilistic approach based on discharge. Because each piece of land is characterised by a susceptibility to flooding, the geographic approach is assumed to be more intelligible to the general public, whose perception is admittedly place-dependent, than the probabilistic approach.

1.4.2 Paper II

Pagneux, E., Snorrason, Á. (2012). High-accuracy mapping of inundations induced by ice jams: a case study from Iceland. *Hydrology Research* 43(4-5) (In press)

Given the importance of ice-jam floods in the magnitude of flooding events in the lower reach of the Hvítá-Ölfusá complex (Paper I), the second paper investigates mapping at high accuracy of past inundations induced by ice jams that are properly documented and for which the likelihood of similar future events is still relevant. Two areas prone to ice-jam floods were selected, Kaldaðarnes and Sorti (Figure 1.2), based on the availability of visual documents of good quality showing ice-jam flooding events, and on the absence of severe modifications of the topography since the documented inundations occurred. Multiple aerial and ground photographs of the flooding events, as well as footage from TV networks, were analysed. The photo interpretation of existing documents was supported with the use of orthophotographs and of a DEM of high vertical accuracy (± 10 cm). The water levels observed on the documents were identified on the orthophotographs, georeferenced as control points in a GIS, and eventually attributed elevation values according to the digital elevation model. In some circumstances, fictitious control points were created to allow a continuous calculation of the floodplain boundaries. The control points created were converted afterwards into multiple triangular irregular networks (TIN) representing complex irregular water surfaces. Both the DEM and the irregular water surfaces created were then converted into raster images at 0.5 meter resolution, to allow analyses of elevation differences. Raster images obtained from the calculation process were ultimately converted into polygonal feature classes to allow manual corrections. Deliverable to the general public and authorities, historical flood maps at scale 1:5000 were produced for areas where the reconstructions were considered highly accurate. Originally obtained at a 10 cm contour interval, the depths of flooding were reclassified for legibility purpose on a 4-class scale reflecting safety and emergency response thresholds.

Despite limitations inherent in the methodology, the reconstructions provide locally robust and unprecedented information on the boundaries and depth of flooding in case of ice-jam floods. Such information is crucial for the constitution of a danger-oriented classification of areas prone to floods applicable to planning and emergency response. Considerable weight is hence given to historical approaches in the assessment of flood hazard and in the management of flood risk.

1.4.3 Paper III

Pagneux, E., Gísladóttir, G., Jónsdóttir, S. (2011). Public perception of flood hazard and flood risk in Iceland: a case study in a watershed prone to ice-jam floods. *Natural Hazards,* 58, 269-287*,* DOI: 10.1007/s11069-010-9665-8

The third paper investigates the public perception of flood hazard and flood risk in the town of Selfoss, the main urban area of the Ölfusá basin (Figure 1.2, Figure 1.3). Perception of the public was assessed as the first part of a two-sided survey that was conducted from May to August 2009 among the population aged above 18. The respondents were invited to provide information on the number of events, dates, and genesis of the flooding events having occurred in town, and to map the boundaries of the flood area on an orthophotograph of Selfoss at scale 1:10.000. The sketches were processed with a regulated grid of 10x10m cells to produce choropleth maps where spatial representations could be adjusted for each predictor and displayed as frequencies of citations. For each parameter, information provided by the respondents was rated as scores that were eventually itemised on a balanced scale. The respondents were also invited to estimate the risk of flooding in their neighbourhood and to tell how much they worry about flood risk. Awareness, risk estimation, and worry, were analysed in the light of several predictors: on the one hand, age, gender, location of residence, tenure, living floor, geographical origin, level of education, the experience of the flooding event in 1968, and the time spent living in Selfoss; on the other hand, the knowledge of the only flood sign existing in town and the attendance to a photographic exhibition about historical floods in Selfoss that was held in town in May 2008.

The results indicate that two thirds of the respondents have an insufficient knowledge of historical inundations. Especially, the genesis and boundaries of inundations induced by ice jams are unknown to an important part of the population. Only 9% of the respondents consider the risk of flooding as important or very important in their neighbourhood, and 5% declare being rather or much worried. Experience of floods in the town is found the most effective source of awareness; the respondents who have the best knowledge on the history and the best understanding on the genesis and extent of the flooding events are the ones who have really experienced them. Although the respondents are aware of more events than personally experienced, the knowledge about flooding events diminishes as the time spent living in Selfoss decreases. Altogether, it indicates a failure in the transfer of knowledge between generations that has led to a loss of collective memory and weakened the development of a culture of living with floods. Being aware of the flood sign does help, but fails to compensate for the lack of experience and inherited knowledge from alternative sources.

1.4.4 Paper IV

Pagneux, E., Jónsdóttir, S., Gísladóttir, G. (Under review). Management of flood risk in Iceland: A case study on public preferences. Submitted to *Landscape and urban planning.*

Paper IV investigates the preferences of the general public in the management of flood risk in the town of Selfoss (Figure 1.2, Figure 1.3). It is the sequel of Paper III, which focused on the public perception of flood hazard and flood risk. The respondents were offered to answer three sets of 20 closed questions focusing on levels of regulation and of responsibility, land use restrictions, and technical measures. The answer modalities for questions related to technical measures and land use restrictions were structured on a forced choice bipolar scale. The socioeconomic profile and flood perception profile of the respondents acquired during the first part of the survey (Paper III) were used in the analysis of the preferences. Emphasis was put, in the analysis, on the jurisdictional, institutional, and spatial scales and levels at which the coping options take effect. A classification focusing on the strategy, objectives, accessibility, and scale of application of the technical options, was developed:

- Strategy: A difference was drawn between active measures aimed at reducing the frequency and magnitude of floods and passive measures aimed at reducing their adverse consequences.
- Objectives: A difference was drawn between structural options aimed at runoff control, ecological options aimed at runoff control, options aimed at protection of developed areas, and flood-proofing options.
- Accessibility: A difference was drawn between options accessible to individuals and options requiring collective action.
- Geographic scale of application: A difference was drawn between options applicable at the home and lot scale, options applicable at the town scale, and options applicable at the basin scale.

The results on the distribution of responsibility between levels of government indicate definite support of the municipal authorities. There is also pronounced defiance towards central government by a significant part of the population. Although expressed preferences on levels of regulation indicate important opposition to the principle of compulsory measures, strong approval of restrictions in land use planning reveals that the principle of flood risk zoning is well accepted by the population. Mitigation actions centred on the people are largely approved. In contrast, there is little support for mitigation measures requiring collective action at the town and river basin scales. Structural runoff control is clearly rejected and support of control of runoff based on ecological processes is mixed. Perception of flood risk looks of marginal influence on the expressed preferences, which may reflect, to some extent, values of self-direction and individualism.

1.5 Perspectives

1.5.1 Impact of the research

The mapping methodology presented in the first paper has been newly recognised by the International Association of Hydrological Sciences as a significant contribution in the field of hydrology (International Association of Hydrological Sciences, 2011), as the methodology can be used with advantage in the preliminary flood risk assessment phase described in the European directive on the assessment and management of flood risks (European Parliament & European Council, 2007). As for the high-accuracy reconstructions described in the second paper, they have been used over the past two years by the planning authorities of the Ölfus and Flói municipalities to support their decision regarding the development of areas prone to floods in their jurisdiction (e.g. Pagneux, 2009; Pagneux, 2011). The reconstructions have also provided, in recent months, precise information to the hydrologists of the Icelandic Meteorological Office for the implementation of warning gauges in the Hvítá and Ölfusá rivers.

1.5.2 Future work

Complementary investigations are needed to improve the assessment and management of ice-jam floods in the Ölfusá basin. More attention should be given, in particular, to geomorphic evidence in the identification of the flood topographic envelope (Lichvar et al., 2004; Ballais et al., 2005). Inclusion, in flood hazard classifications (MATE/METL, 1999; DEFRA, 2006; DEFRA, 2008), of local parameters that are critical for life safety, such as water temperature and presence of drifting river ice, could also be investigated and discussed; the risk of death due to accidental hypothermia (Lloyd, 1996) is particularly high in case of cold-water immersion (Golden et al., 1997), and may be therefore taken into account, as the mean daily temperature of the Ölfusá River during the flood season is only 1°C. Investigations are also needed to get a better understanding, in the Ölfusá basin and in Iceland, of the public acceptability of water policies and management regimes. This cannot be achieved, at the academic level, without the constitution of a research team that would include planners, geographers, environmental sociologists, environmental psychologists, and political scientists. Local authorities should be encouraged to become a partner for such a research; a better elicitation of interests and preferences could be achieved, for instance, by the initiation of an informal participatory process (Moellenkamp et al., 2010) at the municipal level.

1.6 Conclusion

The research focused on both physical and societal dimensions of flood risk in the Ölfusá basin, southern Iceland. Original insight was provided not only on the extent of inundations and depth of flooding associated with ice-jam floods, but also on the public perception of flood hazard and on the preferences of the public in the management of flood risk. Despite remaining uncertainties and knowledge gaps, it forms a new body of regional information and methods that has received international attention in recent months and is already built on, in Iceland, by the hydrologists of the Icelandic Meteorological Office and the planning authorities at the municipal level. Complementary investigations are needed to strengthen the outcomes of the research and provide the Icelandic authorities with a comprehensive basis for the framing of an advanced planning regulation and adoption of a prevention and mitigation strategy.

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2 Inundation extent as a key parameter for assessing the magnitude and return period of flooding events in southern Iceland

Pagneux, E., Gísladóttir, G., Snorrason, Á. (2010). Inundation extent as a key parameter for assessing the magnitude and return period of flooding events in southern Iceland. *Hydrological Sciences Journal* 55(5), 704–716, DOI: 10.1080/02626667.2010.489281

Abstract

River flow conditions in many watersheds of Iceland are particularly disturbed during winter by the formation, drifting and accumulation of river ice, whose impact on water encroachment and extent of inundations is not reflected in the discharge records. It is therefore necessary to use river discharge with great caution when assessing the magnitude of past inundations in Iceland, and to give attention to other flood magnitude parameters. A GIS-based methodology is presented that focuses on inundation extent as an alternative parameter for the assessment and ranking of the magnitude of past flooding events in the Ölfusá-Hvítá basin, known as one of the most dangerous flood-prone river complexes in Iceland. Relying ultimately on a macro-scale grid, the method enabled the reconstruction of the extent of inundations, the delineation of the flood plain, and, finally, some estimation of the likelihood of flooding of exposed areas that include marine submergences and river floods for both open water and ice conditions.

Keywords

Polygenic inundations – Ice jamming – Spatial analysis – Return period – Susceptibility to flooding – Inundation grid – Iceland

2.1 Introduction

Floods, defined as a rise in the water level of a stream to a peak from which the water level recedes at a slower rate (WMO, 1993), have been put at the core of the compulsory mapping of areas liable to flooding enacted by the European Directive on the Assessment and Management of Flood Risks (European Parliament & European Council, 2007). Inundation hazard maps refer in the Directive to flood probabilities which fundamentally derive from return periods of annual river discharge maxima (Gumbel, 1958; Todorovic & Zelenhasic, 1970; Haan, 1977; Castillo, 1988), or peak-over-threshold series (Davison & Smith, 1990; Haan, 1994). Thus, river discharge is considered in the Directive as a suitable parameter for defining the probabilities of inundations, and is assumed to reflect correctly the magnitude of flooding events.

This assumption is not self-evident, although it appears natural at first sight. Indeed, floods and inundations do not refer to the same reality: by definition, discharge is a magnitude parameter referring to streams while inundations characterise exposure of areas to flooding, regardless of water provenance. Irrespective of the chosen probability distribution, a methodology based on river discharge is unlikely to combine inundations related to river floods, marine submergences, and potentially pluvial inundations. Therefore it can hardly reflect the real susceptibility to flooding, of areas exposed to polygenic inundations.

More significantly, the correlation between river discharge and inundation extent is not always verified for river floods, especially in Arctic and sub-Arctic basins where frazil ice and ice jams often interact with flow conditions (Beltaos, 1995; Prowse, 1995; Beltaos & Prowse, 2001). On the one hand, a significant amount of the water diverted from rivers because of ice jams may not return to channels, depending on the morphology of the drainage system, and consequently not appear in discharge records downriver; considering all possibilities, an ice jam-induced flood cannot be identified without reference to parameters such as extent when the related river discharge does not exceed the defined threshold for open-water conditions at the reference gauging site. On the other hand, backwaters and side-waters induced by ice jams lead to flooding in areas which at the same discharge would not be flooded under open-water conditions. Therefore, in this study, we not only question the relevance of identifying inundations related to river floods in terms of discharge, but also investigate the possibility of assessing the extent and the boundaries of flooding on that basis.

The breakthroughs in remote sensing provided by the ESA with Envisat satellite have allowed some rapid mapping on a global scale of recent floods in Europe and China (Yezou et al., 2007a; Yezou et al., 2007b; Henry et al., 2003). This is promising for the assessment of future flooding events independently from discharge-based methodologies, but does not help in assessing the magnitude of past inundations. If the use of historical data has been proven helpful to enrich time series on floods (Archer, 1999; Williams & Archer, 2002), no attempts have been made so far to integrate contextual information in a methodology, especially references on the toponymy (place names), as a tool for assessing the extent and boundaries of past events. Toponymy is thought an important indicator of landscapes and landscape changes (Sigmundsson, 1990; Gunnarsdóttir, 2001; Sousa & Garcia-Murillo, 2001; Bragadóttir & Gísladóttir, 2006).

Based on a GIS study of an Icelandic watershed, in which we integrated remote sensing data and toponymic references, we aim to show that, as a parameter for assessing the magnitude and return period of past inundations, extent is not only accessible but occasionally more reliable than discharge, which we consider a stumbling block in “flood” assessment. Unlike discharge, the spatial grip is a common parameter of magnitude for all types of inundations that best reflects the true susceptibility to flooding of settlement areas and territories.

2.2 Study area

The Ölfusá-Hvítá basin is an Icelandic watershed spreading from the Langjökull and Hofsjökull highland ice-caps down to the Atlantic Ocean (Figure 2.1). It drains an area of 6.190 km^2, whose orogenic and hydrologic configuration is mainly influenced by the rifting of the Eurasian and American tectonic plates (Sigmundsson, 2006; Thordarson & Höskuldsson, 2008). Fissural and central volcanoes related to this rifting there form a NE-SW natural barrier that ensures an important orographic forcing on oceanic air masses circulation above Iceland (Crochet et al., 2007). Mean annual precipitation above the basin is thus important, ranging from 1350 mm by the Atlantic coast up to 3800 mm above the two ice caps (Jóhannesson et al., 2007), and forms a significant seasonal snowpack in the highlands. The study area, which covers roughly 800 km^2, embraces the lower reaches of the Ölfusá basin along with neighbouring wetlands from adjacent basins where those reaches occasionally drain out (Figure 2.2). This area concentrates most of the South Iceland urban areas and population, and can be therefore considered as a risk management district regarding floods.

Post-glacial volcanic activity of the Veiðivötn fissure swarm has refined the longitudinal profiles of glacial rivers in most of the study area (Figure 2.1): fed locally by springs and direct runoff, the River Hvítá, re-named Ölfusá from the confluence with the River Sog, has been separated 8.700 years ago from the River Þjórsá, following the flow of the Þjórsárhraun, the world´s largest Holocene lava field (Hjartarson, 1994). The pahoehoe lava field covers more than 53% of the study area. Still emerging at some locations as rugged and sinuous outcrops, it is mostly a rather flat and smooth interface of wetlands, partially altered into suitable terrains for pasture and agriculture due to the 300 km of channels and ditches that have been dug throughout the 19^{th} and 20^{th} centuries (Thorsteinsson, 1975). This peculiar topography appears to be a predisposing factor for large plain inundations, as suggested by an official manuscript from 1825 which describes how the Þjórsá and Hvítá glacial rivers managed to merge together in the Skeið before draining out onto the lava field which composes most of the lowlands of the Ölfusá basin (Figure 2). Everything is described in the name of the area: the term Skeið is an Old Icelandic toponym that exactly means *flood plain*.

Table 2.1 Types and coverage of gauging stations in the study area.

Station	River	Location	Station type	Data type	Catchment area (km^2)	% of basin	Records since
V41	Hvítá	Iða	Surface water gauge	Water stage	3518	57	2007
V64	Ölfusá	Selfoss	Surface water gauge	Discharge	5678	92	1950
V271	Sog	Ásgarður	Surface water gauge	Discharge	1091	18	1972
V313	Brúará	Dynjandi	Surface water gauge	Discharge	596	10	1948
V516	Ölfusá	Óseyri	Surface water gauge	Water stage	6187	100	2007
V543	Hvítá	Árhraun	Surface water gauge	Water stage	4228	68	2008

Source: National Energy Authority of Iceland, Iceland Hydrological Service.

Measurements in the water wells drilled in the Þjórsá lava field by the coast indicate a local subsidence of 2.5 mm/year for the last 8000 years (Jónsson, 1994). This suggests an average subsidence of 50 cm on a 200-year scale, which may have impacted on the magnitude of flooding events. Results from GPS campaigns in 1993 and 1994 indicate that this same area is now rising at a rate of 2–3 mm/year as a result of the ongoing deglaciation of Iceland (Árnadóttir et al., 2009).

Located in the town of Selfoss, the reference gauging station (V64) is an automatic water-level recorder operating continuously since 1950, which covers 92% of the drainage basin (Figure 2.2, Table 2.1). The rating curve gives 383 m^3/s as the mean discharge until 1997 (Jónsson et al., 1999), and a mean of annual discharge maxima reaching 1300 m^3/s. Fifteen floods from 1900 to 2006 would be acknowledged using this mean of yearly maximum floods, including unmonitored floods from 1930 and 1948 whose discharge was estimated from water marks on the Selfoss bridge, as well as the step-burst flood in February 1968, assumed to have reached a discharge of 2260 m3/s, the highest ever recorded in the basin. This estimation is uncertain due to the formation during the flood of a break-up jam near the gauging station.

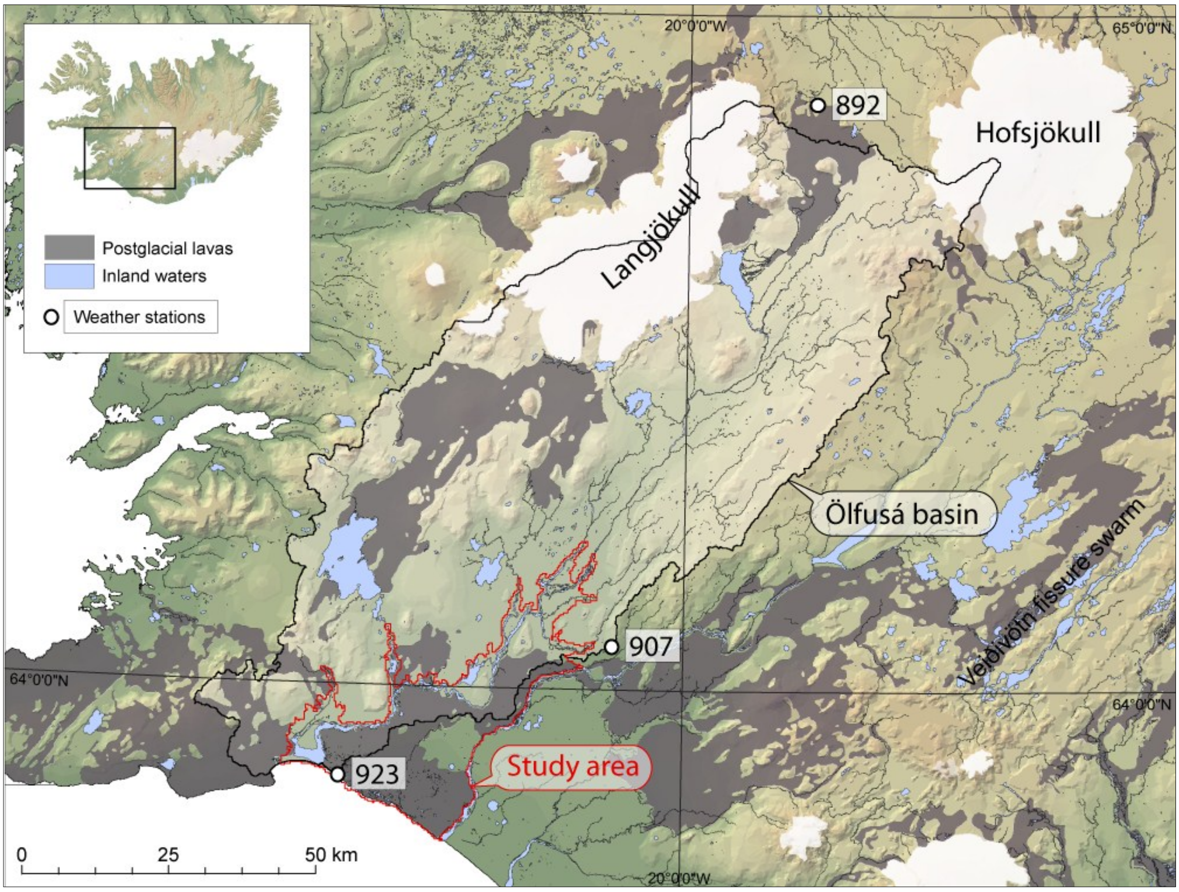

Figure 2.1 Ölfusá-Hvítá basin and study area. The morphology of the hydrographic network and basin are the direct result of the rifting of tectonic plates and Holocene volcanism. The weather stations used in the analysis of the flooding triggers are shown.

Previous studies on flood hazard in the Ölfusá basin suggest that diversion and loss of water upriver from Selfoss was effective during the 19th and 20th centuries for several floods because of ice jams at some sections of the Ölfusá River bed (Thorodssen, 1917; Thordarson, 1970; Rist, 1983; Imsland, 2005). Meanwhile, there is some historical evidence on the basin of several jökulhlaup, or glacial outbursts, from proglacial Lake Hagavatn, at the outlet of the Langjökull ice cap (Thorarinsson, 1939). However, the extent and boundaries of inundations related to known river floods in the Ölfusá-Hvítá basin prior to 2006 have never been assessed, and it is reasonable to suspect that gauged or estimated discharge records from the reference gauging station may not reflect accurately their spatial grip on territories.

The period elected for the research starts with the flood in 1825 and ends with the flood of 22 December 2006, which has been assessed with high precision by the Icelandic Hydrological Service (Snorrason et al., 2007).

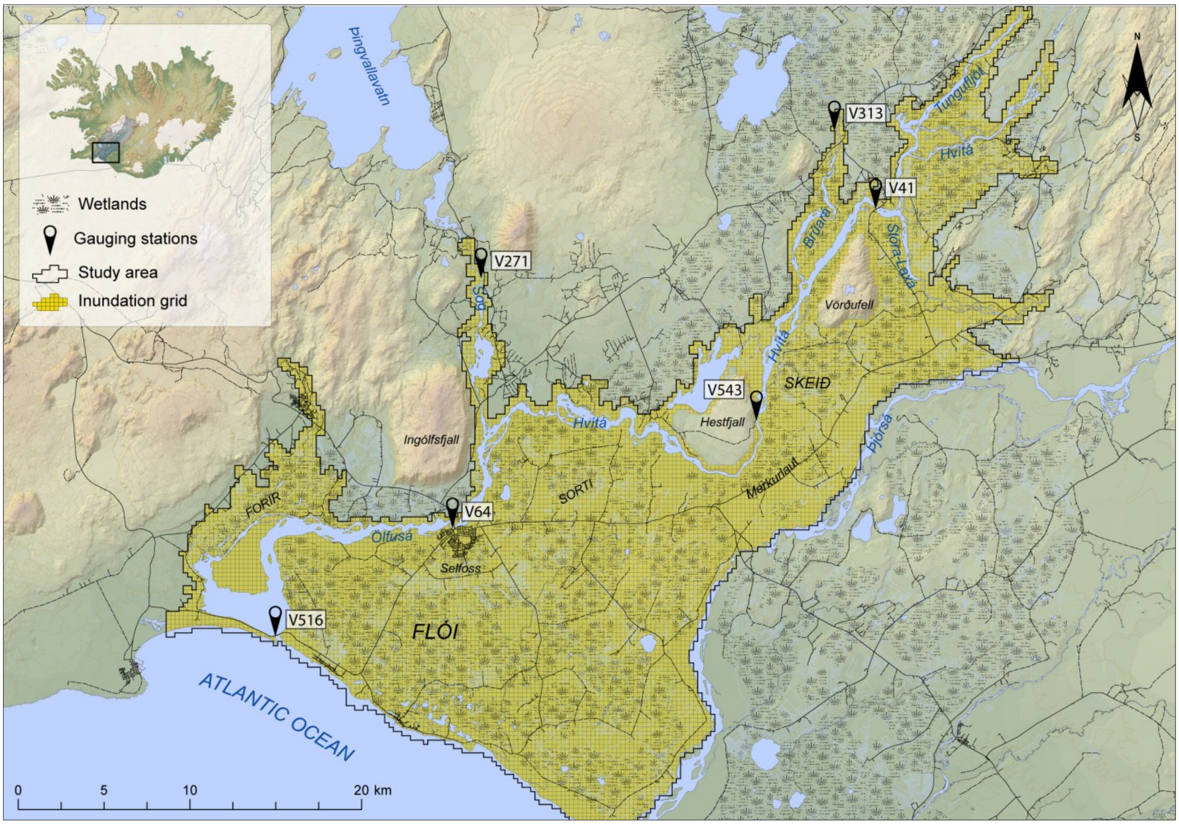

Figure 2.2 Overview of the study area. Wetlands dominate and cover most of the Holocene lava field (Fig.1); the regulated grid aimed at reconstructing the extent of inundations covers the whole area with the exception of the Hestfjall and Vörðufell mountains.

2.3 Methodology

The method developed for assessing the magnitude of past inundations in the Ölfusá basin is a geographic approach based on the integration and combination of monitored, contextual and image data, which aims to: emancipate from discharge records; take full advantage of the place names appearing in the contextual information about floods, and combine it with collected field and remote sensing material to produce georeferenced data; and, finally, compute in a comparable way the boundaries and extent of all substantiated events, which could not be possible by using only GPS measurements and photo-interpretation. Elevation data and orthophotographs produced by Samsýn ehf for the Hydrological Service and the National Power Company (Table 2.2) were used to support the photo-interpretation of inundations that are observable in the ground/aerial pictures and in the footage from the TV networks. The use of place names was necessary and often crucial to provide a continuous mapping of the flooding boundaries. First, they are the unique source of information for placing inundations prior to 1930. Twenty-eight toponyms are mentioned for instance in the sheriff's manuscript reporting the inundation in 1825, including estates and smallholdings, buildings and brooks. Secondly, the place names reflect landscapes in the study area that are too small to be consistently reflected in the available digital elevation models. Iceland is indeed a country of detailed toponymy: outcrops in the lava fields, ponds, brooks, hills or slopes, estates and smallholdings, have been given a proper name, if not many, from the very first years of settlement. Eiríksson (2008) has reported no less than 1919 place names in the former Skeið district, i.e. one toponym every 230 x 230 m of land. Finally, the place names mentioned in newspapers and diaries reflect historical conditions in the topography that are not accessible in the existing DEMs because of the changes induced by erosion, anthropogenic pressure, and by the switch from subsidence to isostatic rebound.

Table 2.2 Digital elevation models used for identification of flooding paths and definition of inundation boundaries.

Institution	Altitudinal resolution (m)	Break lines	% of the assessment area	Year
National Power Company	1	Yes	26,3	2007
Hydrological Service	2	No	62	2007
National Land Survey of Iceland	20	No	11.7	2007

Table 2.3 Availability of daily series on precipitation and temperature from the reference meteorological stations.

Stations	ID	Latitude	Longitude	Elevation (m a.s.l.)	Precipitation records since	Temperature records since
Hveravellir	892	64°52.005'	- 19°33.733'	641	1965	1965
Hæll	907	64°03.904'	- 20°14.471'	121	1933	1949
Eyrarbakki	923	63°51.888'	- 21°09.022'	5	1880	1957

Source: Icelandic Meteorological Office.

2.3.1 Flood census, seasonality and triggers

Contextual information on flooded areas from 1825 to 2006 was collected from residents, newspapers and other media, which together provided continuous information from 1848 (Figure 2.3). Dates found for flooding events were compared with available data from the Hydrological Service and the Icelandic Meteorological Office: daily data on river discharge, daily data on precipitation and temperature, and monthly data on snow cover and soil freezing. Discharge records came from the gauging station in Selfoss (Figure 2.2), while meteorological data were collected from three stations assumed to reflect correctly the meteorological conditions for the basin, from the highlands to the Atlantic Ocean:

Hveravellir, Hæll and Eyrarbakki, which stands at the outfall of the basin (Figure 2.1; Table 2.3). A time buffer was applied to enlarge the spectrum of analysis and embed antecedent hydrometeorological conditions, ranging from two months for winter river floods down to several days for marine submergences. Substantiated inundations were eventually classified according to seasonality and triggering factors, adapting to the scope of the research the frame given by the one-level typology of river floods developed for Iceland by Rist (1983). Since many substantiated flooding events in the study area have been potentially a compound of river flooding, pluvial inundation, and marine submergence, each polygenic event was classified according to its main component.

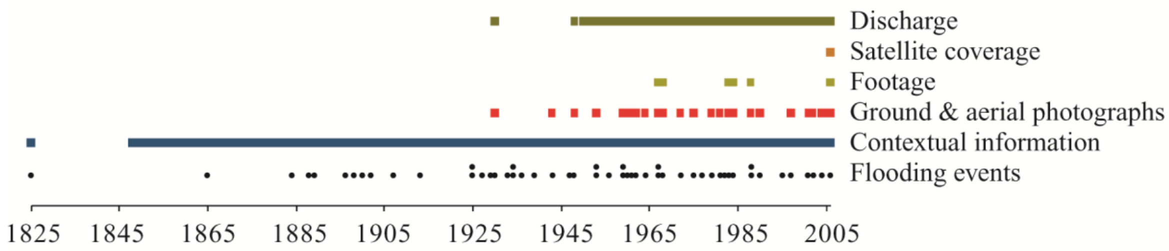

Figure 2.3 Yearly distribution of substantiated flooding events in the study area and availability of sources from 1825 to 2006.

2.3.2 Ice jamming sites and flooding path identification

In contrast to the research on the mechanics, dynamics and extent of ice jams (Beltaos, 1995; Prowse, 1995; Snorrason et al., 2000; Beltaos & Prowse, 2001; Lupachev, 2001; Turutin & Matyushenko, 2001), the purpose of ice-jam identification for this investigation was primarily to make a census of sites where ice jams and ice dams were effectively involved in backwaters and water encroachment during flooding events, and to establish the relationship between ice jamming and the extent of substantiated inundations related to river floods. Considering the main perspective of the work and its scale, it was therefore decided to georeference ice-jamming sites as point features, irrespective of the many forms and extent of river ice found in Iceland (Gröndal, 2003). Reference points for sites where ice formations cover long river sections were assumed to reflect their boundary upriver, which form the basis of water encroachment. Unlike Korytny & Kichigina (2006), river ice formations such as frazil ice and breakup jams were mapped with a uniform symbol. A colour graduation was applied to the ice-jam symbols to reflect the recurring impact of ice jamming on inundations. Following Imsland (2005), lines and arrows were chosen to map the flow directions, irrespective of the path width.

2.3.3 Flooding boundaries and extent computation

The material appropriate for photo-interpretation was analysed to edit flooding boundaries, using orthophotographs from 2005 and the contour lines extracted from the digital elevation models.

A regulated 250 x 250 m grid (Figure 2.2) was then developed to take full advantage of the toponymic references mentioned in newspapers and dwellers' diaries. Considered as surface units, the grid squares were attributed for each substantiated inundation following a binary approach: “0” for squares considered as not flooded, “1” for squares identified as flooded. For the areas covered by the photo-interpretation, the squares whose centroid is within the edited flooding boundaries were considered flooded. For the areas where the place names are the better or unique available reference, a manual selection of squares was done. In such circumstances, the place names replaced the water-level observations. The squares whose centroids are contained by lakes, coastal waters and surface river bodies were excluded from the computation process. Finally, the inundations that could not be mapped continuously with the combined use of photo-interpretation and place names were compared with inundations of a similar genesis, i.e. those related to river floods of similar discharge in open-water conditions on the one hand, or those generated by ice jams involving the same jamming sites and the same flow paths, on the other. When it seemed relevant, they were attributed by analogy the same boundaries in the areas of missing information.

2.3.4 Extent computation, floodplain, and inundation likelihood

The vertical sum of attributes (Table 2.4) gave the number of grid squares flooded for each flooding event, which was then converted into km^2. The extent of the flood plain was given by computing the sum of the grid squares flooded at least once (Table 2.4). Computing the sum of flooding events per grid square for the defined time line and dividing that duration by the number of events, excepting zero values, gave an empirical return period of inundations for each surface unit.

Table 2.4 Grid-based computation of inundations extent and number of events.

	Event 1	Event 2	Event 3	Event 4	Number of events (∑)	Flood plain
Square 1	1	1	1	0	3	1
Square 2	1	0	0	0	1	1
Square 3	1	1	1	1	4	1
Square 4	1	1	1	1	4	1
Square 5	0	0	0	0	0	0
Extent (∑)	4	3	3	2		4

2.4 Results

2.4.1 Flooding census, seasonality and triggers

Investigation of historical data has provided substantiation of 54 flooding events between 1825 and 2006, nine of which were related to marine submergences and 45 to river floods (Figure 2.4), of which 41 from the Ölfusá-Hvítá complex represent more than three times the number of events identified according to discharge thresholds. Of the inundations related to river floods, identified from analysis of historical data, 41% occurred after 1950 and the beginning of river monitoring in the study area. They represent 46% of river floods having a gauged discharge in Selfoss. Floods with lower peak discharges occurred essentially downriver from the city, the smallest peak representing only 1.2 times the mean discharge of the Ölfusá at the reference gauging site. Most events have been winter polygenic inundations, often characterized by the near synchronicity of precipitation, mild temperature, flood peak and inundation start.

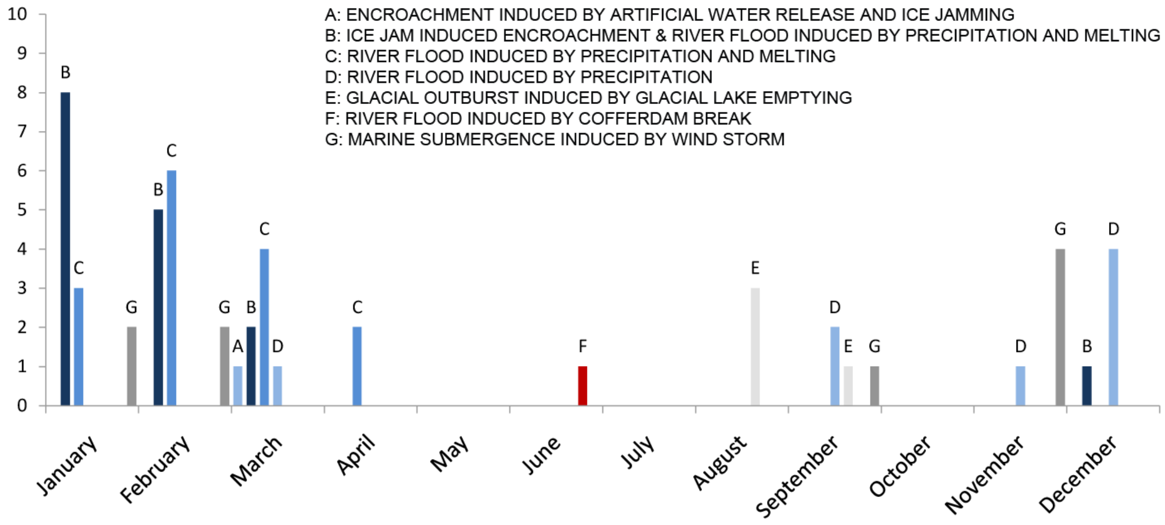

Figure 2.4 Monthly distribution and origin of substantiated flooding events in the study area from 1825 to 2006.

2.4.2 Ice jamming sites and flooding path

Distributed over eighteen sites, thermal and mechanical ice jams were proven to be involved in roughly 40% of inundations related to river floods. With the exception of estuary areas, the identified sites are shallow and constricted sections favourable to accumulation and ridging of drifting river ice following significant precipitation and melting. Some water diverted from the Hvítá/Ölfusá complex because of ice jams occurring between Mt Hestfjall and the confluence with the River Sog was proven to be lost on many occasions, spreading over Sorti and merging during major events with water draining out from the Skeið area through the Merkurlaut outlet, eventually flowing south to the Atlantic Ocean (Figure 2.5). Water diversion has also been effective from the River Þjórsá, flowing not only as side waters from the lower reaches of the river, but also west through the Skeið into the River Hvítá. This occurred on at least two occasions.

In the areas where the Þjórsá lava field shows on the surface, the overflowing waters are channelized through sinuous paths in the lava. Though the paths are obvious in the topography, they are not consistently reflected in the available digital elevation models. Emerging from these paths, the waters fill ditches and brooks to form a shallow but large sheet spreading over the wetlands and pastures in the Sorti and Flói areas (Figure 2.5). In the confluence areas, where sediments are significant and the soils thicker, the overflowing waters are barely channelized. In such areas, there are some thalwegs, obvious on the orthophotographs but hardly discernable from the ground, as they have been progressively filled in with volcanic sands and sediments. With the exception of the Merkurlaut outlet (Figure 2.5), which can be active in both open water and ice-jam conditions, the activation of the paths depends essentially on the location of the jams.

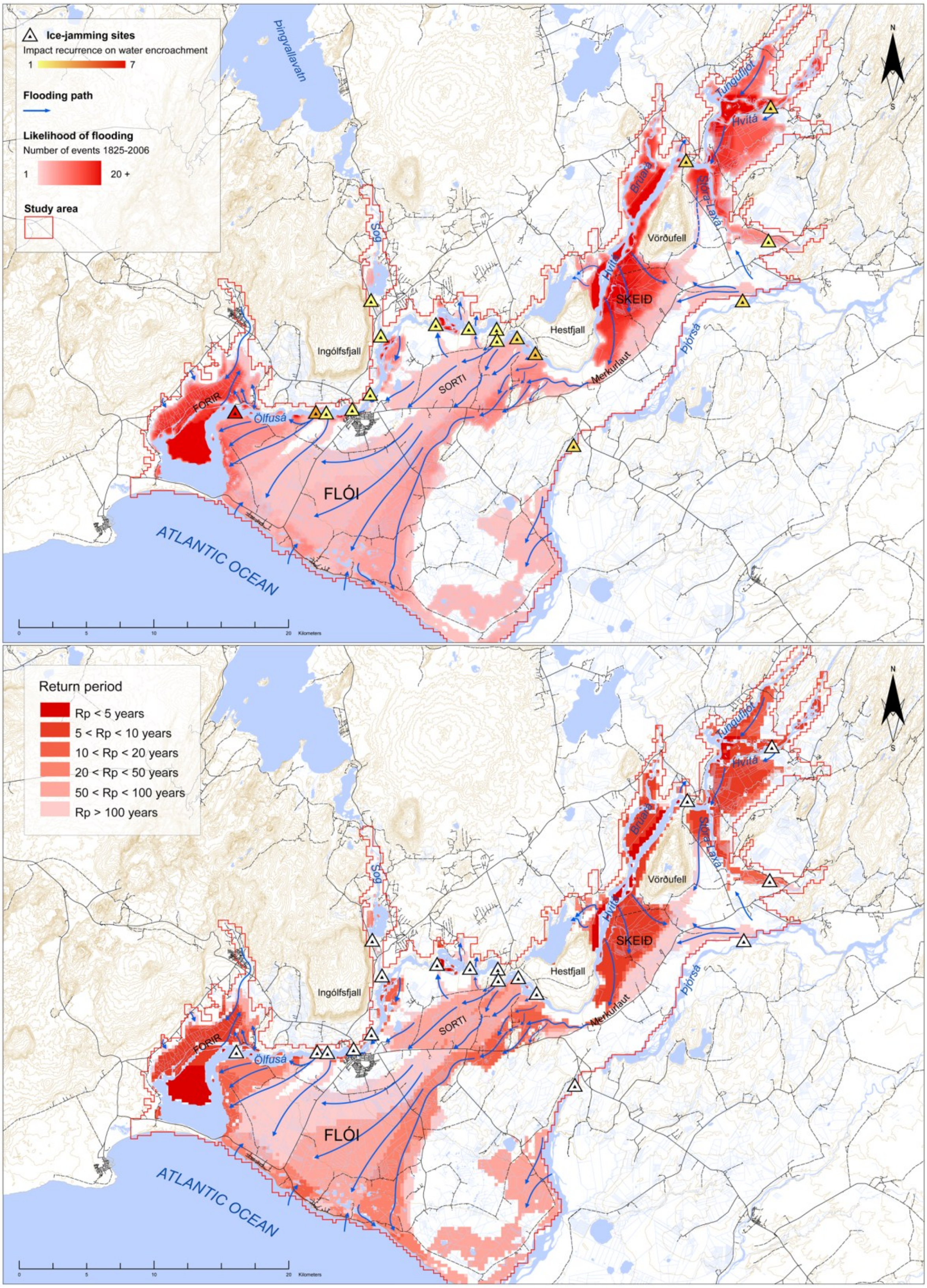

Figure 2.5 Spatial aggregation of inundations from 1825 to 2006 in the study area based on their number (top) and empirical return period (bottom).

Table 2.5 Top ten ranking of flooding events related to river floods from the Ölfusá-Hvítá complex ranked (top ten) according to river discharge and extent of inundations. Discharge values were computed with the Bayesian key V064_B1.1 from the Hydrological Service.

Flood ID	Flood peak VHM64 (m^3/s)	Discharge Rank	Extent (∑ squares)	Converted extent (km^2)	Extent rank
Ranked by river discharge:					
FLOD_OLFS_1968	2260	1	2364	147,8	5
FLOD_OLFS_1948	2230	2	2849	178,1	2
FLOD_OLFS_1930	2120	3	2745	171,6	3
FLOD_OLFS_2006	1840	4	1937	121,1	8
FLOD_OLFS_1960	1780	5	1806	112,9	9
FLOD_OLFS_1962	1760	6	1662	103,9	10
FLOD_OLFS_1967_1	1600	7	1310	81,9	11
FLOD_OLFS_1953_2	1560	8	904	56,5	13
FLOD_OLFS_1983	1460	9	3618	226,1	1
FLOD_OLFS_1953_1	1440	10	697	43,6	16
Ranked by extent of inundation:					
FLOD_OLFS_1983	1460	9	3618	226,1	1
FLOD_OLFS_1948	2230	2	2849	178,1	2
FLOD_OLFS_1930	2120	3	2745	171,6	3
FLOD_OLFS_1825	-	-	2374	148,4	4
FLOD_OLFS_1968	2260	1	2364	147,8	5
FLOD_OLFS_1889	-	-	2191	136,9	6
FLOD_OLFS_1888	-	-	2153	134,6	7
FLOD_OLFS_2006	1840	4	1937	121,1	8
FLOD_OLFS_1960	1780	5	1806	112,9	9
FLOD_OLFS_1962	1760	6	1662	103,9	10

2.4.3 Flood plain, magnitude ranking, and likelihood of flooding

The extent of the flood plain was estimated at 397 km^2, i.e. 55% of the lowlands within the study area (Figure 2.5). The extent of inundations attributable specifically to ice jams was estimated at 259 km^2, i.e. 65%of the flood plain. Only two of the 27 gauged river floods from the Ölfusá-Hvítá complex kept their rank according to extent, while four attained a higher position (Table 2.5). Three gauged floods disappeared from the top ten, replaced by floods that occurred before 1950. Not surprisingly, the most flooded areas are flat banks at the confluence between rivers and low areas in the estuary, such as Forir, under the combined influence of the Atlantic Ocean and fresh water, with a return period of less than 5 years (Figure 2.5).

2.5 Discussion

2.5.1 Reliability of data sources

Only 13% of all substantiated events from 1825 to 2006 occurred before 1900, a period representing about 40% of the whole time series. Rather than there having been a significant evolution of climate in Iceland during the past two centuries, this suggests that a great number of inundations were left unreported – possibly as many as 25 events if one extrapolates the results from 1900.

The scarcity of data is also of concern in assessing the extent and boundaries of several substantiated events. The place names mentioned in the newspapers and dwellers' diaries are the only available references for assessing inundations prior to 1930 (Figure 2.3); however, like other communication media, the newspapers mainly focus on the spectacular aspects of events and everyday life. Regarding inundations, they refer more to the impact of events at local sites, i.e. destruction and disruptions, than to their overall magnitude, which characterizes the hazard itself. That was certainly the case for the step-burst flood in 1968, when the public TV network and the newspapers focused on the specific situation in the city of Selfoss and neglected other flooded areas. Although the toponymic references in the newspapers and dwellers' diaries are accurate enough, there may still be large gaps to close between the place names when the focus of the newspapers is not well balanced between all the areas. Comparing inundations of the same genesis is therefore necessary to complete the mapping process.

2.5.2 Seasonality and triggers

The results on seasonality and triggers confirm the conclusions of earlier studies on river floods in Iceland by Rist (1983) and Snorrason et al. (2000): in the study area, river floods generating inundations have mainly been polygenic winter events related to Atlantic depressions crossing the country. They are characterized by strong winds, intense precipitation and mild temperatures, typically between 7 and 8.5°C along the coast, and involve important snow melting and thawing of ice. Impervious frozen soils increase surface runoff and reduce considerably the times of concentration, explaining the rapid onset of floods, but also the seasonality of inundations, which occur mainly during the winter, with higher discharge peaks but less runoff than in spring.

However, the one-level flood typology of Rist (1983) fails to reflect consistently the chain of causality leading to river floods. There is no example from the period and area considered of ice jams and step-burst floods from the Hvítá-Ölfusá complex having generated inundations independently of precipitation and snow melting. We therefore consider that river floods involving ice jams and step-burst sequences should not be considered as a flood type of the same level as river floods related to precipitation and/or melting, but as a non-exclusive sub-type belonging to their own category. The typology of Rist not only lacks expansion but also mixes triggers and the nature of floods, placing, for instance, glacial outbursts and river floods induced by precipitation at the same level. However, outbursts from the proglacial Lake Hagavatn refer to complex phenomena, from dam overflowing to dam breaching, which involve many possible triggers (Thorarinsson, 1939) and afford many levels of analysis. As suggested by the meteorological records, precipitation could be considered as a possible trigger for the glacial outburst in 1929. If this hypothesis is confirmed, this flood should be rated as a glacial outburst, due, among other triggers, to precipitation and geological failure.

Additionally, it is important to remember that many substantiated flooding events in the study area are truly polygenic, being in reality a compound of river flood, pluvial inundation and marine submergence. The proposed typology of flooding events according to seasonality and triggers (Figure 2.4) is a simplified and provisional classification which does not reflect the true polygenism of inundations in the Ölfusá-Hvítá basin. Thus the development of a more comprehensive typology of inundations clearly separated from flood classification is needed.

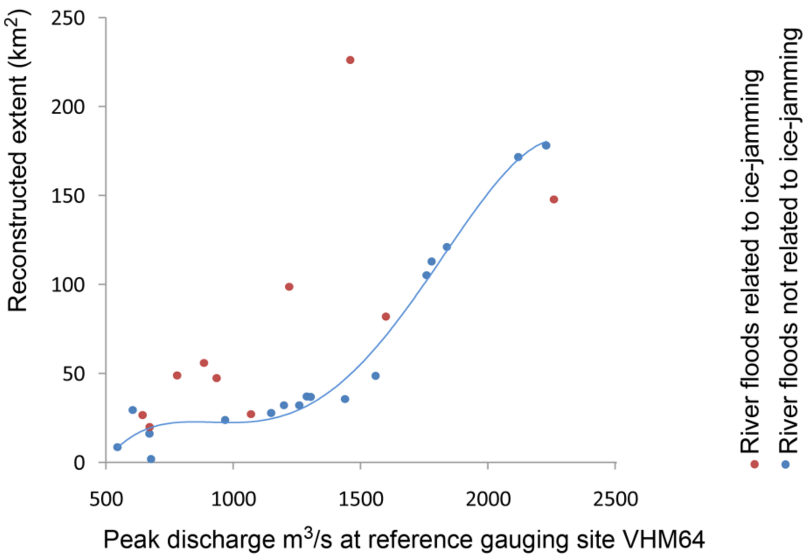

Figure 2.6 Peak discharge of the Ölfusá River at gauging site VHM64 and inundation extent of related river floods in the study area from 1953 to 2006. Polynomial regression is shown for river floods not related to ice jamming.

2.5.3 Flood plain and extent of inundations

Spatial presentation of the available information over the regulated grid allowed the extent of most of the substantiated inundations to be computed and mapped. It also provided the first representation of the flood plain in the study area, and added to the existing knowledge given by Imsland (2005) on flooding paths. The results indicate the existence of a gap between river discharge and extent of inundation in the context of water encroachment generated by ice jams: the boundaries and extent of inundations generated by ice jams depend essentially on the location of the jams, irrespective of the discharge. Relying on discharge leads to a clear underestimation of the extent of inundations in 60% of cases analysed (Figure 2.6); in one case, the extent appears to have been overestimated. This corresponds to the flood in 1968, when a break-up jam formed several metres downstream of the reference gauging site and triggered a backwater which induced an extra water stage, thus skewing the computation of the discharge. In the meantime, an important inflection of the extent of inundations can be seen for open water conditions at a discharge threshold close to 1700 m^3/s (Figure 2.6). This corresponds to a specific scenario when water flowing from the Hvítá on to the Skeið overtops its boundary by the Merkurlaut outlet and spreads eventually over Flói (Figure 2.5).

However, the reconstruction of the extent of inundations can reasonably be discussed taken into account the limitations inherent in the grid methodology: the grid resolution is certainly not high enough to reflect situations in narrow valleys and paths where flow is concentrated. It is nevertheless convenient for covering large areas where sheet wash is the rule and it can be considered suitable at the scale of the analysis, which is primarily aimed at providing macro-scale results.

2.5.4 Susceptibility to inundation

The likelihood of flooding devised for the study area refers to return periods of inundation aggregated spatially (Figure 2.5): each piece of land is characterized by a susceptibility to flooding which refers to a spatial range of inundations independent of stream values. It differs conceptually from the flood probabilities mentioned in the European Directive on the Assessment and Management of Flood Risks (European Parliament & European Council, 2007), which refers exclusively to return periods of river discharge maxima or exceeding thresholds.

Building a methodology based on the spatial aggregation of inundations emanates from a fundamental translation of key concepts in which extent and boundaries replace discharge in the calculation of return periods. Such an approach presents decisive advantages in flood mapping and flood-risk analysis, comprising the inclusion of events that are not in the time line of continuous discharge data, on the one hand, and of events whose extent and boundaries are not consistently reflected in the discharge at the gauging sites, on the other. The results provide a better insight into the hydrological history than shown in a probabilistic approach based on discharge.

2.5.5 Perspectives

The Icelandic Hydrological Service has now acquired a digital elevation model with a relative elevation accuracy of 0.1 metre, which covers 23% of the study area. Aimed at overflow simulation for open water conditions, the DEM will provide an excellent basis for simulating water encroachment caused by ice jams at the substantiated locations. It should bring information on water depth and flow velocity, which reveals a lot of the real danger that inundations may represent, in contrast to the present investigations into extent, which, at that level, remain blind to the quantification of danger. The changes in the topography caused by erosion processes, anthropogenic pressure and glacial rebound are of course challenging for the model assessment of the extent and boundaries of flooding events, both past and in the future. However, the photo-interpretation suggests a relative stability of the topography in the study area over the past 40 years. For instance, the pictures showing the ice jam inundations in 1968 and 1983 show the same jam location and similar flooding boundaries downriver from Selfoss for both events. The model may therefore be helpful for the reconstruction of some recent inundations that are documented with pictures and footage.

2.6 Conclusion

This investigation focused on the extent of inundations in the Ölfusá-Hvítá basin. The approach used has been proven to enrich time series of inundations of historical and contemporaneous events obtained by discharge monitoring. The limitation of working only with annual discharge maxima and discharge thresholds limitations is thus overcome. The results clearly indicate that the boundaries and extent of inundations involving ice jams depend essentially on the location of the jams, irrespective of the discharge. Using discharge scenarios for mapping flood hazard is therefore ineffective for assessing the magnitude of flooding events and the exposure of territories to flooding in the Ölfusá lower basin. Calculating the extent of inundations independently from stream values eventually provided, in contrast to conventional methodologies, a sound basis for defining a synthetic likelihood of flooding for exposed areas based on the number of events and their return period aggregated spatially, which includes theoretically all types of inundations.

Being designed to deal with the specific situation in the Ölfusá basin, the technique developed may be difficult to generalise. Nevertheless, the approach itself and the underlying concepts should be of interest, irrespective of the technical aspects, in regions where discharge records fail to reflect consistently the magnitude of inundations.

Acknowledgements

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3 High-accuracy mapping of inundations induced by ice jams: a case study from Iceland

Pagneux, E., Snorrason, Á. (2012). High-accuracy mapping of inundations induced by ice jams: a case study from Iceland. *Hydrology Research* 43(4-5) (In press)

Abstract

Hydraulic modelling is used widely for deriving, from discharge scenarios, flood hazard maps featuring depth of flooding and flow velocity. Because of uncertainties about flow conditions or inaccurate terrain models, flood hazards maps obtained from hydraulic modelling may be of limited relevance and accuracy. Hydraulic modelling is particularly challenging in arctic regions, where ice jams lead to flooding in areas that are not subjected to inundation under open-water conditions. As numerical models of ice-jam processes require information that may be difficult and expensive to collect, an alternative approach based on the photo interpretation of documented historical events is presented here. Orthophotographs and a digital elevation model at high resolution are used to support the photo interpretation process. Tested in an Icelandic watershed prone to ice-jam floods, the reconstructions provide locally unprecedented and robust information on the extent and depth of flooding of inundations induced by ice-jams.

Keywords

3D analysis - Flood hazard mapping – Ice-jam flood – Iceland – Photo interpretation – Spatial analysis

3.1 Introduction

Depth of flooding and flow velocity are flood hazard parameters of particular concern regarding the safety of structures, the safety of persons, and the emergency response. The impact of flow velocity is, for instance, particularly strong on road infrastructures (Kreibich et al., 2009). Hydrostatic action imparted by water depth and capillarity rise have a strong impact on buildings (Kelman and Spence, 2004), but a medium impact on road infrastructure; depth of flooding has a direct impact on the buoyancy of vehicles and therefore on the efficiency of the emergency response (MATE/METL, 1999). As a result, flow velocity and depth of flooding are widely used in the production of flood hazard maps, which typically display visual information on the magnitude and likelihood of a flooding event, and of flood risk maps, which in turn emphasise on the adverse consequences of flood hazards (Spachinger et al., 2008; de Moel et al., 2009). In the USA and Canada, flood mapping relies on the delineation of a base floodplain corresponding to a 100-year flood, and distinction is made in the base floodplain between the floodway, which includes the main channel and the adjacent overbank areas where water depths and flow velocities are the greatest, and the flood fringe, where depths and velocities are lower (Environment Canada, 1993; NARA, 2009). In countries where the European directive on the assessment and management of flood risks applies (European Parliament and Council, 2007), authorities are required to produce flood hazard maps that should include visual information on the inundation extent, depth of flooding and/or water levels, and flow velocity for discharge exceedance scenarios of low, medium, and high probabilities. A set of flood risk maps displaying visual information on the number of inhabitants and the type of activities affected, and on the "installations which might cause accidental pollution", should also be produced. Finally, flood risk management plans should be developed accordingly.

Table 3.1 Flood hazard parameters and thresholds used for flood hazard classification in France (MATE/METL 1999).

Rating formula	Hazard rate (HR) = d x v d = depth of flooding (m); v = velocity of floodwaters (m/s)		
Depth of flooding (m)	Velocity (m/s)		
	< 0.5	0.5-1	>1
<0,5	Low	Moderate	High
0,5-1	Moderate	Moderate	High
>1	High	High	Very high

Table 3.2 Flood hazard parameters and thresholds used for flood hazard classification in the UK (DEFRA 2006; DEFRA 2008).

Rating formula	Hazard rate = d x (v + n) + DF
	d = depth of flooding (m);
	v = velocity of floodwaters (m/s);
	DF = debris factor (0, 0.5, 1 depending on probability that debris will lead to a hazard)
	n = a constant of 0.5	

Flood hazard rates	Colour scheme	Hazard to People Classification
Less than 0.75	-	Very low hazard – Caution
0.75 to 1.25	Yellow	Danger for some – includes children, the elderly and the infirm
1.25 to 2.0	Orange	Danger for most – includes the general public
More than 2.0	Red	Danger for all – includes the emergency services

Table 3.3 Coercive flood risk zoning derived from flood hazard classification in France (MATE/METL 1999).

Flood hazard classification	Colour scheme	Flood risk zoning
Low, moderate	Blue	Development permitted under conditions (flood proofing)
High, very high	Red	Development not permitted

In many countries of Europe, classifications of areas prone to inundation have been established, based on a combination of flood hazard parameters. In France (Table 3.1) and in Austria, for instance, flood depths and flow velocities corresponding to a 100-year flood are combined to produce a danger-oriented classification of flood hazard (MATE/METL, 1999; EXIMAP, 2007). In the UK (Table 3.2), harm potential of floating debris recruited during the onset of floods is taken into consideration in addition to flow velocity and depth of flooding to characterise the 100-year flood and 1000-year flood (DEFRA, 2006; DEFRA, 2008). Restrictions in development and in land use planning may result directly from the classification of flood hazard. In France, development is strictly forbidden in areas where flood hazard is rated high or very high (French Parliament, 1995; MATE/METL, 1999) (Table 3.3). In contrast with the French approach, flood hazard rates produced in the UK have no binding effect on development (DCLG, 2006).

Mapping of flooded areas according to discharge scenarios is typically obtained from hydraulic modelling (de Moel et al., 2009). Used as input parameter in hydraulic models (Bates and de Roo, 2000), discharge is currently obtained from water levels observed using fitted rating curves (e.g. Moyeed and Clarke, 2005), or derived from runoff coefficients in ungauged catchments (e.g. Merz et al., 2008). The use of hydraulic models for flood mapping purpose is however not self-evident. There are many factors affecting the accuracy of flood extent maps and flood depth maps obtained from hydraulic modelling, such as uncertainties about flow conditions and friction coefficients, or inaccurate terrain models (Bales and Wagner, 2009). Hydraulic modelling is particularly challenging in arctic regions, where ice jams lead to flooding in areas which at same discharge would not be flooded under open-water conditions (Beltaos, 1995; Pagneux et al., 2010). Significant efforts have been devoted to numerical modelling of river ice processes over the past two decades (Beltaos, 2008), with the development of one-dimensional models, e.g. ICEPRO (Carson et al., 2003) and of dynamic and two-dimensional models, e.g. CRISSP2D (Liu et al., 2006). All models have common parameters such as bathymetry, flow conditions, and jam location. Such information is not always available and very expensive to collect. In the absence of information required for hydraulic modelling, the use of historical data and geomorphic evidence may provide a regulatory basis for the delineation of floodplain in areas prone to ice-jam floods. In the regulation of the Canadian province of Alberta, for instance, the design flood should correspond, in areas prone to ice-jam floods, to a historical ice-jam flooding event if a computed 100-year water level that would result from an ice jam cannot be obtained (Government of Alberta, http://environment.alberta.ca/01655.html); before the expiration in 1999 of the Canada-Alberta Flood Damage Reduction program, the possibility of delineating ice hazard zones, defined as areas prone to damages from river ice movement, had been considered in addition to the federal floodway and flood fringe risk zones (Environment Canada, 1993; Government of Alberta, http://www3.gov.ab.ca/env/water/flood/FDRP.pdf). The delineation of such ice hazard zones relies in part on the identification of geomorphic evidence such as bechevniks (Marusenko, 1956; Hamelin, 1979; Ettema, 2002), bank erosion due to collapse of bankfast ice (Ettema, 2002), fluvial gullies and scour holes (Smith and Pearce 2002), or ice scars on trees (Henoch, 1973; Boucher et al., 2009). Confusion should not be made, however, between areas prone to river-ice run and areas that are prone to flooding because of ice-jam floods, the latter areas being potentially much larger, although they are not entirely exposed to river-ice drifting. Additionally, distortion between water levels actually attained during ice-jam floods and elevation of ice-run evidence such as tree scars can be important (Gerard, 1981; Smith and Reynolds, 1983). Along with on-site observations, archival documents such as aerial photographs taken during or soon after ice-jam floods are known to provide valuable information on the extent of breakup water levels (Kriwoken and Brown, 1988).

The use, in hydraulic models, of high resolution digital elevation models (DEM) obtained from airborne laser altimetry (LIDAR) or photogrammetric surveys has increased dramatically in recent years to map the extent and depth of floods of given discharge. Although ice-jams floods are difficult to assess with hydraulic models (Beltaos, 2008), there is no indication, by now, that high resolution DEMs have been used to support the production of flood hazard maps showing the extent and depth of flooding of historical ice-jam floods, based on the photo interpretation of aerial and ground photographs.

This paper presents high accuracy mapping of inundations induced by ice jams in an Icelandic watershed prone to ice-jam floods. In the absence of the information required for deriving flood extent maps and flood depth maps from hydraulic modelling, photographs and aerial footage taken during recent ice-jam floods were used. The water levels observed on documents were identified on orthophotographs, georeferenced in a Geographic Information System (GIS), and converted into irregular water surfaces. The aim was to provide robust information on the extent and depth of flooding in case of ice-jam floods by analysing the differences of elevation between the topography and the water surfaces created.

3.2 Study area

The Lower Reach of the Hvítá/Ölfusá hydrological complex was selected as a test area for the mapping at high accuracy of documented inundations induced by ice-jam floods. The network pattern of the Ölfusá basin is controlled by tectonics and volcanism (Sigmundsson, 2006; Thordarson and Höskuldsson, 2008); from Mount Hestfjall down to the Ölfusá estuary, the Hvítá/Ölfusá complex flows at the margin of the Great Þjórsá lava field (Hjartarson, 1994), upon which the floodplain has developed (Figure 3.1): on the northern bank, the terrain slopes down to the river, while on the southern bank, the terrain slopes from the river down to the ocean at a mean rate of 0.13% (Figure 3.2). This nearly-flat area, partially altered into suitable terrains for farming during the 19th and 20th centuries, has been repeatedly flooded over the past 200 years because of ice jams that caused water encroachment and submersion of large areas that are safe from inundation under open water conditions (Pagneux et al., 2010). The boundaries and extent of such inundations depend essentially on the location and nature of ice jams, irrespective of the discharge estimated at gauging sites.

Reliable flood mapping of the areas that are prone to ice-jam floods cannot be achieved yet with resort to hydraulic modelling:

- Although significant efforts have been devoted in recent years to the densification of gauges in the lower reach, relevant upstream discharge information is missing for 2/3 of known ice-jamming sites;
- Extensive information about the nature of ice jams involved is missing; The bathymetry of the Hvítá River and of the Ölfusá River remains unknown at most of the relevant sections;
- High permeability of the lava favours subsurface flow in areas where the Great Þjórsá lava field shows up at the surface; during river floods, hundreds of ponds can form on the lava outcrops and large areas behind topographic obstacles can be flooded as water is dissipated through the lava.

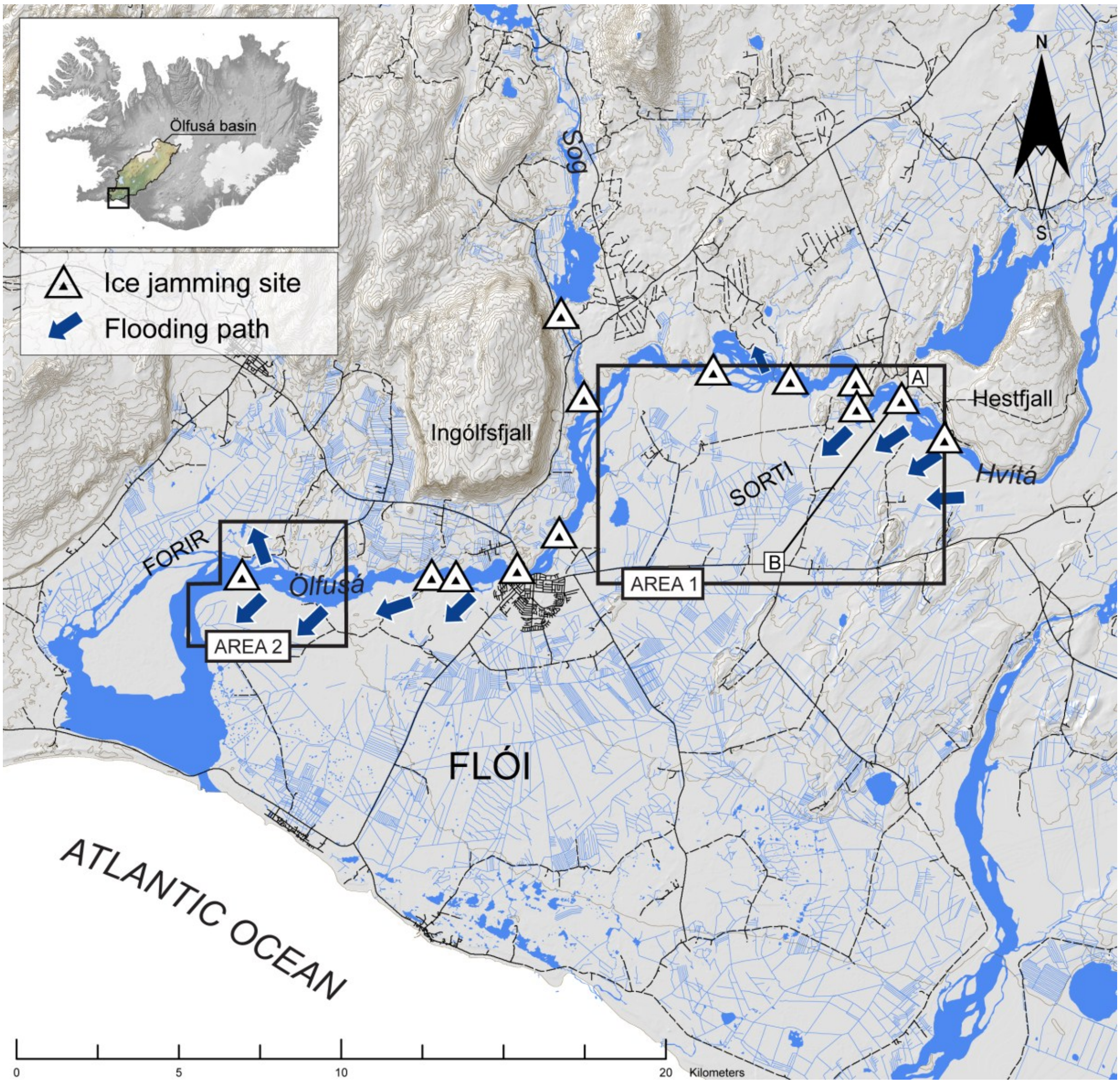


Figure 3.1 Lower reach of the Ölfusá/Hvítá Rivers complex. Known ice-jamming sites and associated flow paths active over the past 200 years (Pagneux et al. 2010) are shown.

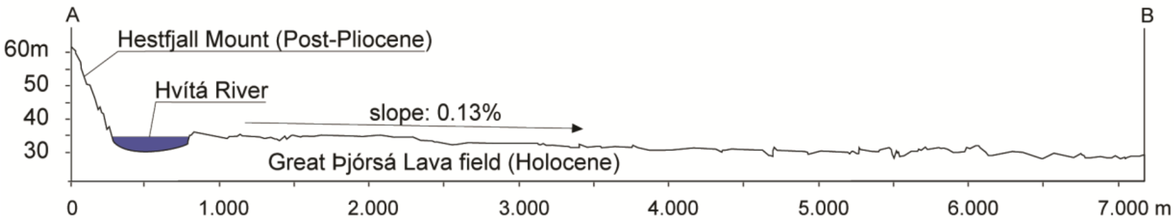


Figure 3.2 Topographic transect from Mount Hestfjall (A) to Road 1 (B). Transect's location is shown in fig. 1; bathymetry of the Hvítá River is fictitious.

The hydrogeomorphological approach, which derives delineation of flood envelope from the identification of active terraces and erosion forms (e.g. Lichvar et al., 2004; Ballais et al., 2005), brings some interesting information on areas that are prone to river-ice run. At the vicinity of some ice-jamming sites, drifting river ice blocks have removed the histic and brown soil layers that cover most of the lower reach, and uncovered the Great Þjórsá lava field; soil removal is particularly obvious on aerial infrared imagery. Fluvial gullies can also be observed on holms at specific river sections. The absence of forests in the flood plain makes the delineation of ice hazard zones based on the identification of tree scars (Boucher et al., 2009) impossible. At longer distances from the river, there is no more evidence of river ice scouring. Eventually, the photographs and footage showing past ice-jam floods indicate that such ice hazard zones represent only a small fraction of the areas prone to inundation because of ice-jam floods.

3.3 Methodology

Based on the simple analysis of elevation differences between water surfaces and topography (Priestnall et al., 2000), mapping of areas prone to ice-jam floods relied on the photo interpretation of documented flooding events induced by ice jams. The photo interpretation of existing documents was supported with the use of orthophotographs and of a DEM of high vertical accuracy (± 10 cm) which both originate from an airborne photogrammetric survey realised during the summer 2008 from a mean altitude of 300 meters above topography. Because of suspended glacial flour, the bathymetry of the Ölfusá River could not be estimated from the photogrammetric survey which only reflects the water levels observed during the flight. Two areas prone to ice-jam floods were selected in the lower reach of the Hvítá/Ölfusá hydrological complex (Figure 3.1; Table 3.4). The selection was based on the availability of visual documents of good quality showing ice-jam flooding events, and on the absence of severe modifications of the topography since the documented inundations occurred.

Table 3.4 Ice jam flooding events selected for reconstruction. Rated 50-year flood, the reference historical flood for open-water conditions occurred on 21.12.2006, with a peak discharge of 1840 m3/s.

Flooding event	Peak discharge at reference gauging site	Area	Place name	Documents	Control points created
14.1.2001	644 m^3/s	1	Sorti	12 aerial pictures, 4 ground pictures	267
23.1.1983	1460m^3/s	2	Kaldaðarnes/ Arnarbæli	1 aerial footage 17 ground pictures	51

3.3.1 Data production and calculation

Multiple aerial and ground photographs of the flooding events, as well as footage from TV networks, were analysed. The water levels observed on the documents were identified on the orthophotographs, georeferenced as control points in a GIS, and eventually attributed elevation values according to the digital elevation model (Table 3.5). In some circumstances, fictitious control points were created to allow a continuous calculation of the floodplain boundaries. The control points created were converted afterwards into multiple triangular irregular networks (TIN) representing complex irregular water surfaces. Both the DEM and the irregular water surfaces created were then converted into raster images at 0.5 meter resolution, to allow analyses of elevation differences with the raster calculator in ArcGis Desktop 9.3. Raster images obtained from the calculation process were ultimately converted into polygonal feature classes to allow manual corrections.

Table 3.5 Data production and calculation steps in ArcGis Desktop 9.3; extensions required are indicated.

Steps	Description	Extension required
1	Creation of control points reflecting the water levels observed. • Elevation values are attributed according to DTM	
2	Conversion of control points into irregular water surfaces (TINs) • Triangulation as mass points	3D Analyst
3	Conversion of terrain and irregular water surfaces into raster • Output Data Type: FLOAT • Method: LINEAR • Sampling distance: CELLSIZE 0,5 meter	3D Analyst
4	Analysis of elevation differences (raster calculator) • Inundation extent = [Water raster] >= [Terrain raster] • Depth of flooding = [Water raster] – [Terrain raster]	Spatial Analyst
5	Conversion into polygons for manual corrections	

Table 3.6 Definition of confidence indices reflecting the reliability of reconstructions.

Confidence index	Description
1- High	Area mapped is entirely covered by visual documents. Number and density of control points reflecting water levels observed guaranty high accuracy of mapping.
2- Medium	Area mapped is not directly covered by visual documents. Distance between control points is too large to guaranty high accuracy of mapping

Table 3.7 Reclassification of water depth based on safety and emergency response thresholds (MATE/METL 1999).

Thresholds	Description
0.5m	Wading in water is unsafe for children
1m	Buoyancy of vehicles; efficiency limit of individual water gates; wading in water is impossible for children, very difficult for elders
2.5m	Upper limit of ground floor without construction level freeboard
4-class reclassification	**Gridcode**
Depth <0.5m	1
0.5m < depth < 1m	2
1m < depth < 2.5m	3
Depth > 2.5m	4

3.3.2 Product delivery

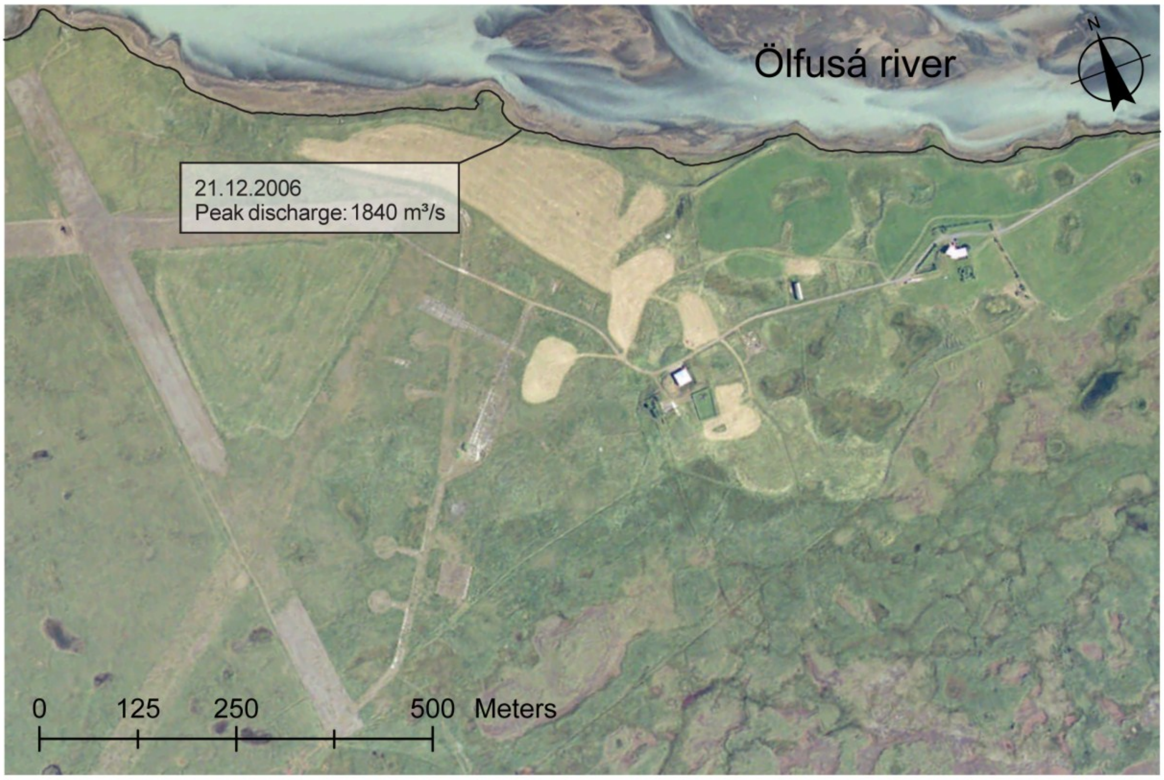
Because the available documents barely cover the whole extent of past flooding events, reconstruction at high resolution could not feature homogeneous levels of accuracy. The reconstructions were divided into regular cells of 1 km^2, each cell being applied a confidence index reflecting locally the reliability of reconstructions (Table 3.6). Deliverable to the general public and authorities, historical flood maps at scale 1:5000 were produced only for areas where the reconstructions were considered highly accurate. Originally obtained at a 10 cm contour interval, the depths of flooding were reclassified for legibility purpose on a 4-class scale reflecting safety and emergency response thresholds (Table 3.7).

3.4 Results and discussion

Relying on the constitution of complex irregular surfaces, the reconstructions provide robust information on the boundaries and depth of flooding in case of ice-jam floods (Figure 3.3) at a cost by far inferior to the financial resources that should be allocated only to survey the river parameters required in hydraulic modelling. Information on bathymetry, discharge, friction values, and more importantly on the exact mechanics of ice jams involved, are not required. Only visual documents of good quality showing inundations induced by ice-jam floods as well as orthophotographs and DEM at high resolution are needed, in a favourable context where identification of water levels is facilitated by the absence of forests.

From a theoretical perspective, the use of a documented flooding event as reference is however challenging. Because the reconstructions do no rely on a probabilistic approach but on historical data, they provide information on flood hazard related to ice-jam floods which cannot be considered as strictly predictive.

Some technical limitations are also challenging. Reliability of the documents is of course questionable with consideration of the timeline of flooding events. There is no guarantee that inundation boundaries obvious in the documents match actually the highest waters levels attained during the corresponding flooding events. Another important limitation comes from the fact that the material eligible to photo interpretation is often fragmentary for the reconstruction of past flooding events. Although information on boundaries and depth of flooding is robust in areas well documented, the use of confidence indices is necessary when considering the whole extent of the flooding events reconstructed (Table 3.6; Figure 3.4). Some areas known to have been flooded in recent history (Pagneux et al., 2010) could not be mapped at high resolution because of the lack of observable water levels. The use of imagery from sub-meter satellites could insure high accuracy at a large scale to reconstructions of future events. Imagery from the sub-meter satellite IKONOS (Dial et al., 2003) has been used, for instance, by the Icelandic Meteorological Office to complete the boundary mapping of the glacial bursts on April 14-15 2010 triggered by the eruption of Eyjafjallajökull Volcano. Limitations due to the fragmentation of documents and the absence of flood routing may thus be overcome in the future.



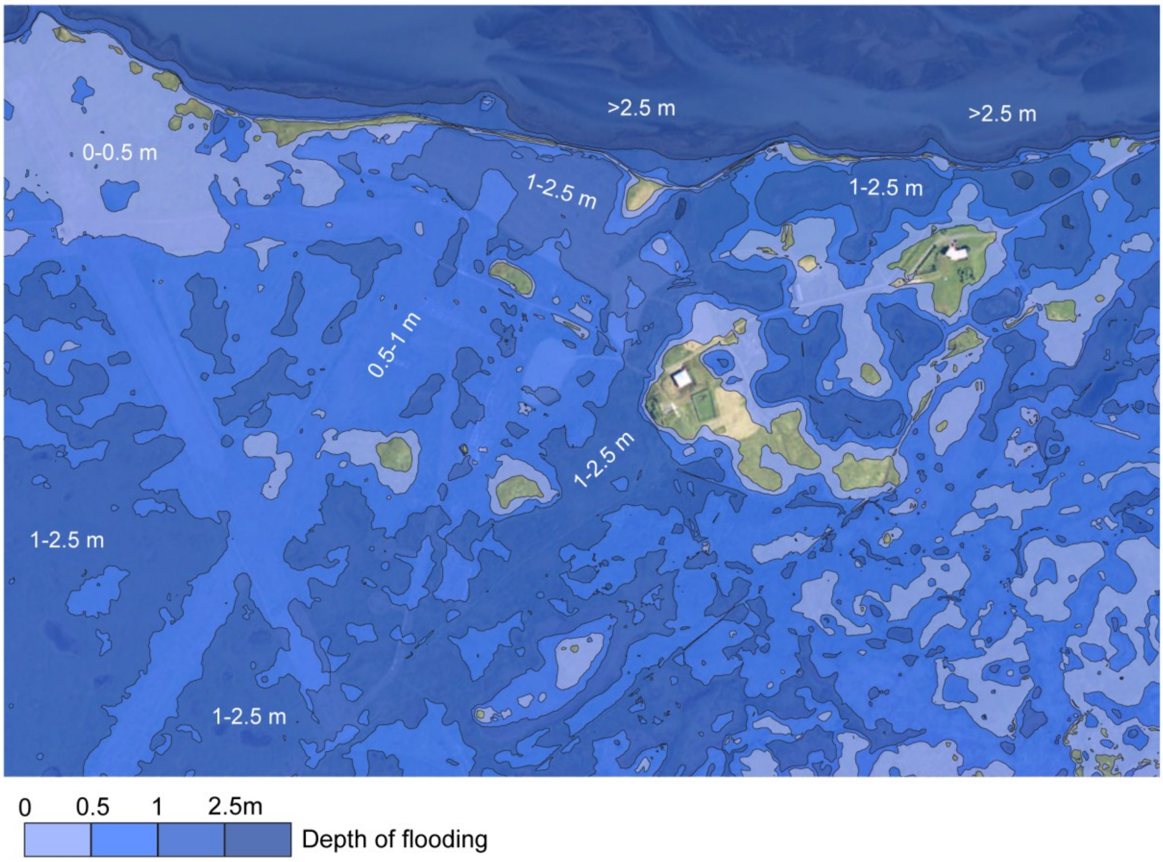


Figure 3.3 Depth of flooding on 23.1.1983 by the farming estate of Kaldaðarnes (area 2 shown in Figure 3.1). Estimation is based on the photointerpretation of aerial footage and ground pictures. Boundary of the reference open-water flood, which occurred on 21.12.2006, is shown on the upper map for comparison. Orthophotograph: Samsýn ehf.© 2008.

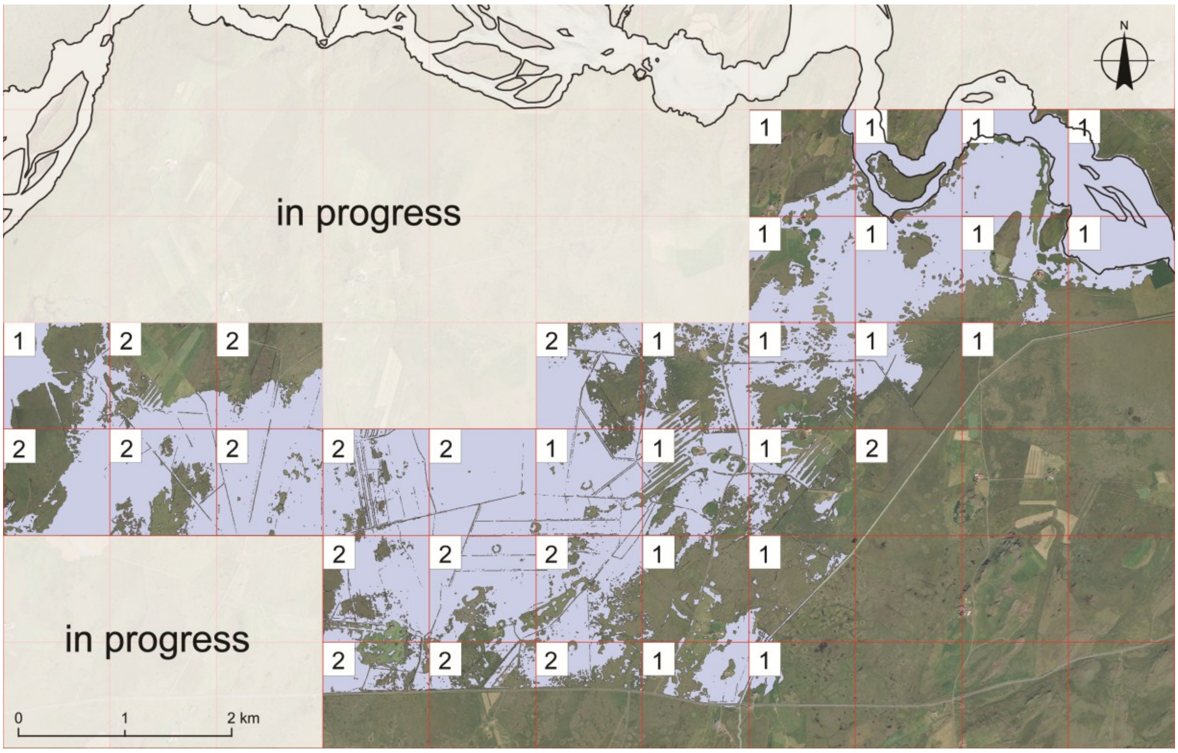


Figure 3.4 Reconstruction of the flooding event on 14.1.2001 in area 1 (Figure 3.1). Boundaries of the Hvítá River are shown as dark lines. Confidence indices reflecting the reliability of the reconstruction (Table 3.6) are shown per cell of 1 km^2.

The cleaning phase, which partly consists in the deletion of polygons, may also be problematic in areas prone to hypodermic or subsurface flows. This is especially the case in areas where the postglacial Great Þjórsá lava field shows up at the surface. Also an issue for hydraulic modelling, subsurface flow makes the use of aerial survey indispensable.

Unlike storage cell models, e.g. LISFLOOD-FP (Bates and de Roo, 2000), and 1D-2D hydraulic models, the reconstructions of past flooding events according to photo interpretation do not include flood routing formulae; estimation of the extent and depth of flooding events only relies on the analysis of elevation differences between the topography and the irregular water surfaces created. The reconstructions, therefore, require extra caution when placing and selecting the control points in the interpolation process; a great number of control points may be necessary when topography is complex and flow is multi-channelised.

An ultimate limitation comes from the fact that a same area can be flooded from different encroachment sites (Figure 3.1), each one having a specific impact on the extent, boundaries, and depth of flooding events (Pagneux et al., 2010). Unfortunately, ice-jam floods in the lower reach of the Ölfusá River that are documented with pictures and footage refer only to 1/5 of known ice-jamming sites.

Despite limitations inherent in the methodology, the reconstructions provide locally unprecedented information on the boundaries and depth of flooding in case of ice-jam floods. Because ice-jam floods are extreme events in comparison to open-water floods, the reconstructions should be regarded as providing essential information for a danger-oriented classification of areas prone to floods liable to be used for planning purpose as well as for emergency response; in the absence of information about flow velocity, such a classification could rely on water depth thresholds only (MATE/METL, 1999). Regarding the assessment of flood hazard, the reconstructions should be useful for the calibration of hydraulic models in the assessment of ice-jams floods once the river bathymetry and the nature of ice jams are known and a relevant discharge is estimated upstream. They may be also used with field and remote sensing data for the calibration of hydraulic models for open-water floods.

3.5 Conclusion

The use of orthorectified imagery and a high resolution DEM allows accurate reconstruction of past ice-jam floods that are well-documented and still of relevance. Although not being strictly predictive, robust information on the boundaries and depth of inundations induced by ice-jam floods is provided locally; as depth of flooding is a crucial parameter, considerable weight is given to historical approaches in the assessment of flood hazard and in the management of flood risk. Tested in an Icelandic watershed where topographic conditions are admittedly difficult, such an approach could be of interest in cold-climate regions prone to ice-jam floods, when information necessary for the use of hydraulic models is lacking and financial resources are limited.

Acknowledgements

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4 Public perception of flood hazard and flood risk in Iceland: a case study in a watershed prone to ice-jam floods

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Abstract

Understanding and improving the public perception has become an important element in the management of flood risk worldwide. In Iceland, studying perception of flood hazard and flood risk is, however, in its early stages. This paper presents a case study on the public perception of flood hazard and flood risk in an Icelandic town prone to ice-jam floods. Awareness of the population regarding historical inundations, self-estimation of flood risk and worry is considered. The factual knowledge of the residents is deconstructed in flood hazard parameters accessible to the lay population: number of events, dates, genesis and boundaries. The performance of the respondents is rated for each parameter and the influence of several predictors evaluated. The research shows three significant patterns: there is poor awareness and little worry about historical inundations in the area; experience of the past flooding events in town is the most effective source of knowledge; awareness, risk estimation and worry are not correlated.

Keywords

Flood risk perception – Spatial representations – Ice-jam floods – Iceland

4.1 Introduction

Understanding public perception is important in the top-down communication process that takes place between authorities and lay population in the management of risks related to natural hazards. It also gives a basis of knowledge for a more democratic process where lay population is entitled as a partner in hazard assessment and in a broader perspective, as a partner in risk management (Arnstein, 1969; Fischhoff, 1995; Renn, 1998; Aven and Kristensen, 2005). Risk is, however, difficult to apprehend. Defined as ‘‘the combination of the probability of an event and its negative consequences’’ (UNIDSR, 2009), risk is tributary of uncertainties of different types and of different nature (Refsgaard et al., 2007; Van der Keur et al., 2008); with laymen, it is foremost a subjective assessment, a ‘‘perception’’, which has been extensively described as a construction reflecting psychometric factors such as worry or fear (Slovic et al., 1984; Slovic, 1987), social values (Wildavsky and Dake, 1990; Dake, 1991), and affects (Slovic and Peters, 2006; Slovic et al., 2007). In the field of natural hazards, public perception has been analysed and subsumed over the years under the notions of knowledge and experience (Dominey-Howes and Minos-Minopoulos, 2004; Bird et al., 2009) or awareness (Gregg et al., 2004; Krasovskaia, 2006; Burningham et al., 2008; Raaijmakers et al., 2008) which have been found to depend on criteria such as gender, age and education (Smith 2003), location of residence (Gaillard et al., 2001; Brilly and Polic, 2005) or tenure (Burningham et al., 2008). Identified as a power engine fuelling demand for risk reduction (Slovic et al. 1984; Slovic, 1987), worry is often admitted to be correlated with levels of awareness and preparedness (Raaijmakers et al., 2008). Sjöberg (1998a, b) has, however, found that public demand for risk reduction is driven by the estimation of severity of consequences more than by the estimation of their probability of occurrence; he pointed out the necessity to make the difference, in analysis of risk perception, between emotions and risk judgments, i.e. between worry and risk estimation, which he has found to be not necessarily correlated.

In Iceland, studying perception of flood hazard and flood risk is in its early stages. Academic studies on the perception of natural hazards and natural risks began in the aftermath of two deadly snow avalanches in the Western Fjords, which took the lives of 35 people in 1995; although some results indicate that most of the residents ignored they were exposed (Decaulnes, 2001), there is conflicting indication that the need for sustainable livelihood (Kelman and Mather, 2008) led the population to settle areas in the Western Fjords it knew being at risk. The first studies on the public perception of flood hazard started in 2005; the focus was on the perception of the residents about extreme floods generated by eruptions from Katla volcano (Jóhannesdóttir, 2005; Bird et al., 2009; Jóhannesdóttir and Gísladóttir, 2010). Remarkably, it was found that many residents did not acknowledge living in a flood area, although most of them had a good understanding of the physical processes involved.

Following the large river flood that struck the lower Ölfusá basin in December 2006, the Icelandic government authorised the Hydrological Service to assess the boundaries of the inundations and to realise preliminary flood risk assessment in the basin. Reconstruction of the hydrological history in the basin indicates that 40% of the known flooding over the past 200 years was related to ice jams in rivers (Pagneux et al., 2010); extent and boundaries of such inundations depend essentially on the location and on the nature of ice jams involved, irrespective of discharge estimated at reference gauging sites (Pagneux et al., 2010). A public meeting was organised on February 2009 in Selfoss, the main urban area of the Ölfusá basin, to disclose the preliminary results of the assessment phase. The discussions held during the meeting between the scientists, the national authorities and the residents revealed contention on the effects that the possible implementation of flood-risk zoning in Iceland would have on planning issues: despite of the danger ice-jam floods represent, some land owners firmly stated that flood risk was acceptable to them and expressed their concern on possible restrictions in land use. Their statement was rather in compliance with individualistic values (Wildavsky and Dake, 1990; Dake, 1991), which Ólafsson (2003) estimates a prominent archetype in the Icelandic society. In the end, the discrepancy of statement between the population and the experts put to a light the necessity of assessing the actual public perception of flood hazard and flood risk in Selfoss, which has suffered from severe ice-jam floods in the past. A survey was hence organised in Selfoss during the summer 2009, whose results are disclosed in the present paper. Awareness of the population regarding historical inundations, self-estimation of flood risk and worry about flood risk was analysed. Number of events, dates, genesis and boundaries of historical inundations were used as hazard input parameters in the assessment of the population's awareness. The practical objective was to identify the paramount patterns in the perception of the population; relation between awareness, risk estimation and worry were also considered from a theoretical perspective.

4.2 Study area

Selfoss is the administrative and economic centre of South Iceland, which is one of the main agricultural areas of the country. Only 50 km away from Reykjavík, the nineteenth century estate has turned into a fast spreading town of 6,500 inhabitants in a few decades time, taking full advantage of its proximity with the Icelandic capital area. The urban sprawling in the surroundings is currently of low intensity, characterised by the emergence of scattered summerhouses and residential islets for which Selfoss has become a service town (Nouza and Ólafsdóttir, 2009). There is, however, indication of an extended urban fabric within the next decades. Multifamily houses are numerous in town, featuring lookout basement typically used as living space.

4.2.1 Flood hazard

The town is located by the glacial river Ölfusá. Some 54 flooding events have been substantiated in the Ölfusá lower basin from the beginning of the nineteenth century (Pagneux et al., 2010). Those inundations are essentially polygenic winter events resulting from precipitation, melting and ice jamming. No fatalities have been to deplore, in a context of a small and dispersed population, but losses of livestock have been significant, as well as damages to the road network with several bridges destroyed and roads recurrently entrenched. Twelve inundations are known to have affected Selfoss, the last flooding event having occurred in 2006 (Table 4.1). Inundations in 1930, 1948 and 1968 are considered major events due to the water levels attained. The inundation on February 1968 has had the greatest local magnitude of the known events. It is the result of two ''javes'' (jam release waves) in the River Ölfusá, following the break-up of ice jams upriver, which caused the quick formation of new ice jams within the boundaries of Selfoss. Known as step-burst flood, this phenomenon is well known in arctic regions (Snorrason et al., 2000). A first wave struck the town centre at night, taking the residents by surprise while they were asleep. In less than 30 min, the river bed was totally obstructed with ice, triggering a backwater loaded with ice blocks flowing over the banks. Another wave came the following afternoon, after a second break-up jam had formed downriver. One day later, water had receded, leaving the streets paved with ice blocks (Figure 4.1). Thirty-five buildings were flooded, including homes, commercial and industrial buildings. Furnishings, machine tools and vehicles were lost. Several concrete walls, that were poorly tied, collapsed because of the repeated impact of ice blocks. Filmed interviews of residents flooded, that were realised during the event, show people shocked, scared and anxious.

4.2.2 Other natural hazards

Selfoss is also exposed to volcanic eruptions and earthquakes that both result from divergent plate tectonics. It is not in the scope of this paper to present thoroughly the geodynamics of the area; readers may consult for extensive description Hjartarson (1994) Sigmundsson (2006) and Thordarson and Höskuldsson (2008).

4.2.3 Flood risk management

Mapping of flood hazard in Selfoss according to discharge scenarios (Commission of the European Communities, 2007) is in its preparatory stage for open-water floods. Because extent and boundaries of inundations induced by ice-jams floods depend essentially on the location and on the nature of ice jams (Pagneux et al., 2010), hydraulic modelling cannot be used for the delineation of the flood area in town without monitoring ice jams in the Ölfusá River in the long term. Instead, the Icelandic Meteorological Office has built a provisional GIS model of the flood area based on three documented flooding events: 1948, 1968 and 2006 (Figure 4.2); documents provide evidence of inundations in two areas of special interest: Þóristún, in the western part of the city, which was flood during the ice-jam flood in 1968, and Fagurgerðisflatir, in the Eastern part, flooded both in 1948 and 1968.

Table 4.1 Implication ratio of flooding triggers in Selfoss.

Trigger	Implication ratio (%)
Precipitation	92
Melting	67
Ice jam	17
Glacial burst	8

Figure 4.1 Drifting ice blocks left ashore on the streets during the ice-jam flood in 1968. Some blocks are 50 cm thick and weight several hundred kilos. They are of major concern regarding structures and safety to persons. Source: Icelandic Meteorological Office/Davíð Guðnason (photographer).

In the aftermath of the flooding event in 1968, several home buildings severely flooded were removed, later replaced with a hotel. A trench was later realised to drain water from Þóristún, and a parallel dyke was raised with the excavation material to protect the area laying south (Figure 4.2). This defence work does not prevent ice blocks from drifting on to the streets by Þóristún; furthermore, the presence of river ice west from the trench would restrict on the one hand the drainage of water flowing from Þóristún and trigger on the other hand a side-water south-west from the trench, making it therefore useless for the protection of residential buildings behind. In recent years, valves were put on pipes by Fagugerðisflatir to avoid flooding from sewage and sanitary system, which is considered by the local authorities the main issue in that part of town. Although the national planning legislation restricts development of areas exposed to natural hazards (Parliament of Iceland, 1997), the current General Plan for Selfoss (Árborg, 2006) has authorised development of residential buildings in new areas that are prone to inundations. As a consequence, a 1968- like event may flood more buildings if appropriate measures are not taken and have serious consequences for residents and people in the area.

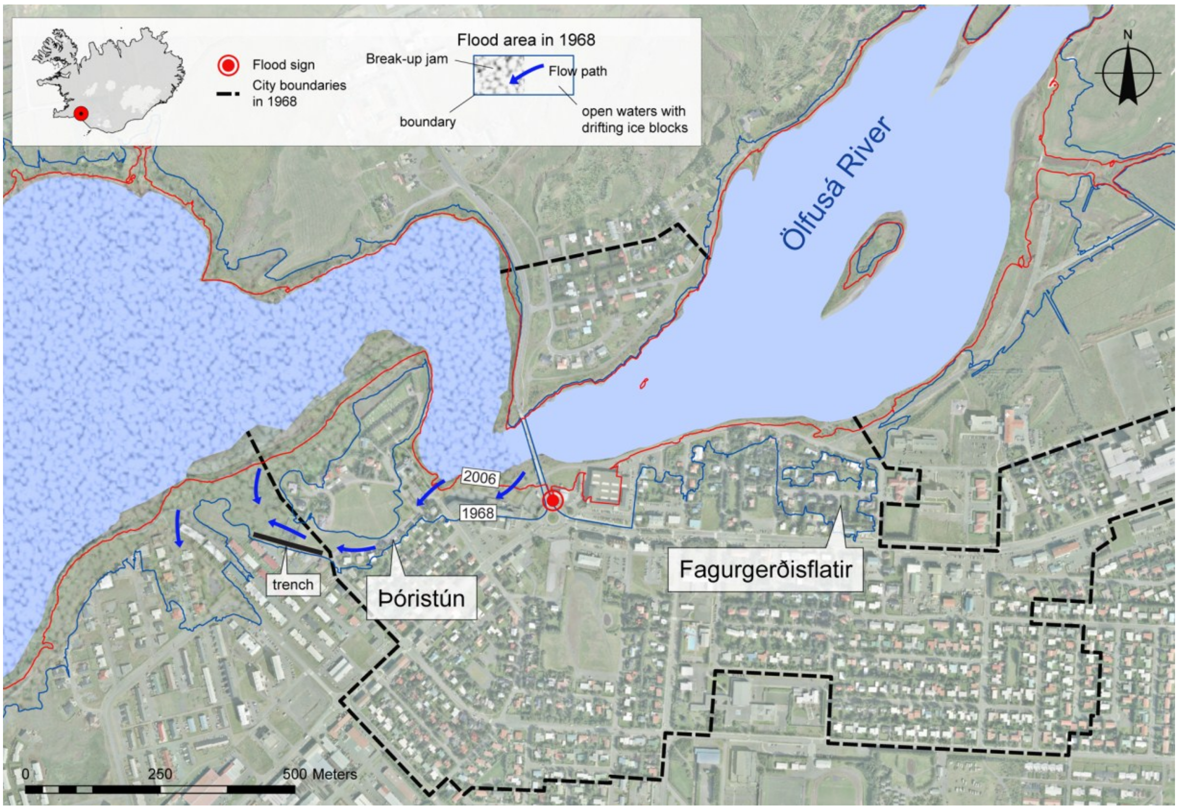


Figure 4.2 GIS model of the flooded area in 1968 according to footage and ground pictures. Inundation boundaries outside of the city limits from 1968 are uncertain due to anthropogenic modifications of the topography. Boundary of the last flooding event in 2006 is shown. Source: Icelandic Meteorological Office; orthophotograph: Samsýn ehf. 2008.

Despite the significant damages caused in Selfoss by the flooding event in 1968, and irrespective of the potential risk to persons associated with streams, depth of flooding, and ice blocks drifting (Figure 4.1), little has been done to inform the population about flood hazard in town. Over the past decades, the preventive information has been leaning prominently on a single flood sign, standing by the southern pier of the bridge crossing the Ölfusá River (Figure 4.2). Displaying information in Icelandic and in English, the sign refers in its current form to the three major events in 1930, 1948 and 1968, indicating for each the water level attained (Figure 4.3); a top-centred sketch depicts the situation by the bridge during the flooding in 1948. Precipitation, melting and ice jamming are mentioned as flood triggers, but are not explicitly prioritised; ice jamming is not mentioned in the English version.

During the annual Culture Festival of the Árborg municipality (that includes Selfoss) in May 2008, a photographic exhibition was held, displaying pictures of the inundations in 1948 and 1968 as well as snapshots of newspapers articles. The photographs from 1968 clearly show the presence of an ice jam by the river as well as streets flooded with water and drifting ice blocks. Financed by the municipality, the exhibition was the initiative of a Selfoss-born photographer who experienced the flooding event in 1968, which he admits to have had a huge impact on the teenager he was at that time. Interestingly, about 1,400 individuals, equivalent to one-third of the Selfoss population, attended the exhibition during the festival.

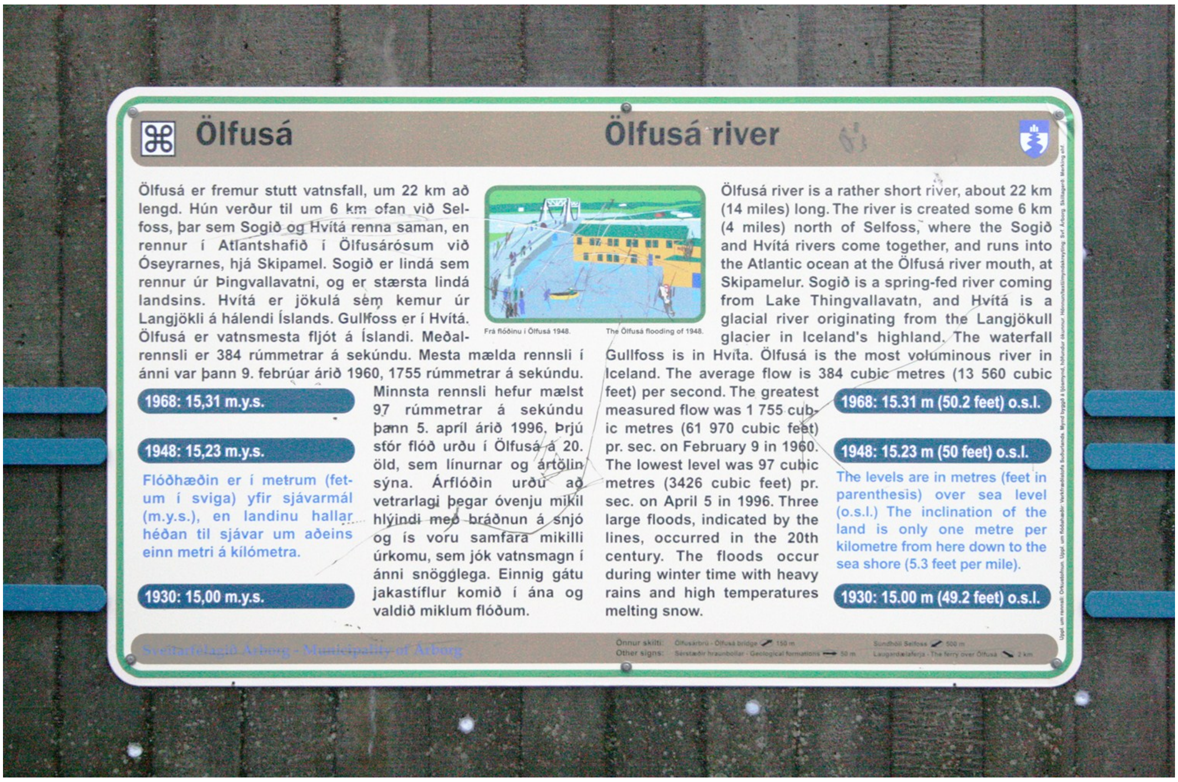


Figure 4.3 Flood sign standing by the bridge. Flooding events in 1930, 1948 and 1968 are mentioned with the water levels attained, as well as information on the genesis of inundations. Unlike its Icelandic counterpart, the English version does not mention ice jamming, which however has been causing the worst event in records.

4.3 Methodology

A two-sided survey was conducted in the urban area of Selfoss from May to August 2009. The objectives were to estimate the public perception of flood hazard and flood risk on the one hand, to assess the public preferences in flood risk management on the other hand. The present paper only refers to the public perception of flood hazard and flood risk. Results on public preferences will be published in a separate paper. An accidental sampling (Bird, 2009) was made among the residents of Selfoss aged above 18 (4,688 individuals). During the time allocated to the survey, 112 residents were visited, at home or at work, and offered to fill in a questionnaire of closed and open questions in a 30-min time approximately. Supervision and assistance of a surveyor were necessary to give some questions a better legibility. The survey was advertised on the municipality's web site and in two local newspapers beforehand. Some group sessions were organised in specific circumstances with no possibility of interference between the respondents. Additional questions about preventive information, for which a visual control from the surveyor was not considered necessary, were later addressed by email or telephone to the respondents having declared knowing about inundations in Selfoss.

Out of the 112 residents visited, a total of 90 individuals participated to the survey. Respondents were 44 males and 46 females aged 46 years on average (min. 19 years and max. 89 years) with a prevailing education level being upper secondary (Table 4.4). Half of the respondents are native from Selfoss and two-thirds are from the Ölfusá basin; 91% own their homes, 84% live at the ground floor. The flood sign is known by 75% of the population; one-third of the respondents saw the photographic exhibition in 2008. Nine-tenths of the population could have experienced the flooding event in 2006 but only 31% in 1968 and 7% in 1948.

4.3.1 Descriptive variables

Public perception of flood hazard and flood risk was deconstructed in three components: awareness of historical inundations, self-estimation of flood risk and worry.

The awareness of the residents was assessed with open questions focusing on four hazard parameters considered as accessible to the lay population: number of events, dates, genesis and boundaries of historical inundations (Table 4.2). Knowledge of the flooding boundaries was estimated from cognitive maps (Gould and White, 1974): the respondents were proposed to draw the boundaries of the flood area from the beginning of the twentieth century on an orthophotograph of Selfoss at scale 1:10.000. The spatial representations of the flood area were processed with a regulated grid of 10 x 10 m squares and results compared with the flood hazard map from the Icelandic Meteorological Office (Figure 4.2). The approach is based on the method used by Leone and Lesales (2005, 2009) for mapping the collective representation of the volcanic risk in the Lesser Antilles. In contrast with methods relying on the raw superposition of drawings like in Brilly and Polic (2005), which are hard to read and difficult to incorporate in multi-purpose maps, the use of grid allows the constitution of choropleth maps where spatial representations can be adjusted for each modality tested and displayed as frequencies of citations (Gaillard et al., 2001). The respondents were instructed to report only what they do know about historical inundations. The performance of the respondents on each of the awareness parameters was rated as scores, summed up on an ordinal scale and itemised eventually on a balanced scale ranging from ‘‘very poor’’ to ‘‘excellent’’ (Table 4.3). The parameters were considered of unequal relevance for rating the awareness of the population; genesis and boundaries were given the prevalence and were therefore weighted to take into account the specificity of the ice-jam-induced flooding event in 1968, ranked locally by the experts the most and worst inundation.

The respondents were eventually invited to estimate the risk of flooding in their neighbourhood and qualify their level of worry on comparable five-point semantic unipolar scales (Table 4.2); they were also asked whether they were considering moving to a safer place because of flood risk (Table 4.2).

4.3.2 Explanatory variables

Eleven variables were used to explain the results on awareness, risk estimation and worry (Table 4.4): on the one hand, age, gender, location of residence, tenure, living floor, geographical origin, level of education, the experience of the flooding event in 1968 and the time spent living in Selfoss; on the other hand, the knowledge of the flood sign and the attendance to the photographic exhibition. The influence of the predictor variables on awareness, risk estimation and worry was estimated using analyses of variance. The influence of awareness itself on risk estimation and worry was estimated with bivariate correlations.

Table 4.2 Questions on flood hazard and flood risk perception.

Questions	Perception	Modalities (grades)
Do you know about inundations having occurred in Selfoss?	Hazard	No; yes
If yes, how many?	Hazard	Digit
If yes, when?	Hazard	Dates
If yes, do you have any idea about their triggers?	Hazard	Text
If yes, when did happen the worst inundation?	Risk	Date
Have you experienced inundations in Selfoss?	Hazard	No; Yes
If yes, how many times?	Hazard	Digit
If yes, when?	Hazard	Dates
If yes, when was the worst inundation you have experienced?	Risk	Date
Would you say that flood risk in your neighbourhood is?	Risk	None (0) ; Of some importance (1); Medium (2); Important (3); Very important (4)
Do you worry about flood risk?	Risk	Not at all (0); Little (1); Moderately (2); Rather (3); Much (4)
Do you think about moving out because of flood risk?	Risk	No; Yes

Because of its genesis and magnitude, the flooding event in 1968 is of paramount importance for understanding the perception of flood risk in Selfoss. Some respondents may have witnessed the flooding event in 1968 but forgotten the date or indicated a wrong year. Hence, it was necessary to include in the category of respondents having experienced the flooding event in 1968 all the respondents old enough in 1968 (aged above 5) who were already settled in Selfoss at the time of the flooding event. Because propagation of floods is forced by topography, isometres reflecting distance from the river cannot be considered a relevant parameter for classifying answers from the respondents with regards to their location of residence. How well topography is perceptible by population in an urban context, where lines of sight are constrained horizontally by networks and vertically by buildings is difficult to appreciate but of paramount importance. The respondents were distributed in 3 groups based on the susceptibility to inundations of their location of residence:

- The population living in areas where inundations have been substantiated throughout the twentieth century (Figure 4.2).

- The population living in areas suspected to be at risk during extreme events because of their elevation, although there is actually no evidence of flooding in recent history. Since hydraulic modelling is not reliable in the Ölfusá basin (Pagneux et al. 2010), the identification of the envelope relied only on the topography.
- The population living in areas considered as safe whatever the scenarios.

Table 4.3 Weight of each awareness component.

Factual knowledge	Weight	Points range	Attribution method
Numbers of events	1	0 - 4	One point per event in the limit of 4
Dates	1	0 - 4	One point per right dates in the limit of 4
Genesis	2	0 - 8	Precipitation: +1; melting: +1; glacial burst: +2; ice jam: +4
Boundaries	2,5	0 - 10	Cognitive map divided in sectors: +0.66 point for each sector in the flood area; -0.66 point for each sector outside
Awareness (Sum)	-	0 - 26	Scores itemised on a balanced scale based on equal interval: very poor (<4.33); poor (4.33-8.66); somewhat poor (8.66-13); somewhat good (13-17.33);good (17.33-21.66); excellent (>21.66)

Table 4.4 Explanatory variables and modalities; number of respondents for each category is shown in brackets. [a]: n=90; [b]: n=79.

Predictors	Modalities (n)
Age (birth)[a]	<1940 (5); 1940-1950 (11); 1950-1960 (19); 1960-1970 (23); 1970-1980 (26); 1980-1990 (6)
Gender [a]	Male (44); Female (46)
Location of residence [a]	Flood area (7); Close to the flood area (21); Away from the flood area (62)
Tenure [a]	Owner (82); At parent's home (3); Renter (5)
Living floor [a]	Basement (7); Ground floor (76); Other (7)
Geographic origin [a]	Selfoss /Árborg (45); Other municipality from Árnessýsla county (15); Other Icelandic county (28); Foreign country (2)
Level of education [a]	Compulsory school (12); Upper secondary school (50); University / Bachelor level (21); University / Master and PhD level (7)
Flooding experience [a]	Experienced the flooding event in 1968 (24); Did not experience the flooding event in 1968 (66)
Length of time in Selfoss [a]	Settling year <1948 (5); 1949-1958 (10); 1959-1968 (12); 1969-1978 (22); 1979-1988 (8); 1989-1998 (12); 1999-2006 (15); >2006 (6)
Knowledge of the flood sign [b]	Yes (59); No (20)
Attendance to the photographic exhibition [b]	Yes (25); No (54)

4.4 Results

4.4.1 Awareness

Almost all the population surveyed (97%) declared knowing about inundations in Selfoss, of whom 9% have though experienced none. However, about two-thirds of the respondents have a factual knowledge and understanding of historical inundations quite insufficient (Figure 4.4):

- Only 26% of the respondents acknowledge more than 3 flooding events in town. Dates of the major flooding events in 1968, 1948 and 1930 are correctly cited by respectively 38, 17 and 7% of the respondents.
- Understanding of the causes of flooding is mixed. Sixteen per cent of the respondents consider inundations the consequence of water increase in the river without description of factors causing the increase; 52% cite melting as a trigger, 50% ice jam, one-third mentions precipitation, 7% only mention glacial bursts.
- Knowledge of the boundaries of historical inundations is really poor: less than 40% of the respondents identify Þóristún, which was flooded during the ice-jam flood in 1968, as a flow path (Figure 4.6); the exposure of Fagurgerðisflatir, flooded in 1948 and in 1968, is largely ignored by a majority of respondents.

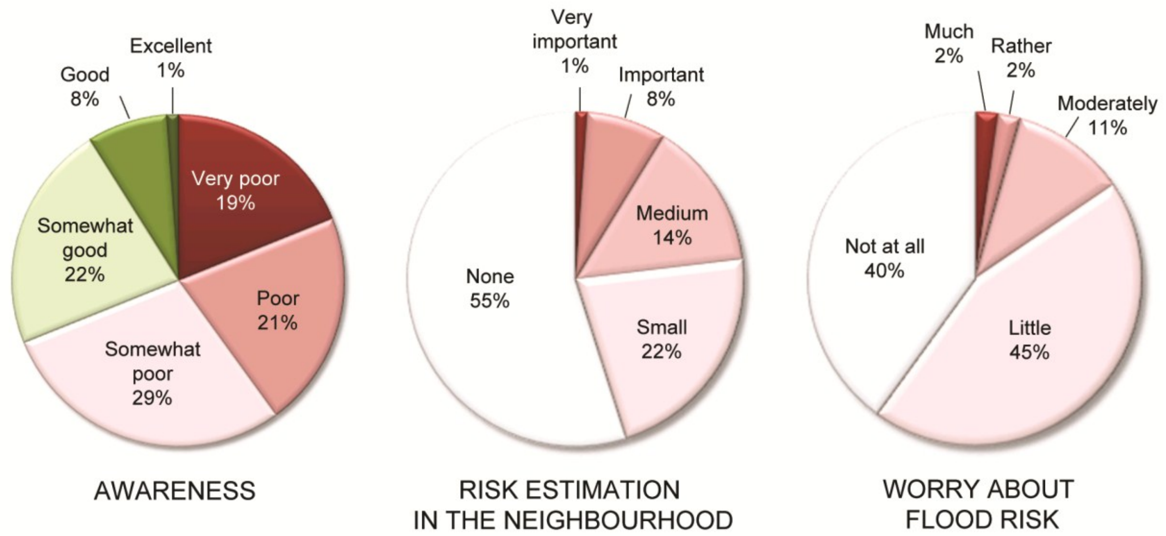


Figure 4.4 Results on awareness, estimation of flood risk in the neighbourhood and worry about flood risk.

Experience of the flooding event in 1968 appears to be the most effective source of awareness (Table 4.5; Figure 4.5). The time spent living in Selfoss, the tenure, the knowledge of the flood sign are also influential, but only with the respondents who have not experienced the flooding event in 1968 (Table 4.5). The geographical origin is only of significance when including the foreigners. Age does matter neither with the respondents having experienced the flooding event in 1968, nor with the respondents who did not (Table 4.5). The overall effect of age seems to reflect the importance of the experience in the awareness of the respondents. Gender and location of residence do not really matter

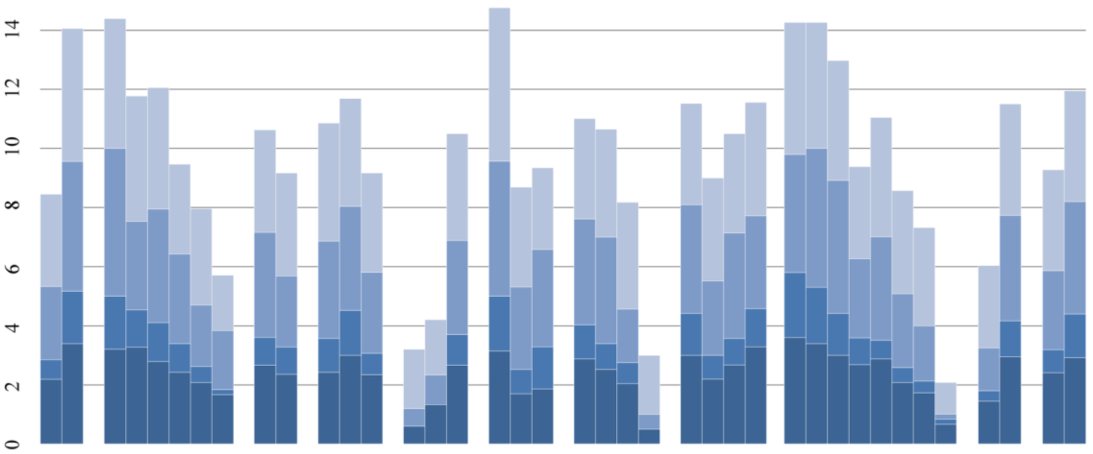
(Table 4.5). Levels of education have no significant effect on the actual knowledge of the population, whatever the situation of the respondents regarding the experience of the flooding event in 1968 (Table 4.5); levels of education are neither influential with the respondents born in Árborg after 1968, whose actual knowledge is unlikely to result from local school programs at the compulsory and upper secondary levels ($p = 0.578$). Influence of the tenure with the respondents having experienced 1968 is not possible since they are all owners.

Table 4.5 Statistical relation between scores on awareness and explanatory variables.

	Whole sample					Did not experience 1968					Experienced 1968				
	Number of events	Dates	Genesis	Boundaries	General awareness	Number of events	Dates	Genesis	Boundaries	General awareness	Number of events	Dates	Genesis	Boundaries	General awareness
Flooding experience	*	*	*	*	*	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
Age	*	*			*										
Gender			*												
Location of residence		*										*			
Tenure	*	*	*	*	*	*				*	n.a	n.a	n.a	n.a	n.a
Living floor		*		*	*										
Geographic origin	*		*		*	*							*		
Level of education	*					*									
Time spent living in Selfoss	*	*	*	*	*	*		*	*	*					
Knowledge of the flood sign	*	*	*		*	*	*	*		*					
Attendance to the photographic exhibition	*	*	*		*			*				*			

n.a.: not applicable
*: $p < 0.05$ (ANOVA)

Genesis of the flooding events is well understood by the respondents having experienced the inundation in 1968 but is unknown for most of the residents recently settled: ice jamming is cited by 86% of the respondents settled in Selfoss before 1968, but only by 40% of those who settled Selfoss after the ice jam-induced inundation; genesis of the flooding events has not been described by 80% of the respondents established in Selfoss after 2006. The photographic exhibition about historical inundations in Selfoss looks to have been influencing positively understanding of the genesis with the respondents who have not experienced the flooding event in 1968: 60% of those who attended the exhibition cite ice jams as a trigger against 33% of the respondents who did not.



		Number of events	Dates	Genesis	Boundaries	Total
Experienced 1968	No	2.19	0.66	2.48	3.12	8.45
	Yes	3.39	1.78	4.39	4.5	14.07
Age	<1940	3.2	1.8	5	4.4	14.4
	1940-1950	3.27	1.27	3	4.24	11.78
	1950-1960	2.79	1.32	3.84	4.11	12.06
	1960-1970	2.43	0.96	3.04	3.04	9.48
	1970-1980	2.08	0.54	2.08	3.26	7.95
	1980-1990	1.67	0.17	2	1.87	5.7
Gender	Male	2.66	0.95	3.55	3.47	10.63
	Female	2.35	0.93	2.41	3.48	9.18
Location of residence	Flood area	2.43	1.14	3.29	4	10.86
	Close to the flood area	3	1.52	3.52	3.65	11.7
	Away from the flood area	2.34	0.73	2.74	3.36	9.16
Tenure	Renter	0.6	0	0.6	2	3.2
	At parent´s home	1.33	0	1	1.87	4.2
	Owner	2.66	1.04	3.18	3.62	10.5
Living floor	Basement	3.14	1.86	4.57	5.19	14.76
	Ground floor	1.7	0.82	2.79	3.38	9.41
	Other	1.86	1.43	3.29	2.77	10.2
Geographical origin	Árborg	2.87	1.16	3.58	3.4	11
	Other municipality from Árnes county	2.53	0.87	3.6	3.65	10.65
	Other Icelandic county	2.04	0.71	1.82	3.61	8.18
	Foreign country	0.5	0	0.5	2	3
Level of education	Compulsory school	3	1.42	3.67	3.43	11.51
	Upper secondary school	2.2	0.8	2.52	3.48	9
	University (Bachelor level)	2.67	0.9	3.57	3.36	10.5
	University (Master and PhD level)	3.29	1.29	3.14	3.84	11.56
Time spent living in Selfoss	<1948	3.6	2.2	4	4.46	14.26
	1949-1958	3.4	1.9	4.7	4.27	14.27
	1959-1968	3	1.42	4.5	4.05	12.97
	1969-1978	2.68	0.91	2.68	3.12	9.4
	1979-1988	2.88	0.63	3.5	4.04	11.04
	1989-1998	2.08	0.5	2.5	3.49	8.58
	1999-2006	1.73	0.4	1.87	3.32	7.32
	>2006	0.67	0.17	0.17	1.07	2.07
Flood sign	No	1.45	0.35	1.45	2.79	6.04
	Yes	2.95	1.22	3.56	3.78	11.51
Photographic exhibition	No	2.41	0.78	2.67	3.42	9.28
	Yes	2.92	1.48	3.8	3.75	11.95

Figure 4.5 Scores on awareness parameters for each explanatory variable.

As for the dates and genesis, the respondents having experienced the flooding event in 1968 are the more aware of the boundaries of the flood area (Figure 4.5); 60–80% of those with the experience of 1968 identify the path by Þóristún against 40% and less for inexperienced respondents, whether they are aware or unaware of the date 1968 and of ice jams as a trigger (Figure 4.6). Cognitive maps indicate that about 30% of the respondents living in the flood area have been excluding their home from the area they think at risk, while 10% of the respondents living close to the flood area have been including it.

Some patterns in the results make the real influence of the flood sign questionable. Dates 1968, 1948 and 1930 are correctly cited by respectively 49, 20 and 8% of the respondents knowing the flood sign; only 5% of the respondents knowing the flood sign cite the 3 dates. Ice jam, melting and precipitation are respectively cited by 63, 58 and 36% of the respondents knowing the flood sign; only 16% of them do cite the three triggering parameters together.

4.4.2 Risk estimation and worry

Only 9% of the respondents consider the risk of flooding as important or very important in their neighbourhood while 55% consider there is no risk at all. The risk estimation varies significantly with the location of residence ($p = 0.038$): 29% of the respondents living in the flood area consider flood risk as important or very important in their neighbourhood, 14% as none; figures are 9.5 and 38% with the population living close to the flood area, and 6.5 and 65% with the population living away. The respondents living in the basement are significantly lesser to rate the risk of flooding in their neighbourhood as none than respondents living at the ground floor or above ($p = 0.041$).

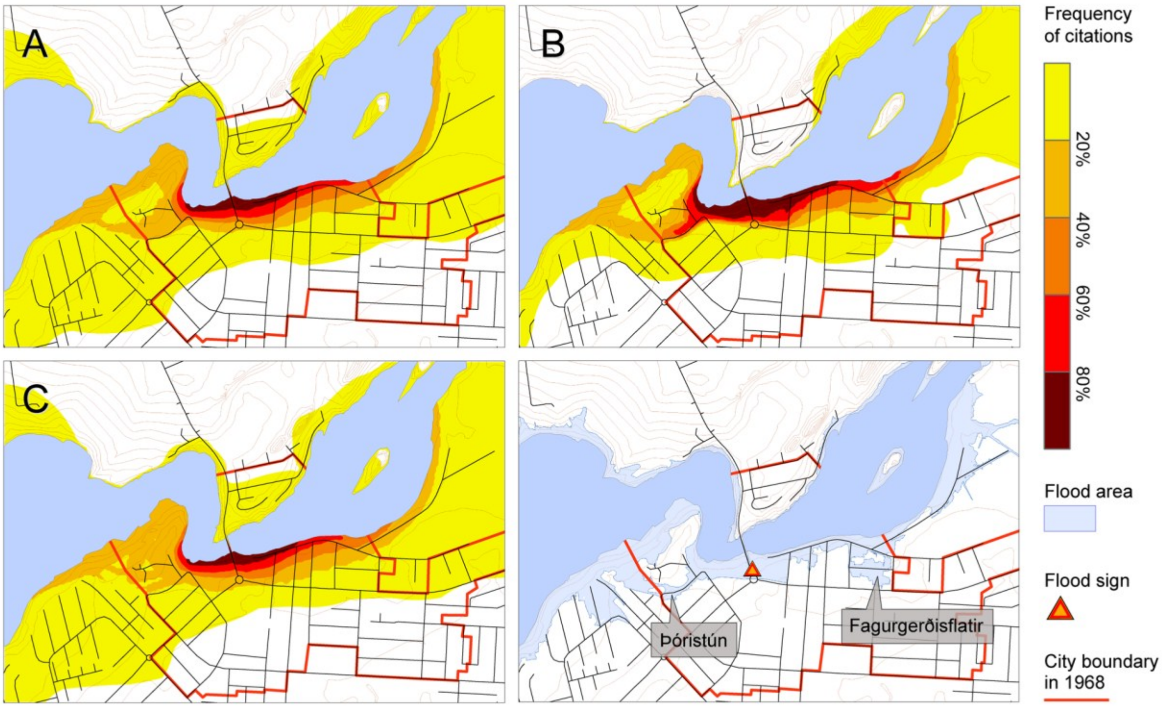


Figure 4.6 Spatial perception of the flood area from the beginning of the twentieth century. A: Whole population; B: Respondents having experienced the flooding event in 1968; C: Respondents who did not experience the flooding event in 1968.

The estimation of the risk (Figure 4.4) gives interesting information on the perception of the flood area which exceeds the results obtained from the cognitive maps (Figure 4.6): 43% of the respondents who do not include their home in the area that they think has been flooded from the beginning of the twentieth century however consider that there is a risk of flooding in their neighbourhood.

There is little worry about flood hazard among the respondents, which looks much a nonissue to them. Only 5% declare being rather or much worried while 37% do not worry at all. None of the predictors tested looks of influence; levels of worry are neither correlated to levels of awareness ($r^2 = 0.004$) nor to risk estimation rates ($r^2 = 0.017$): half of the respondents who consider their home within the flood area, as well as 57% of the respondents who consider the danger as significant in their neighbourhood, declare not being worried about of flood hazard. On the other hand, 6% of the population rating the risk as none confess being rather or much worried with flood risk. No respondents have either considered moving to a safer place because of flood risk.

4.5 Discussion

4.5.1 Experience and time

Experience is the most effective source of awareness. The respondents who have the better knowledge on the history and the better understanding on the genesis and on the extent of the flooding events are the ones who have experienced them. There is a clear chasm between experience and inexperience, which does attest to the importance of the autobiographical memory (Tulving, 1972) in the performance of the population. The overall effect of age reflects only the importance of the experience in the awareness of the respondents. Levels of education have no significant effect on the actual knowledge and understanding of the population; comparable pattern on education levels was already observed in Iceland, close to Katla volcano, in a context of knowledge resulting from oral transmission through generations (Jóhannesdóttir, 2005; Jóhannesdóttir and Gísladóttir, 2010). In contrast with findings from Brilly and Polic (2005), the location of residence has not been shown a significant differentiating factor in the perception of flood hazard; it may be due to the size of Selfoss, which is rather small.

Although the population is aware of more events than actually experienced, the knowledge about flooding events follows a downward trend as the time spent living in town decreases; the residents recently settled, among them the foreigners, are really unaware of historical inundations in town (Figure 4.5). Altogether, it indicates a failure in the transfer of knowledge through generations that has led progressively to a loss of collective memory and weakened the development of a culture of living with floods. Being aware of the flood sign does help, but fails to compensates for the lack of experience and inherited knowledge from alternative sources; although 75% of the respondents know the flood sign, very few have completely assimilated the information delivered. Reaching the population in a more systematic way is therefore clearly needed if the authorities will enhance the awareness of the population of living in an at-risk area. Several options could be implemented such as compulsory meetings at regular interval (French Parliament, 2003), flood signs (Petrow et al., 2006) at the boundary of the flood area or even school programs at the secondary level.

4.5.2 Severity of consequences vs. probabilities

The affirmation that a society tends to forget about risks associated with infrequent events (Raaijmakers et al., 2008) is not verified in the present study. The results show the prominence of the flooding event in 1968 in the knowledge of the respondents, which looks a case of salience biasing the availability heuristic (Tversky and Kahneman, 1973, 1974). One could expect the date and triggers of the most recent event to be the best remembered by the population. However, only one-third of the population cite correctly the flood in 2006 while 84% of the population surveyed acknowledge one event from the beginning of the twenty-first century. Meanwhile, 37% of the population clearly cite the flooding event in 1968 while only 31% could have experienced it; Precipitation is involved in 90% of inundations and still, only one-third of the population mention it as a trigger. In contrast, ice jamming is clearly cited by half of the pool though involved in one-fifth of inundations only. Despite the aperiodicity of ice-jam floods, the prominence of 1968 in the awareness of the population suggests that severity of consequences is more important than their probability in the public perception.

4.5.3 Awareness, risk estimation and worry

No correlation was found between the factual knowledge of the respondents about historical inundations and their estimation of flood risk. It may result from the estimation of risk conveys information on perception that overcomes the factual knowledge of the respondents. The public estimation of risk opens a door on the objective incertitude of the population, not only regarding the past, but also regarding the future, especially in a context of climate change. It does lead to responses that call upon knowing and remembering activities, but also upon guessing (Gardiner et al., 1998). It is therefore not surprising to have a risk estimation independent from ''factual'' awareness with, for instance, a spatial distribution of the risk rates exceeding the boundaries of the flood area given in the cognitive maps (Figure 4.7): while the cognitive maps mainly reflect the residents' knowledge, their risk estimation mainly reflects their guess, i.e. what they consider possible. People's recognition that their property is in an area potentially at risk may reveal another form of awareness, i.e. the consciousness of living in a changing environment. This contrasts with denial observed in several countries of Europe with populations living in areas prone to inundations (Krasovskaia, 2006; Burningham et al., 2008).

No correlation was found between estimation of risk and levels of worry. As pointed out by Sjöberg (1998a, 1998b), it is necessary to make the difference in the public perception between the estimation of the severity of consequences, which may fuel worry and demand for risk reduction, and the estimation of their probability of occurrence, which does not necessarily call upon emotions or affects. Furthermore, the questions on risk estimation and worry apply in the study to different risk targets (Sjöberg, 2000): the question on risk estimation in the neighbourhood is targeted spatially but not personally; on the contrary, the question on worry is personally targeted but is spatially loose. One may consider for instance the risk in its neighbourhood as small but worry a lot because of the exposure of some relatives who live elsewhere in the city or because the workplace is at risk. The differences in the targets (personal vs. spatial) are meaningful enough to create a bias when analysing the correlation between the two variables. Making the difference between risk for life and risk of economic loss (Krasovskaia et al., 2001), as well as analysing itineraries (Ruin et al., 2007) of the residents in town would certainly help refining the assessment on the public perception of flood risk in Selfoss.

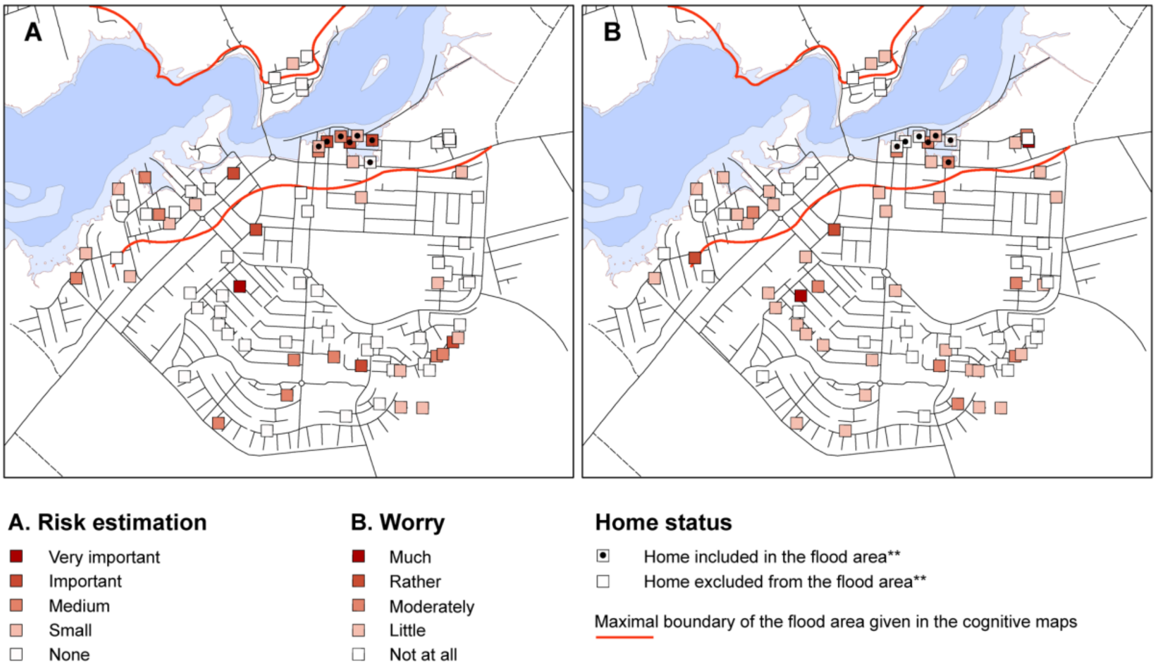


Figure 4.7 Risk estimation and worry of the population regarding inundations. The squares show the location of residence of respondents. ** flood area according to cognitive maps (Figure 4.6).

The individualistic values found in Iceland (Ólafsson, 2003) may be accountable for the lack of correlation observed in Selfoss between awareness and worry. Situational factors may also have their toll on the lack of correlation observed, which multi-hazard and single-hazard approaches within the psychometric paradigm may help to understand. When the surveyor presented himself to the residents, several confessed that they thought first of a survey on their experience of the Mw 6.3 earthquake that occurred on May 29, 2008 a few kilometres away west from the town (Sigbjörnsson et al., 2009). Few structural damages and no fatalities were to deplore. Two 6.5 earthquakes occurred east from Selfoss on June 17 and June 21, 2000 with lesser damages on structures (Akason et al., 2006). Significant post-traumatic stress disorders such as anxiety were, however, consigned by psychologists (Bödvarsdóttir and Elklit, 2004). It does suggest that the lack of worry regarding flood risk in Selfoss should not be considered only from an intrinsic perspective, but also in relation to local risks from other natural hazards pregnant in the area such as volcanic eruptions and seisms. Feelings of worry and anxiety comparable to disorders reported in the aftermath of the earthquakes were observed in the hours following the flooding event in 1968. Such feelings contrast with the lack of worry observed in this survey. It suggests that worry and anxiety related to disasters are bound to vanish as time goes by. It may explain, from an intrinsic perspective, the lack of correlation observed in the survey between awareness and worry, in a context where 40 years have passed since the last severe inundation occurred in Selfoss.

In the end, strategies linking preparedness to both awareness and worry (Raaijmakers et al., 2008) may not to be successful in Selfoss; they rely on a questionable grounding, as shown by the lack of correlation found in the survey between awareness and worry. The local importance of social values (Ólafsson, 2003) but also of livelihood (Burningham et al., 2008; Kelman and Mather, 2008) may hinder the efficiency of better awareness in the preparedness of the population. It is either ethically questionable to build a strategy in risk management based on arousing fears, if ever sustainable from a technical point of view. Raising worry for increasing preparedness may have no place in a society where authorities, experts and lay public have to become partners in flood risk management (Arnstein, 1969; Aven and Kristensen, 2005) and produce a cooperative discourse (Renn, 1998) reflecting shared knowledge and mutual understanding.

4.6 Conclusion

The research led in Selfoss shows insufficient awareness of the public about flood hazard, in a context where experience of past flooding events has been found the most effective source of knowledge. The deconstruction of factual knowledge about historical inundations into hazard components has put a light on the necessity to better inform on the outcome of inundations induced by ice jams, whose genesis and boundaries are unknown by an important fraction of the population. Although being useful, the existing flood sign has failed to arouse at high levels the population's awareness, which has been shown to decrease as time goes by. Comprehensive preventive information is needed to insure development and sustainability of a culture of living with floods.

Little worry about flood risk has also been observed, but no correlation has been found between levels of worry and levels of awareness. It obliges, on the one hand, to use with great caution strategies in flood risk management linking preparedness to both awareness and worry; to pay more attention on the other hand to situational factors, but also to social values and livelihood that in Selfoss may be the main issue in flood risk management. Still, it is possible to develop a culture of risk based on shared knowledge and mutual understanding between stakeholders. In that perspective, preventive information should not be seen as a way to ''educate'' people; it should neither be seen as a way to increase worry and incidentally demand for risk reduction, but considered a neutral contribution to cooperative ''discourse'' and coproduction of solutions in the management of flood risk that integrate both expertise and social values. Such an approach requires beforehand not only to assess how flood hazard and flood risk are perceived but also to assess how they may correlate with the spontaneous public preferences in flood risk management.

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5 Management of flood risk in Iceland: A case study on public preferences

Pagneux, E., Jónsdóttir, S., Gísladóttir, G. (Under review). Management of flood risk in Iceland: A case study on public preferences. Submitted to *Landscape and Urban Planning.*

Abstract

Public preferences in the management of flood risk were assessed in an Icelandic municipality that has been prone to severe inundations in the recent past. The survey sought a public rating of governance style, technical options, and restrictions in land use planning. The aim of the study was to provide a first set of information on public preferences in the management of flood risk in Iceland. Preferences were analysed in the light of the socioeconomic profile of the respondents and of their perception of flood risk. In the analysis, an emphasis was put on the jurisdictional, institutional, and spatial scales and levels at which the coping options take effect. Survey results on governance indicate definite support of the municipal authorities and pronounced defiance towards central government by a significant part of the respondents. Although expressed preferences on levels of regulation indicate important opposition to the principle of compulsory measures, strong approval of restrictions in land use planning reveals that the principle of flood risk zoning is well accepted by the population surveyed. Actions centred on the people are largely approved. In contrast, there is little support for mitigation measures requiring collective action at the town and river basin scales. There is clear rejection of structural runoff control and mixed support of runoff control based on ecological processes. Perception of flood risk is found of little influence on the expressed preferences.

Keywords

Flood risk – Iceland – Land use – Management – Planning – Public preferences

5.1 Introduction

Shared knowledge and mutual understanding among stakeholders have become one of the main goals of risk communication (Renn, 2004) and form one of the key principles of the adaptive and integrated management paradigm (Aven and Kristensen, 2005; Huntjens et al., 2010). Production of cooperative discourse is, nevertheless, difficult to achieve (Patt and Schröter, 2008; Harries and Penning-Rowsell, 2011) because of discrepancies of views among stakeholders on the nature and importance of risk and on the coping measures that should be implemented (Krasovskaia et al., 2001). Public acceptability of policies and behavioural adaptation of the public to risk are, in particular, of great complexity. In simple terms, public acceptability of coping measures can be presented as reflecting a balance between risk perception (or threat appraisal) on the one hand, that is to say appraisal of both the likelihood and severity of hazards (Rogers and Prentice-Dunn, 1997; Sjöberg, 1998), and appraisal of coping options on the other hand (Rogers and Prentice-Dunn, 1997). Factors influencing risk perception have been well debated over the past 30 years. Followers of the psychometric paradigm consider that preparedness and demand for risk reduction are correlated to worry and fear and are together driven by factors such as the visibility and controllability of hazards (Fischhoff et al. 1978, Slovic et al., 1984; Slovic, 1987; Sjöberg, 1998). In turn, cultural theorists have emphasised on worldviews as drivers of risk perception: for instance "orienting dispositions" such as individualism, hierarchism, egalitarianism, and fatalism (Wildavsky and Dake, 1990; Dake, 1991), or "fundamental values" such as self-direction, power, or universalism (Schwartz, 1996; Glenk and Fischer, 2010). Appraisal of coping options is rather a matter of intelligibility of options and of trade-off between perceived benefits (Glenk and Fischer, 2010) and perceived drawbacks, which can be, to name a few, financial, political, environmental, or aesthetical, as suggested by recent case studies on public preferences in the management of flood risk (e.g. Brilly and Polic, 2005; Krasovskaia, 2005; Kenyon, 2007; Kriebich and Thieken, 2009; Glenk and Fischer, 2010; Lara et al., 2010) and management of climate change (e.g. Leiserowitz, 2006). Reinforcement of building structures, for instance, may be a difficult technical choice for home owners because of the complexity and cost of required adaptations (Kreibich and Thieken, 2009). Under some circumstances, hard mitigation may be preferred to ecological mitigation and adaptation; in the Netherlands, for instance, the population seems ready to accept major changes on the environment to increase life safety (Krasovskaia, 2005). The situation is different in Scotland, where afforestation is preferred to flood walls and embankments (Kenyon, 2007). Afforestation itself may not necessarily be a first choice when forest is not perceived as a natural landscape element or when it affects the scenic beauty of landscapes (Gobster et al., 2007). Like risk perception, appraisal of coping options reflects values and beliefs. Ecocentrism and collective interest, for instance, were found to activate pro-environmental behaviours (Stern et al., 1995; Nordlund and Garvill, 2003). Studies on acceptability of transport policy measures have shown that potential infringement on personal freedom and perceived fairness of measures should also be considered as factors influencing acceptability (Eriksson et al., 2006).

This paper investigates preferences of the public in the management of flood risk in an Icelandic municipality prone to ice-jam floods. Iceland is a country where little is known of the psychological and social dimensions of flood risk. The investigations led so far suggest that local culture and flood experience in areas prone to extreme floods are the prominent drivers of the public perception of flood hazard and flood risk (Bird et al., 2009; Jóhannesdóttir and Gísladóttir, 2010; Pagneux et al. 2011). Views of the public on policies and strategies that should prevail in the management of flood risk are unknown. Preferences were analysed in the light of the socioeconomic profile of the respondents and of their perception of flood risk. Emphasis was put, in the analysis, on the jurisdictional, institutional, and spatial scales and levels at which the coping options take effect in so far as such scales and levels are critical in understanding opposing perspectives in the management of flood risk between top-down and consensual regimes (Pottier et al., 2005; Huntjens et al., 2010), and more generally, in understanding the human-environment interactions (Cash et al., 2006).

5.2 Regional settings

5.2.1 Jurisdictional and institutional context

Unlike the countries of North America (Environment Canada, 1993; NARA, 2009) and of Europe (MATE/METL, 1999; DEFRA, 2006; EXIMAP, 2007; de Moel et al. 2009), Iceland does not have a classification of flood hazard from which flood risk zoning could be derived. The national planning legislation predicts that areas exposed to natural hazards should be clearly identified in planning documents (Ministry of Justice and Ecclesiastical Affairs, 1998; Parliament of Iceland, 2010). Municipal plans in Iceland are subject to a Strategic Environmental Assessment (Parliament of Iceland, 2006), which requires that areas prone to natural hazards be identified in the preparation phase of any planning (National Planning Agency 2010a, 2010 b). It should also be noted that all local plans are reviewed by the Icelandic National Planning Agency, which takes national interest and civic protection into account in their review. Nevertheless, besides the legal requirements regarding the identification of flood hazard zones, binding documents and guidelines applicable to the designation of flood risk zones and to the enforcement of building codes exist only for low areas prone to coastal flooding (National Planning Agency, 1992; Icelandic Maritime Administration et al., 1995). Similar documents do not exist for river flooding. As a result, the Icelandic local municipalities, which are legally responsible for spatial planning within their jurisdictions, are relatively free to manage flood risk from rivers according to their own standards. It should be noted that damages due to river floods are covered by a national insurance scheme against natural disasters (Parliament of Iceland, 1992; Ministry of Justice and Ecclesiastical Affairs, 1993); in the absence of compulsory flood risk zones, compensation for covered damages due to river floods is effective without consideration of the location of properties and of the design of buildings. Hence, considerable freedom is granted in Iceland to municipalities in the management of flood risk but also to homeowners living in flood prone areas. Such freedom is quite in line with the Icelandic culture where centralism is not a major value or goal, respect for authorities moderate, and individualism admittedly the prominent social value (Tomasson, 1980; Ólafsson, 2003). Eventually, it should be noted that the Icelandic national authorities are making preparations for implementing the European Flood directive. The directive applies to the development of flood risk management plans, “focusing on prevention, protection, preparedness”, and promotion of “sustainable land use practices, improvement of water retention” and “controlled flooding of certain areas in the case of a flood event” (European Parliament & European Council, 2007). As the directive also requires that flood risk be managed at the organisational level of river basin districts, its implementation in Iceland is not only expected to have a catalytic effect on flood hazard assessment and flood risk zoning but also to impact, in the management of flood risk, the distribution of responsibilities between the existing jurisdictional levels.

5.2.2 Study area

Assessment of public preferences concerning flood risk management was carried out in the town of Selfoss, Southern Iceland. With 6,500 inhabitants, Selfoss is the largest community in the Árborg municipality and the biggest settlement in the basin of the River Ölfusá, which covers 6,190 km^2 between the Hofsjökull and Langjökull glaciers and the Atlantic Ocean (Figure 5.1). Due to harsh climatic conditions, only a fraction of the basin below 240 meters a.s.l. is permanently settled and cultivated. Forests were decimated during the Middle Ages by settlers who needed the timber for fuel and warmth (e.g. Hallsdóttir, 1987; Erlendsson, 2007). As a result, forest trees at least 2 meters high and transitional woodland shrubs cover less than 1% of the basin at present (Arnason and Matthiasson, 2009). The amount of cultivated land, which covers 4% of the basin, has increased throughout the 19th and 20th centuries, mainly through wetland drainage (Thórhallsdóttir et al., 1998).

The town of Selfoss is located on the River Ölfusá (Figure 5.1), on a nearly flat lava field that has been repeatedly flooded over the past 200 years as a result of large open-water river floods but also because of the formation and release of ice jams at specific sections of the Hvítá-Ölfusá river complex (Pagneux et al., 2010). During the 20th century, inundations due to ice-jam floods have occurred at an interval of 15-20 years. Selfoss itself was severely flooded on February 28-29, 1968, after the breakup of ice jams that had formed upriver and later within the town boundaries. During night time, ice-cold water flooded look-out basements and ground floor levels in two areas, taking the population by surprise. In the meantime, river ice blocks were carried onto the streets, impacting building structures. Many homes, as well as commercial and industrial buildings, were severely damaged. Fortunately, no fatalities occurred. Since then, no critical inundation has taken place in Selfoss. Although being one the most important in the past 50 years at the regional scale, the last open-water flood, in December 2006, caused no significant damage in town.

Despite the potential threat from ice jams in the River Ölfusá, little has been done for the management of flood risk at the municipal level since 1968. Valves were implemented in recent years on municipal pipes to avoid flooding from the sewage and sanitary systems, and areas within town that were flooded in 1968 partly kept as green ways. At the same time, areas prone to floods that are adjacent to the town were opened for residential development (Árborg, 2006; 2010). The Árborg municipality is currently exploring on its own the potential flood hazard mitigation benefits of a low-head dam upriver from Selfoss primarily aimed at power generation (Figure 5.1). Claimed beneficial to the Árborg municipality, the dam would be located at the junction of two neighbouring municipalities where an increase in the ground water table and accumulation of river ice would be induced. Landsvirkjun, an energy company owned by the Icelandic State, has explored in recent decades the feasibility of hydro-power generation at many different locations in the Hvítá-Ölfusá river complex. To date, however, only the Sog River, a tributary of the Ölfusá, has been regulated for energy production. The use of dams as flood risk mitigation structures has not been explored at the basin scale.

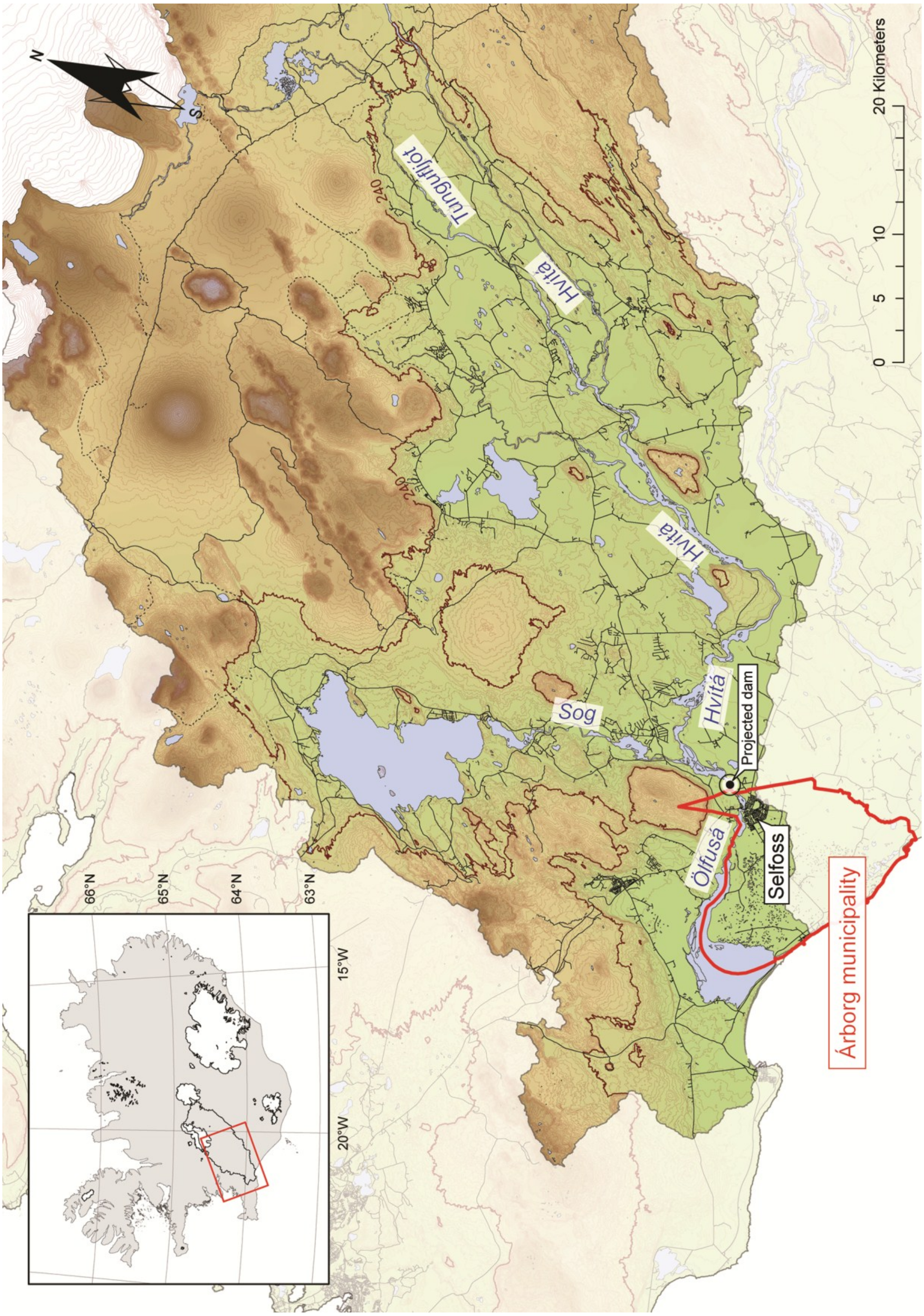

Figure 5.1 Selfoss is located on the lower reach of the Hvítá-Ölfusá complex in the settled fraction of the Ölfusá basin (<240 metres a.s.l., shown by the contour line in bold); the whole extent of the Ölfusá basin is shown on the map of Iceland in the upper left thumbnail.

5.3 Methodology

The assessment of preferences was conducted as the second part of a two-sided survey organised in town during the summer of 2009. A convenience sample of the population aged over 18 (4688 individuals) was made. Residents were visited at work places and at home in commercial, industrial, and residential areas. During the time allocated for the survey, 90 residents agreed to participate (for information, a random sample based on a standard error of 5% would have given a number of 97 respondents). They were mostly homeowners living on the ground floor, natives of Selfoss, with an average age of 46 and usually with upper secondary education (Table 5.1). Results of the first part of the survey, that was dedicated to the assessment of the public perception of flood hazard and flood risk, indicated not only poor awareness of historical inundations among the respondents, but also a low appraisal of flood hazard threat and little worry about flood risk (Pagneux et al., 2011;Table 5.1). Experience of inundations in Selfoss was found the most effective source of knowledge in a context of inconsistent public information about historical floods. Eventually, no correlation was found between awareness, threat appraisal, and worry.

Table 5.1 Socioeconomic profile and flood perception profile of the respondents (modified from Pagneux et al., 2011). Number of respondents (n) for each modality is shown in brackets.

Background information		Modalities (n)
SOCIOECONOMIC PROFILE	Age (birth)	<1940 (5); 1940-1950 (11); 1950-1960 (19); 1960-1970 (23); 1970-1980 (26); 1980-1990 (6)
	Gender	Male (44); Female (46)
	Location of residence	Flood area (7); Close to the flood area (21); Away from the flood area (62)
	Tenure	Owner (82); At parent's home (3); Renter (5)
	Living floor	Basement (7); Ground floor (76); Other (7)
	Geographic origin	Selfoss /Árborg (45); Other municipality from Árnessýsla county (15); Other Icelandic county (28); Foreign country (2)
	Level of education	Compulsory school (12); Upper secondary school (50); University / Bachelor level (21); University / Master and PhD levels (7)
	Length of time in Selfoss	Settling year <1948 (5); 1949-1958 (10); 1959-1968 (12); 1969-1978 (22); 1979-1988 (8); 1989-1998 (12); 1999-2006 (15); >2006 (6)
FLOOD PERCEPTION PROFILE	Flooding experience	Experienced the flooding event in 1968 (24); Did not experience the flooding event in 1968 (66)
	Flood hazard awareness	Very poor (17); Poor (19); Somewhat poor (26); Somewhat good (20); Good (7); Excellent (1)
	Flood threat appraisal	None (49); Small (20); Medium (13); Important (7); Very important (1)
	Worry because of flood risk	Not at all (36); Little (40); Moderately (10); Rather (2); Much (2)

5.3.1 Questionnaire design and data processing

A minimum of fifteen minutes was allowed to the respondents to answer three sets of 20 closed questions:

- 2 questions on governance style, focusing on jurisdictional levels (ascription of responsibility) and levels of regulation (Table 5.2);
- 5 questions related to land use restrictions (Table 5.2; Table 5.3)
- 13 questions related to technical measures (Table 5.2; Table 5.4);

The answer modalities for questions related to technical measures and land use restrictions were structured on a forced choice bipolar scale (Table 5.2).

The technical measures surveyed for public rating (Table 5.4) were selected from a list of feasible options (FEMA, 1986; MATE/METL, 2002). Although being of special interest in the study area, ice control structures (Morse et al., 2006; Beltaos, 2008) and ice removal techniques (Beltaos, 2008) were avoided in the questionnaire so as not to interfere with answers related to knowledge of the genesis of flooding events that was collected during the first part of the survey dedicated to flood hazard perception (Pagneux et al., 2011). Sketches describing the technical measures were presented along with the questionnaire; technical explanations were given by the questioner if requested by the respondents.

Table 5.2 Questions and answer modalities (Technical measures and restrictions in land use planning are listed in Table 5.3 and Table 5.4).

Questions	Answer modalities (grades)
Should authorities issue recommendations or enforce planning and building codes with compulsory measures to reduce flood risk in flood-prone areas?	Neither recommendations nor compulsory measures; Recommendations only ; Both recommendations and compulsory measures; Compulsory measures only
Should the elaboration of recommendations and/or compulsory measures be under the responsibility of the Central State or of the Municipalities?	Neither municipality nor Central State; Municipalities only; Both Central State and municipalities; Central State only
Which restrictions in land use planning would you support to reduce flood risk in Selfoss?	Totally disagree (-2) ; Rather disagree (-1); Rather agree (+1); Fully agree (+2)
Which technical solutions would you support to reduce flood risk in Selfoss?	Totally disagree (-2) ; Rather disagree (-1); Rather agree (+1); Fully agree (+2)

Table 5.3 List of restrictions in land use planning submitted for public rating. Options already implemented in Selfoss are in bold.

Land use restrictions
Do not allow constructions in flood areas where flood hazard is critical to life safety
Do not allow basements in flood areas
Set aside undeveloped flood areas within town as parks and green ways
Set aside unconstructed flood areas outside town as natural sites and/or grazing lands
Compensated housing expropriation in flood areas where flood hazard is critical to life safety

Table 5.4 List of technical measures surveyed for public rating. Classification provided according to strategy, objective, initiative, and scale of application. Options already implemented in Selfoss are in bold.

Technical solutions	Strategy	Objective	Accessibility of action	Scale of application
Adjust the axis of new buildings	Passive	Flood proofing	Accessible to individuals	Building, lot
Blind walls	Passive	Flood proofing	Accessible to individuals	Building, lot
Dams upriver	Active	Structural run off control	Collective only	Basin
Flood control reservoirs	Active	Structural run off control	Collective only	Basin
Levees in town	Passive	Protection	Collective only	Town
Design new buildings with crawl space	Passive	Flood proofing	Accessible to individuals	Building, lot
Divert river	Active	Structural run off control	Collective only	Town
Afforestation	Active	Ecological run off control	Collective only	Basin
Raise habitable floors	Active	Flood proofing	Accessible to individuals	Building, lot
Replace floor and wall covering with waterproof material	Active	Flood proofing	Individual	Building, lot
Wetland restoration	Active	Ecological run off control	Collective only	Basin
Secure networks (electricity, telephone, water pipes, etc.)	Passive	**Flood proofing**	**Accessible to individuals**	**Building, lot, town**
Contingent flood shields	Active	Flood proofing	Accessible to individuals	Building, lot

One-way ANOVA was used to estimate the influence, on the expressed preferences, of the socioeconomic profile and flood perception profile of the respondents (Table 5.1). Although of high interest for understanding preferences, income and political beliefs were considered sensitive topics that respondents would deliberately misreport (Epstein, 2006). Assessment of the preferences through the prism of the willingness to pay (Glenck and Fischer, 2010) was therefore avoided; such an approach requires not only a consistent approximation of income levels but also monetising each measure. This requires addressing per capita the direct and indirect cost of both individual and collective measures in order to avoid the introduction of a bias in the rating of measures requiring, on the one hand, direct individual financing and, on the other, collective financing through taxes.

The technical options were additionally classified in the light of a framework focusing on the strategy, objective, accessibility, and spatial scale of application of the technical options (Table 5.4):

- Strategy: A difference was drawn between active measures, which are aimed at reducing the frequency and magnitude of a given hazard, and passive measures, aimed at reducing the corresponding adverse consequences.
- Objectives: A difference was drawn between structural options aimed at runoff control, ecological options aimed at runoff control, options aimed at protection of developed areas, and flood-proofing options (adaptation).
- Accessibility: A difference was drawn between options accessible to individuals and options requiring collective action.

- Spatial scale: A difference was drawn between options applicable at the home and lot scale, options applicable at the town scale, and options applicable at the basin scale.

The classification was not appearing in the questionnaire to avoid the framing of options appraisal by the respondents. It should be noted that passive strategy, accessibility of the options to individual action, and applicability of the options at the home scale are perfectly correlated.

5.4 Results

All the respondents favour the intervention of authorities in the management of flood risk, but preferably at the local level (Figure 5.2). An overwhelming majority of respondents estimates that the municipality should take responsibility for the development of recommendations and/or compulsory measures. An important fraction of the population (27%) rejects the involvement of the central authorities; only 3% of respondents favour having the central authorities exercise exclusive responsibility. Comparable proportions are observed regarding the preferred levels of regulation (Figure 5.2): two thirds favour a mix of recommendations and compulsory measures, one third exclusive non-binding measures and just 4% favour required measures only. Neither the socioeconomic profile and nor the flood perception profile of the respondents have any influence on the preferred levels of responsibility (Table 5.5). As to the preferred levels of regulation, threat appraisal is a significant factor: there is no wish for exclusive non-binding measures when flood threat is considered important or very important. Age and tenure are also important factors, with preferences for exclusive non-binding measures significantly more important for young adults still living with their parents. Despite similar trends, the preferences concerning regulation and preferences concerning responsibility are not correlated: 54% of those who were against intervention by the state government are favourable to a mix of recommendations and compulsory measures; 64% of those favourable only to recommendations opt for a shared level of responsibility between the municipality and the state government. Finally, only 10% of the respondents are both opposed to binding measures and the intervention of the government in the management of flood risk.

On the whole, restrictions in land use planning are largely approved (Figure 5.3). Of all restrictions proposed, only housing expropriation is well debated. Interestingly, most of the respondents opposed to coercion nevertheless agree upon restrictions to development: 79% approve interdiction of buildings in flood areas where flood risk is critical for life safety, 64% approve interdiction of basements in flood areas, 82% approve setting aside unconstructed flood areas within town as parks and green ways, and 90% approve setting aside unconstructed flood areas outside town as natural sites and grazing land. Finally, only 7% of the respondents opposed to coercion disapprove the entire set of restrictions proposed. Approval of basement interdiction in flood areas is significantly higher among the respondents in favour of compulsory measures and among the respondents who have experienced the flooding event in 1968 (Table 5.6); influence of age on the approval of basement interdiction reflects the experience of the flooding event. Unlike the respondents favourable to recommendations, the respondents who support only compulsory measures disapprove the interdiction of construction in flood areas where flood risk is critical to life safety (Table 5.7).

The survey ratings of technical options clearly indicate preferences favouring flood proofing options (Figure 5.3; Figure 5.4). Approved by respectively 55% and 46% of the respondents, implementation of blind walls and adjustment of building axis are flood proofing options that are much debated. Options aimed at structural runoff control (μ:-1.17) and at protection of developed areas (μ:-0.41) are rejected. No significant relation is found between disapproval of structural run-off control and approval of ecological runoff control. Approval of afforestation (%: 51.2; μ:-0.14) and approval of wetland restoration (%: 48.9; μ:-0.11) are mixed and poorly correlated (r^2: 0.24).

Some preferences are significantly different between owners and renters (Table 5.7). On the whole, owners reject structural and ecological runoff control solutions, as well as options aimed at reinforcing building structures, which renters, in contrast, approve. Opposition about structural runoff control is also observed between Icelanders and foreigners but not among Icelanders of different geographic origin. Approval of flood proofing options is more pronounced among the female population. Differences observed between males and females are not correlated to differences in the perception of flood hazard and flood risk, which were found to be independent from gender (Pagneux et al., 2011). As for basement interdiction, approval of flood proofing options and of ecological runoff control is significantly higher with respondents who have experienced the flooding event in 1968 but less so among the respondents who exclusively favour non-binding measures; the preferred levels of regulation show through the chosen preferences for technical options. Structural solutions aimed at runoff control are rejected less strongly by residents who are rather or greatly worried about flood risk, who also approve the construction of levees in town (Table 5.7).

The flood perception profile of the respondents does not seem to play a major role in their preferences (Table 5.5; Table 5.7). Marginal pattern among the respondents (Pagneux et al. 2011), worry only influences expressed preferences on levees, reservoirs, and dams in a rough proportion of 14-23%. Flood threat appraisal only influences preferences on levels of regulation, in a proportion of 14%. The influence of personal flood experience on preferences for most of the flood proofing options is really marginal, close to 5%. Finally, awareness of flood hazard is only influential regarding the preferences for wetland restoration and for safety of buildings networks, in proportions not exceeding 15%. Tenure, geographical origin, and gender are also of marginal influence on the preferences of the public (Table 5.7).

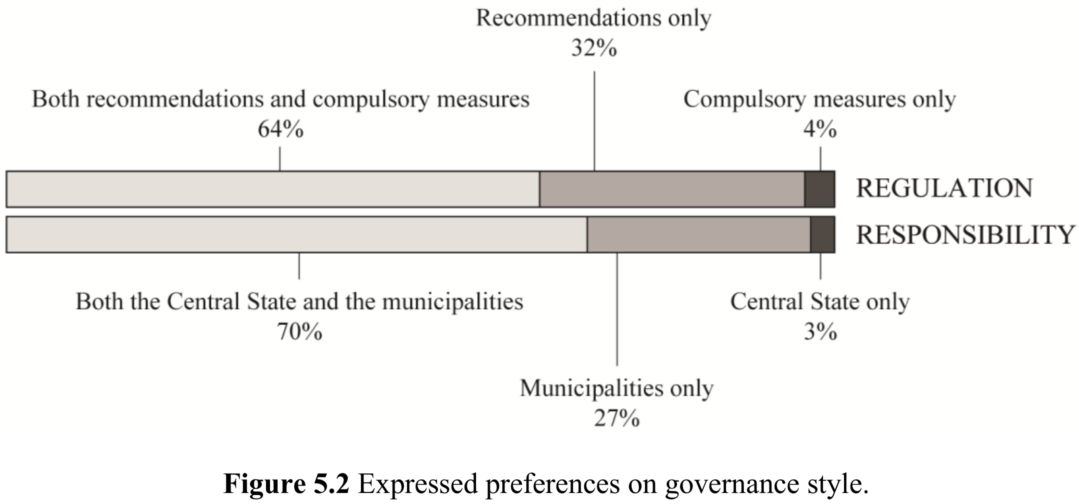

Figure 5.2 Expressed preferences on governance style.

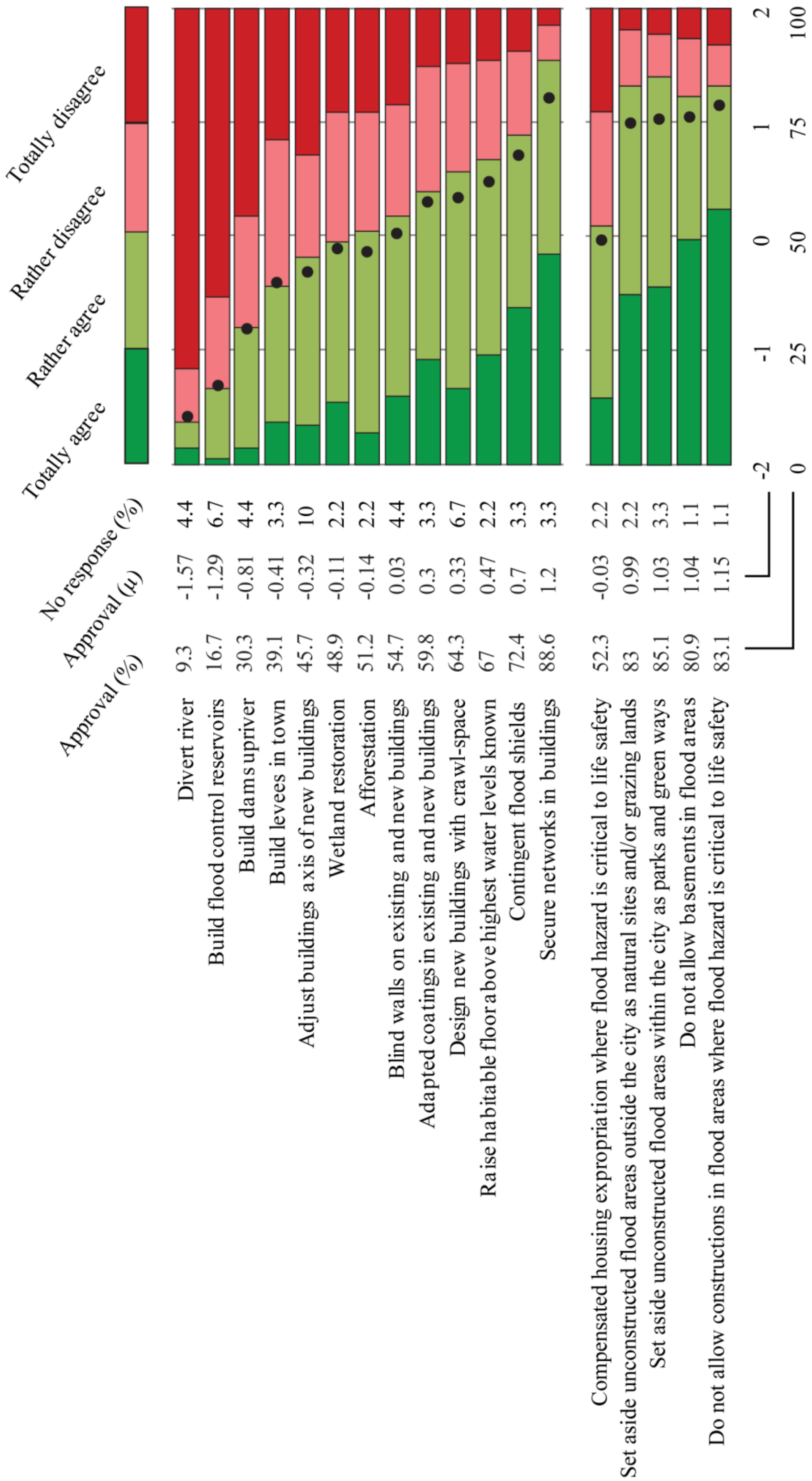

Figure 5.3 Rating of technical solutions and of restrictions in land use planning expressed as approval percentage (100% stacked bars) and approval means (scatter ranging from -2 to +2). Percentage of no response is also given.

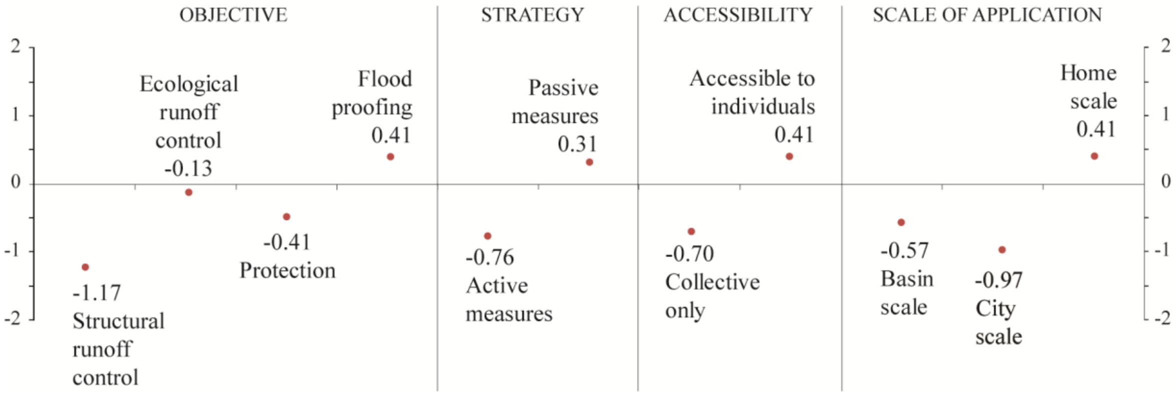

Figure 5.4 Public preferences about technical solutions expressed as means (scatter) and classified according to objective, strategy, accessibility, and scale of application (Table 5.4).

Table 5.5 Relation between socioeconomic/flood perception profiles and preferences on regulation and responsibility.

Governance style	Socioeconomic and flood profiles	p	η^2
Levels of regulation	Age*	*	0.13
	Tenure*	*	0.10
	Flood threat appraisal	**	0.14

*: $p<0.05$; **: $p<0.01$. Measures of association (η^2) are shown

Table 5.6 Relation (ANOVA) between socioeconomic/flood perception profiles and preferences on restrictions in land use planning.

Restrictions	Socioeconomic and flood profiles	p	η^2	Means: Totally disagree (-2); rather disagree (-1); Rather agree (+1); Totally agree (+2)
Natural sites and/or grazing lands	Living floor	*	0.07	Basement or ground floor (1.06); Other (0.14)
Forbid basements in flood areas where flood hazard is critical to life safety	Age	*	0.16	<1940 (2.00); 1940-1950 (1.36); 1950-1960 (1.47); 1960-1970 (1.17); 1970-1980 (0.32); 1980-1990 (0.83)
	Experience	*	0.05	No (0.88); Yes (1.50)
	Levels of regulation	**	0.12	Recommendations only (0.43); Recommendations and/or compulsory measures (1.33)
Forbid constructions in flood areas where flood hazard is critical to life safety	Levels of regulation	**	0.16	Compulsory measures and/or recommendations (1.24); Compulsory measures only (-075)

*: $p<0.05$; **: $p<0.01$. Measures of association (η^2) are shown

Table 5.7 Relation (ANOVA) between sociological/flood perception profiles and preferences about technical options.

Technical options	sociological and flood profiles	p	η^2	Means: Totally disagree (-2); rather disagree (-1); Rather agree (+1); Totally agree (+2)
Secure networks in buildings	Gender	*	0.08	Males (0.91); Females (1.49)
	Experience	*	0.58	Did not experienced 1968 (1.06); Did experience 1968 (1.59)
	Levels of regulation	*	0.06	Recommendations only (0.82); Recommendations and/or compulsory measures (1.37)
	Awareness	*	0.15	Very poor, poor (0.76); Somewhat poor (1.38); Somewhat good (1.53); Good, excellent (1.63)
Contingent flood shields	Experience	*	0.11	Did not experienced 1968 (0.45); Did experience 1968 (1.45)
	Levels of regulation	*	0.06	Recommendations only (0.21); Recommendations and/or compulsory measures (0.93)
Raise habitable floor	Gender	*	0.05	Males (0.16); Females (0.77)
	Experience	*	0.06	Did not experienced 1968 (0.30); Did experience 1968 (0.95)
	Levels of regulation	*	0.16	Recommendations only (-0.32); Recommendations and/or compulsory measures (0.83)
Crawl-space	Experience	*	0.06	Did not experienced 1968 (0.14); Did experience 1968 (0.90)
	Levels of regulation	*	0.13	Recommendations only (-0.33); Recommendations and/or compulsory measures (0.65)
Blind walls	Gender	*	0.06	Males (-0.33); Females (0.4)
Afforestation	Tenure	*	0.10	Renters (1.00); Owners (-0.25)
	Levels of regulation	*	0.07	Recommendations only (-0.63); Recommendations and/or compulsory measures (0.08)
Wetland restoration	Experience	*	0.05	Did not experienced 1968 (-0.34); Did experience 1968 (0.52)
	Levels of regulation	*	0.09	Recommendations only (-0.7); Recommendations and/or compulsory measures (0.15)
	Awareness	**	0.12	Very poor, poor (-0.62); Somewhat poor (-0.12); Somewhat good (0.35); Good, excellent (0.88)
Building axis adjustment	Gender	*	0.05	Males (-0.63); Females (0.00)
	Tenure	*	0.05	Owners (-0.41); Renters (1.00)
Levees in town	Worry	*	0.16	Not at all (-0.97); Little, moderately (-0.16); Rather, much (1.67)
	Geographical origin	*	0.07	Icelanders (-0.47); Foreigners (2.00)
Dams upriver	Worry	*	0.14	Not at all (-1.29); Little, moderately (-0.51); Rather, much (-0.33)
	Tenure	*	0.10	Owners (-0.88); Renters (0.60)
Flood control reservoirs	Worry	*	0.23	Not at all (-1.62); Little, moderately (-1.15); Rather, much (0.33)
	Geographical origin	*	0.10	Icelanders (-1.34); Foreigners (1.00)
	Tenure	*	0.27	Owners (-1.43); Renters (1.00)
Divert river in town	Geographical origin	*	0.22	Icelanders (-1.64); Foreigners (1.50)
	Tenure	*	0.13	Owners (-1.63); Renters (0.00)

*: $p<0.05$; **: $p<0.01$. Measures of association (η^2) are rounded to 2 decimal places

Table 5.8 Classification of flood proofing options with consideration of their impact on the architecture of buildings.

Building dimensions affected	μ	Flood proofing options
neither the vertical dimension nor the horizontal dimension	0.73	Securing networks Waterproof covering Contingent flood shield
vertical dimension only	0.42	Raising of habitable floor level Crawl space
horizontal dimension only	0.10	Blind walls Axis adjustment

5.5 Discussion

Rejection of structural runoff control observed in this survey is comparable to findings from Brilly and Polic (2005) in Slovenia and from Lara et al. (2010) in Spain. It can be noticed in the present case that strong rejection of hard mitigation is not correlated with approval of active environmentally sound measures, which were not much desired and poorly intercorrelated. One respondent declared being opposed to afforestation because forests do no match the naturalness of Icelandic landscapes. The "natural" argument (Gobster et al., 2007) is, however, unlikely to prevail as there was not much support for restoration of wetlands, a true natural element of the Icelandic environment, as a way to control runoff. Rejection of structural mitigation measures may result, to some extent, from a lack of intelligibility and of familiarity of the coping options. Several respondents confessed that they rejected some mitigation options because they did not really understand how they operate. To the opposite, the technical measure most approved from the list surveyed, i.e. securing networks, is the only one already implemented in Selfoss. Since very little time was given to rate the technical options, there is little doubt that the same respondents would have chosen the middle option if a non-forced bipolar scale had been proposed. Active mitigation might have been better valued if ice control structures and ice removal techniques had been proposed to the respondents who identified ice jams as flooding trigger in the first part of the survey (Pagneux et al., 2011).

It is reasonable to assume that renters are more prone than owners to accept reinforcement of building structures, since they do not have to support the cost of improvements. The complexity and cost of implementation (Kreibich and Thieken, 2009) are, however, unlikely explanations of the mixed rating of blind walls and building-axis adjustment obtained in the survey, as suggested by the strong approval of raising the habitable floor level (%: 67; μ: 0.47), which is, in and of itself, a complex and costly measure. It is noteworthy that the flood proofing options that would impact the building structures horizontally are less approved than options that would impact the structures vertically (Table 5.8). The drawback that blind walls potentially obstruct a straight view of the river should be taken into account. The consequences of building axis adjustment on exposure to sunlight during winter, as buildings in Iceland are oriented to get the most daylight with large south-facing windows without shutters, should also be taken into account. Structural measures that severely affect the visual amenities in town like river diversion (%: 9.3; μ:-1.57) may appear an unacceptable trade-off.

The lack of a centralist tradition in Iceland (Tomasson, 1980; Ólafsson, 2003) and the long-standing emphasis on independence may explain the strong defiance expressed towards central authorities. Situational factors may also have had an impact, causing the people's trust in central government to be unusually low. As later confirmed in a public report (SIC, 2010), the responsibility of the central authorities in the magnitude of the domestic financial collapse in 2008 was heavily suspected at the time of the survey. Of all the dimensions trust relies upon (Höppner, 2009), honesty, reliability, and competence of central authorities were seriously questioned by the Icelandic population. However, the fiduciary argument may be regarded insufficient, as lack of trust towards authorities does not necessarily prevent populations from delegating their personal responsibilities in flood risk management (Krasovskaia, 2006).

Preferences going for individual options and strong disinclination to support measures requiring collective action may reflect, to some extent, values of self-direction (Schwartz, 1996) and individualism (Wildavsky and Dake, 1990; Dake, 1991). A sociological interpretation of the results is difficult, however, as passive strategy, accessibility of the options to individual decision, and applicability of the options at the home scale are perfectly correlated in the framing of the classification. Further investigation, based on alternative elicitation methods such as focus groups (Hare and Krywkow, 2005), is definitely needed. The potential influence, on preferences, of beliefs and values should be assessed in a more direct way. In a situation of pronounced localism, the interest of the population for cooperation between municipalities should also be assessed; only the attitude towards the Árborg municipality and the central government was addressed in this survey of the public. Additionally, the potential (dis)incentive effect (Treby et al., 2006) on public preferences of the Icelandic risk-sharing policy should be investigated.

5.6 Conclusion

Preferences of the population surveyed in this study lean toward polycentric governance, restrictions in land use planning, and actions centred on people: passive measures, which are individual solutions applicable at the home level. Rejection, from a significant part of the respondents, of compulsory measures is obvious in the preferences, but strong approval of restrictions in land use planning indicates, on the contrary, that the principle of opposable flood risk zones is not really disputed. Further investigation is required, in Selfoss as well as in other built areas of Iceland where flood risk is substantiated, to understand which flood management regime the population is supportive of. A window of opportunity may already exist for the implementation of flood risk zoning and for the enforcement of the planning and building codes in relation to flood risk. In Árborg, strong public support for local authorities may however prompt the municipality to make an effort to preserve its room to manoeuvre and ignore as long as possible integrative solutions that would include neighbouring municipalities and central authorities. Although the European Flood directive advocates a "fair sharing of responsibility" between levels of government, the requirement to manage flood risk at the level of river basin districts could appear as a significant drawback to local authorities. The existence, at the national level, of an active minority opposed to the intervention of the central authorities in the management of flood risk might also have an impact on the evolution in the regulation towards more supervision and responsibility of the central state. The prospect of institutional blockage should not be underestimated. Defiance of the Icelandic population towards central authorities, should it be confirmed, would be of concern as most of the Icelandic municipalities cannot explore flood risk zoning within their jurisdiction without the financial, technical, and professional support from the central government.

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Figures

Tables