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Classification of different sustainable flood retention basin types

Michelle Robinson[1], Miklas Scholz[2,*], Nicolas Bastien[3], Jennifer Carfrae[1]

1. Scottish Agricultural College, Peter Wilson Building, The King's Buildings, West Mains Road, Edinburgh EH9 3JG, Scotland, UK. E-mail: michellerobinson@mail.com
2. Institute for Infrastructure and Environment, School of Engineering, The University of Edinburgh, William Rankine Building, The King's Buildings, Edinburgh EH9 3JL, Scotland, UK
3. School of Built Environment, Heriot-Watt University, Edinburgh EH14 4AS, Scotland, UK

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Abstract

Using a revised version of a previously published expert classification system, a database of potential Sustainable Flood Retention Basins has been developed for Scotland. The research shows that the majority of small and former (often old) drinking water reservoirs are kept full and their spillways are continuously in operation. Utilising some of the available capacity to contribute to flood control could significantly reduce the costs of complying with the European Union Flood Directive. Furthermore, the application of a previously developed classification model for Baden in Germany for the Scottish data set showed a lower diversity for basins in Scotland due to less developed infrastructure. The classification system appears to be robust and has the potential, with minor modifications, to be applied across Europe. The principle value of this approach is a clear and unambiguous categorisation, based on standard variables, which can help to promote communication and understanding between stakeholders.

Key words: classification system; diffuse pollution control; principal component analysis; runoff control; sustainable flood retention basin

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Introduction

There are a wide range of traditional engineering solutions which can be applied to provide flood defences in urban and rural areas. These traditional approaches predominately utilize hard engineering solutions such as barriers and dykes to protect the public from the economic and social costs of flooding (Kendrick, 1988). These traditional approaches are now supplemented by the availability of sustainable drainage systems, which generally operate by absorbing water and slowing down the rate of runoff from urban areas (Scholz, 2006). An emerging challenge for new and existing systems is climate change and the potential increase in rainfall and severe rainfall events that are expected to intensify in the future. Moreover, flooding often results in significant pollutant inputs to the water environment.

In light of this discussion, traditional flood retention basins have recently received increasingly more attention by politicians, planners and developers on the local and regional scale (Scholz, 2007). For example, the current design of German flood retention basins is based on outdated statistical rainfall events (ATV-DVWK, 2001), which are now called into question because of the reality of climate change.

Most natural and constructed retention basins keep runoff for subsequent release, thus avoiding downstream flooding problems. Some basins such as wetlands do perform other tangible albeit less visible roles including diffuse pollution control and infiltration of treated runoff, promoting groundwater recharge. The diversity of retention basins is therefore high and further complicated by often multiple and competing functions that these structures fulfil.

A classification system is therefore needed to allow clear communication between stakeholders such as politicians, planners, engineers, environmental scientists and public interest groups. The absence of a universal classification scheme for retention basins leads to confusion about the status of individual structures and their functions. This can lead to conflicts between stakeholders concerning the management of retention basins including wetlands. Therefore, Scholz and Sadowski (2009) proposed a conceptual classification model based on 141 sustainable flood retention basins (SFRB) located in the River Rhine Valley, Baden, Germany. Six SFRB types were defined based on the expert judgment of engineers, scientists and environmentalists.

The European Union has acknowledged that member states may face significant challenges in complying with the flood directive and has therefore established

* Corresponding author. E-mail: m.scholz@ed.ac.uk

programs such as the Strategic Alliance for Water Management Actions (2009) to develop guidance on adaptive measures such as SFRB to assist the member states in developing flood risk management plans. This on-going project will produce a database of adaptive structural and non-structural measures for the use of a wide range of stakeholders to aid them in the design of sustainable flood defence plans and to aid communication between the parties. It follows that a common classification system for water bodies, applicable across similar climatic conditions, would aid communication, planning and understanding.

The aim of this research article is to characterize subclasses (i.e., types) SFRB in Scotland with the help of a revised rapid conceptual classification model, originally proposed by Scholz and Sadowski (2009). The key objectives are: (1) to aid stakeholder communication by avoiding misunderstandings with respect to planning and legal matters concerning the status of Scottish SFRB; (2) to determine and characterize all relevant and particularly the key independent classification variables using a principal component analysis (PCA) and a sensitivity analysis using the Wilcoxon test; (3) to develop a universal conceptual classification methodology with the support of a large and detailed example case study data set; and (4) to illustrate and discuss examples of the most dominant Scottish SFRB types that are also highly relevant for civil and environmental engineers, and landscape planners.

1 Methodology

1.1 Identification of sites and definitions

Specifically for this research article, 167 sites were selected for classification using the 1:50000 scale Ordnance Survey Maps for the wider central Scotland area between Edinburgh and Glasgow. In the context of this investigation, the sites of interest are those which may be able to play a role in either flood management or diffuse pollution control. Structures which may be able to play a role in flood control are considered to be those where the water level can be controlled either manually or automatically, and are typically former or current engineered water supply reservoirs. Sites with the potential to contribute to diffuse pollution control are typically more natural and relatively small water bodies.

The most important classification variables for various types of SFRB in Scotland were identified and subsequently grouped (see below). Variables were determined on the basis of literature reviews, various recent site visits in Germany, UK, Sweden, Ireland and Denmark, and group discussions among British, German, Swedish, French, Irish and American engineers, scientists, and landscape and urban planners.

The case study site investigation is a two stage process comprising a desk study and site visit. During the desk study, the catchment boundaries for the water body, wet perimeter, area of the water body, length of the dam, elevation, basin gradient and composition of the catchment (urban, arable, forestry and natural grassland proportion) are measured, using digital maps. The site visit then ground truths these findings and the water body inflows and outflows are documented. Details regarding variables concerning the presence of a potential dam, its outlet control operation, basin catchment proportions, vegetation cover and drainage are documented during a site visit and by taking photographic evidence.

The user should be able to estimate most variables during a desk study, which should take approximately 20 min, and during a site visit of typically 40 min. A certainty percentage point (i.e., low: 1%–40%; medium: 40%–60%; high: 60%–100%) was attributed to each variable during the desk and field studies to reflect the likelihood of selecting a correct value. Certainty estimations depend very much on the expertise and bias of the user.

The authors' own revised definitions and characteristics for six subclasses of SFRB as a function of their predominant purpose based on expert judgment, feedback from collaborators including landscape planners, data collected during desk studies and field visits have been listed (Table 1). Furthermore, the characteristics of each SFRB type are also based on the interpretation of findings obtained from the statistical evaluation (see below). The six subclasses are the following: hydraulic flood retention basin (type 1), traditional flood retention basin (type 2), sustainable flood retention wetland (type 3), aesthetic flood retention wetland (type 4), integrated flood retention wetland (type 5) and natural flood retention wetland (type 6). The revised definitions of SFRB subclasses are independent of all statistical analyses, and were formulated considering expert judgment based on empirical observations.

1.2 Identification of classification variables

Data analyses were performed in Minitab Inc. (2003) if not stated otherwise. Most variables characterizing water bodies in Scotland were adopted from those initially proposed by Scholz and Sadowski (2009): (1) Engineered (%); (2) Dam Height (m); (3) Dam Length (m); (4) Outlet Arrangement and Operation (%); (5) Aquatic Animal Passage (%); (6) Land Animal Passage (%); (7) Floodplain Elevation (m); (8) Basin and Channel Connectivity (m); (9) Wetness (%); (10) Proportion of Flow within Channel (%); (11) Mean Flooding Depth (m); (12) Typical Wetness Duration (day/yr); (13) Estimated Flood Duration (yr^{-1}); (14) Basin Bed Gradient (%); (15) Mean Basin Flood Velocity (cm/sec); (16) Wetted Perimeter (m); (17) Maximum Flood Water Volume (m^3); (18) Flood Water Surface Area (m^2); (19) Mean Annual Rainfall (mm); (20) Drainage (cm/day); (21) Impermeable Soil Proportion (%); (22) Seasonal Influence (%); (23) Site Elevation (m); (24) Vegetation Cover (%); (25) Algal Cover in Summer (%); (26) Relative Total Pollution (%); (27) Mean Sediment Depth (cm); (28) Organic Sediment Proportion (%); (29) Flotsam Cover (%); (30) Catchment Size (km^2); (31) Urban Catchment Proportion (%); (32) Arable Catchment Proportion (%); (33) Pasture Catchment Proportion (%); (34) Viniculture Catchment Proportion (%); (35) Forest Catchment Proportion (%); (36) Natural Catchment

Table 1 Revised definitions for the sustainable flood retention basin (SFRB) types

Type	Name	Definition of SFRB type	Typical examples
1	Hydraulic flood retention basin (HFRB)	Managed traditional SFRB that is hydraulically optimized (or even automated) and captures sediment in a controlled manner.	Drinking water reservoir (in operation); highly engineered and large flood retention basin.
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 basin.
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 treatment wetland (AFTW)	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 wetland.
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.

Proportion (%); (37) Groundwater Infiltration (%); (38) Mean Depth of the Basin (m); (39) Length of Basin (m); (40) Width of Basin (m).

Variables such as Engineered, Floodplain Elevation, Basin and Channel Connectivity, Mean Flooding Depth, Flood Duration, and Relative Total Pollution were refined and clarified to fit within the Scottish context. It has been appreciated that there are differences in the build environment and landscape. For example, the variable Mean Flooding Depth recognizes high slope values for the Scottish landscape and deep flooding depths of some rather natural lakes.

The methodology has been updated by including the new variables Mean Depth of the Basin, Length of the Basin and Width of the Basin in the classification template. The previous variable Aquatic and Land Animal Passage was divided into the following separate variables: Aquatic Animal Passage and Land Animal Passage. This accounts for fundamentally different obstacles concerning the freedom of unrestricted movement for animals.

Similarly, the old variable Forest and Natural Catchment Proportion was split into Forest Catchment Proportion and Natural Catchment Proportion. The former variable Viniculture Catchment Proportion was not suitable for Scotland, so it was removed from the classification template.

The variable Wetness was further refined to make a strong distinction between permanently wet systems such as reservoirs and lakes (Scottish data set) and SFRB, which may be dry and become wet only occasionally (German data set). Typical Wetness Duration became more important because it distinguishes between permanently flooded features such as reservoirs and lakes and SFRB designed for occasional flood control. The variable Flood Frequency is very difficult to determine with high certainty. Moreover, this variable is obsolete if no flood frequency data are available.

The variable Wetted Perimeter, also previously used by Scholz and Sadowski (2009) for the classification of the German data set, is highly important for the Scottish data set, which predominantly comprises wet basins in contrast to the dry basins dominating the German data set. A high Wetted Perimeter value is likely to indicate a higher diffuse pollution control potential. Vegetation Cover has been further specified, considering that the vegetation within a predominantly dry basin is completely different to the aquatic vegetation within a wet basin. Furthermore, the following new purposes for Scottish basins were identified: industrial production and drinking water reservoir. These are in addition to the purposes flood retention, sustainable drainage, environmental protection, recreation and landscape enhancement identified for the German data set.

1.3 Rationale for the elimination of less relevant variables

The application of the PCA with the help of Matlab Version 7.1 (Pratap, 2002) helped to get a better overview of the underlying data structure. On the basis of the loading plot, it is possible, where several variables are grouped closely together, to extract one single variable, which may then replace the entire group. Besides the obvious timesaving advantages to this, the main point of the PCA is to remove redundant variables, hence reducing the risk of multi-collinearity.

The cluster analysis and classification was performed twice: (1) using 39 variables, and (2) using only 18 variables. Groups of variables formed by containing similar principal components have been highlighted by circles around their corresponding labels. The final classification system was intended to be based on variables, which are accurate, easy to obtain and associated with a high confidence value assigned to them during their determination.

Dominant variables were retained and used for a subsequent cluster analysis. The remaining variables within each group were discarded. This procedure has been followed because too many variables may over-complicate the decision-making tool, making the end product rather user-unfriendly. Furthermore, variables with similar principal components were effectively measuring the same fundamental variable. By keeping one variable representing a specific group, the other variables within this group naturally become redundant for the decision support tool.

Another technique to assess the suitability of a characterisation variable is to evaluate its repeatability. Therefore, three groups assessed the same set of variables for 17 randomly selected case study sites independently from each other. The Wilcoxon signed rank test, also known as the Wilcoxon matched pairs test, is a non-parametric test used to assess the median difference in paired data. The test avoids the distributional assumption, because it is based on the rank order of the differences rather than the actual value of the differences. A non-directional hypothesis was made, there would be a significant difference between paired data (the initial site visit and the revisits). The statistical analysis was carried out in the SPSS software (SPSS, 2009) based on a two-tailed hypotheses.

1.4 Assignment of SFRB types with the help of a cluster analyses

The statistical software package Matlab 7.1 (Pratap, 2002) was used to perform cluster analyses on the standardized example data set. The clustering technique used was an agglomerative method (otherwise known as a "bottom up approach"). The results are displayed on a dendrogram which allows an unambiguous appreciation of the cluster properties of the data.

The cluster analysis technique "Ward's linkage", which effectively forced the data into a predefined number of clusters thus eliminating outliers, was applied (Kaufman and Rousseauw, 1990). In this case, the objective was to obtain as many clusters as there are SFRB subclasses, of which there are six.

After the Ward cluster analysis had grouped the 167 data points (one point corresponds to all 39 variables (Viniculture Catchment Proportion excluded) into seven groups (six groups of SFRB and one group of non-SFRB), the general statistics of each cluster were found. The objective was to determine which SFRB type corresponded best to which newfound cluster, and this was done on the basis of expert judgment, supported by the case study information obtained during the site investigation. The dominant basin purposes greatly influences the selection of the most likely SFRB type; e.g., a modern drinking water reservoir is likely to be a Hydraulic Flood Retention Basin (Table 1).

2 Findings and discussion

2.1 Reduction exercise for the classification variables

An attempt was made to reduce the total number of variables based on the results of the PCA and a sensitivity analysis. The loading plot allowed seven definite independent variables and eleven groups of dependent variables to be identified. For Scotland, Wetted Perimeter, Maximum Flood Water Volume, Flood Water Surface Area, Engineered, Catchment Size, Outlet Arrangement and Operation, Dam Height, Land Animal Passage, Impermeable Soil Proportion and Mean Sediment Depth were the most important independent SFRB characterization variables, which greatly contributed to the variability expressed by the first and second component. The remaining variables were regarded as redundant.

Dependencies were found for the following groups of variables: Engineered, Dam Height, Outlet Arrangement and Operation, and Impermeable Soil Proportion; Flood Duration and Urban Catchment Proportion; Drainage, Vegetation Cover and Relative Total Pollution; Mean Flooding Depth and Mean Depth of the Basin; Site Elevation and Natural Catchment Proportion; Mean Basin Flood Velocity, Mean Annual Rainfall and Seasonal Influence; Pasture Catchment Proportion, Forest Catchment Proportion and Groundwater Infiltration; Algal Cover in Summer, Flotsam Cover and Arable Catchment Proportion; Aquatic Animal Passage and Floodplain Elevation; Wetness, Proportion of Flow Within Channel, Typical Wetness Duration and Organic Sediment Proportion; Wetted Perimeter, Maximum Flood Water Volume and Length of Basin. It follows that variables with the following identification numbers are dependable: 2, 31, 24, 37, 23, 19, 34, 29, 7, 9 and 38. The remaining variables are redundant, and could be omitted in the future.

2.2 Cluster analyses

The cluster analysis was performed on all 39 variables and based on the reduced set of 18 variables. The analysis performed on the reduced set of variables (independent, and easy and reliable to determine) indicated seven clusters containing the six SFRB types and a group comprising non-SFRB sites (predominantly unmanaged natural lakes). Figure 1 shows the dendrogram for six SFRB based on 39 variables.

Concerning Fig. 1, the clusters from left to right correspond to type 5 (group A; 16 sites), type 2 (group B; 57 sites), type 1 (group C; 4 sites), type 6 (group D; 68 sites), type 4 (group E; 9 sites) and type 3 (group F; 5 sites). Moreover, 8 sites were identified as non-SFRB. With respect to the analysis based on the reduced set of variables, the clusters correspond to SFRB type 6 (group A; 61 sites), type 3 (group B; 11 sites), type 5 (group C; 13 sites), type 4 (group D; 12 sites), type 2 (group E; 52 sites) and type 1 (group F; 5 sites). In addition, 13 sites were identified as non-SFRB.

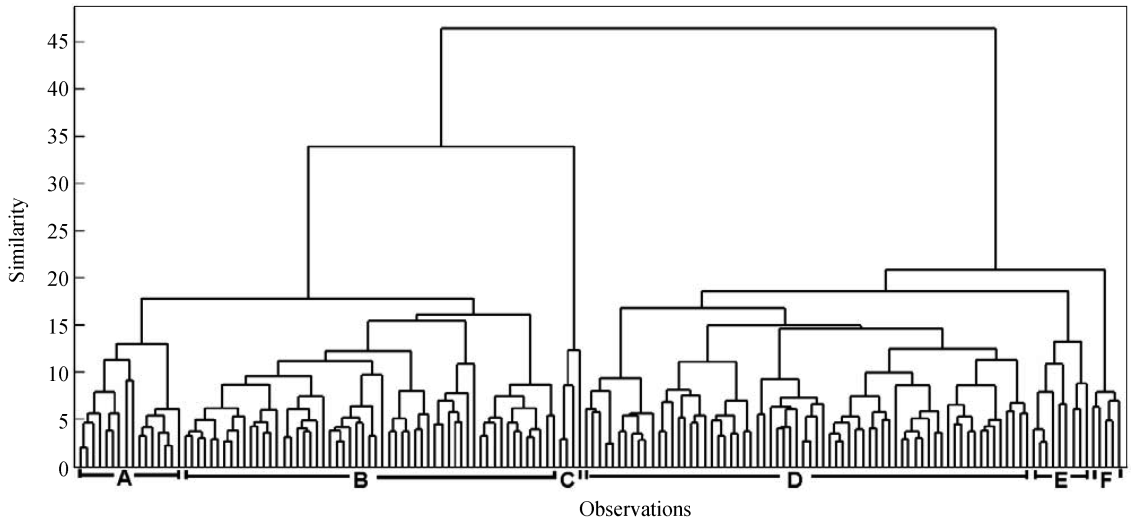

Fig. 1 Dendrogram based on 39 variables for the data set of 167 retention basins (observations on *X*-axis) with Ward linkage and Euclidian distance used to identify the six Sustainable Flood Retention Basin types.

2.3 Groupings based on cluster analysis

Each cluster can be directly linked to a SFRB type, thus justifying their original choice, definition and number. The distribution of cluster entries in the corresponding SFRB types was both explainable and expected. The reason is that virtually all artificial retention basins are initially built purely for flood protection and/or drinking water supply purposes. As a result, this purpose and hence this SFRB type still dominates even decades after construction or the last significant flood.

What has changed is that after years of absence of major local floods, total dryness (or total wetness) or neglect, the purposes of many sites have changed, and the types have shifted from the original purely hydraulic function to something more sustainable, aesthetic and/or natural. Some sites have become so overgrown that they would not be able to handle the design flood anymore, and have instead become nature reserves, some are even protected by law (usually type 6; Table 1). The conceptual model provides rapidly clear definitions for the past and current (i.e., after aging) status of SFRB aiding therefore communication between different stakeholders.

2.4 Application of the classification methodology for Scotland

The number of classification variables was reduced with the help of a PCA. With respect to flood control, Dam Length, Basin Bed Gradient, Flood Water Surface Area, Catchment Size and Width of the Basin were the most important independent SFRB characterization variables, which greatly contributed to the variability expressed by the first and second component.

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This finding may have two principle reasons. The first reason may be bias in the selection of water bodies for investigation. However, this was not the case during this study, which was undertaken by a large and diverse team of experts over three years. The second reason is that there is a lower diversity of SFRB types in Scotland due to a simple or under-developed flood infrastructure, which lacks retention structures overall.

The fieldwork program has identified a large number of water supply reservoirs, which are currently surplus to requirements. In the vast majority of cases, these structures now fulfil multiple roles providing opportunities for recreation, nature conservation and angling with many former drinking water or industrial water supplies being managed as fisheries.

A feature of these sites, based on the majority of current drinking water supply reservoirs (operated by Scottish water) surveyed, is that they are maintained at their maximum volumes, and the spillways are continually in operation. In this mode of operation, this extensive infrastructure is making very little contribution to water retention in the upper reaches of catchments.

It follows that a change in management practice of these structures could assist in sustainable flood risk management planning, and result in more sustainable reservoirs. Effectively, this would require some water to be released from the reservoirs prior to expected heavy rainfalls. As the vast majority of former drinking water reservoirs have manual level control, this would require someone to visit the sites and open the valves to release the water, returning prior to the main rainfall event to close the valves. This simple operation would create capacity to enhance water storage in the upper reaches of the catchments, and retard the peak flows from the upper catchment, which has the potential to reduce the chances of flooding downstream. Combining this approach with conventional solutions such as sustainable drainage systems, barriers and dykes will help to reduce the size, cost and land take of other flood defences. It is critical to the success of such an approach that appropriate compensation is provided to the owners of the structures to reflect the value of this service and the mild inconvenience it may cause.

As the most severe rainfall and storm events are usually predicted for the winter months, the reservoirs could be used for flood control purposes outside the fishing season. A major concern of the fisheries owners will be the retention of the fish within the reservoirs during periods of water release, and this may require the fitting of screens onto the valve controlled outlets of a reservoir. Equally, water supply organisations such as Scottish Water will need to be reassured that the change of management practice will not impact negatively on the water quality within the basin and any management action would need to ensure that all the SFRB purposes and uses were maintained.

The proposed methodology can be used directly for planning purposes. For example, the SFRB concept could support the Water of Leith Flood Prevention Scheme to protect Edinburgh from flooding (Scottish Government, 2010). A proper classification of the water bodies located within the Water of Leith catchment area that have flood control potential would clarify their individual planning status. Clarification regarding their current purpose (e.g., water supply, flood attenuation, recreation and/or environmental protection) would benefit communication between all stakeholders (e.g., local authority, land owners and Scottish Water) involved with this case study to optimise their planning effort.

3 Conclusions

The Scottish data set contained only two main SFRB types. Traditional flood retention basins comprising predominantly former drinking water reservoirs are a clearly noticeable component of the Scottish landscape. These structures could be used for low-cost flood control purposes if their water level would be actively controlled, which is currently not the case. Natural flood retention wetlands also dominate the case study area, and could make a significant contribution to diffuse pollution control, if they are managed appropriately. The most important independent and accurately determined SFRB variables that resemble wetland systems with a high diffuse pollution treatment function were Wetted Perimeter, Flood Water Surface Area, Engineered, Catchment Size, Outlet Arrangement and Operation and Mean Sediment Depth.

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