Civil Engineering and Environmental Systems
Vol. 24, No. 3, September 2007, 193–209

Expert system outline for the classification of sustainable flood retention basins (SFRBs)

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(Received 7 May 2006)

The aim of this paper is to recommend a rapid classification system for sustainable flood retention basins (SFRBs) to control runoff in a temperate climate. The system should improve communication among engineers and scientists, and was developed with a general database (approximately 660 basins) and a very detailed database (56 basins), using the River Rhine catchment in the South of Baden (Germany) as a case study. The classification system can be used by civil engineers, environmental scientists and planners to determine the following types of SFRBs: hydraulic flood retention basin, traditional sustainable flood retention basin, sustainable flood retention wetland, aesthetic flood retention wetland, integrated flood retention wetland and natural flood retention wetland. The most important system variables were rainfall, dam height, flood water volume, elevation, dam length, flotsam, floodplain elevation, forest and animal passage. However, 34 variables were applied to determine the different types of SFRBs, which were predominantly used for hydraulic purposes.

Keywords: Classification system; Floodplain management; Civil engineering and environmental planning; Sustainable flood retention basin; Rural and urban runoff; Water resources design

1. Introduction

1.1 *Climate change, flooding risk and landscape planning*

In the northern part of Europe, the total annual amount of rainfall significantly increased in the last century, which cannot be explained by the natural variability of the climate (Scholz 2006). In accordance with Bardossy and Caspary (1990), a statistically significant increase of precipitation has been observed, particularly during winter and spring. This finding is supported by the observation that the mean flow rate in the largest German rivers, for example, has increased by approximately 25% since 1930. Further changes of precipitation patterns are predicted independently from different climatic models, which will lead to more precipitation (predominantly rain) during winter and spring, causing an increased risk of flooding in Central and Northern Europe (Scholz 2006).

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Civil Engineering and Environmental Systems
ISSN 1028-6608 print/ISSN 1029-0249 online © 2007 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/10286600701240377

Pfister *et al.* (2004) claim that land use change such as urbanization in headwater areas can lead to flooding during storms. Future changes in peak flow will depend on the variability of extreme rainfall in combination with land use management. High urban runoff and diffuse pollution from agricultural sources are increasingly becoming a serious problem for the management of retention basins. These problems need to be addressed by civil and environmental engineers and urban and landscape planners.

Hooijer *et al.* (2004) have outlined the European Union-funded IRMA-SPONGE project that aimed to assess the impact of flood risk reduction measures, and changes to land use and climate change on the international River Rhine catchment planning process. The project focused specifically on climate change, land use planning and management (particularly retention basins), and ecological quality of rivers and floodplains.

Most recently, Nijland (2005) has proposed a sustainable floodplain development strategy, which is based on a project funded by the European Interregional IIIb Programme. The aim is to promote the sustainable development of floodplains in the River Rhine valley by finding a compromise between flood prevention and the protection of nature and the natural landscape. However, it is too early to assess any long-term impact of revised landscape design on the river runoff.

1.2 *General classification of floodplains and retention basins*

Schnitzler *et al.* (1992) indicated that floodplains could be classified according to plant species (*i.e.* the corresponding life-form, place in the successional stage, phenology and abundance), which usually segregate according to their habitat:

- geochemistry such as the lime content and texture;
- water stress including the depth of water; and
- fluvial dynamics such as flooding.

Moreover, vegetation, soil and geomorphologic data can be used to classify floodplains and possibly also sustainable flood retention basins (SFRBs) according to their degree of succession. The corresponding classes or groups could be used as a basis for rehabilitation strategies (Schoor 1994).

Carbiener *et al.* (1995) proposed a hierarchical classification of factors responsible for the distribution of vegetation. The following list shows the levels in order of decreasing importance: water mineralization, trophic status (particularly phosphate and ammonia), rheology, sedimentology and morphology. Moreover, aquatic macrophyte communities can be used as bio-indicators to classify floodplain areas and potentially also SFRBs according to their spatial and temporal trophic quality status. The reasoning behind this approach is that bio-indicators respond well to river–groundwater interchanges, and have a 'memory' of hydrological events such as floods.

Haase (2003) examined indicators such as the expansion of loam due to flooding, groundwater table, relief and land use to characterize floodplain functionality in urban areas. However, he used only one case study to test his classification variables. Unless this case study is typical for a vast majority of cases (unlikely but not proven), the research is only incremental.

Furthermore, the Rhine basin, for example, is divided into eight different action areas with corresponding action plans to combat floods according to the following criteria (Bohm *et al.* 2004): prevailing flood danger, geophysical situation and potential effects of retention measures. Priority zones to prevent any risk increases, and reserve zones, which demand precautionary measures concerning construction only, have been recommended by Bohm *et al.* (2004). The level of risk is reflected in the retention basin location and selection of the

corresponding engineering measures. This approach is logical and important for flood risk and landscape managers, but offers little help for civil and environmental engineers, and landscape and urban planners in characterizing different types of SFRBs with the aim of identifying their individual function and defining corresponding policies and detailed guidelines for their management.

A classification of floodplains based on their compartmentalization is also possible. However, such a classification would need to be dynamic, because dykes of secondary importance (predominantly located in lowland areas) are frequently being either removed or restored without trans-federal and/or trans-national agreements being arranged. Alkema and Middelkoop (2005) claim that neither a simple removal or total restoration of secondary dykes would reduce the risk of overall flood damage, but that this could be achieved by a strategic compartment plan, which would certainly be a useful tool for a multi-purpose floodplain classification scheme at the same time. Any classification of retention basins needs to be simple, transparent and dynamic, and should consider the entire catchment.

Furthermore, any classification system or model should be tested on a 'real' data set containing sufficient numbers of case studies (*i.e.* SFRBs). Different degrees of system complexity and their impact on the correctness of results need to be judged (*e.g.* Van Lienden and Lund (2004)).

1.3 *Need for a classification system for flood retention basins*

The author is not aware of any systematic classification scheme for different types of flood retention basins. For example, German flood retention basin guidelines describe different components (*e.g.* dam height and basin volume) of basins, but fall short of classifying flood retention basins according to types (Gesellschaft zur Förderung der Abwassertechnik (ATV-DVWK) 2001).

Virtually all retention basins featuring in official German databases are classified as flood retention basins, including drinking water reservoirs, basins used for hydropower generation, offline polders for active river regulation, covered reservoirs, fish ponds and even some traditional village ponds. Such a loose grouping of different retention basin types into one category frequently leads to legal disputes and misunderstandings between practitioners and the public. A classification scheme for SFRBs is therefore timely and urgently required to assist communication.

Moreover, a rapid classification methodology is relevant for stakeholders such as local authorities and non-governmental organizations, and it will greatly assist them with urban and landscape planning. For example, an SFRBs that was initially built for flood protection purposes only might have become a site of scientific interest where the flora and fauna should now be under legal protection. Finally, the mathematical relationships among the classification variables will help engineers and scientists to identify 'cause and effect' phenomena, especially, for example, when an SFRBs requires upgrading.

1.4 *Aim and key objectives*

The aim of this paper is to define sub-classes (*i.e.* types) for SFRBs. The key objectives are as follows:

- to determine all relevant variables, particularly the key classification ones;
- to assess the certainty of accurate determination associated with each classification variable;
- to determine weightings for all classification variables according to their relative importance depending on various basin applications;

- to provide civil and environmental engineers with a rapid expert classification system;
- to apply the classification system on a large and detailed case study data set; and
- to illustrate and discuss examples of the most relevant SFRBs types for civil and environmental engineers.

2. Expert system for classifying SFRBs

2.1 *Classification variables and their numerical values and corresponding certainty*

The most important classification variables (*i.e.* 34 in total) for various types of SFRB to control runoff during floods in a temperate climate were identified and grouped based on a literature review, various recent site visits in Germany, the UK, Ireland and Denmark, and group discussions among British, German, French, Irish and US engineers, scientists, and landscape and urban planners. The identified classification variables and their corresponding identification numbers are as follows (tables 1–2): naturalness (1), dam height (2), dam length (3), outlet flexibility (4), animal passage (5), floodplain elevation (6), connectivity (7), wetness (8), channel system (9), flooding depth (10), flooding duration (11), flood frequency (12), slope (13), velocity (14), embankment length (15), flood water volume (16), water surface area (17), rainfall (18), drainage (19), clay (20), season (21), elevation (22), vegetation (23), algae (24), pollution (25), sediment depth (26), sediment composition (27), flotsam (28), catchment size (29), urban (30), arable (31), pasture (32), forest (33) and groundwater (34). The qualitative and quantitative characterization (*i.e.* grouping in bins) of these variables for flood retention basins regardless of their purpose is shown in table 1. A bin number (*i.e.* point between 1 and 5) and a numerical value were assigned to each quantitative variable. In contrast, qualitative variables (*i.e.* 5, 21, 23, 25 and 28) received points based on their corresponding bin numbers (table 1).

Furthermore, the experienced and trained user should be able to estimate most variables during a desktop study, which should take <50 min and a site visit of <40 min; that is, total investigation time of <1.5 h. A certainty value (*e.g.* very low = 0%; medium = 50%; very high = 100%) should be assigned to each variable to reflect the estimated risk of selecting a false value. The assessment should always be carried out by the same team comprising at least one engineer and one scientist to reduce the risk of bias and inconsistency. In this case study, the author (chartered engineer, chartered scientist and chartered environmentalist) was joined, for example, by Dr Bernoît Sittler (scientist).

2.2 *Rationale for the selection of weightings*

Table 2 summarizes the classification variables and associated weightings with a bias towards hydraulics, sustainable drainage, environmental protection, recreational activities and landscape aesthetics. The use of sums of weightings implied the assumption of additivity of variable importance, which is obviously a simplification of reality and does not hold true for all scenarios. This is a simplification of a complex reality and there are obviously exceptions, which the experienced user needs to identify. The scores associated with the weightings should be seen as recommendations, which could be changed by the expert user, depending on regional and national differences reflected in federal, national and/or international guidelines.

The weightings were chosen based on a literature review and comprehensive discussions between civil, environmental and water engineers, environmental scientists, sociologists and landscape managers. Representatives from different subject disciplines have provided the author with suggested relative weightings based on their own experience. The findings were then collected and mathematical relationships were identified. For example, the arrangement

Table 1. Variable determination template: qualification and quantification of 34 classification variables for SFRBs to control runoff during typical floods.

No.	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5
1	Old, permanently filled and man-made structure with full engineering control; *i.e.* similar to a traditional flood retention basin (>60%)	Mostly permanently filled and man-made traditional structure (>50 to 60%) with some natural elements, but automatically controlled	Engineered structure (40–50%) fitted well into the natural landscape with passive control	Aesthetically pleasing natural and occasionally dry formation with some engineered (30 to <40%) features, but relatively natural channel base	Almost entirely natural and occasionally dry formation including a wide natural channel base (<30% engineered; *e.g.* inlet and outlet)
2	Relatively high dam (>10 m) as the dominant feature of the engineered structure; local climate change	Part of engineered structure features a dam (height between >8 and 10 m)	Small dam (height between 5 and 8 m) and natural containment combined	Ecologically engineered and aesthetically pleasing structure with a small dam (height between 2 and <5 m)	Insignificant dam (<2 m embankment height) but natural containment of water (*e.g.* in a valley)
3	Very long dam (>2000 m)	Long dam (1000–2000 m)	Normal dam length (>100 to <1000 m)	Short dam (50–100 m)	Very short dam (<50 m)
4	Combined or separate very flexible outlets (>90% flexibility)	Combined or separate flexible outlets (>70–90% flexibility)	Combined and partly flexible outlets (30–70% flexibility)	Separate outlets; at least one outflow is fixed (10 to <30% flexibility)	Separate and fixed base flow and/or flood flow outlets (<10% flexibility)
5	Very problematic animal passage	Problematic animal passage	Standard animal passage	Easy animal passage	Very easy animal passage
6	Retention basin predominantly elevated (>3 m; *e.g.* valley in the highlands with normal slopes)	Basin elevated (>2 m–3 m) and not well integrated into the landscape	Basin elevated (1.5–2 m), but well-integrated into the landscape	Retention basin partly elevated (1 to <1.5 m) and structure perfectly integrated into the landscape	Retention basin not elevated (<1 m) and virtually level with the river; *e.g.* lowland stream
7	Basin directly connected (<5 m) with the watercourse (*i.e.* basin and stream are virtually on-line)	Short connectivity (5 to <10 m), but well-integrated into the landscape	Short connectivity (10–20 m), but elements are clearly separated from each other	Long connectivity (>20–50 m)	Very long connectivity (*i.e.* separate structures are far away (>50 m) from each other)
8	Very wet basin (virtually entirely submerged; *i.e.* >70% wet area); similar to a pond	Wet basin with minor natural components (>60–70% wet area)	Partly wet basin with minor natural components (40–60% wet area)	Dry basin or pond, but with natural components (30 to <40% wet area)	Very dry area with natural components; *i.e.* dry basin or pond (<30% wet area)
9	Permanently flooded main channel (*i.e.* on-line basin with no by-pass); *i.e.* >95% of water volume	Permanently flooded main channel (>90–95% of water volume) and very occasionally flooded by-pass	Partly flooded main channel (80–90% water volume) and occasionally partly flooded by-pass	Main channel (70 to <80% water volume) and partly flooded by-pass	Main channel (<70% water volume) and by-pass (*i.e.* off-line basin) taking most of the flood water
10	Mostly very deep flooding depth as in reservoirs (>3 m); virtually permanently wet	Deep flooding depth (>2–3 m)	Partly flooded; normal flooding depth (1–2 m)	Partly flooded; shallow flooding depth (0.5 to <1 m)	Only occasionally and partly flooded; shallow flooding depth (<0.5 m); virtually a dry basin

(*continued*)

Table 1. Continued.

No.	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5
11	Very prolonged flooding event due to intense and long storms (>70 d); virtually a wet basin	Prolonged flooding event due to long storms (>50–70 d)	Occasional flooding event (30–50 d)	Mostly short flooding event (7 to <30 d)	Mostly very short flooding events (<7 d); virtually a permanently dry basin or pond
12	Very high flood frequency due to high storm frequencies (>15 per a) leads to landscape destruction	High flood frequency due to high storm frequencies (>12 to 15 per a) leads to landscape damage	Normal flood frequency (9 to 12 per a) controlled by management strategies	Low flood frequency, which does not lead to any not aesthetically sights (5 to <9 per a)	Very low flood frequency (<5 per a); rarely monitored
13	Very low gradient (<1%)	Low gradient (1 to <3%)	Normal gradient (3–6%)	High gradient (>6–9%)	Very high gradient (>9%)
14	Mostly very high velocity due to intense storms (>80 cm s^{-1})	High velocity (>60–80 cm s^{-1})	Variable velocity (40–60 cm s^{-1})	Low velocity (25 to <40 cm s^{-1})	Mostly very low velocity, but never stagnant (<25 cm s^{-1})
15	Very short embankment (<200 m)	Short embankment (200 to <350 m)	Normal embankment length (350–500 m)	Aesthetically pleasing long embankment (>500–700 m)	Very long embankment (>700 m); very variable topography
16	Very high volume (>1,000,000 m^3)	High volume (>100,000–1,000,000 m^3)	Standard volume (50,000–100,000 m^3)	Low volume (5000 to <50,000 m^3)	Very low volume (<5000 m^3)
17	Very large surface area reflecting a very large basin (>100,000 m^2)	Large surface area reflecting a large catchment (>20,000–100,000 m^2)	Normal surface area covered with water (10,000–20,000 m^2)	Small aesthetically pleasing surface area (2000 to <10,000 m^2)	Very small surface area reflecting a very small catchment area (<2000 m^2)
18	Very high precipitation due to intense and long storms (>1500 mm a^{-1}) in the catchment; highland climate	High precipitation due to long storms (>1200–1500 mm a^{-1}) in the catchment; partly highland climate	Normal precipitation (800–1200 mm a^{-1}) in the catchment; wet temperate climate	Relatively low precipitation (600 to <800 mm a^{-1}) in the catchment; temperate lowland climate	Very low precipitation (<600 mm a^{-1}) in the catchment; sometimes semi-arid climate
19	Very well-drained with a high infiltration rate (>50 cm d^{-1})	Well-drained with a relatively high infiltration rate (>30–50 cm d^{-1})	Drained with a moderate infiltration rate (10–30 cm d^{-1})	Not well-drained with a low infiltration rate (2 to <10 cm d^{-1})	Mostly not drained (<2 cm d^{-1}); usually a boggy area
20	Very high proportion of clay present (>40%)	High proportion of clay present (>20–40%)	Variable proportions of clay present (10–20%)	Some clay present (5 to <10%)	Clay mostly absent (<5%)
21	Very weakly seasonally influenced (*i.e.* insignificant seasonal variation)	Weakly seasonally influenced	Moderately seasonally influenced	Mostly seasonally influenced (*e.g.* area around Freiburg in Baden, Germany)	Strongly seasonally influenced (*e.g.* typical temperate climate)
22	Very high elevation (>500 m); *e.g.* highlands	High elevation (>300–500 m)	Typical elevation (150–300 m)	Low elevation (50 to <150 m)	Very low elevation (<50 m); *e.g.* marshes
23	Predominantly not vegetated area (*e.g.* only short mowed lawn)	Partly not vegetated area (*e.g.* some grassland or submerged aquatic vegetation)	Vegetated area with low roughness (*e.g.* bushes and some reeds); early succession of plants	Vegetated area with moderate roughness (*e.g.* predominantly reeds, bushes and some trees)	Vegetated area with high roughness (*e.g.* reeds and mature trees such as willows)

24	Virtually no algae present (<5% cover)	Low numbers of algae detected (5 to <10% cover)	Normal algal presence (10–30% cover)	Dominant algal bloom (>30–90% cover)	Very dominant algal bloom (>90% cover)
25	Polluted (high organic and inorganic solids content; occasionally sewage)	Occasionally polluted with solids and/or organics	Occasionally partly polluted	Minor occasional pollution; environment may still be rich in species	Rarely minor pollution; environment may be rich in species
26	Occasional presence of sediment (<3 cm) due to passive and/or occasional basin management	Occasional presence of sediment (3 to <6 cm) due to passive and/or occasional basin management	Aesthetically pleasing sediment layer (6–8 cm); occasional basin management	Deep sediment layer (>8–10 cm) present (*i.e.* mature system)	Very deep and potentially natural sediment layer (>10 cm) present (*i.e.* mature and stable system)
27	Deep inorganic sediment (>10 cm) requiring regular removal	Inorganic sediment layer (>5–10 cm), which is sometimes managed	Mixed sediment layer (≤5 cm of each type)	Organic and predominantly man-made sediment layer (>5–10 cm)	Deep organic and potentially natural sediment layer (>10 cm)
28	Virtually no flotsam	Occasional presence of flotsam	Typical presence of flotsam	Partly covered with flotsam; regular removal required	Dominant cover with flotsam causing problems; immediate removal required
29	Very large catchment (>50 km^2)	Large catchment (>20–50 km^2)	Normal catchment size (10–20 km^2)	Small catchment (0.5 to <10 km^2)	Very small catchment (<0.5 km^2)
30	Very high urban catchment proportion (>50%); *e.g.* city or town	High urban catchment proportion (>30–50%); *e.g.* town or village	Significant urban catchment proportion (20–30%); *e.g.* village	Insignificant urban catchment proportion (10 to <20%); *e.g.* small village	Not urbanised catchment (<10%); *e.g.* only individual houses and/or farms
31	Not agriculturally used; some isolated arable fields (<7%)	Insignificant agriculture; arable fields (7 to <10%)	Significant arable land use (10–15%); typical for Central Europe	Highly intensively used (mostly cash crops) agricultural catchment (>15 to 20%)	Very highly intensively used (mostly cash crops) agricultural catchment (>20%)
32	Not agriculturally used; some isolated pastures used for grazing (<7%)	Insignificant agriculture; predominantly pastures used for grazing (7 to <10%)	Significant pasture (10–15%); typical for Central Europe	Highly intensively used pasture catchment proportion (>15–20%)	Very highly intensively used pasture (>20%)
33	Not intensively used for forestry purposes (<8%)	Virtually an insignificant forested catchment proportion (8 to <15%)	Significant forested catchment proportion (15–20%)	High forested catchment proportion (>20 to 30%)	Very high forested catchment proportion (>30%)
34	Not significantly groundwater-fed (<10%), but may exfiltrate into the local groundwater	Minor groundwater infiltration (10 to <20%)	High groundwater infiltration (20–30%)	Very high groundwater infiltration (>30–50%)	Most of the system depends on groundwater infiltration (>50%)

Note: Each bin number for each variable corresponds to a score in Table 2.

Table 2. Classification matrix: classification variables and associated weightings for different bins (*i.e.* 1 to 5 per application) with and without bias towards different applications of SFRBs.

	Hydraulics bias					Sustainable drainage bias					Environmental protection bias				
No.	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1	25	20	15	10	5	15	12	9	6	3	5	10	15	20	25
2	25	20	15	10	5	15	12	9	6	3	5	10	15	20	25
3	5	4	3	2	1	1	2	3	4	5	4	8	12	16	20
4	25	20	15	10	5	2	4	6	10	8	1	2	3	4	5
5	10	8	6	4	2	2	4	6	8	10	5	10	15	20	25
6	5	4	3	2	1	2	4	6	8	10	4	8	12	16	20
7	10	8	6	4	2	1	2	3	4	5	3	6	9	12	15
8	2	4	6	8	10	4	8	12	16	20	3	6	9	12	15
9	10	8	6	4	2	1	2	3	4	5	2	4	6	8	10
10	2	4	6	8	10	3	6	9	12	15	3	6	9	12	15
11	2	4	6	8	10	2	4	6	8	10	2	4	6	8	10
12	1	2	3	4	5	2	4	6	8	10	3	6	9	12	15
13	10	8	6	4	2	4	5	3	2	1	5	4	3	2	1
14	1	2	3	4	5	2	4	6	8	10	2	4	6	8	10
15	20	16	12	8	4	1	2	3	4	5	3	6	9	12	15
16	25	20	15	10	5	1	2	3	4	5	2	4	6	8	10
17	1	2	3	4	5	3	6	9	15	12	3	6	9	12	15
18	1	2	3	4	5	3	6	9	12	15	5	4	3	2	1
19	1	2	3	4	5	25	20	15	10	5	1	2	3	4	5
20	2	4	6	8	10	3	6	9	12	15	1	2	3	4	5
21	5	4	3	2	1	10	8	6	4	2	2	4	6	8	10
22	10	8	6	4	2	2	4	5	3	1	1	2	3	4	5
23	1	2	3	4	5	2	4	6	8	10	3	6	9	12	15
24	10	8	6	4	2	15	12	9	6	3	2	4	5	3	1
25	1	2	3	4	5	1	2	3	4	5	5	10	15	20	25
26	25	20	15	10	5	25	20	15	10	5	10	8	6	4	2
27	5	4	3	2	1	5	4	3	2	1	1	2	3	4	5
28	20	16	12	8	4	10	8	6	4	2	3	6	9	12	15
29	15	12	9	6	3	5	4	3	2	1	1	2	3	4	5
30	1	2	3	4	5	5	4	3	2	1	3	6	9	12	15
31	10	8	6	4	2	5	4	3	2	1	10	8	6	4	2
32	5	4	3	2	1	5	4	3	2	1	10	8	6	4	2
33	2	4	6	8	10	2	4	6	8	10	1	2	3	4	5
34	10	8	6	4	2	15	12	9	6	3	1	2	3	4	5

	Recreational bias					Landscape aesthetics bias					No obvious bias				
No.	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1	2	4	6	8	10	4	8	16	20	12	16	14	13	12	9
2	5	4	3	2	1	4	8	12	20	16	16	14	12	11	9
3	4	5	3	2	1	5	10	15	20	25	4	5	6	6	7
4	5	4	3	2	1	5	4	3	2	1	14	12	9	7	4
5	2	4	6	8	10	1	2	3	4	5	6	7	7	8	8
6	3	6	15	12	9	3	6	12	15	9	4	5	7	8	7
7	2	4	6	10	8	1	2	3	5	4	6	6	6	6	5
8	3	6	9	15	12	4	8	10	6	2	3	5	8	10	11
9	2	4	5	3	1	4	5	3	2	1	6	6	5	4	3
10	2	4	6	10	8	2	4	6	8	10	2	5	7	9	11
11	2	4	6	8	10	2	4	6	8	10	2	4	6	8	10
12	3	6	9	12	15	3	6	9	12	15	2	4	6	8	9
13	5	4	3	2	1	5	4	3	2	1	7	6	5	3	2
14	3	6	9	12	15	1	2	3	4	5	2	3	5	6	8
15	3	6	9	12	15	3	6	9	12	15	11	11	10	9	8
16	8	10	6	4	2	12	15	9	6	3	15	14	10	8	5
17	2	4	8	10	6	8	10	6	4	2	2	4	6	7	7
18	2	6	10	8	4	1	2	3	5	4	2	3	5	5	5

(*continued*)

Table 2. Continued.

	Recreational bias					Landscape aesthetics bias					No obvious bias				
No.	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
19	2	4	5	3	1	5	4	3	2	1	4	4	5	4	4
20	2	4	5	3	1	1	2	3	5	4	2	4	5	7	8
21	4	5	3	2	1	4	8	12	20	16	5	5	5	5	4
22	1	2	3	4	5	8	10	6	4	2	6	6	5	4	3
23	3	6	12	15	9	3	6	12	15	9	2	4	6	8	8
24	15	12	9	6	3	20	16	12	8	4	11	9	7	5	2
25	5	10	15	20	25	2	4	6	8	10	2	5	7	9	11
26	15	12	9	6	3	20	6	12	8	4	21	16	12	8	4
27	1	2	3	5	4	5	4	3	2	1	4	3	3	3	2
28	5	4	3	2	1	16	20	12	8	4	14	12	10	7	5
29	10	8	6	4	2	4	5	3	2	1	10	8	6	5	3
30	3	6	12	15	9	1	2	3	5	4	2	3	5	7	7
31	1	2	4	5	3	4	8	10	6	2	8	7	6	4	2
32	1	2	4	5	3	4	6	10	8	2	5	5	4	3	2
33	2	4	8	10	6	1	3	5	4	2	2	4	6	7	8
34	1	2	3	5	4	4	5	3	2	1	7	6	5	4	3

Note: The calculation of the sum must be undertaken with the help of table 1, and the sum should be compared with the corresponding entry in table 3.

of weightings for individual classification variables was based on linear and second-order polynomial relationships between opposites such as deep versus shallow, or presence or absence of clay. However, the application of alternative weighting methodologies based on fuzzy logic, case-based reasoning and neural networks could also be considered (Lee *et al.* 2005).

2.3 *Definition of SFRB types*

The variable determination template (table 1) and classification matrix (table 2) are based on similar principles as the novel classification key for ditches in wetlands (Scholz and Trepel 2004a, b; Scholz and Lee 2005; Scholz 2006) and the Sustainable Urban Drainage System Decision Support Key, Matrix and Model (Scholz *et al.* 2005; Scholz 2006).

The purpose of the variable determination template (table 1) is to guide the user in working through the list of classification variables. The corresponding weighting matrix (table 2) can be used individually, if only one purpose of the retention basin dominates (*e.g.* 90% purpose of enhancing the landscape aesthetically), or collectively, depending on their individual proportion of use (*e.g.* 40%, 25%, 25% and 10% use for sustainable drainage, environment protection, recreation and aesthetics, respectively). Table 2 recommends also weightings for SFRBs where their purpose is unclear or not obvious.

Finally, table 3 defines and characterizes six different types of SFRBs as a function of their predominant purpose based on data collected during desktop studies and field visits. The determination of characteristics for all SFRB types is based on experience, and therefore on the expert judgement of the author and his multi-disciplinary research group. In theory, some SFRBs types could be combined or alternatively more types could be identified. However, the proposed classification system is practical and was supported by observations on site.

2.4 *Outline of a worked example*

Step 1 For a particular SFRB (*e.g.* figure 1), use the variable determination template in table 1. Go through each row and note the most appropriate bin number for each variable.

Table 3. Definition of the SFRB types according to their predominant purposes with total scores obtained from table 2 after applying table 1.

Type	Name	Definition of SFRB type	Hydraulics bias	Sustainable drainage bias	Environmental protection bias	Recreational bias	Landscape aesthetics bias	No obvious bias
1	Hydraulic flood retention basin	Managed, traditional and large SFRB that is hydraulically optimized (or even automated) and captures sediment	>260	<130	<160	<110	<140	>240
2	Traditional sustainable flood retention basin	Usually large retention basin used for active flood protection adhering to best management practices	>240–260	>170–190	160 to <190	110 to <130	>140 to <160	>220–240
3	Sustainable flood retention wetland	Aesthetically pleasing retention and treatment wetland used for passive flood protection adhering to sustainable drainage and best management practices	>220–240	>210	190–220	130–150	160–180	>200–220
4	Aesthetic flood treatment wetland	Treatment wetland for the retention and treatment of contaminated runoff, which is aesthetically pleasing and integrated into the landscape, and has some social and recreational benefits	200–220	>190–210	>220–250	>170–190	>220	180–200
5	Integrated flood retention wetland	Integrated semi-natural flood retention wetland for passive treatment of runoff, passive flood retention and enhancement of recreational benefits	180 to <200	150–170	>250–280	>190	>200–220	160 to <180
6	Natural flood retention wetland	Passive natural flood retention wetland that became a site of scientific interest requiring protection from adverse human impacts	<180	130 to <150	>280	>150–170	>180–200	<160

Figure 1. SFRB in Merzhausen (near Freiburg, Baden) on 4 April 2006. Applying tables 1 and 2, the score was 277 (*i.e.* hydraulic flood retention basin).

For example, bin 3 for variable 1 (40%), bin 1 for variable 2 (12 m), (. . .) and bin 1 for variable 34 (5%).

Step 2 Decide on the most appropriate SFRB application. Each selected bin number (table 1) corresponds to a score in table 2. Write all scores down and sum them up. For example, the main application bias is towards hydraulic optimization; therefore, $15 + 25 + (\ldots) + 10 = 277$.

Step 3 Define the SFRB type with table 3. For example, select the column 'hydraulics bias' based on step 2 and identify the type and name of the SFRB as '1' and 'hydraulic flood retention basin', respectively.

3. Results and discussion

3.1 *Classification variables and their wider context*

Voeseneck *et al.* (2004) discussed the following habitats that are important for a decision support system: river, river banks, natural levees, floodplain, floodplain channel, back swamp areas (with or without flood channels), areas protected by summer flooding embankments and areas protected by flood dykes. In addition, structures such as SFRBs are likely to develop their own habitats after years or decades, depending on management, flooding characteristics and climate. These habitats are indirectly reflected in the selection and characterization of the classification variables (table 1).

Van den Brink *et al.* (1994a, b) highlighted the importance of topographical, geomorphologic, hydrological and habitat characteristics. They discussed variables including location (*i.e.* hydrological habitat; *e.g.* site in open connection and isolated site in river foreland or behind the main dyke), water surface area, water depth, distance from river (*i.e.* connectivity; variable number 7 in table 1), flood duration, sediment composition (sandy, clayey and organic)

and vegetation (submerged, nymphaeid and emergent). Table 1 summarizes most of these variables either directly or indirectly.

Van den Brink *et al.* (1994b) related phytoplankton and zooplankton to their feeding characteristics (*i.e.* predator, filter feeder, scraper and sucker) and their habitat (*i.e.* open water, sediment and macrophyte). These criteria are relevant, if the retention basins should have ecological benefits. However, most of these ecological variables are too specific for civil engineers and time-consuming to determine for the purpose of a 'global' SFRBs classification system. Nevertheless, animal passage (variable number 5; table 1) accounts for the functioning of the SFRBs (*i.e.* particularly the dam and its outlet arrangement) as a barrier in the landscape restricting animal movement.

Concerning the final variable on groundwater infiltration (*i.e.* groundwater; variable 7 in table 1), Trémolières *et al.* (1993) and Scholz and Trepel (2004a, b) indicated that this variable is important, if a watercourse is being fed by groundwater (particularly on high ground). However, reservoir water exfiltration (particularly on high ground) can be a more frequent problem in practice.

3.2 *Application of the SFRB classification system for Baden-Württemberg*

The author estimates that there are more than 3000 areas within the River Rhine catchment of the federal state of Baden-Württemberg (South-west Germany), which could be classified as retention basins using the widest possible definition in agreement with German guidelines (ATV-DVWK 2001). The author revised and applied an active database provided by Mr. Bernd Karo (Federal Environmental Ministry of Baden-Württemberg), and updated by Mr. Daniel Siepmann-Schinker (Institute for Landscape Management), which characterizes approximately 660 of the known important and strongly man-made retention basins. It was obvious that there is a bias towards large engineered and permanent retention basins in this database. However, the author estimates that the volume of these known retention basins is likely to be >95% of the total basin volume in the River Rhine catchment (*i.e.* for Baden-Württemberg only). The remaining retention basins are dominated by watercourses such as wet meadows, ditches and semi-natural ponds.

For the purpose of this paper, an SFRBs is defined as an aesthetically pleasing retention basin predominantly used for flood protection adhering to sustainable drainage and best management practices. The adjective aesthetic means visually pleasing, and is defined in the context of landscaping as pertaining to the appreciation of beauty and good taste. The noun that corresponds to aesthetic is aesthetics, which means the study of the appreciation of beauty and good taste. Landscape design and management is concerned both with aesthetic and functional elements of landscaping. For example, a long, large and grey concrete dam is usually seen as less aesthetically pleasing than a short, small and planted dam. An SFRBs has therefore to be visually attractive. This obviously goes beyond a characterization based purely on traditional engineering variables such as dam height, retention volume and surface area.

An overwhelming majority of 92% of all recorded retention basins in Baden-Württemberg had a clear flood protection purpose. With respect to the approximately 660 flood retention basins, 77% were classified as SFRBs. However, this was expected considering the dominant flood retention purpose of the basins.

3.3 *Application of the SFRB classification system for South Baden*

There is a relatively great variability among the variables summarizing the key characteristics of SFRBs (tables 3 and 4), which are used predominantly for hydraulic purposes such as water retention and sedimentation, and which are located in the same area (*i.e.* South Baden).

Table 4. Prioritization example for classification variables (see table 1 for details) used for a detailed data set of 56 SFRBs in South Baden (Germany).

Variable	No.	PP†	Correlation‡	Certainty§	Mean	SD¶
Nine key classification variables						
Rainfall (mm)	18	648	7.72	84	731	99.3
Dam height (m)	2	624	7.77	80	4	3.1
Flood water volume (m^3)	16	622	7.92	78	54,100	82,900.0
Elevation (m)	22	603	6.56	92	237	42.1
Dam length (m)	3	601	7.16	84	286	426.8
Flotsam (−)	28	594	7.92	75	1.9	1.25
Floodplain elevation (m)	6	593	7.47	79	0.5	1.52
Forest (%)	33	535	8.82	61	23	23
Animal passage (−)	5	515	6.63	78	1.8	0.92
Other classification variables						
Algae (% cover)	24	490	5.60	88	5	16.5
Channel system (%)	9	470	5.27	89	93	21.0
Water surface area (m^2)	17	464	7.53	62	83,100	52,100.0
Embankment length (m)	15	459	7.67	60	420	438.9
Pollution (−)	25	449	7.18	63	2.8	1.13
Wetness (%)	8	441	5.68	78	22	28.0
Pasture (%)	32	422	6.76	63	29	26.0
Naturalness (%)	1	417	5.99	70	52	20.8
Connectivity (m)	7	401	4.24	95	0.9	2.69
Season (−)	21	397	4.59	87	3.9	0.49
Arable (%)	31	387	6.20	63	27	26.6
Sediment composition (cm)	27	385	5.91	65	3.9	5.99
Vegetation (−)	23	377	4.80	79	3.1	1.26
Groundwater (%)	34	375	5.68	66	4	8.7
Sediment depth (cm)	26	370	5.77	64	5.2	7.93
Catchment size (km^2)	29	363	7.52	48	7.6	10.78
Flooding depth (m)	10	358	5.90	61	1.7	0.83
Slope (%)	13	341	4.84	71	2.7	2.02
Urban (%)	30	330	4.68	71	12	13.1
Outlet flexibility (%)	4	262	3.71	71	20	24.4
Flood frequency (a^{-1})	12	218	4.79	46	7	6.1
Flood duration (d)	11	209	3.90	54	27	75
Clay (%)	20	156	4.86	32	11	13.1
Drainage ($cm\,d^{-1}$)	19	144	4.62	31	14	13.5
Velocity ($cm\,s^{-1}$)	14	126	4.29	29	49	56.8

†Priority points = (column 4) × (column 5). ‡Sum of all absolute correlation coefficients for one particular variable with all other variables. §Certainty of a correct value expressed in % by the author and his research team. ¶Standard deviation.

Therefore, the variable determination template (table 1) and the corresponding classification matrix (table 2) can be used to sub-classify SFRBs (table 3).

For example, figures 1–4 show four closely related engineered SFRBs sub-classified as types 1 to 4 (table 3), respectively. The selected SFRB examples all had a dominant hydraulic bias (table 2). The first example (figure 1) shows a hydraulically optimized basin, which captures large amounts of sediment during floods. Figure 2 shows a retention basin used predominantly for flood protection but adhering to best management practices including water treatment. Figure 3 shows an aesthetically pleasing retention and treatment wetland, which has an important treatment and infiltration function, and is used for passive flood protection adhering to sustainable drainage and best management practices. The final example (figure 4) is an aesthetic flood treatment wetland. This is a permanently wet treatment wetland for the retention and active purification of contaminated runoff, which is not hydraulically optimized but perfectly integrated into the landscape, and has some social, recreational and ecological benefits.

A careful estimation based on a randomly (*i.e.* 1 in 3) selected sub-sample of 56 thoroughly researched SFRBs in South Baden shows that the predominant use is for hydraulic purposes

Figure 2. SFRBs in Müllheim (Baden) on 26 April 2006. Applying tables 1 and 2, the score was 250 (*i.e.* traditional SFRBs).

Figure 3. SFRBs near Denzlingen (Baden) on 19 April 2006. Applying tables 1 and 2, the score was 232 (*i.e.* sustainable flood retention wetland).

(48 basins), followed by environmental protection (3 basins) and recreational (3 basins), and finally by sustainable drainage (1 basin) and landscape aesthetics (1 basin) purposes. The mean hydraulic, drainage, environmental, recreational and landscape bias estimated values for all 56 SFRBs are 50%, 11%, 16%, 13% and 10%, respectively. The corresponding standard deviations were 17.8%, 8.1%, 8.1%, 8.9% and 6.2%, respectively.

Figure 4. SFRBs near Königschaffhausen (Baden) on 18 April 2006. Applying tables 1 and 2, the score was 212 (*i.e.* aesthetic flood treatment wetland).

Moreover, 15, 21, 9, 8, 1 and 2 of the thoroughly researched SFRBs belong to sub-classes 1–6, respectively (table 3). This bias towards engineered SFRBs is likely to be representative for the remaining SFRBs in Baden-Württemberg.

3.4 *Prioritization exercise for classification variables*

A correlation analysis was performed between all classification variables. Some variables such as outlet flexibility, flood duration and connectivity can be seen as independent due to their lack of correlation with other variables. In contrast, the variables forest, flotsam and flood water volume, for example, correlated very well with other variables, and should therefore be regarded as dependent variables (table 4). However, this does not necessarily mean that they could be replaced by other variables or that they may replace other variables, because their relationships among each other and with other variables are also functions of the retention basin use and specific local boundary conditions such as storm characteristics and local management policies not captured by the classification system.

Table 4 presents an unbiased attempt to prioritize the classification variables based on their correlation with other variables (*i.e.* concerning the sum of absolute correlation coefficients, the more the better) and the certainty (*i.e.* confidence of the expert team in choosing the data point) associated with the correctness of the corresponding numerical value. The variables rainfall (mm), dam height (m), flood water volume (m^3), elevation (m), dam length (m), flotsam (−), floodplain elevation (m), forest (%) and animal passage (−) were the most promising variables. A cutoff point at 500 priority points based on expert judgement (*i.e.* high correlation value for forest and high certainty value for animal passage) was chosen.

Tables 1–3 were also applied for only the top nine variables listed in table 4 and for the 48 SFRBs with a clear hydraulic application bias. However, the relative importance of the nine selected variables based on their corresponding proportion of summed-up scores in relation to the maximum possible score was applied to adapt tables 1 and 2. The relative adjusted mean

absolute error between the original scores (based on 34 variables including the key variables) and the new scores (based on the 9 key variables only) was 8.6%. The corresponding standard deviation was 5.86%, which is relatively low considering the relatively high diversity of SFRBs.

It follows that this variable reduction exercise (*i.e.* 9 instead of 34 variables) would result in a mean shift of only 0.7 of a type of SFRBs (table 3); *e.g.*, type 2 or type 4 would have been selected instead of type 3. This loss in SFRBs identification accuracy might be justified in some cases by the reduction in assessment time to approximately 20 min, considering that all of these key variables (except for flotsam) can be easily determined during a desktop study.

4. Conclusions

This paper provides clear definitions for different types of SFRBs associated with different applications, including hydraulic purposes, sustainable drainage, environmental protection, recreational activities and landscape aesthetics. The following new types were defined: hydraulic flood retention basin, traditional sustainable flood retention basin, sustainable flood retention wetland, aesthetic flood treatment wetland, integrated flood retention wetland and natural flood retention wetland.

The definitions for the different types of SFRBs are based on a set of tables with weightings for 34 classification variables. Weightings can be obtained with the support of the variable determination template containing qualitative and frequently also quantitative descriptions for the classification variables.

The River Rhine catchment with particular bias towards the upper river catchment in Baden has been used as a case study. A bias towards engineered SFRBs in South Baden was obvious. The nine most important variables were rainfall, dam height, flood water volume, elevation, dam length, flotsam, floodplain elevation, forest and animal passage, considering a correlation analysis and estimating the certainty of numerical correctness based on the confidence of the research team in the field. A variable reduction exercise has shown that 9 instead of 34 variables could also be used but that the SFRBs identification accuracy would decrease too much to justify the gain in assessment time reduction.

The characterization methodology outlined could be implemented worldwide. However, the specific variable determination template, the classification matrix and the associated SFRBs type definitions are likely to be only applicable for Europe, Northern America and other regions with a temperate climate.

Acknowledgements

This original research paper is part of the output of the research project entitled *Classification of Vegetated Flood Water Retention Areas in the River Rhine Catchment* funded by the Alexander von Humboldt Foundation. A research fellowship was awarded to the author in December 2005. The author thankfully acknowledges his host Prof. Werner Konold (Institute for Landscape Management, University of Freiburg, Baden, Germany) and technical support provided by Dr Bernoît Sittler, Mr. Rainer Dietrich and Mr. Daniel Siepmann-Schinker.

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