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Case study: Design, operation and water quality management of a combined wet and dry pond system

Pond structures as cost-effective water treatment, storage and “source control” drainage techniques can be applied in order to reduce wastewater treatment costs, produce water for subsequent recycling and reduce the risk of downstream flooding. However, there is a need for detailed design, operation and maintenance data. The purpose of this study was to optimise design and operation guidelines, and to assess the water treatment potential of stormwater pond systems. Performance data (15 months) for a stormwater pond pilot plant were collected. The system is based on a combined silt trap, attenuation wet pond and dry pond system applied for drainage of roof water run-off from a single domestic property. United Kingdom Building Research Establishment and Construction Industry Research and Information Association, and German Association for Water, Wastewater and Waste design guidelines were tested. These design guidelines were insufficient because they do not consider local hydrological and soil conditions. The infiltration function for the dry pond is logarithmic and depends on the season. Furthermore, biochemical and physical algal control techniques were successfully applied, and passive water treatment of rainwater run-off with a wet pond was found to be sufficient. However, seasonal and diurnal variations of biochemical oxygen demand, dissolved oxygen and pH were recorded. Finally, capital and labour costs for small ponds are high.

Keywords: roof run-off; wet pond; dry pond; design guidelines; infiltration; water quality; control of algae.

List of notations and abbreviations

a	=	Coefficient (unknown function of variables including rainfall intensity and infiltration rate)
ATV-DVWK	=	German Association for Water, Wastewater and Waste
b	=	Maximum (experimental) depth (mm) within the dry pond during an individual storm
BOD	=	Five-day @ 25 °C biochemical oxygen demand (mg/l)
BRE	=	Building Research Establishment
CIRIA	=	Construction Industry Research and Information Association
D	=	Dry pond design depth (mm)
DO	=	Dissolved oxygen (mg/l)

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DP	=	Dry pond
GAC	=	Granular activated carbon
ETAAS	=	Electrothermal Atomic Absorption Spectrometer
ICP-OES	=	Inductively Coupled Plasma Optical Emission Spectrometer
IR	=	Infiltration rate (m/s)
NTU	=	Nephelometric turbidity unit
R	=	Mean product moment correlation coefficient
SS	=	Suspended solids (mg/l)
T	=	Infiltration time (s)
TS	=	Total solids (mg/l)
WP	=	(Attenuation) wet pond
Z ₁	=	Factor (defined by the BRE method)
Z ₂	=	Growth factor

1. Introduction

1.1 Roof run-off

Conventional stormwater and urban drainage systems have the purpose of disposing rainfall-runoff water as quickly as possible. This results in “end of pipe” solutions that often involve the provision of large interceptor and relief sewers, huge storage tanks in downstream locations and centralised wastewater treatment facilities.¹

In contrast, combined wet and dry ponds as cost-effective “end of pipe” drainage solutions can be applied for local “source control”; e.g., diversion or collection of roof drainage. It is often possible to divert all roof drainage for infiltration or storage and subsequent recycling. As runoff from roofs is a major contributor to the quantity of surface water requiring disposal, this is a particularly beneficial approach where suitable ground conditions prevail.

Apart from design issues related to “source control”, this paper addresses also water quality aspects associated with the run-off from roofs, which is a research area often neglected in engineering literature^{1,2}. Rain is by its nature fairly unpolluted but the run-off is often contaminated with SS (e.g., weathered building materials, decayed leaves, bird droppings and particles from atmospheric pollution) and requires at least passive treatment before recycling or disposal.

1.2 Case study

A domestic property in Sandy Lane (Bradford, West Yorkshire, England) was selected for this pilot plant case study. The study area is located approximately 1.8° West of Greenwich and 53.8° North of the Equator. The surface water (subject to disposal) came from the house roofs and the roof of a tandem (double) garage. In the original pipeline layout plan dated 1972, rainwater drained into the public sewer. However, in April 2001 this layout was changed in order to feed a semi-natural attenuation wetland structure (Figs. 1 and 2) with rainwater. The storage water was predominantly used for watering garden plants in summer, but there is a much greater potential for other usage; e.g., recycling of surface water to flush toilets. If the

attenuation wet pond structure overflows, the water is transferred to a dry pond structure designed to hold up to approximately 1.9 m³ water (Fig. 2).

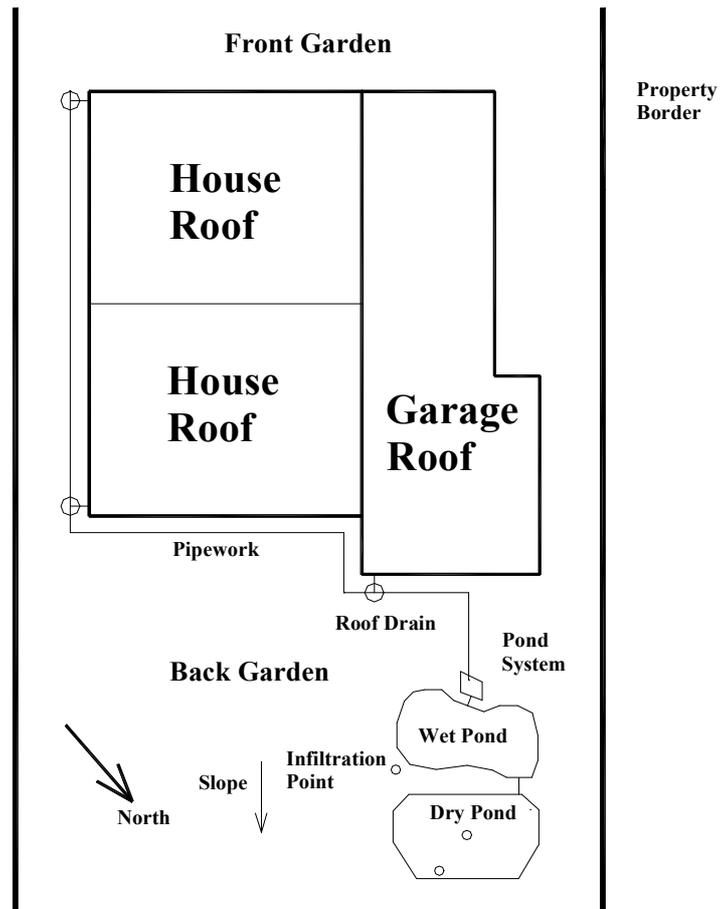


Figure 1: Drawing (not to scale) of the case study site showing roof areas, pipework and the combined attenuation wet and dry pond system.



Figure 2: Attenuation wet pond (top picture) and dry pond (bottom picture) in winter 2001/02.

1.3 Purpose

The purpose of this paper is not only to investigate a case study of a sustainable urban drainage system designed according to best management practice² but also to address the following key objectives in order to assess the potential for up-scaled systems:

- to identify technical difficulties and constraints associated with the design, operation and maintenance,
- to characterise infiltration relationships,
- to assess the water treatment efficiency of the pond system for roof run-off water,
- to suggest water quality management strategies including algal control techniques, and
- to identify economic issues influencing the design, operation and maintenance.

2. Materials and Methods

2.1 Study site design

The pilot plant was designed considering BRE³, CIRIA^{2,4} and ATV-DVWK⁵ sustainable urban drainage system guidelines. The study site system allows flooding to occur not more than once within ten years. However, the German guideline recommends construction for a five-year design storm only.⁵ Detailed tables summarising the design calculations based on statistically sound synthetic hydrographs are available on request.

The system is based on a combined silt trap, attenuation wet and dry pond design (Figs. 1 and 2). Rainwater run-off from two house roofs (one house only) and the flat roof of a tandem garage was drained directly into a silt trap. It has to be noted that the roof areas have not been cleaned for at least five years before the start of the study. This information is based on the statements (verbal communications) provided by the current and previous owners of the property.

The distances between the building (garage) and the attenuation wet and dry pond are 1.5 and 5.0 m, respectively (Fig. 1). The surface areas of both house roofs are 29 m² each. The angle between each roof and the ceiling of the house is 23°. The total theoretical horizontal area of the house roofs is 53 m². The roof area of the tandem garage is 33 m². It follows that the total horizontal area to be drained is 86 m².

The total length of the plastic pipework (mean angle of 2°) is 19.6 m. The inside diameter of the pipe is 6.5 cm. The maximum horizontal average dimensions (length × width) of the silt trap and attenuation wet pond are 0.3 × 0.4, 0.7 × 0.4 and 3.2 × 1.7 m, respectively (Figs. 1 and 2). The maximum depths of the attenuation wet pond and dry pond are 39.5 and 40.0 cm, respectively. All water level measurements are taken daily at a reference level stone that is part of the wet pond outflow structure (Figs. 1 and 2).

The semi-natural pond structure consists of two water bodies with a total effective volume of approximately 1.7 m³ during dry and 1.9 m³ during storm events. The rainwater drains in the silt trap with a maximum capacity of 0.1 m³ (Fig. 1). Water from the silt trap overflows into



the wet pond (mean volume of approximately 1.7 m^3), which is designed as both an attenuation wet pond and storage pond. The dry pond will take a maximum of approximately 1.8 m^3 during very heavy storm events before it overflows.

The total area of the experimental attenuation wet pond is 5.5 m^2 when completely filled with water. In comparison, the effective horizontal maximum dimensions of the dry pond are $3.7 \times 2.5 \text{ m}$ (Figs. 1 and 2). The associated slope ratios are 1 : 1.6 (towards the wet pond in the West), 1 : 1.9 (towards North and South) and 1 : 2.4 (towards the lower garden in the East).

The dominant macrophytes are Common Reed (*Phragmites australis*), Reedmace (*Typha latifolia*) and Yellow Iris (*Iris pseudochorus*). Water Starwort (*Callitriche stagnalis*) and Frogbit (*Hydrocharis morsus-ranae*) are common floating aquatic plants. Canadian Waterweed (*Elo-dea canadensis*) is the dominating submerged plant. Common Reed and Reedmace (both deep-rooting) were also planted in the dry pond in order to enhance infiltration properties. All planted aquatic plants were collected locally from natural habitats.

At the top of the food chain (attenuation wet pond) are two Koi fish (introduced during pond construction in April 2001), at least 25 European Three-spined Sticklebacks (*Gasterosteus aculeatus*; introduced in September 2001) and the Common Grass Frog (*Rana temporaria*; approximately 20 adults and at least 2,500 tadpoles during spring and summer).

2.2 Engineering methods

A simple rain gauge comprising a measurement cylinder fed through a funnel (diameter of 9 cm) was used in order to estimate rainfall depth. Two gauges were used to give a more representative estimate of rainfall. Experimental rainfall data were compared with official data (Bradford measurement station) supplied by the Meteorological Office.⁶ The rain gauges were located between the wet and dry ponds (Figs. 1 and 2).

Direct infiltration rates were determined fortnightly or monthly by measuring the actual infiltration time of 200 ml tap water through the first 4 cm of a 24 cm long drainage pipe (diameter of 6.5 cm). The pipe was buried vertically in the ground at a depth of approximately 20 cm. The infiltration test was carried out at three infiltration point stations (marked on Fig. 1) in parallel under varying natural and particularly meteorological conditions.

2.3 Water quality analysis

Temporal (daily or weekly) sampling schemes were applied. Daily sampling and subsequent analysis took place at approximately 06:00 and/or 18:00. All analytical procedures to determine water quality were performed according to standard methods⁷ that outline also the corresponding water quality criteria. Water samples were tested for temperature (air and water), BOD, SS, TS, conductivity, turbidity, DO and pH. Hanna instrumentation, HI 9033 conductivity, C 102 turbidity, HI 9142 DO and HI 8519N pH meters were used throughout the study.

Oxidised aqueous nitrogen was determined as the sum of nitrate and nitrite. Nitrate was reduced to nitrite by cadmium and determined as an azo dye at 540 nm (using a Peristorp Analytical EnviroFlow 3000 flow injection analyser) following diazotisation with sulfanilamide and subsequent coupling with N-1-naphthylethylenediamine dihydrochloride. This technique



measures also nitrite at the same time. Furthermore, ammonia in waters reacted with hypochlorite and salicylate ions in solution in the presence of sodium nitrosopentacyanoferrate (nitroprusside). Phosphate present in waters reacts with acidic molybdate to form a phosphomolybdenum blue complex. The associated coloured complexes were measured spectrophotometrically at 655 and 882 nm, respectively, using a Bran and Luebbe Autoanalyser (Model A411). All analyses for nutrients were carried out in triplicates.

An ICP-OES TJA IRIS instrument (ThermoElemental, USA) operated at 1350 W with coolant, auxiliary and nebuliser argon gas flows of 15, 0.5 and 0.7 ml/min, respectively, and a pump flow rate of 1 ml/min was used to screen for total elemental concentrations in filtered (applying Whatman 0.45 µm cellulose nitrate membrane filters) water samples and digests. Multi-element calibration standards in the concentration range 0.1-10 mg/l were used and the emission intensity measured at appropriate wavelengths in nm. Further information on elements and corresponding wavelengths selected is available on request. For all elements, analytical precision (relative standard deviation) was typically 5-10% for individual aliquots. Three replicates for each sample were analysed.

To prepare acid digests of the vegetation, samples were dried at 105 °C overnight in a drying oven (UM500, Memmert) prior to being ashed at 400 °C for 12 h in a muffle furnace (ELF 11/14, Carbolite). Ashed samples (approximately 0.2-0.6 g) were then digested under reflux in *aqua regia* for 2 h, cooled, filtered through Whatman No. 5412 filter papers and made up to 100 ml with de-ionised water ready for analysis.

An electrothermal Varian SpectrAA 400 Spectrometer, ETAAS, (Varian Inc., Australia) with auto-sampler and powered by a GTA-96 graphite tube atomiser was used to analyse some of the water samples by ETAAS for their zinc content. An injection volume of 20 µl was used to introduce both samples and standards into a coated, notched partition tube. Nitrogen was used as the carrier gas. The char temperature was 300 °C with a ramp rate of 10 °C/s and a hold time of 3 seconds. For atomisation, the temperature was set to 1900 °C with ramp and hold times of 1 °C/s and 2 s, respectively. Precision in terms of the relative standard deviation was typically less than 5% for triplicate injections.

2.4 Control of algae

Visual algal cover estimations were undertaken by using a 0.2 × 0.2 m reference grid (Fig. 2); metal grid located on top of the attenuation wet pond during the experiment that could also be used permanently to minimise danger to children.

Moreover, microorganisms including algae like *Microspora spp.* (dominates blanket weed) were counted using a Sedgewick-Rafter Cell S50 (counting chamber: 1 × 50 × 20 mm) and a Wang Biomedical Research Microscope 6000 (bright field and phase-contrast).

Excess algae and decomposing litter were occasionally removed from the study site. Wet algae and litter were weighed after the biomass was drained for two minutes by applying maximum pressure with both hands to small portions of organic waste. Blanket weed control with barley straw (commercial product called Frogmat) was also practiced. Approximately 0.2 kg straw per bale was located at eight sites (approximately 1.6 kg straw in total) near the wet pond margins between 31 August and 31 October 2001, and 22 February and 18 May 2002.



Between 15 March and 12 August 2002, an experimental GAC filter cleaned the roof run-off before it reached the silt trap. Approximately 1.4 kg GAC (Grade 207 EA, US mesh: 12×40) was used to test the purification potential with respect to trace elements which might contribute to algal growth.

3. Results and Discussion

3.1 Hydrological considerations

The pilot plant was designed in line with United Kingdom BRE and CIRIA, and German ATV-DVWK guidelines.²⁻⁵ Findings are based on the design assumption that flooding for the case study site might statistically occur only once within ten years (defined as return period). The estimated mean IR applied for all methods is 10^{-4} m/s (Table 1).

The return periods during the experimental duration were exceeded for the CIRIA, ATV-DVWK and BRE guidelines 16, 7 and 1 times, respectively (Fig. 3). Figure 3 indicates also that 1, 5 and 10 severe storms were recorded in spring (May), summer (July and August) and winter (February). The two most severe storms were short but intense summer rainfall events. It follows that the BRE method would be the only acceptable guideline if calculations required for short but intense summer storms had been incorporated.

At the case study site, 2160 mm precipitation was recorded between summer 2001 and spring 2002. There is no official long-term rainfall record available for Sandy Lane. However, the experimental measurement period contained wet but representative seasons because the study site is located on an exposed hill (approximately 240 m above sea level). In comparison, the annual average rainfall for Bradford City (located in a valley) is approximately 830 mm.⁶

It was not the purpose of this study to concentrate on hydrograph analysis based on actual local measurements. The study time of 15 months would have been too short to come up with representative hydrographs. In comparison, the official synthetic hydrographs for Sandy Lane, which are based on decades of national measurement programmes and associated with the BRE calculation procedure³, were used to demonstrate the shortcomings of the BRE, CIRIA and ATV-DVWK guidelines.

Nevertheless, the effect of the actual daily rainfall on the wet and dry pond water levels is summarised in Fig. 3. Furthermore, hourly measurements (sometimes even during storms) were applied to specify infiltration curves as indicated in Figs. 4 and 5.

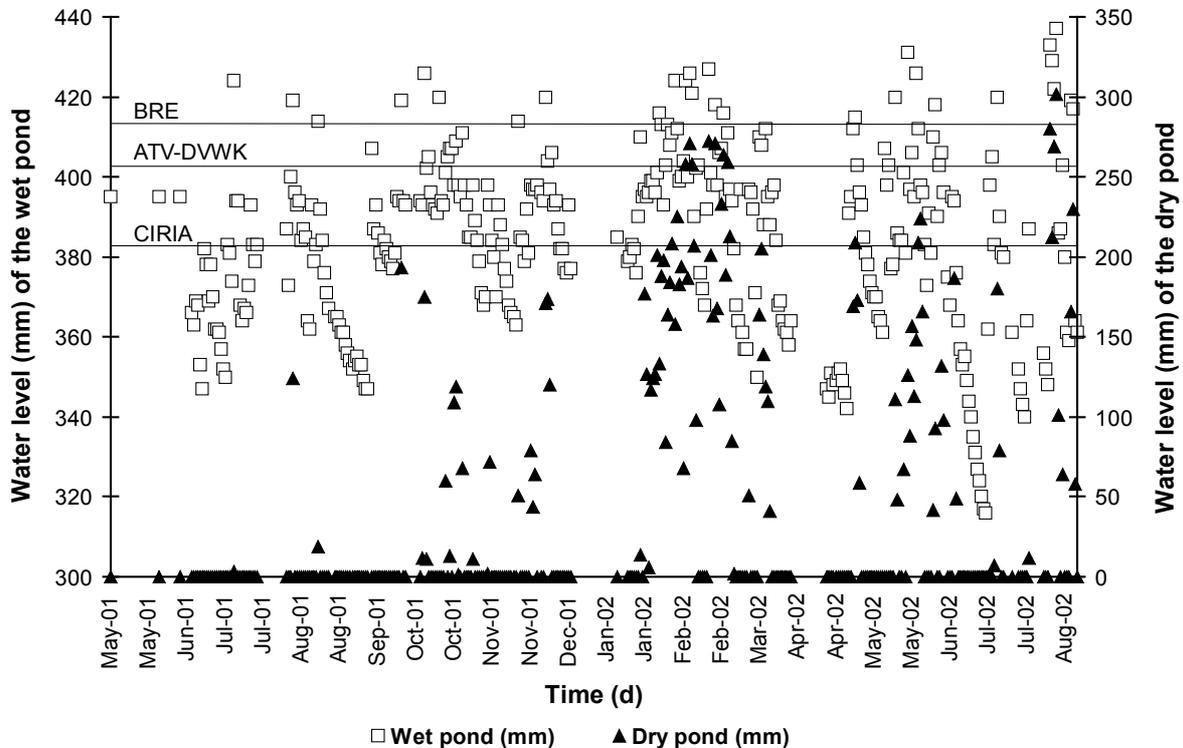


Figure 3: Maximum daily water level fluctuations within the attenuation wet pond and dry pond between 13 May 2001 and 12 August 2002. Maximum dry pond height requirements calculated according to Building Research Establishment (BRE²), Construction Industry Research and Information Association (CIRIA³) and German Association for Water, Wastewater and Waste (ATV-DVWK⁴) guidelines are indicated by horizontal lines.

3.2 Design

The critical storm durations for the BRE, CIRIA and ATV-DVWK design calculations were 1.0, 0.5 and 1.0 h, respectively. The associated maximum dry pond height (and storage volume) requirements were 28 (1.41), 21 (1.04) and 26 (1.27) cm (m³), respectively.

Maximum dry pond height requirements calculated according to BRE³, CIRIA⁴ and ATV-DVWK⁵ guidelines were not sufficient for the period of the experiment. Figure 3 indicates when the system would have failed if the recommended design depths for the dry pond would have been applied.

Equation (1) shows the mathematical relationship between the dry pond design depth D in mm and the infiltration time T in h. The corresponding mean product moment correlation coefficient R for the function is 0.90.

$$D = -a + \ln(T) + b \quad (1)$$

Figures 4 and 5 demonstrate the mathematical relationship between the terms “a” and “b”. Both “a” and “b” are based on logarithmic trendline functions for 36 recorded storms (between 3 and 8 depth measurements each) between May 2001 and August 2002. Term “a” is a coefficient whereas “b” represents the maximum depth within the dry pond during an individual storm. The corresponding R indicates the closeness of the fit for a system that is either shallower or deeper than about 185 mm. Furthermore, the infiltration behaviour for heavy storms during winter is considerably different from the infiltration behaviour during other seasons (for quantification; Fig. 5). The soil is usually saturated with water in the winter.

The mathematical relationships summarised in Figs. 4 and 5 will give the design engineer the opportunity to estimate design depths related to different infiltration times and vice versa. However, the findings are only applicable for constructions with similar specifications.

3.3 Design comparisons

The actual design for the dry pond (40 cm depth and 1.7 m³ volume) was acceptable when compared to BRE³, CIRIA⁴ and ATV-DVWK⁵ guidelines. Any signs of system failure (e.g., flooding of the lawn and structural damage) have not yet been observed. However, strict application of all tested guidelines (without adding a higher safety factor than recommended) would have led to system failures during the first year of operation.

It has been shown in Fig. 3 that all three official designs have failed at least once during the first 15 months of their ten-year design period. However, the period of study can be described as a particularly wet time (see above).

Considering a maximum depth of 40 cm, the dry pond has theoretical “spare heights” (associated with under-utilised storage capacity) between 12 and 19 cm.³⁻⁵ However, observations (Fig. 3) have shown that a depth of 40 cm is justified considering that rainfall-runoff events have led to maximum design water depths being exceeded (see above). It follows that there would have been no “spare heights” for strict applications of the standard design guidelines. In comparison, the “spare height” of the actual design by the authors was 9 cm.

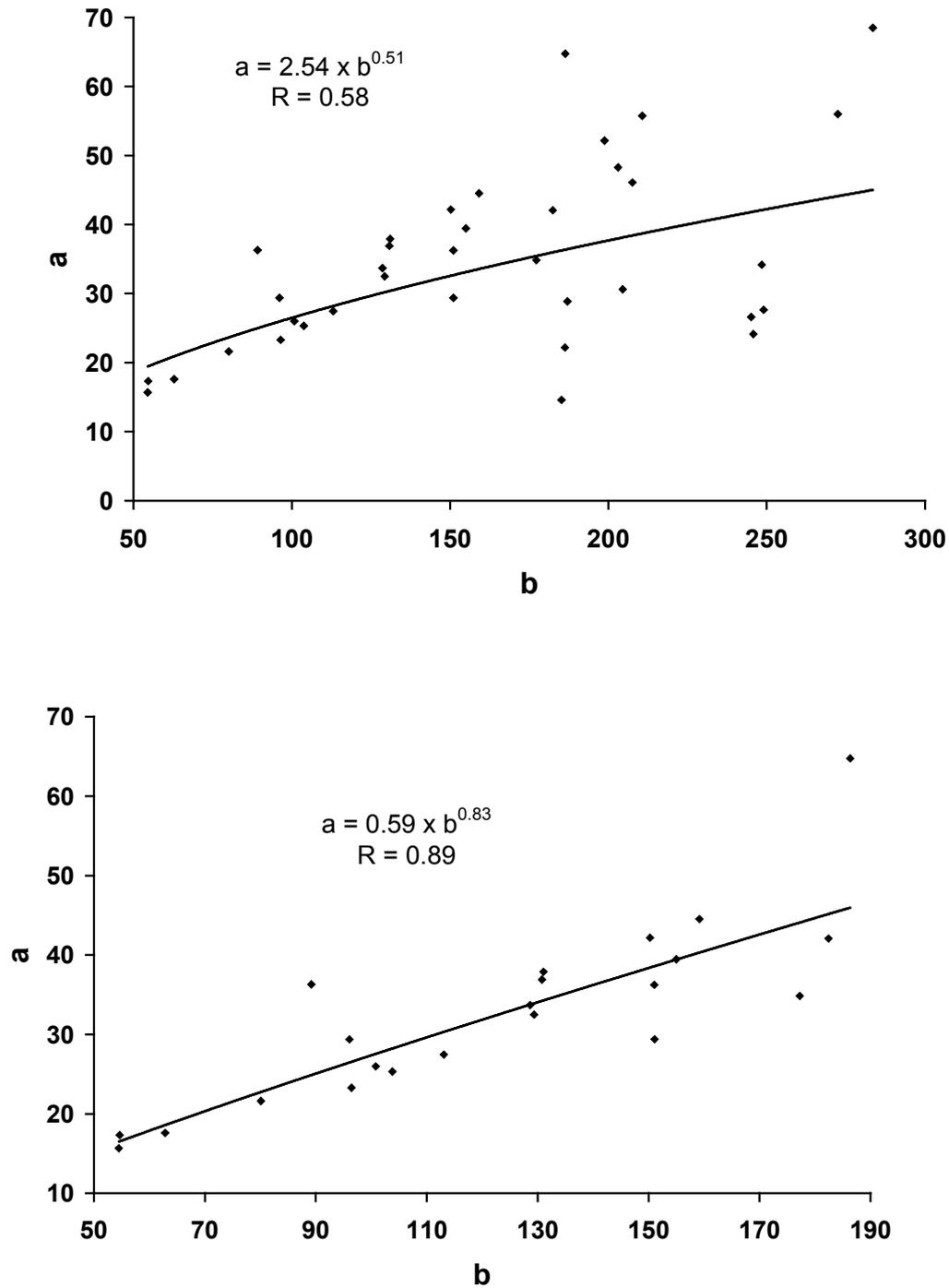


Figure 4: Relationships between the coefficient “a” and the maximum depth “b” (mm) within the dry pond during an individual storm (top and bottom figures). The bottom figure indicates an optimised trendline fit for small values of “b”. R = mean product moment correlation coefficient.

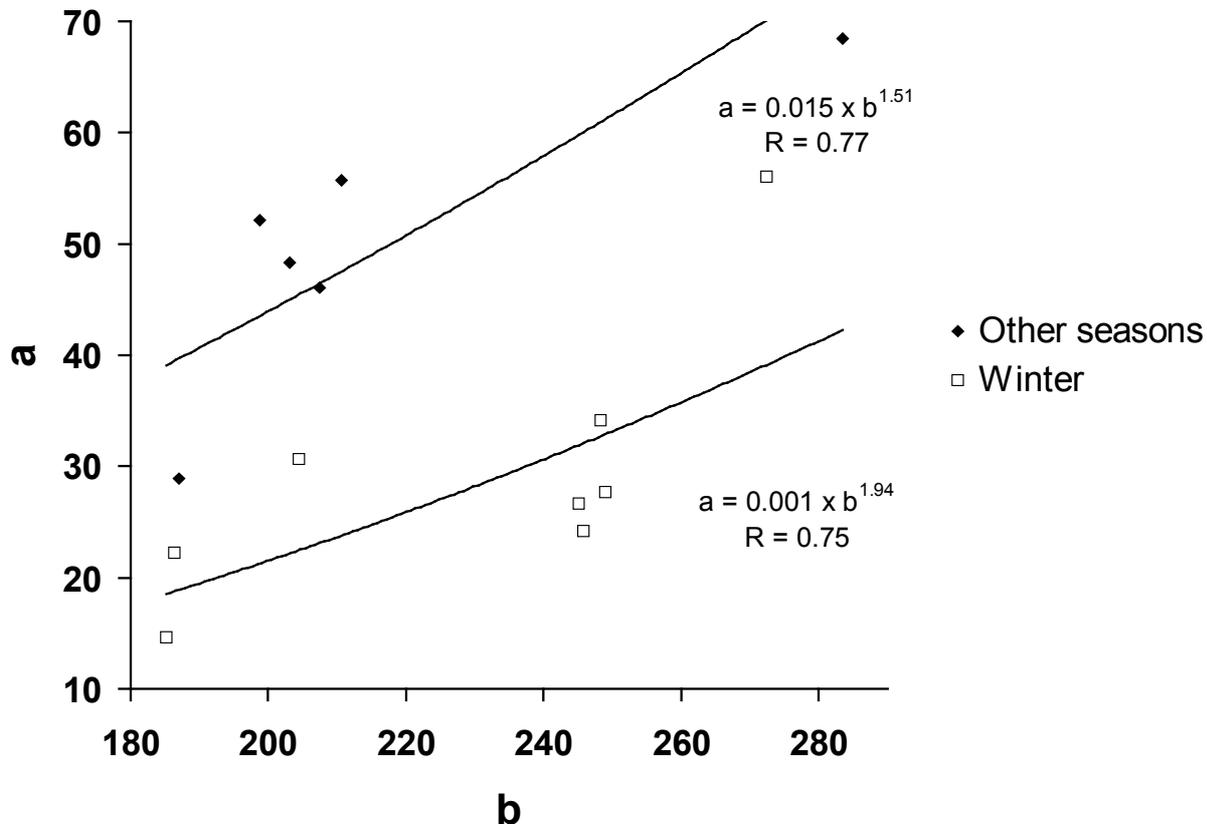


Figure 5: Seasonal relationships between the coefficient “a” and the actual maximum depth “b” (mm) for water levels > 185 mm within the dry pond during an individual storm. R = mean product moment correlation coefficient.

3.4 Water quality management

The water quality of the attenuation wet pond (Tables 1 to 3) was acceptable for disposal (e.g., sustainable drainage) and recycling (e.g., irrigation, toilet flushing and washing cars)¹. The attenuation wet pond functions as a source (components are released) for BOD, TS and turbidity, and as a sink (incoming components are stored) for SS and particulate lead (Table 2).

The concentration of lead (a representative indicator for urban water pollution⁸) within the unfiltered wet detritus on top of the garage roof and bottom of silt trap were approximately 0.73 and 0.26 mg/l, respectively (one off samples only). High dissolved lead concentrations would have caused harm to aquatic life if there had been no silt trap, GAC filter and if a transformation from a particulate to a dissolved stage would have taken place (e.g., during periods of low pH)⁸.

All measured elemental concentrations were either low (boron, barium, calcium, magnesium, manganese and zinc), close to the detection limit (aluminium, copper and iron) and for most heavy elements (were analysed but not listed; complete list available on request) below the detection limit.

Table 1: Summary statistics: Water quality of the attenuation wet pond and infiltration rates (IR) for the dry pond (26 April 2001 to 12 August 2002).

Variable	Unit	Time	Sample number	Mean	1 st Summer ³ mean	Autumn ⁴ mean	Winter ⁵ mean	Spring mean ⁶	2 nd Summer mean ⁷
Air temperature	°C	PM ⁸	345	12.2	16.9	8.9	6.5	13.2	17.1
Water temperature	°C	PM	325	11.1	15.4	8.6	9.1	11.9	15.3
BOD ¹	mg/l	AM ⁹	57	4.3	4.2	3.1	5.6	6.7	2.5
Suspended solids	mg/l	AM	40	46.8	132.5	51.3	3.8	54.8	3.4
Total solids	mg/l	AM	40	193.3	238.7	293.8	104.7	151.5	91.7
Conductivity	µS	PM	281	39.8	75.1	37.5	33.0	37.7	34.2
Turbidity	NTU ⁸	AM	39	2.8	4.3	2.7	2.2	2.0	1.5
Dissolved oxygen	mg/l	PM	319	9.3	11.5	4.8	10.1	12.4	7.3
pH	-	PM	263	7.77	8.36	7.27	7.86	8.69	6.84
Algal cover	%	PM	306	44	61	50	36	39	38
IR (Station 1) ²	10 ⁻⁷ m/s	PM	23	8	3	23	1	2	5
IR (Station 2) ²	10 ⁻⁷ m/s	PM	23	158	4270	95	42	36	580
IR (Station 3) ²	10 ⁻⁷ m/s	PM	24	9946	8152	4778	1286	6342	31841

¹BOD = five-day @ 25°C biochemical oxygen demand; ²IR = infiltration rates were calculated for the soil layers located 20 cm below the bottom of the dry pond centre (Station 1), the middle of the slope of the dry pond (Station 2) and the lawn (Station 3); ³Summer: 21/06-21/09/01; ⁴Autumn: 22/09-20/12/01; ⁵Winter: 21/12/01-19/03/02; ⁶Spring: 20/03-20/06/02; ⁷Summer: 21/06-12/08/02 (reduced sampling period); ⁸NTU = nephelometric turbidity unit ⁹PM = afternoon; ¹⁰AM = morning.

Table 2: Summary statistics: Water quality of the inflow, wet pond, wet pond outflow and dry pond for days where the wet pond overflowed; i.e. water level > 395 mm (26 April 2001 to 12 August 2002).

Variable	Unit	Time	Inflow		Wetland		Wetland outflow		Dry pond	
			Number	Mean	Number	Mean	Number	Mean	Number	Mean
BOD ¹	mg/l	Morning	14	0.8	23	4.7	7	1.7	14	3.7
SS ²	mg/l	Morning	6	7.7	13	33.1	4	2.3	9	174
Total solids	mg/l	Morning	7	102.2	14	360.2	2	142.0	7	507.3
Turbidity	NTU ⁴	Morning	9	3.3	16	2.4	5	3.6	10	20.0
Turbidity	NTU ⁴	Afternoon	13	1.5	26	4.0	16	2.2	18	6.5
Lead ³	µg l ⁻¹	Morning	4	0.03	5	0.01	NED ⁵	NED	2	0.01

¹BOD = five-day @ 25°C biochemical oxygen demand; ²SS = suspended solids; ³unfiltered; ⁴NTU = nephelometric turbidity unit; ⁵NED = not enough data.



The liquid phase (rainwater) within the treatment chain is actually taking up soluble contaminants from the debris on the roof and wet pond sediment; i.e., the sediment acts as a source and is actually polluting the liquid phase. For example, the zinc concentrations for the rainwater, inflow into the silt trap and outflow from the wet pond were <0.001, 0.017 and 0.020 mg/l, respectively.

It follows that the treatment potential of the wetland is limited to total SS. Contaminants build up within the sediment of the wet pond and a release is prevented by macrophytes allowing limited turbulence and subsequent re-suspension during storm events.

Furthermore, sampling over 24 h was conducted on 15 March 2002 (Table 3). Despite the cold weather conditions, diurnal water quality variations were apparent for water temperature, BOD, nitrate-N (including nitrite-N), ammonia-N, conductivity, pH, manganese, zinc and barium. However, of the elements detected by ICP-OES, zinc was the only one that had a high overall standard deviation (approximately 0.0060 mg/l, for triplicate analyses of each sample) as measurements were made close to the detection limit. Analysing the same samples using ETAAS reduced the overall standard deviation to 0.0036 mg/l (three replicates for each sample). It follows that there are no significant fluctuations of zinc concentrations during the day.

Table 3: Summary statistics: 24 hour sampling on 15 March 2002.

Variable	Unit	Total number	Mean				Standard deviation			
			00:00-05:30	06:00-11:30	12:00-17:30	18:00-23:30	00:00-05:30	06:00-11:30	12:00-17:30	18:00-23:30
Water temperature	°C	23	3.4	4.3	7.4	4.8	0.6	2.1	0.7	1.4
BOD ¹	mg/l	36	1.3	1.1	0.7	2.0	0.8	0.6	0.5	1.1
Nitrate-N ⁴	mg/l	40	0.54	0.38	0.39	0.47	0.37	0.18	0.17	0.19
Ammonia-N	mg/l	40	0.06	0.03	0.04	0.07	0.06	0.04	0.05	0.07
Phosphate-P	mg/l	40	0.07	0.04	0.06	0.13	0.06	0.04	0.06	0.09
Total solids	mg/l	43	99.8	97.8	180.7	139.2	18.8	14.6	59.1	31.3
Conductivity	µS	24	36.0	42.0	43.1	41.3	1.2	1.5	1.7	2.0
Dissolved oxygen	mg/l	24	10.0	9.8	11.3	11.6	0.7	1.2	0.8	1.3
pH	-	24	7.54	7.57	7.89	8.01	0.39	0.51	0.24	0.58
Calcium ²	mg/l	21	10.37	10.89	11.08	10.96	1.19	0.96	1.23	0.07
Magnesium ²	mg/l	21	1.13	1.14	1.14	1.14	0.08	0.07	0.04	0.06
Manganese ²	mg/l	21	0.006	0.006	0.005	0.010	0.002	0.002	0.002	0.009
Zinc ²	mg/l	21	0.007	0.010	0.012	0.010	0.003	0.005	0.009	0.001
Zinc ^{2,3}	mg/l	39	0.009	0.006	0.006	0.006	0.004	0.004	0.003	0.002
Barium ²	mg/l	21	1.57	1.57	1.66	1.72	0.24	0.09	0.28	0.31

¹BOD = five-day @ 25°C biochemical oxygen demand; ²filtered (0.45 µm pore size); ³analysis with the graphite furnace (atomic adsorption); ⁴values include nitrite.

Despite considerable annual and daily water quality variations, water quality monitoring is not required frequently because most variables are within their natural ranges¹ as long as proper plant management is conducted. The authors recommend monthly sampling and weekly visual inspections as a general rule of thumb.



3.5 Plant management

High DO levels due to photosynthetic activities are beneficial for aquatic wildlife but result often in the flotation of large green algae (e.g., *Microspora spp.*) on top of the pond surface (blanket weed). This process is natural during spring and summer but causes aesthetical problems for the local community. Floating algae are often (wrongly) associated with eutrophication and severe organic water pollution.

The authors propose therefore a mixture of algal growth control strategies: biodiversity enhancement, small barley straw bale distribution within the wet pond and mechanical removal of algae should be practised in order to reduce algal growth and subsequent washout into the dry pond during storm events. The washout into the dry pond would lead to a decrease of the infiltration capacity due to the blockage of fine pores with decaying algae (see also Table 1).

Apart from biological (grazing zooplankton⁸ and tadpoles) and physical (removal by hand) algal control, biochemical algal control with barley straw extracts can also be practised. The presence of straw extracts reduces algal growth by releasing a “cocktail” of phytotoxic chemicals.⁹

The wet weights of litter removed during summer 2001, autumn 2001, winter 2001/02 and spring 2002 were 1.1, 4.6, 1.0 and 6.2 kg, respectively. The numbers of occasions where maintenance activities took place during these seasons were 6, 10, 3 and 14, respectively. Litter production depends on the season. Fresh biomass is usually produced in spring and summer that require harvesting in late autumn⁸. Furthermore, algae (predominantly *Microspora spp.*) require frequent removal in spring. In contrast to summer and winter, the maintenance was more efficient during autumn and spring because less labour time was required and more litter and algae were removed during these sessions.

The aquatic plants were Common Reed, Reedmace, Yellow Iris, Water Starwort and Frogbit. Common Reed and Reedmace located in the wet pond contained higher concentrations of calcium, magnesium and manganese in comparison to macrophytes located in the dry pond. For example, manganese (important trace mineral) concentrations for Common Reed planted in the wet and dry ponds were 0.190 and 0.063 mg/l, respectively. In comparison, manganese concentrations for Reedmace grown in the wet and dry ponds were 0.610 and 0.162 mg/l, respectively.

The highest concentrations of zinc, an indicator for urban water pollution⁸, were estimated for Frogbit (0.315 mg/l), Reedmace (0.121 mg/l) and Common Reed (0.084 mg/l). Frogbit is associated with high concentrations of various elements in general; e.g., barium (1.084 mg/l), iron (7.746 mg/l), magnesium (8.093 mg/l) and manganese (5.749 mg/l). All other aquatic plants investigated were associated with low but detectable concentrations of magnesium, manganese and zinc. Measured concentrations of these elements for aquatic plants were higher than for the liquid phase (pond water) but comparable to associated sediment samples. For example, the concentration ranges for the wet pond plants, water and sediment were 0.052-0.315, 0.006-0.020 and 0.090-0.130 mg/l, respectively. These concentrations are based on five plants (see above) and four randomly selected sampling stations within the wet pond.

Therefore, plant harvesting has the potential to reduce nutrients and pollutants (in addition to BOD, SS, etc.) in the wet pond⁸. This also helps to avoid algal blooms. A minimum of monthly intensive plant management during the growing season is recommended.



3.6 Economics

The water utility (Yorkshire Water Services Ltd) gives domestic customers who are not connected for traditional water drainage a rebate of £25 (Pound Sterling). Assuming that the domestic property user recycles approximately 0.3 m³ of pond water approximately 30 times per annum in order to water plants during summer, the owner would save an additional £15. Further savings of up to £30 are possible if rainwater is recycled for toilet flushing and car washing, for example. These savings are low in comparison to the overall costs. However, the amenity value enhancement due to the presence of an attractive water feature like a wet pond is subjective but is difficult to quantify in economic terms.

These savings have to be contrasted to expenditures. The capital and labour costs for the pond structure were approximately £1960 (£800 and £1160, respectively). Labour costs were based on the assumption that 1 h of work equates to costs of £7. The expenditure of £500 for the construction of the wet pond was the largest single capital cost item. Expenditures for the new pipeline layout (£120) and aquatic plants (£100) were also significant.

Cost figures for on-going pond maintenance and water quality monitoring are not included in the previous calculation. For the removal of organic material from the wet and dry pond, 13 and 5 h per annum, respectively, were required between June 2001 and June 2002. This includes 8 h for the mechanical removal of algae from the wet pond. The total costs for labour are consequently approximately £130 per annum.

4. Conclusions

1. The case study describes the successful design, operation and maintenance of a novel stormwater pond structure during the first 15 months of operation.
2. The BRE, CIRIA and ATV-DVWK design guidelines were unsuitable for this case study.
3. Infiltration through the base of the dry pond is low (despite the presence of macrophytes) and should not be considered during the design.
4. The infiltration function for the dry pond is logarithmic and non-linear as assumed by most international design guidelines.
5. The water quality of the attenuation wet pond was acceptable for recycling.
6. Roof run-off pollution is low and therefore only passive treatment like extended storage within a wet pond is required.
7. The treatment potential of the wetland is limited to total SS.
8. Seasonal and diurnal variation in water quality for BOD, phosphate (only evidence for diurnal variation provided), dissolved oxygen and pH were apparent.
9. Excess algae and litter biomass requiring mechanical removal in order to avoid eutrophication in the wet pond and low infiltration rates in the dry pond weighted 2.3 kg wet weight per m² of wet pond area per annum.
10. Plant harvesting reduces BOD, nutrient and trace element levels within the pond system.



11. Capital or labour costs for experimental or small (<math><10\text{ m}^2</math>) stormwater ponds are high and need to be indirectly offset by amenity value enhancements leading to property value increases.

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6. References

1. Butler D. and J.W. Davies (2000). Urban drainage. E & FN Spon, London, UK.
2. Martin P., B. Turner, K. Waddington, J. Dell, C. Pratt, N. Campbell, J. Payne and B. Reed (2000). Sustainable urban drainage systems – design manual for England and Wales. Construction Industry Research and Information Association (CIRIA), London, UK, CIRIA C522.
3. Building Research Establishment (1991). Soakaway design. Building Research Establishment (BRE) Bookshop, Watford, UK, BRE Digest 365 (replaces 151).
4. Bettes R. (1996). Infiltration drainage – manual of good practice. Construction Industry Research and Information Association (CIRIA), London, UK, CIRIA Report 156.
5. ATV-DVWK-Arbeitsgruppe ES-41 (2002). Planung, Bau und Betrieb von Anlagen zur Versickerung von Niederschlagswasser (Design, construction and operation of rainwater drainage systems). ISBN 3-935669-83-6, ATV-DTWK (German Association for Water, Wastewater and Waste), Gesellschaft zur Förderung der Abwassertechnik e.V., Hennef, Germany, Regelwerk A-138.
6. Meteorological Office (2002). Bradford monthly long-term average rainfall. Online data between 1908 and 2001, URL address:
<http://www.metoffice.gov.uk/climate/uk/stationdata/bradforddata.txt>.
7. Clesceri L.S., A.E. Greenberg and A.D. Eaton (1989). Standard methods for the examination of water and wastewater. 20th edition, American Public Health Association (APHA)/ American Water Works Association (AWWA)/ Water Environment Federation (WEF), Washington DC, USA.
8. Scholz M., P. Höhn and R. Minall (2002). Mature experimental constructed wetlands treating urban water receiving high metal loads. *Biotechnology Progress*, 18 (6): 1257-1264.



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9. Everall N.C. and D.R. Lees (1997). The identification and significance of chemicals released from decomposing barley straw during reservoir algal control. *Wat. Res.*, 31: 614-620.

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