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DAM FAILURE ASSESSMENT FOR SUSTAINABLE FLOOD RETENTION BASINS IN SCOTLAND

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ABSTRACT: This study aims to provide a rapid screening tool for assessment of Sustainable Flood Retention Basins (SFRB) dam failure. First, the authors propose three new variables for SFRB in terms of dam safety. Then, a rapid expert-based assessment method for dam failure of SFRB is elaborated. Furthermore, Ordinary Kriging is applied to map the distribution of *Dam Failure Hazard* and *Dam Failure Risk* across the study area. The results show that different types of SFRB are associated with different levels of hazards and risks, e.g. SFRB types 1 and 2 have higher risks than do types 3, 4, 5 and 6. The spatial distribution maps show that most SFRB in the research area have a *Dam Failure Hazard* ranging from 5% to 10% while the *Dam Failure Risk* lies between 0% and 6%. The dam failure risks of SFRB located near cities are higher than those situated in rural locations.

Keywords: *Dam Condition*, *Dam Failure Hazard*, *Dam Failure Risk*, Dam safety, Flood risk management plan, Kriging, Reservoir, Screening tool.

1. INTRODUCTION

1.1 Background

Traditionally, dams are considered safe because they have been built according to high technical standards. However, many dams that were constructed decades ago do not meet the current state-of-the-art dam design guidelines anymore. Moreover, many reservoirs are located immediately upstream of or adjacent to heavily populated areas. Dam failure could therefore have catastrophic consequences for life, property, critical infrastructure and the economy (Evans and Hohl, 2010; Scholz, 2010). To adapt to climate change, the European Community has introduced the Flood Directive 2007/60 EC (EC, 2007), which requires member states to first carry out a preliminary assessment by 2011 to identify the river basins and associated coastal areas at risk of flooding and secondly to develop flood risk management plans (FRMP).

Supporting the implementation of the Flood Directive, the European Union has financed consortia such as the Strategic Alliance for Water Management Actions (SAWA, 2009) to

Table 1
Revised Definitions for the Sustainable Flood Retention Basin (SFRB) Types

Type	*Name*	*Definition ofSFRB type*	*Typical examples*
1	Hydraulic Flood Retention Basin (HFRB)	Managed SFRB that is hydraulically optimized (or even automated) and captures sediment in a controlled manner	The hydroelectric station; highly engineered and large purpose-built flood retention basins
2	Traditional Flood Retention Basin (TFRB)	Aesthetically pleasing retention basin used for flood protection, potentially adhering to sustainable drainage practice and operated according to best management practices	Former drinking water reservoir; traditional flood retention basins
3	Sustainable Flood Retention Wetland (SFRW)	Aesthetically pleasing retention and treatment wetland used for passive flood protection adhering to sustainable drainage and best management practices	Sustainable drainage systems or best management practices such as some retention basins, detention basins, large ponds or wetlands
4	Aesthetic Flood Retention Wetland (AFRW)	Treatment wetland for the retention and treatment of contaminated runoff, which is aesthetically pleasing and integrated into the landscape, and has some minor social and recreational benefits	Some modern constructed treatment wetlands; integrated constructed wetlands
5	Integrated Flood Retention Wetland (IFRW)	Integrated flood retention wetland for passive treatment of runoff, flood retention and enhancement of recreational benefits	Some artificial water bodies within parks or near motorways that have a clear multi-purpose function such as water sport and fishing
6	Natural Flood Retention Wetland (NFRW)	Passive natural flood retention wetland that became a site of specific scientific interest, potentially requiring protection from adverse human impacts	Natural or semi-natural lakes and large ponds, potentially with restricted access

develop guidance on adaptive measures such as SFRB to assist member states in the assessment of flood risks associated with retention basins. The use of the term SFRB in sustainable flood risk management practice is relatively new (Scholz, 2007a,b; Scholz and Sadowski, 2009). An SFRB is defined as an impoundment, reservoir or integrated wetland which has a pre-defined or potential role in flood defense and diffuse pollution control that can be accomplished cost effectively through best management practice, supporting sustainable flood risk management and enhancing sustainable drainage, pollution reduction, biodiversity, green space and recreational opportunities for society. The word "sustainable" in SFRB means capable of being maintained at a steady level without exhausting natural resources, harming the environment or causing severe ecological damage (McMinn, 2010). Based on expert judgment, feedback from collaborators, including landscape planners, empirical study, and statistical evaluations, six types of SFRB (see Table 1) have been developed as follows: Hydraulic Flood Retention Basin (type 1), Traditional Flood Retention Basin (type 2), Sustainable Flood Retention Wetland

Table 2
Characteristic Variables of Sustainable Flood Retention Basins

ID	*Variable and unit*	*ID*	*Variable and unit*
1	Engineered (%)	21	Impermeable Soil Proportion (%)
2	Dam Height (m)	22	Seasonal Influence (%)
3	Dam Length (m)	23	Site Elevation (m)
4	Outlet Arrangement and Operation (%)	24	Vegetation Cover (%)
5	Aquatic Animal Passage (%)	25	Algal Cover in Summer (%)
6	Land Animal Passage (%)	26	Relative Total Pollution (%)
7	Floodplain Elevation (m)	27	Mean Sediment Depth (cm)
8	Basin and Channel Connectivity (m)	28	Organic Sediment Proportion (%)
9	Wetness (%)	29	Flotsam Cover (%)
10	Proportion of Flow within Channel (%)	30	Catchment Size (km^2)
11	Mean Flooding Depth (m)	31	Urban Catchment Proportion (%)
12	Typical Wetness Duration (d/a)	32	Arable Catchment Proportion (%)
13	Estimated Flood Duration (d/a)	33	Pasture Catchment Proportion (%)
14	Basin Bed Gradient (%)	34	Viniculture Catchment Proportion (%)
15	Mean Basin Flood Velocity (cm/s)	35	Forest Catchment Proportion (%)
16	Wetted Perimeter (m)	36	Natural Catchment Proportion (%)
17	Maximum Flood Water Volume (m^3)	37	Groundwater Infiltration (%)
18	Flood Water Surface Area (m^2)	38	Mean Depth of the Basin (m)
19	Mean Annual Rainfall (mm)	39	Length of Basin (m)
20	Drainage (cm/d)	40	Width of Basin (m)

(type 3), Aesthetic Flood Retention Wetland (type 4), Integrated Flood Retention Wetland (type 5), and Natural Flood Retention Wetland (type 6). Previous studies (Scholz and Sadowski, 2009; Scholz and Yang, 2010) of SFRB characterized by 40 characteristic variables (see Table 2) did not address the dam safety of SFRB. In the context of the Flood Directive, the issue of dam failure assessment for SFRB has attracted much interest.

Various approaches have been studied for flooding risk associated with dam failures. The U.S. Bureau of Reclamation published risk assessment methods for dam safety decision making (Hennig *et al*., 1997). The German technical standard DIN 19700 for dams and reservoirs (DIN 19700, 2004) referred to the dam risk. More tools such as portfolio risk assessment (Bowles, 1996), risk-based profiling system (Harrald, *et al*., 2004), risk and reservoir in the UK (Morris *et al*., 2000), and condition indexing method (Harrald, *et al*., 2004), also have been developed. However, the critical information of interest for emergency services includes flood extent, water depth, flood water velocity, hazard level, time of initial inundation and time of peak arrival. The shortcomings associated with these variables are that their determinations are relatively costly and not very accurate. Moreover, the total complexity and process dynamic of freak storms can never be fully captured, and changes rapidly over time and in space (Scholz, 2010). Therefore, the real risk and hazard of dam failure can only be estimated or guessed based on expert opinion, which is a good, very important and widely used assessment method. Furthermore, it is a significant challenge if using these methods to assess a huge amount of basins (e.g. there are estimated to be 28,500 water bodies >1 ha in Scotland) in such a short time. So, it follows that it is highly needed to have an expert-based rapid screening tool of assessing dam safety of SFRB in a neither labour nor resource intensive way.

Previous research into the spatial and temporal risk of flooding has largely been restricted to empirical estimates of risk measures. For example, Baggaley *et al*., (2009) indicated that an analysis of long-term seasonal data suggested a shift towards increased flows in spring (March to May) and decreased flows in summer (June to August) for the River Dee in Scotland. A weakness with such an empirical approach to risk is that there is no basis for extrapolation of estimates to rare events, which is often required as empirical evidence suggests that larger storm events tend to be more localized in space.

Therefore, Keef *et al*., (2009) adopted a model-based approach, which accounts for missing values. However, as the complexity of flooding risk increases, the number of missing data or even missing variables increases rapidly as well, justifying expert judgment to be made at reasonable expense.

1.2 Aim and Key Objectives

This paper aims to propose an effective and rapid screening tool to primarily assess hazards and risks of dam failure of SFRB across the study area and to identify the sites requiring a detailed standard risk assessment. It emphasizes practical results but not the accuracy of the data. The key objectives are as follows:

- to propose three novel risk-related variables and their corresponding components to characterize SFRB in terms of dam safety;
- to develop a rapid and cost-efficient survey method to assess *Dam Condition*, *Dam Failure Hazard* and *Dam Failure Risk*;
- to assess and compare the dam failure for different SFRB types;
- to assess the spatial variability of the *Dam Failure Hazard* and *Dam Failure Risk* across the study area;
- to distinguish the different risk categories of SFRB in central Scotland.

2. METHODOLOGY

2.1 Data Acquisition

Precisely 199 SFRB were identified and surveyed for this study using the 1:50 000 scale survey maps for central Scotland (Fig. 1). In the context of this paper, the sites of interest are those, which have dams and where the water level can be controlled either manually or automatically. Specifically, most of the studied sites are typically former or current engineered reservoirs for water supply in Scotland.

The investigation of any SFRB is a two stage process combining a desk study and a field visit (McMinn *et al*., 2010). The desk study provides estimations of variables with the help of websites, publications and digital databases. The site visit typically aims to verify the parameters

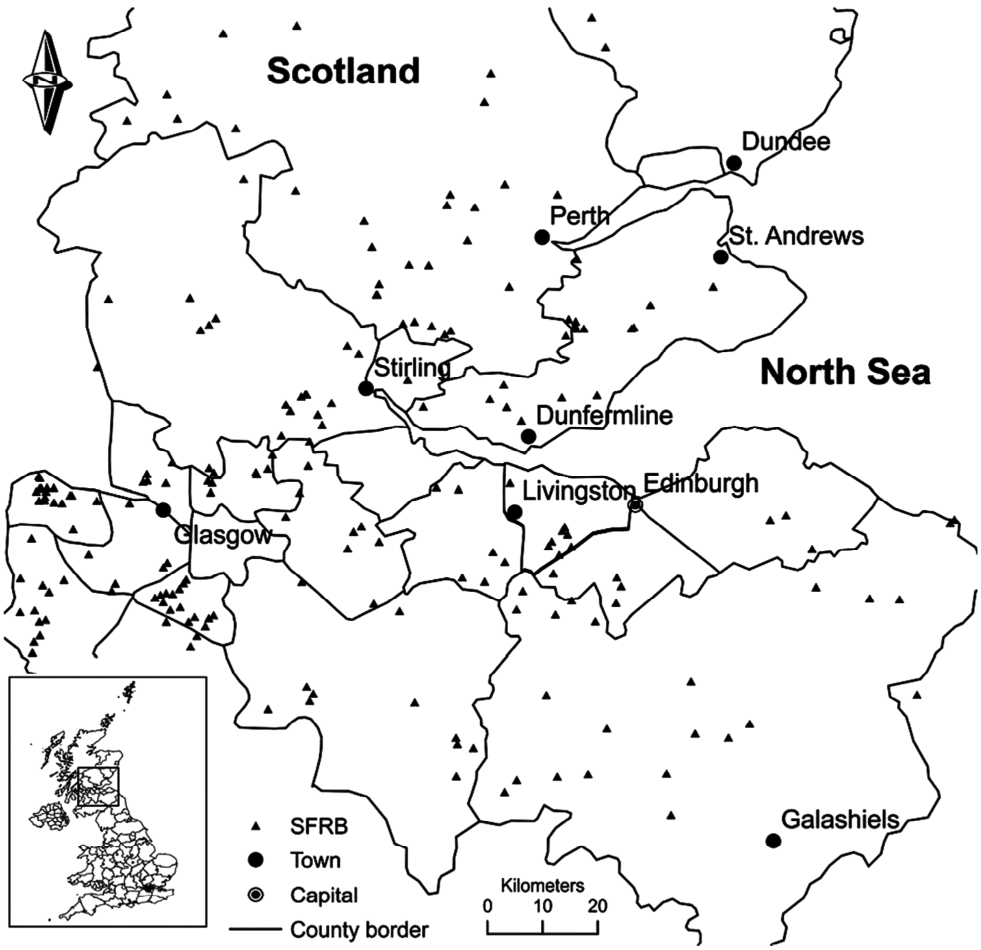

Figure 1: Study Area, Administrative Boundaries and the 199 Sustainable Flood Retention Basins (SFRB) with Dams in Central Scotland Area (United Kingdom)

determined during the desk study and to collect/create a photographic record of any dam structure along with the SFRB inlets and outlets. Forty variables, as shown in Table 2, were proposed to capture the properties of SFRB (McMinn *et al.*, 2010). The guidance on how to determine these variables has been published by Scholz and Yang (2010). In response to an increased interest in risk assessment of SFRB, three new risk-related variables (*Dam Condition* (%), *Dam Failure Hazard* (%) and *Dam Failure Risk* (%)) and their components were proposed to complement the existing 40 variables.

2.2 A Rapid Screening Tool for Surveying Dam Failure of SFRB

This study proposes a rapid screening tool for flood risk assessment of SFRB based on expert judgment. Firstly, three new risk-related variables, each of which consists of several components, were proposed and discussed by a group of international experts in engineering and science from The University of Edinburgh, the University of Freiburg, and from the 22 partner institutions from five countries involved in the SAWA program. Based on empirical study and international discussion, the different components were given different weightings. For instance, since the importance of life was viewed as the first priority, the component related to life loss was given the highest weighting. Finally, each component (see Tables 3 to 5) was split up into five bins, and guidance on how to determine values for each component was provided to support the field survey. However, here the guidance only includes some conditions adjusting to the research area but not covering all possibilities elsewhere in the world. Users can modify and adapt the guidance accordingly when applying it in different situations. As uncertainty is always associated with the assessment, a specific confidence value (i.e. low = 1 to 40%; medium = 40 to 60%; high = 60 to 100%) is assigned to each risk-related variable and each component. To put it briefly , the rapid tool is using Tables 3 to 5 to survey and assess the risk of each SFRB. Here, it is important to distinguish clearly between hazard and risk. Hazard, as far as a dam is concerned, refers only to the possible consequences of the structure failing regardless of the likelihood that it might do so. The risk of that failure occurring is determined by factors such as the lack of dam management and maintenance. However, no statistical relationships can be used to accurately determine these complex variables, and expert judgement is therefore needed.

Dam Condition. The variable *Dam Condition* (%) is intended to be predominantly empirical, largely based on site visits and photographic evidence. Table 3 shows a brief characterization of this variable in terms of five assessment bins, as well as its components and corresponding weightings. The bin boundaries were selected purely on the basis of convenience and simplicity. The assessor should record the overall dam condition and associated maintenance undertaken. The higher the score recorded, the better the dam condition. A composite score will be based on several components associated with different weightings (Table 3). Default values for weightings have been suggested based on expert opinion. However, other default values may be chosen by dam inspectors elsewhere. If either the weighting or the estimated numerical value for a variable such as *Dam Structure* changes, *Dam Failure Hazard* and *Dam Failure Risk* will subsequently change as well. The proposed expert system is sufficiently flexible to allow dam inspectors to revise the system according to their national or regional needs.

The first component *Dam Structure* (%) accounts for 30 percentage points overall. This variable is intended to assess the overall condition of the dam. Account should be taken of the dam size, the material used (e.g. concrete, rock and earth), and how tidy the dam appears as an indication of the overall maintenance. The face of the dam should also be examined for stability and any obvious signs of surface cracking. If surface cracking or seepage is apparent, then a low score should be awarded.

Spillway Condition (%) is weighted at 30 percentage points. Spillway failures can be a significant cause of overall dam failure should water penetrate and begin to erode the dam face. Spillways associated with traditional drinking water reservoirs are typically masonry or concrete structures, though in some cases hybrid structures can be found. Concrete spillways should typically receive higher scores than masonry structures, unless they are poorly maintained. Masonry spillways are, however, safe as long as they are properly maintained. Spillways that

Table 3
Brief Characterisation of the Variable *Dam Condition* (%) in Terms of Five Assessment Bins, and its Components and Corresponding Weightings

Component	*Bin 1*	*Bin 2*	*Bin 3*	*Bin 4*	*Bin 5*
Dam Structure (30%)	Very good condition; very tidy; most likely be well looked after by a water authority or council (>80%)	Good condition; most likely be looked after by a local authority or private owner (>60 to 80%)	Not tidy; potentially only little maintenance; minor signs of neglect, decay and erosion (40 to 60%)	Not tidy; most likely no maintenance since a long time; clear signs of decay and erosion (20 to <40%)	Very poor condition; surface cracking likely; seepages are present; dam unlikely to be still in use (<20%)
Spillway Condition (30%)	Usually concrete slipways; re-enforced grass-lined dams possible; no unwanted vegetation growth; well maintained (>80%)	Usually masonry or re-enforced grass-lined dams; no unwanted vegetation growth; well maintained; often well-integrated into the outlet (>60 to 80%)	Grass-lined dams; partially covered by unwanted vegetation; often well integrated within the outlet as a passive structure (25 to 60%)	Often a grass-lined earth dam with unruly vegetation cover; high proportion of vegetation growing within the pointing (5 to <25%)	No or at least no obvious spillway exists; obviously missing blocks; structure is in a state of urgent need of attention (<5%)
Wave Wall Condition (20%)	Well-maintained wave wall; concrete, masonry or large bolder; no unwanted vegetation growth (>90%)	Masonry or bolder; little proportion of pointing (i.e. mortar or cement between stones) containing vegetation (>70 to 90%)	Often a re-enforced earth dam; about 50% of pointing (i.e. mortar or cement between stones) containing vegetation (40 to 70%)	Often an earth dam; almost all the pointings (i.e. mortar or cement between stones) contain unwanted vegetation (10 to <40%)	Minor signs of erosion of the earth dam; clear indication of no maintenance; obvious missing blocks or masonry (<10%)
Operational Volume Impact (10%)	Operational volume often >20 km^3; major impact on dam due to constantly high pressure (>80%)	Operational volume often >10 and £20 km^3; major impact on dam due to high pressure (>60 to 80%)	Operational volume often >5 and £10 km^3; major impact on dam due to occasionally high pressure (40 to 60%)	Operational volume often >0.5 and £5 km^3; occasionally filled with water (20 to <40%)	Operational volume often £0.5 km^3; very rarely filled with water and therefore little pressure on dam (<20%)
Other Factors Influencing Dam Condition (10%)	Reservoirs currently operated by a water authority for drinking water or flood protection purposes (>85%)	Water bodies operated by councils, fishing groups and sailing clubs (>65 to 85%)	Partially managed water bodies; often warning information or other related signs indicating a legal responsibility waiver (25 to 65%)	Large semi-natural lake with little need for regular maintenance; sometimes an off-line retention basin (10 to <25%)	Small semi-natural lake, wetland or off-line water body without any need for regular maintenance (<10%)

are obviously poorly maintained typically have a high proportion of uncontrolled vegetation growing through the pointing. In cases where masonry dams have obviously missing blocks, a score of between 0 and 5 should be awarded.

In comparison, a lot of modern, purpose-built SFRB are earth dams covered by short grass. Spillways are frequently integrated within these earth dams and reinforced by stone linings or large gravel. These structures are usually designed to cater for conveyance of shallow and brief flood waves.

The component *Wave Wall Condition* (%) accounts for 20 percentage points overall. The wave wall is an essential structural element of earth dams and is typically a masonry wall lining the front face of the dam. The masonry is essential in preventing erosion of the earth dam itself. Therefore, its condition is vital for the safety of the dam. A well maintained wave wall with no visible vegetation would receive a score of close to 100. The proportion of pointing (i.e. mortar or cement between stones) containing vegetation should be taken into account when estimating the overall score. In the case of a concrete dam, the inside face of the reservoir should be assessed and its general visible condition determined.

The component *Operational Volume Impact* (%) is weighted at 10 percentage points. Dams are not designed to be continuously maintained at their maximum volume indicated by spillways continually discharging. Dams maintained in this condition should be assigned a value close to 0. For an initial assessment, the previously determined variable *Maximum Flood Water Volume* (McMinn *et al*., 2010) could be standardized (after removal of outliers) and the corresponding values may be taken times 100 to obtain the *Operational Volume Impact*.

Other Factors Influencing Dam Condition (%) is the final component accounting for 10 percentage points overall. Other site-specific observations not related to the points mentioned above may receive an overall score of not more than 10. For example, overall site management and maintenance is often a good indicator of dam condition. Furthermore, off-line reservoirs are likely to contribute less to flood risk than on-line reservoirs, which have been constructed on the original river bed. Moreover, reservoirs currently operated by water authorities such as Scottish Water for drinking water purposes are likely to score around 90%, which reflects the company's likely commitment to the safe operation of their water infrastructure. Other operators such as councils, fishing clubs and sailing clubs may have less stringent safety standards.

Dam Failure Hazard. The variable *Dam Failure Hazard* (%) is intended to provide an overall estimate of the potential damage resulting from dam failure. Table 4 shows a brief characterization of the variable *Dam Failure Hazard* in terms of five assessment bins, and its components and corresponding weightings. High scores are assigned to dams where the hazard of failure is likely to be high.

Relevant information for this variable can be obtained via site visits and careful assessments of the geographical characteristics downstream of the structure in combination with the outputs from hydrological and hydraulic models (SEPA, 2010). The damage potential is particularly affected by hazardous processes, particularly if they vary spatially and/or temporally. A site posing the maximum hazard would be a large dam of more than 25,000 m^3 located within or

Table 4
Brief Characterisation of the Variable *Dam Failure Hazard* (%) in Terms of Five Assessment Bins, and its Components and Corresponding Weightings

Component	*Bin 1*	*Bin 2*	*Bin 3*	*Bin 4*	*Bin 5*
Overall Force on Dam (30%)	Dam height is often more than 35 m; very high permanent force on dam; very poor construction regarding clay core, embankment or plastic liner; serious wave damage possible; blockage of spillway trash screen likely (>80%)	Dam height is often more than 25 m; high force on dam; poor construction of clay core, embankment or plastic liner; wave damage possible (>60 to 80%)	Dam height is often more than 15 m; sometimes high force on dam; some dam construction weaknesses (40 to 60%)	Dam height is often more than 5 m; rarely force on dam; good construction; good construction (20 to <40%)	Dam height is often less than 5 m; very rarely force on dam (empty basin); very good construction (<20%)
Potential Loss of Life (35%)	Very large water body; very high permanent and dense urban area proportion in the catchment just below of the failed dam; people are likely to be killed (>80%)	Large water body; high urban area proportion in the catchment just below of the failed dam; people may be killed (>60 to 80%)	Medium-sized water body; occasionally high urban area proportion in the catchment, but far away from the failed dam (40 to 60%)	Small water body; very low urban area proportion in the catchment, but just below of the failed dam (10 to <40%)	Very small water body; significant rural area; only few people can ever be effected in the remote area (<10%)
Importance of Infrastructure Affected by Dam Failure (25%)	Main airports, major railways, major roads and bridges, gas pipelines, key industry areas and key electricity supply structures are affected in a large urban area just below the failed dam; very serious loss of water (>80%)	Railways, major roads, bridges, major industry and electricity supply structures are affected in a small urban area just below the failed dam; very serious loss of water (>60 to 80%)	Railways, roads, schools, small industry and electricity supply structures are affected in an urban area located far away from the failed dam (40 to 60%)	Farming infrastructure, minor roads and electricity supply structures are affected in an urban area far away from the failed dam (5 to <40%)	Significantly high rural area proportion; no important infrastructure; only single-track roads affected in a remote area (<5%)
Other Factors Influencing Dam Failure Hazard (10%)	Serious erosion and damage of the dam; cloudy seepage or leakage water; dam covered by trees and bushes (hazard of internal erosion); blocked or damaged spillway (hazard of overtopping); severe rodent and/or crayfish attack; key nature protection area below dam (>80%)	Erosion and damage of the dam; some trees and bushes; slightly damaged spillway; minor rodent attack; nature protection area below dam (>50 to 80%)	Little erosion and damage of the dam; some bushes and high grass; some reeds at wet areas; apparent reasons to raise concern (25 to 50%)	All dam structures are well-maintained; clear spillway and pipes; short grass cover; no indication of any imminent hazard (10 to <25%)	Semi-natural water body with no apparent signs of any anticipated hazard; public park (<10%)

just upstream of a dense urban area with housing immediately down gradient of the dam or reservoir. The Environment Agency has published a guideline on reservoir safety, which elaborates on individual aspects of maintenance (EA, 2010). The key factors are trees, grass cover, maintenance of spillways and animal activity. Some of these issues have been addressed in Table 4.

Sites such as the drinking water storage reservoirs in Milngavie (near Glasgow, Scotland) would receive a very high hazard score of close to 100. This approach is consistent, for example, with the A-E reservoir hazard ratings used in the Reservoirs Act 1975 (as Amended) as outlined by the Office of Public Sector Information (2010). In contrast, a small dam located in an upland area, where dam failure would follow a river valley (potentially without affecting any housing or other infrastructure), would receive a very low score in the range of between 0 and 10. The following components and associated weightings for *Dam Failure Hazard* have been proposed:

Overall Force on Dam (%) accounts for 30 percentage points overall. The higher the force on the dam, the more likely there will be dam failure. The component *Overall Force on Dam* is largely affected by a combination of the previously defined SFRB variables *Dam Height* and *Dam Length*.

Potential Loss of Life (%) represents 35 percentage points overall. Essentially, the more people would be affected by flooding, the higher would be the score for this component. An indication for potentially high losses would be urban areas in the catchment just downstream of the failed dam. One useful source of information to estimate *Potential Loss of Life* is the Indicative River and Coastal Flood Map for Scotland (SEPA, 2010). Moreover, Haynes *et al*., (2008) predicted the social impact of flooding by using statistical evaluation techniques from census data. This is a valuable alternative approach, which reduces the likelihood of any error in the estimate.

Importance of Infrastructure Affected by Dam Failure (%) has a weighting of 25 percentage points. This component scores high if important infrastructure would be affected by flooding due to dam failure. Infrastructure elements may comprise airports, railways, major roads, retail parks, universities and schools, farming infrastructure and assets, and water and electricity supply structures. A useful source of information to estimate *Importance of Infrastructure Affected by Dam Failure* is the Indicative River and Coastal Flood Map for Scotland (SEPA, 2010) in combination with detailed geographical maps.

Finally, *Other Factors Influencing Dam Failure Hazard* (%) represent 10 percentage points overall. These factors are very much site-specific and may include unusually poor dam conditions such as erosion and damage due to rodents, e.g. “honeycombing” of embankments as a result of rabbit burrowing (Gilvear and Black, 1999). Moreover, nature reserves protecting endangered species and amenity areas could get destroyed.

Dam Failure Risk. The variable *Dam Failure Risk* (%) is intended to capture the risk of a major structural failure. Therefore, this variable has to consider the hazard posed by the structure, and how it is maintained and managed. Utilizing this approach, a composite variable can be derived based predominantly on the variables *Dam Condition* and *Dam Failure Hazard*.

Table 5

Brief Characterisation of the Variable *Dam Failure Risk* (%) in Terms of Five Assessment Bins, and its Components and Corresponding Weightings

Component	*Bin 1*	*Bin 2*	*Bin 3*	*Bin 4*	*Bin 5*
Structural Failure Risk (20%)	Very high dam pressure; poorly maintained; unsafe operation; very narrow, tall and long dam with many potential weak points (>80%)	High dam pressure; poorly maintained; unsafe operation; very narrow and tall dam (>60 to 80%)	Medium dam pressure; poor maintenance; unsafe operation; narrow, tall and long dam (40 to 60%)	Medium dam pressure; good maintenance; safe operation; safe structures such as a wide and shallow dam (10 to <40%)	Low dam pressure; very good maintenance; safe structures such as a very wide, shallow and short dam (<10%)
Loss of Life Risk (50%)	Very dense urban areas with a very high proportion of permanent population in the catchment just below the failed very high dam; no apparent emergency plan in operation (>80%)	Dense urban areas with a high proportion of permanent population in the catchment just below the failed high dam; poor emergency plan in operation (>60 to 80%)	Dense urban areas with a high proportion of permanent population in the catchment far from the failed medium-sized dam; only some emergency planning evident (35 to 60%)	Sparse urban areas with a low proportion of permanent population in the catchment just below the failed small dam; minor emergency measures required (10 to <35%)	Sparse urban areas with a low proportion of permanent population far from the failed very small dam; no need for any emergency planning (<10%)
Risk of Infrastructure Failure (20%)	Poorly protected from flooding; located in low lands; low embankments; close to watercourse; very deep flood water; no adaptation to climate change evident (>80%)	Poorly protected from flooding; located in low lands; high embankments; close to watercourse; deep flood water; little evidence for adaptation to climate change (>60 to 80%)	Poorly protected from flooding; located in high lands; high embankments and close to watercourse; shallow water; some adaptation to climate change apparent (40 to 60%)	Well protected from flooding; located in high lands; low embankments; far from watercourse; shallow water; adapted to climate change (15 to <40%)	Well protected from flooding; located in high lands, high embankments; far from watercourse; very shallow water; fully adapted to climate change (<15%)
Other Factors Influencing Dam Failure Risk (10%)	Excessive embankment erosion during particularly wet years likely; risk of contaminated sediment deposition in populated areas due to prolonged flooding; very likely failure of a further reservoir downstream; extreme shifts in weather patterns due to climate change likely; possibility of reservoir cascade failure; risk of war damage; risk of terror attack or sabotage; seismic activity likely (>80%)	Excessive embankment erosion during particularly wet years likely; risk of contaminated sediment deposition in populated areas due to prolonged flooding; likely failure of a further reservoir downstream; extreme shifts in weather patterns due to climate change likely; occasional seismic activity (>60 to 80%)	Embankment erosion during particularly wet years likely; shifts in weather patterns due to climate change likely; potential failure of a further reservoir located downstream (30 to 60%)	Embankment erosion during particularly wet years likely; shifts in weather patterns due to climate change likely (10 to <30%)	Well maintained; safe operation; no apparent risk identified (<10%)

However, no accurate single equation can be used to determine this complex variable accurately, and expert judgement regarding the assessment of various risk components is therefore required. Table 5 shows a brief characterization of the variable *Dam Failure Risk* in terms of five assessment bins, and its components and corresponding weightings. The following components for *Dam Failure Risk* have been proposed:

The first component *Structural Failure Risk* (%) accounts for 20 percentage points overall. The more neglected a dam is due to poor maintenance, the more likely it is that there will be a dam failure due to excessive pressure on the dam during a flood event of high duration. A dam maintained well with appropriate materials and a safe operational mode would receive a low score, and a poorly maintained and therefore unsafe structure would obtain a high score (Table 5).

Loss of Life Risk (%) represents 50 percentage points overall. Essentially, the more people who would actually be present in an affected area during the flooding event, the higher would be the score for this component. Furthermore, the flooding depth and water velocity would need to be high and rapid, respectively, over long periods (Evans and Hohl, 2010). An indication for potentially high losses would be dense urban areas with a high proportion of permanent population in the catchment just downstream of the failed dam (Spachinger *et al*., 2008).

Risk of Infrastructure Failure (%) receives a weighting of 20 percentage points overall. This component scores high if important infrastructure which is poorly protected against flooding would be affected by dam failure. Furthermore, the flooding depth would need to be deep over long periods. Infrastructure elements particularly at risk would be airports with low-lying runways close to watercourses, railways with low embankments, major roads with bridges through deep valleys, and water and electricity supply structures in lowlands that are close to watercourses. For an initial relative indication of *Risk of Infrastructure Failure*, an assessor may wish to 'multiply' *Structural Failure Risk* with the *Importance of Infrastructure Affected by Dam Failure*. Nevertheless, the outcome would need to be adjusted subject to the likelihood of various scenarios.

The final component, *Other Factors Influencing Dam Failure Risk* (%), is weighted at 10 percentage points. These factors may include excessive embankment erosion during particularly wet years, contaminated sediment deposition in populated areas due to prolonged flooding, and damage because of uncontrolled rodent population expansion, if ideal breeding conditions prevail (Gilvear and Black, 1999). Other factors may also include unforeseen circumstances such as extreme shifts in weather patterns due to climate change (Kay *et al*., 2006), war damage, sabotage, or terror attacks. Moreover, if the failure of a particular reservoir would result in the likely failure of a further reservoir situated downstream, a high score should be awarded for *Other Factors Influencing Dam Failure Risk*.

2.3 Ordinary Kriging

The key application of kriging in SFRB for dam failure assessment is to predict the attribute values (*Dam Failure Hazard, Dam Failure Risk*) at unknown locations. Kriging uses weights from a semi-variogram based on surrounding measured values to predict unmeasured sites.

The measured values nearest to the unmeasured locations have the greatest influence. Ordinary kriging provides best linear unbiased estimations with a minimum error variance and is the most commonly used type of kriging. Assumptions for the practical application of ordinary kriging are based on constant but unknown mean and sufficient observations to estimate the variogram.

Kriging weighs the surrounding measured values to derive a prediction for an unmeasured location. Equation 1 is formed as a weighted sum of the data. The weight λ_i depends on a fitted model to the measured points, the distance to the prediction location, and the spatial relationships among the measured values around the prediction location. The weights λ_i are calculated by finding solutions of a system of linear equations, which are obtained by assuming that a real-valued function is a sample path of a random process, and that the error of prediction is to be minimised.

$$Z(S_0) = \sum_{i=1}^{N} \lambda_i Z(S_i) \qquad (1)$$

where $Z(S_i)$ denotes the measured value at the i^{th} location, λ_i is an unknown weight for the measured value at the *i*th location, S_0 is the prediction location, and N means the number of measured values.

3. FINDINGS AND DISCUSSION

3.1 Dam Failure Assessment for Different Types of SFRB in Scotland

In the area of natural hazards, risk is defined as a function of probability of occurrence, the intensity and extent of damage, and vulnerability. Furthermore, risk assessments may also take relevant geographical and statistical data into account (Spachinger *et al.*, 2008). These components have been addressed by the composite variable *Dam Failure Risk*.

The European Flood Directive (CEC, 2007) recommends the creation of flood risk maps with different hazard criteria: (a) flood events with a high probability (HQ 10); (b) flood events with a medium probability (HQ 100); and (c) flood events with a low probability (extreme event). Any risk variable should also include information on water depth and velocity (Evans and Hohl, 2010), as well as consideration for areas with embankment erosion and sediment deposition. For SFRB sites, this information was available, which considerably influenced the variables *Dam Failure Hazard* and *Dam Failure Risk*, subsequently increasing the corresponding confidence values.

The amount of damage to habitation, business and the environment has been addressed by the proposed new variables *Dam Failure Hazard* and *Dam Failure Risk*. Hence, vulnerability indicators may vary between low (such as agricultural areas and individual farm estates), moderate (such as dispersed settlements and small villages), and high values (city centres and industrial zones) as discussed by Spachinger *et al.*, (2008). Moreover, economical scores differentiating between industries under varying scenarios could be used to inform *Dam Failure Risk*. For example, a paper mill storing chemicals is under this system, given a greater weighting than a domestic garage.

This project combined the above approaches to risk management and assessment into a rapid tool. The 199 surveyed SFRB consist of 6 types, and most of them belong to Type 2 (134 sites). Table 6 shows the summary statistics for the three risk-related variables as well as the relevant key variables. It indicates that different types of SFRB are associated with different levels of hazards and risks of dam failure. For instance, SFRB of Type 1 (9 sites) have the highest *Dam Failure Hazard* (12.6%) and *Dam Failure Risk* (6.4%). These basins have the largest mean values for the variables of *Engineered*, *Dam Height*, *Dam Length*, *Depth of Basin*, *Flood Water Volume* and *Catchment Size*, which influence dam failure hazards and risks to a significant degree. Since the SFRB in Type 1 are usually used to feed hydraulic electric stations, they are well maintained and thus have the highest *Dam Condition* (91.8%). Type 2 SFRB, on the other hand, which mainly comprise Scottish drinking water reservoirs and have relative large *Dam Height*, *Dam Length*, *Maximum Flood Water Volume* and *Catchment Size*, are often associated with relative high hazard (10%) and risk (6.2%) of dam failure. Most of the SFRB in Type 2 are reservoirs and are managed by agencies or regional authorities; therefore, the *Dam Condition* (78.5%) is relatively high.

Table 6
Summary Statistics for Key Variables Relevant for the Determination of the Risk-Related Sustainable Flood Retention Basin (SFRB)

Variables	*Type 1 (9sites)*	*Type 2 (134 sites)*	*Type 3 (24sites)*	*Type 4 (10 sites)*	*Type 5 (16 sites)*	*Type 6 (6 sites)*
E	98.6±0.9	70.3±10.4	28.3±8.0	26.5±9.7	32.2±10.5	13±2.7
DH	30.7±18.9	11.5±8.9	2.1±1.0	2.3±0.9	2.4±2.2	0.5±0.9
DL	289.8±172	278.3±199	132.5±96.2	68.5±52.2	98.8±107	10±14.1
MFWV	116.3±320.4	3.1±6.9	0.1±0.2	0.1±0.0	0.9±1.6	16.4±25.1
MAF	1002.2±367.6	1071.3±287	1147.1±301.5	969±262.1	940±232.6	884±147.6
CS	129.8±189.3	7.9±11	1.7±1.5	4.3±5.9	11±26.7	39.6±71.5
MDB	14.9±14.6	6.3±3.7	2.4±0.7	2.4±0.8	2.8±0.9	6.6±9.0
DC	91.8±4.9	78.5±7.5	58.2±12.4	47.8±19.9	57±22.1	62.2±17.8
DFH	12.6±12.5	10±13	2.8±3.3	1.2±1.8	4.3±5.1	1.8±2.3
DFR	6.4±3	6.2±3.8	4.5±3.9	4.4±3.1	5.1±3.6	3.7±4.4

Note: E: *Engineered* (%); DH: *Dam Height* (m); DL: *Dam Length* (m); MFWV: *Maximum Flood Water Volume* (million m^3); MAF: *Mean Annual Rainfall* (mm/a); CS: *Catchment Size* (km^2); MDB: *Mean Depth of Basin* (m); DC: *Dam Condition* (%); DFH: *Dam Failure Hazard* (%); DFR: *Dam Failure Risk* (%).

Basins of SFRB types 3 and 4 are often small in size and have low engineered structures; therefore, *Dam Failure Hazard* and *Dam Failure Risk* are both low. Type 6 of SFRB has low *Dam Failure Hazard* (1.8%) and lowest *Dam Failure Risk* (3.7%). These basins are mainly lochs and rivers, and they have relative large *Flood Water Volume*, *Catchment Size* and *Depth of Basin* but the lowest mean values for *Engineered*, *Dam Height* and *Dam Length*. In contrast, SFRB in Type 5 have slightly higher dam failure hazards and risks than those in types 3, 4 and 6. It might because these Type 5 basins are mainly located near residential areas and used for public parks, recreation and water sport.

3.2 Spatial Distribution of the Hazard and Risk of Dam Failure

To illustrate the spatial characters of the levels of *Dam Failure Hazard* and *Dam Failure Risk* across the research area, ordinary kriging was applied. Figures 2 and 3 show the spatial distribution maps based on ordinary kriging interpolations of the *Dam Failure Hazard* and *Dam Failure Risk* for SFRB in Scotland, respectively. The graphical output needs to be assessed and interpreted by using expert judgement. Figure 2 indicates that the *Dam Failure Hazard* for Scottish SFRB varies from 0 to 66%. *Dam Failure Hazard* over a large part of the research area lies between 5% and 10%, such as the areas around Edinburgh, Livingston, Stirling and Dunfermline. However, *Dam Failure Hazard* near the city of Glasgow and the northeast of Stirling is relative high, between 10% and 15%. Sites with high *Dam Failure Hazard* should call for greater focus of managers.

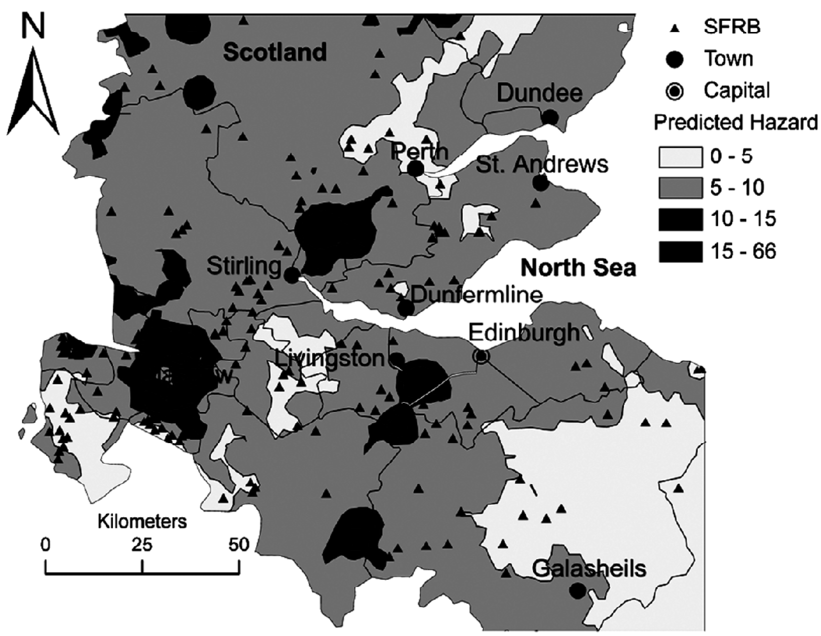

Figure 2: Spatial Distribution of the *Dam Failure Hazard* for Sustainable Flood Retention Basins in Central Scotland

Figure 3 shows that SFRB situated south of Livingston and northwest of Stirling have low *Dam Failure Risk*, ranging from 0 to 5%. SFRB located around Edinburgh, Livingston, Dunfermline and Stirling have higher risk of between 5% and 6%. Most of the research area is covered by the above two ranges, though the SFRB near Glasgow and Perth have even higher *Dam Failure Risk*, between 6% and 7%. Some sites that have high *Dam Failure Risk* are located in the south-west of Glasgow. However, the corresponding *Dam Failure Hazard* is relatively low (Fig. 2). This can be explained by the fact that the risk associated with SFRB dam failure near towns and urban areas is higher than for those areas located in relatively remote areas.

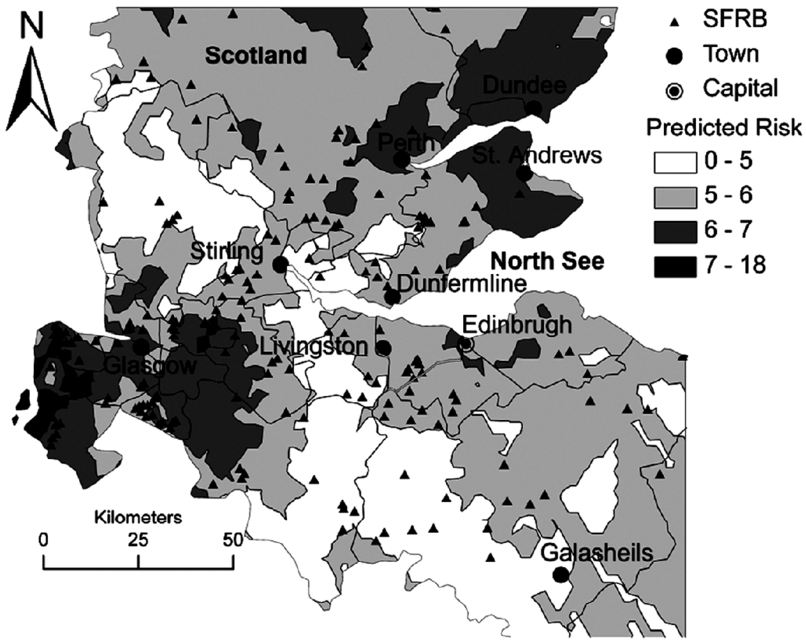

Figure 3: Spatial Distribution of the *Dam Failure Risk* for Sustainable Flood Retention Basins in Central Scotland

The above findings provide the decision-makers or planners with spatial support for flood risk management. With a clearer picture of the distribution of hazard and risk levels, they will be able to develop more specific plans or strategies for different regions in order to lower hazard and risk resulting from dam failure.

3.3 Risk Categories

For legislative purposes the dam safety community is discussing the categorization of reservoirs according to simple risk-related criteria. Table 7 shows an overview of the risk categories of the surveyed SFRB with respect to *Dam Height*, *Maximum Flood Water Volume*, *Loss of Life Risk* and infrastructure damage. The bin borders have been selected according to recent discussions at governmental level predominantly in the UK and Germany. For example, the first three risk categories agree with those currently proposed by the Scottish Government (Scottish Government, 2010).

Table 7 indicates that most SFRB sites in Scotland are in the low and moderate risk categories. This is consistent with the spatial distribution as illustrated on Fig. 3. Precisely 88 SFRB are considered to be low risk sites, while 99 SFRB belong to the moderate risk category. Only 3 SFRB are assigned to the high risk category, all of which have relative high dams of more than 5 m. Seven SFRB are regarded as very high risk. This might be because these sites have both high dams and *Maximum Flood Water Volume* ($>10^5$ m^3), and are frequently located in densely populated areas.

Table 7
Overview of Sustainable Flood Retention Basins (SFRB) with Respect to *Dam Height, Maximum Flood Water Volume, Loss of Life Risk* and *Risk of Infrastructure Failure* (damage). The First Three Risk Categories are Equivalent to Scottish Definitions

		SFRB in Scotland			
		Dam Height			
Death and damage	*Maximum flood water volume (m^3)*	*No dam*	< 5 *m*	≥ 5 *to* ≤ 15 *m*	> 15 *m*
1. *Low risk (minor risk of damage to property downstream)*					
< 1 person dies and minor damage	< 10k	0	0	0	0
	≥ 10k to 25k	0	2	1	0
	≥ 25k to 100k	1	12	2	0
	≥ 100k	5	19	34	12
2. *Moderate risk (moderate risk to damage to property and infrastructure downstream)*					
< 1 person dies and moderate damage	< 10k	0	1	0	0
	≥ 10k to 25k	0	2	0	0
	≥ 25k to 100k	0	12	2	0
	≥ 100k	1	14	47	20
3. *High risk (risk to life and/or significant risk to property and critical infrastructure)*					
≥ 1 to £20 people die and high damage	< 10k	0	0	0	0
	≥ 10k to 25k	0	0	0	0
	≥ 25k to 100k	0	0	0	0
	≥ 100k	0	0	3	0
4. *Very high risk (high risk to life and significant risk to property and critical infrastructure)*					
≥ 20 people die and high damage	< 10k	0	0	0	0
	≥ 10k to 25k	0	0	0	0
	≥ 25k to 100k	0	0	0	0
	≥ 100k	0	1	5	1

Note: k, 1000.

4. CONCLUSIONS AND RECOMMENDATIONS

1. Different SFRB types have different dam failure hazard and risk levels. Generally, Type 1 SFRB (e.g. those feeding hydroelectric power stations) have the highest hazards and risks, followed by SFRB Type 2 (mainly reservoirs). In comparison, Type 5 basins (e.g. public parks used for recreational activities) have lower hazards and risks, while SFRB types 3, 4 and 6 (mainly small basins with low engineered structures or lochs) are associated with even lower dam failure hazards and risks.

2. The spatial distribution maps of *Dam Failure Hazard* and *Dam Failure Risk* have been produced using Ordinary Kriging. They show the variant levels of hazards and risks for different regions of research areas, helping decision-makers to intuitively identify the high emergency areas requiring further assessment. Furthermore, they provide the EU member states with an effective tool to implement the Flood Directive for developing the Flood Risk Management Plan.

3. The proposed rapid tool for risk assessment may be used elsewhere by stakeholders and environmental engineering scientists for decision-making processes. The rapid methodology is effective and has the potential, with minor modifications, to be applied across temperate oceanic and temperate continental regions in Europe and, perhaps, North America.

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