



Aalborg University
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Task B, 3rd delivery: General design criteria and guidelines compiled into a design manual

Contract text to which this deliverable refers:

Generally applicable design guidelines (Action B1). The scientific knowledge on technologies and processes for removal of pollutants from stormwater is collected, analyzed and transformed into general applicable design criteria. Special focus is on innovative technologies for removal of colloidal and dissolved pollutants. In this phase, the knowledge obtained in the EC 5th framework R&D project DAYWATER is utilized together with other European and international scientific knowledge. Knowledge on economic, cultural, social and architectural aspect relating to the innovative technologies are researched and included in generally applicable design guidelines.



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GENERAL DESIGN CRITERIA AND GUIDELINES FOR WET DETENTION PONDS

1. OBJECTIVES

It is the main objective of this report to specify the scientific and technological basis that is central for design and operation of wet detention ponds (wet ponds) for treatment of stormwater runoff from urban areas and roads. Design criteria and guidelines that determine the general performance and treatment efficiency of wet ponds are dealt with, particularly those related to the removal of particle bound pollutants. Furthermore, focus is on processes, technologies and criteria for extended treatment in wet ponds directed to the removal of dissolved and colloidal pollutants.

In addition to these focal objectives, the basic characteristics of stormwater are described in view of possibilities for treatment in wet ponds. The characteristics of the pollutants in stormwater runoff, the level of pollutant loads onto the environment from impervious areas and the associated potential effects are in this respect central. Furthermore, and in addition to the wet ponds, a number of Best Management Practices (BMPs) for treatment of stormwater are outlined.

2. INTRODUCTION

Treatment and reuse of stormwater runoff from urban impervious areas and highways have until now only sporadically and uncoordinated been an issue within the European Union and stormwater is therefore in general discharged untreated to receiving waters. However, the Water Framework Directive (WFD) issued in 2000 by EC is expected to change this situation (EC, 2000). The purpose of the WFD is to establish a framework for protection of inland surface waters, transitional waters, coastal waters and groundwater. In this respect it is the ultimate objective to achieve concentrations in the environment near background levels for naturally occurring substances and close to zero for man-made synthetic substances. A “good chemical and ecological status” in all water bodies is what should be achieved. By the end of 2015, all surface waters in Europe must fulfill the criteria set.

Although the pollutants originating from urban and road surfaces occur in rather low concentrations, both concentrations and loads onto receiving waters are potentially high enough to cause harmful effects. Because of the requirements set by WFD, an appropriate treatment strategy for the runoff is crucial for the EU Member States. Handling of the runoff from rain events by correctly designed and operated BMPs that are based on naturally occurring physical, chemical and biological processes is a sustainable way of managing stormwater. Because of high treatment efficiency and flexibility, a wet pond is a BMP with a potential for being widespread implemented. By being a semi-natural lake, a wet pond combines characteristics for treatment at the same time it can contribute to “water in the city”. Furthermore, a wet pond has unique possibilities to observe high water quality requirements by being extended with simple and robust technologies removing



pollutants in either dissolved or colloidal form. These technologies include simple versions of unit operations and unit processes like filtration, adsorption, flocculation and precipitation.

3. BMP SOLUTIONS TO IMPROVE QUALITY OF STORMWATER RUNOFF

The impacts onto the environment caused by stormwater runoff (SWR) call for control and mitigation methods. BMPs (Best Management Practices) are methods that are particularly directed to the management of stormwater runoff from impervious urban surfaces and roads.

BMPs – in the UK known as Sustainable Urban Drainage Systems (SUDS) – are by nature both structural and non-structural technologies. Structural BMPs are technologies that can be characterized as “low-impact development approaches” and that mimic the pre-development hydrology of a site as much as possible. In general, structural BMPs combine measures to reduce flooding and erosion of stormwater runoff with the removal of pollutants that are associated with the runoff. The non-structural BMPs include a wide range of measures, e.g. regulations, management and public education with the purpose to reduce spreading of pollutants into the environment.

Briefly, a BMP is defined as follows (Strecker et al., 2001):

A devise, practice or method for removing, reducing, retarding or preventing targeted stormwater runoff quantity, constituents, pollutants and contaminants from reaching receiving waters.

The reference list includes a number of selected references that give a more comprehensive description of BMPs, e.g. Debo and Reese (2003), DayWater (2003) and Field et al. (2005).

From practice, it is well known that several obstacles exist for efficient performance of BMPs for stormwater management and that no ideal device exists. However, among a number of possible BMPs, cf. Section 7.1, the flexibility of a wet pond makes it a unique candidate designed to observe different treatment levels and to be implemented under varying local conditions.

4. BASIC POLLUTANT CHARACTERISTICS AND ENVIRONMENTAL EFFECTS

4.1. Pollutants and Effects

The pollutants relevant in stormwater runoff from urban areas and roads can be subdivided in different ways. The following grouping is typical and relevant for a number of corresponding potential effects:

- Biodegradable organic matter
- Nutrients
- Heavy metals
- Organic micropollutants
- Solids (suspended solids)
- Pathogenic microorganisms



These pollutants may cause different effects. In addition to the effects related to these pollutants, the hydraulic conditions also cause an impact on the environment. The combined effects of both pollutants and flow of water can be organized as shown in Table 1.

TABLE 1. Types of effects relevant for pollution from stormwater runoff.

Effect	Subdivision and comments
Physical habitat changes	1) Flooding in urban and rural areas 2) Erosion caused by overland flow and peak flows in channels and rivers 3) Sediment deposition in receiving waters
Dissolved oxygen depletion	Effects on the biological communities
Eutrophication	Effects of both nutrients (N and P) and organic matter as substrates for excessive biological growth and activity
Toxic pollutant impacts	Effects of both heavy metals and organic micropollutants
Public health risks	1) Direct impacts by pathogenic microorganisms and viruses 2) Indirect impacts via contaminated animal food
Aesthetic deterioration and public perception	E.g. caused by the discharge of gross solids and sediments

In terms of modeling and engineering of the stormwater infrastructure, it is crucial to relate the discharge of the pollutants to their specific adverse effects. Table 1 is a first estimate in this respect. Particularly in case of design, it is of importance to point out pollutants that can be considered indicators for effects that are central.

4.2. Time Scale Effects of the Pollutants Discharged

The event characteristics of stormwater pollution make it important to introduce the concept of “time scale” related to the pollutants’ effects from stormwater discharges. This time scale in terms of the pollutants’ effects is associated with – but not equivalent to – the recovery time of the receiving environment following the intermittent pollutant discharges. The following example will illustrate this: Ammonia that is discharged during a rain event into a river may cause a direct effect in terms of fish kills. However, the recovery time of the river following this harmful event may last for a very long time until the river is re-populated by the affected fish species. When dealing with pollution from urban wet weather discharges, it is typical to focus on the “direct” effect of a pollutant and not the associated “recovery time” of the environment. What is important is, however, to compare the time length of a discharge event with the time length of a discharged pollutant’s effect.

In the context of wet weather urban discharges there is no well-defined terminology how to clearly distinguish between the word “impact” and the word “effect”. In this text it is considered appropriate to define that urban wet weather discharges cause impacts onto the environment and that these impacts can result in adverse effects. From the receiving system’s point of view, it is therefore considered appropriate to use the term “effect” as a more specific and precise indication of what is a harmful response of the environment to the discharges.



Basically, the effect of a pollutant is acute or accumulative, i.e. an adverse effect of a pollutant at a specific location is either a result in a “shock effect” that decreases relatively fast or the pollutant will accumulate in a system and result in a long-term effect. Such pollutant and receiving water related characteristics are of course also valid for discharges from continuous point sources. However, under such conditions, a pollutant effect reaches a kind of “equilibrium value” in the environment irrespective of its type. For Intermittent point discharges like urban storm pollution, the time scale effect of a pollutant will more directly manifest itself.

If the effect is acute, the impacts from single events are important, particularly for those of extreme magnitude and frequency. If the effect is of the cumulative type, it is important to consider the discharge over a certain time period, typically a season or a year. In this case the variability of the pollutant load from storm to storm is not important. Figure 1 depicts the principles of the time scale concept for pollutants relevant for discharges of urban runoff into receiving waters.

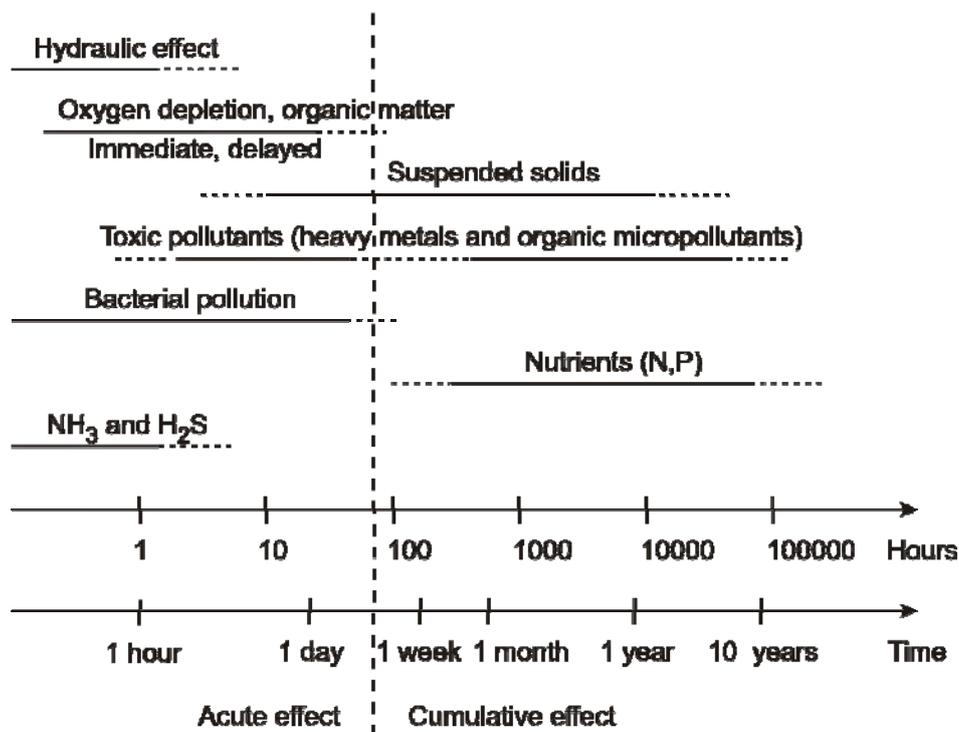


FIGURE 1. Time scale for receiving water effects from intermittent pollutant discharges (Hvitved-Jacobsen et al., 1994).

With reference to Figure 1 and as examples, dissolved oxygen depletion that is primarily caused directly by easily biodegradable organic matter results in an acute effect whereas e.g. nutrients resulting in eutrophication are pollutants with a long-term, cumulative effect. Figure 1 only shows the principle and therefore also just serves the purpose of basic understanding and distinction between the two phenomena. Details concerning the distinction between acute and accumulative effects are determined by the kinetics of the relevant processes dealt with.

Because of the time scale of the effects of the pollutants, corresponding computational and treatment aspects are affected:



- Acute effects

Because the short-term effect in principle is related to a single event, computation of pollutant discharges becomes relevant for each event that causes a discharge, particularly the extreme ones. It is therefore important to focus on extreme event statistics of a historical rainfall or runoff series. It is also important to deal with the extreme events when focusing on possible methods and measures for reduction and treatment of the discharges.

- Accumulative effects

The focal point – in contrast to the acute phenomenon – is that all discharge events during a season or a year contribute to the observed effect. Therefore, the relevant measure for the effect is basically changed from an actual concentration for a given event to the total amount of a pollutant that is discharged during a number of events corresponding to the period considered. A variability of the pollutant load from storm to storm is in this case not important and emphasis is on a mean pollutant concentration for the site. These facts are relevant in terms of which method should be selected for computation and which measures should be used for a total load reduction during the period in question.

When dealing with computation for an acute effect, more information on urban runoff characteristics is required compared with what is needed in case of an accumulative effect. It also becomes more difficult to find efficient measures for pollutant reduction in case of a single extreme event than it is the case if the reduction of the pollutant load is relevant for all events, the small ones included. In terms of engineering solutions to given urban runoff pollution problems, we are therefore generally faced with the most difficult situations in case of acute effects.

5. POLLUTANT CONCENTRATIONS AND LOADS

5.1. Definitions of Concentrations

The pollutants dealt with in stormwater runoff require in terms of their stochastic and event-based nature, their source characteristics and their variability a different approach of characterization compared with the continuous fluxes of pollutants. The quantification of pollutant matters in terms of mass balances has shown that two different definitions of concentrations are suitable:

- Event Mean Concentration (EMC)

The EMC is a concentration that characterizes an event in terms of a mean value.

- Site Mean Concentration (SMC)

The SMC is a concentration that characterizes a site in terms of a mean value for all events at that site.

5.1.1. Event Mean Concentration

The Event Mean Concentration (EMC) is defined as a flow-weighted mean concentration of a constituent in the runoff water from a runoff event. The EMC is therefore defined corresponding to the total transport of mass over an individual event, M_{tot} , divided by its total volume of runoff water:

$$\text{EMC} = M_{\text{tot}} / V_{\text{tot}} \quad (1)$$



where

M_{tot} = total mass of a constituent for the event (g)

V_{tot} = total volume of runoff water for the event (m^3)

An EMC value refers to the entire event and does not take into account intra-event characteristics like the first flush phenomenon. The determination of an EMC is directly related to a monitoring procedure. The concrete implementation of this procedure therefore affects the magnitude and the interpretation of the EMC. In general, the monitoring procedure takes place in the flowing stream of a pipe or an open channel during the runoff event. Typically, the flow is monitored continuously and regular sampling from the flowing stream for following analysis takes place proportional with the flow. The direct relation to the EMC follows from Equation 1. The EMC is thereby a characteristic event-based value for the pollutant concentration of the flow into receiving water or into a treatment facility.

5.1.2. Site Mean Concentration

A Site Mean Concentration, SMC, is a concentration that is characteristic for a given site or a given use of a catchment, i.e. “land use”. A number of EMC values from a site-specific monitoring program are therefore required for its determination. A 50% percentile – the median value – is typically defined as the SMC.

5.2. General Characteristics for Pollutant Concentrations and Loads

Pollutant concentrations and loads related to urban and road runoff are subject to a considerable variability in time and space. Typically, the coefficients of variation (COVs) for EMC or SMC values are in the order of 0.8-1.2, i.e. a standard variation can easily reach the same level of magnitude as a mean value. The pollutant concentrations and loads given in the following tables must therefore only be considered as “order of magnitude” and examples. Although such literature values are widely used in practice, there is basically no reliable substitute for monitoring to determine a “correct” pollutant level in a specific case.

The information available in terms of quantification of pollution from urban and road runoff is often given in the following units:

- g m^{-3} : For EMC and SMC values in stormwater runoff from urban catchments and roads
- $\text{g ha}^{-1} \text{yr}^{-1}$ or $\text{g m}^{-2} \text{yr}^{-1}$: Yearly unit area loads (export coefficients) from a catchment
- $\text{g km}^{-1} \text{yr}^{-1}$ or $\text{g m}^{-1} \text{yr}^{-1}$: Yearly load from a unit length of a road or highway

The characterization of a catchment in terms of pollution is basically given by the sources for the pollutants. For practical applications, the loadings of pollutants can pragmatically be defined by the “land use”. The following terms related to a catchment are in this respect often used to distinguish between different levels of pollution:

- Residential areas (different densely populated urban areas)
- Industrial areas
- Commercial areas

- Parking areas
- Average Daily Traffic (ADT) for roads and highways

5.3. Specific Information on Pollutant Concentrations and Loads

In Table 2, characteristic pollutant concentrations (SMC values) and corresponding COV values are given for runoff from residential areas. These results originate from an extensive monitoring program, the Nationwide Urban Runoff Program (NURP), performed in the USA during the period 1979-1982. Twenty years later, the use of unleaded gasoline has reduced pollution with lead to a concentration level typically 3-4 times lower than stated in Table 2. However, results from more recent investigations in the USA indicate that, other than lead, most pollutants did not vary significantly from the NURP-information (Debo and Reese, 2003). Similar observations have been made in other countries too. In addition, Table 3 shows characteristic values (SMC values) for stormwater runoff from urban surfaces and roads in Denmark. Although there are differences between the pollutant concentrations shown in Tables 2 and 3, they cannot be considered conflicting when taking into account the variability.

TABLE 2. Characteristic pollutant concentrations (SMCs) for stormwater runoff depending on land use (USEPA, 1983). Data show median concentrations (C_m) and corresponding coefficients of variation (COV = the standard deviation divided by the mean value).

Pollutant (unit)	Residential		"Open" urban area	
	C_m	COV	C_m	COV
BOD ₅ (g m ⁻³)	10	0.41	-	-
COD (g m ⁻³)	73	0.55	40	0.78
TSS (g m ⁻³)	101	0.96	70	2.92
Total Kjeldahl Nitrogen, TKN (g m ⁻³)	1.9	0.73	0.97	1.00
Total P (g m ⁻³)	0.38	0.69	0.12	1.66
Total Pb (mg m ⁻³)	144	0.75	30	1.52
Total Cu (mg m ⁻³)	33	0.99	-	-
Total Zn (mg m ⁻³)	135	0.84	195	0.66

TABLE 3. Characteristic pollutant concentrations (SMC values) for stormwater runoff from urban catchments in Denmark (PH-Consult, 1989).

Pollutant	Concentration
TSS (g m ⁻³)	30 – 100
COD (g m ⁻³)	40 – 60
BOD ₅ (g m ⁻³)	5
Tot. N (g m ⁻³)	2
Tot. P (g m ⁻³)	0.5
Pb (mg m ⁻³)	50 – 150*
Zn (mg m ⁻³)	300 – 500
Cu (mg m ⁻³)	5 – 40
Cd (mg m ⁻³)	0.5 – 3
E. coli (100 ml) ⁻¹	1.000 – 10.000

* Typically 20 – 40 (mg m⁻³) 10 years later



Rather than applying values for pollutant concentration and loads originating from the general available literature, it is possible to use information from a catchment where the conditions for pollutant load are considered comparable to the site in question. Several municipalities and highway authorities around the world have collected and published such information. As an example, Table 4 summarizes results for micropollutants found in urban runoff in Norway.

TABLE 4. Typical minimum and maximum SMC values for heavy metals and PAH based on stormwater runoff measurements from 7 catchments in Norway (Storhaug, 1996).

Pollutant (mg m^{-3})	Central urban areas	Residential areas	Commercial areas
Cd	0.1 – 0.5	0.1 – 0.4	0.1 – 0.5
Hg	0.2 – 1.2	< detection limit	< detection limit
Pb	1 – 33	1 – 8	1 – 19
Ni	3 – 190	1 – 10	1 – 11
Cr	1 – 170	1 – 12	1 – 7
Zn	10 – 300	5 – 140	8 – 92
Cu	6 – 120	3 – 15	4 – 31
PAH	0.1 – 2.7	0.1 – 0.8	0.01 – 0.3

The results shown in Table 4 can be compared with the results shown in Table 5 on snowmelt runoff, also originating from Norway. The pollutant concentrations in runoff from snowmelt are considerably higher than those obtained from the runoff of rain. High concentrations during snowmelt events – in general about twice the values for stormwater runoff – have been reported by FHWA (1987).

TABLE 5. Concentrations of heavy metals and PAH from snowmelt runoff in Norway (Bækken og Jørgensen, 1994).

Pollutant (mg m^{-3})	Snowmelt runoff
Cd	3.9 – 26
Hg	0.19 – 13.2
Pb	max. 690
Ni	42 – 106
Cr	30 – 150
Zn	200 – 740
Cu	13 – 430
PAH	1,500 – 11,600

The stormwater runoff loadings shown in Table 6 are by urban land use in the USA given per unit area of catchment and time (e.g. Horner et al., 1994; Burton and Pitt, 2002). Such data are named export coefficients. The main part of the results originates from a period of time before unleaded gasoline was commonly used. The table shows that it is crucial to be aware of the fact that such pollutant load values are subject to considerable variability. Similar results have been published by other authors too, e.g. Gilbert and Clausen (2006).

Table 6 indicates that stormwater pollutant loads from freeways are relatively high compared with the contribution from other types of land use. This fact is in agreement with a statement by Ellis et al. (1997) who in general concluded that available data indicate that highway runoff pollution is of



concern – in terms of toxicity – in the case of urban highways with a traffic load of more than 30,000 vehicles d⁻¹.

TABLE 6. Typical unit area and unit time loadings (export coefficients) of pollutants from stormwater runoff by land use (Horner et al., 1994; Burton and Pitt, 2002).

Pollutant (kg ha ⁻¹ yr ⁻¹)	Commercial	Residential High- density	Residential Medium- density	Residential Low- density	Industrial	Freeway	Parking
TSS	1,100	450	270	10	550	1,000	450
Total P	1.7	1.1	0.4	0.05	1.5	1.0	0.8
TKN	7.5	4.7	2.8	0.3	3.7	8.9	5.7
BOD	70	30	15	1	NA	NA	53
COD	470	190	60	10	230	NA	300
Pb	3.0	0.9	0.06	0.01	0.2	5.0	0.9
Zn	2.3	0.8	0.1	0.05	0.4	2.3	0.9
Cu	0.4	0.03	0.03	0.01	0.1	0.4	0.07

NA = Not Available

In general, the wet weather loads of pollutants onto receiving waters from urban areas and roads must be integrated with the loads from other sources. Such pollutant sources do not only include the dry weather inputs via e.g. wastewater treatment plants but also those associated with rural runoff.

The specific characteristics of pollutant concentrations and loads can briefly and in general terms be summarized as follows:

- Concentrations (EMCs) of pollutants in stormwater runoff are subject to considerable variability, typically with a standard deviation in the same order of magnitude as the mean value.
- The level of pollutant load in terms of concentrations or export coefficients (unit area loads) depends on the land use.

6. PHYSICAL, CHEMICAL AND BIOLOGICAL CHARACTERISTICS OF POLLUTANTS RELATED TO TREATMENT

In addition to the basic characteristics of pollutants dealt with in the preceding sections, a number of physical, chemical and biological characteristics and principles are important to consider when treating stormwater runoff.

Firstly, the fundamental aspect in the treatment of urban and highway runoff is the fact that large volumes of runoff water can be generated over a short period of time. Secondly, low concentrations – but not sufficiently low in terms of effects onto the environment – must be reduced to even lower levels. In addition to these fundamentals, a large number of pollutants with different characteristics in terms of treatment must be dealt with. All these facts call for treatment methods that in principle must be performed differently compared with well-known treatment of the more or less continuous municipal and industrial wastewater flows. The fact that the generation of stormwater per definition occurs widespread is also a constraint that affects in practice the implementation and costs of the treatment systems and their operation.



For each specific case, it is important to know which pollutants are the most important to treat and following consider which BMPs will best observe a given requirement for treatment. Those pollutants that typically result in effects onto the environment and that originate from urban and road runoff, are in general found among the nutrients, the heavy metals and the organic micropollutants. Treatment must therefore in general be performed for pollutants with accumulative effects although it is realized that pollutants with toxic effects may also exert acute effects, particularly in case of relatively high concentrations. As a first approach, it becomes important to secure efficient treatment over a period of time rather than for a single event. If a first flush phenomenon exists or is expected to occur, it can be relevant to limit a treatment capacity of a BMP to capture the first part of the runoff. In some countries, e.g. the USA, a “first flush volume” is typically defined as being about 13 mm (0.5 inch) of runoff.

To observe these basic characteristics in the management and treatment of the runoff, the following are ideally considered major points to observe when selecting a management or treatment method:

- Methods with kinetic characteristics of the governing treatment processes that make these processes proceed rather fast.
- Methods for which a detention capacity for the runoff volume can be rather easily integrated.
- Methods with a rather broad (and efficient) capacity in terms of treatment of pollutants with different physical, chemical and biological characteristics.

In the following, main physical, chemical and biological characteristics and processes for pollutants originating from urban and road runoff are briefly outlined with particular relation to the three points mentioned.

- **Physical characteristics and processes**
Sedimentation and filtration are central unit processes for treatment because particulate matter in urban and road runoff plays a dominating role and because pollutants typically to a rather high extent are associated with particles. Pollutants can thereby be removed from the water phase and accumulated at a bottom surface or retained in a filter. The removal from the water phase can be associated with degradation, e.g. in case of organic matter, but often “treatment” must be understood as “removal” or “accumulation”, which is the case for e.g. phosphorus and heavy metals.
- **Chemical characteristics and processes**
It is in practice often not possible to distinguish clearly between a chemical reaction and adsorption – as a physico-chemical process. For practical reasons – e.g. in case of modeling – it is therefore often appropriate to consider adsorption as a chemical process in a BMP. Adsorption of soluble, colloidal and particulate species is often central and “interaction” between chemical and physical characteristics and processes are therefore important.
- **Biological characteristics and processes**
Compared with physical and chemical processes, biological processes often proceed with a rather low transformation rate. Compared with the rate of “water volume generation” during a runoff event, a biological process is per definition often less



important for control and treatment of pollutants in the runoff. However, in case where a detention of the runoff volume is possible – and integrated in the BMP – the biological characteristics and processes may, however, turn out to be significant. In addition to degradation, such processes include e.g. uptake of pollutants in the macrophytes.

For several reasons, e.g. in terms of the number of different pollutants and the varying conditions under which they occur, it is important to make use of the physical, chemical and biological processes in combination whenever possible for control and mitigation of stormwater and road runoff.

7. OVERVIEW OF METHODS FOR REDUCTION OF POLLUTANT LOADS

The following list outlines main types of BMPs intended for management and treatment of urban and road runoff. It must, however, be emphasized that the number of types are basically legion and that varying names and characteristics for the different types are in use. The list in Section 7.1 focus on main characteristics of structural BMPs, to some extent following the definitions used by US and Canadian agencies, cf. FHWA (1996). In Section 7.2, a number of non-structural BMPs are listed.

7.1. Structural Types of BMPs

Extended detention basins

This type is also named a “dry pond” expressing that the “pond” (berm-encased area, excavated pond or tank) does not necessarily have a permanent water pool between storm runoff events. The basin temporarily stores the stormwater runoff or a portion of it, e.g. to attenuate peak runoff flows for the protection of downstream located facilities or receiving waters. The extended detention basin thereby mainly serves the purpose of a hydraulic control measure with a structure that restricts outlet discharges. The water in the pond is mainly discharged following the runoff event, however, may also to some extent undergo evaporation/transpiration and infiltration. Furthermore and at least to some extent, settling of suspended particulate materials takes place.

Wet ponds

This type of pond is basically similar to an extended detention basin except that it is designed with a permanent pool of water and a temporary storage volume above this permanent pool. This type of BMP is also named a “wet detention pond” or a “retention pond”. The design makes it like a small and shallow lake – also between storm events – with sufficient residence time for the water to allow for a number of pollutant removal processes to proceed. The wet pond thereby acts as a BMP for removal of particulate and to some extent also soluble pollutants. In addition to the hydraulic control and the improved water quality of stormwater runoff, a wet pond can also have a recreational value, e.g. obtained by proper design and use of plants in the pond and integrated with the surrounding environment.

Constructed wetlands

Constructed wetlands are characterized by being rather dense vegetated with low water depth areas of typically 0.1-0.3 m. The water depth end thereby the entire structure and performance varies dependent on the rainfall pattern and the season of the year. The structure of a wetland is diverse with free water table, dense vegetated surface waters and even small islands, i.e. characterized as a



shallow wet ecosystem. Dependant on the detailed structure and its variability, the relative importance of physical, chemical and biological processes in a wetland system may vary.

Infiltration trenches

Traditionally, an infiltration trench is an excavation that is lined with a filter fabric and backfilled with stones to form an underground basin. In a more modern type, the underground basin is established by piling up plastic boxes with a high degree of cavity. From the infiltration trench, the runoff either exfiltrates into the surrounding soil or enters a perforated pipe from where the flow is routed to an outflow facility. In a complete trench, all runoff is exfiltrated into the soil whereas in a partial trench with a perforated pipe, only part of the runoff exfiltrates. In a water quality exfiltration system, only the first part (first flush volume) of the runoff is typically managed.

Infiltration basins

Runoff water is temporarily stored in an open infiltration basin – also named infiltration pond – from where infiltration takes place into the underlying soil. Often an infiltration basin is designed to capture only a first flush volume.

Filters

Sand filters are designed to remove particulate matter, i.e. sediments and associated pollutants from the runoff. Removal of pollutants in the runoff is enhanced by a biofilm attached to the filter medium. A filter media can also be selected having specific adsorption characteristics, e.g. a limestone material for removal of phosphorus.

Water quality inlets

These types of BMPs cover a variety of devices that appear more “technical” compared with the previously described units that more or less mimic the elements of nature. Often these water quality inlets are designed having a chamber structure. The outflow from these treatment devices can be routed to other BMPs, i.e. the structure acts as a pre-treatment unit. In some cases, these types of BMPs are also named hydrodynamic devices referring to e.g. oil and grit separators, sand traps, swirl separators and underground sand filters. Also more advanced treatment units for stormwater belong to this group, e.g. ballasted flocculation.

Swales

Swales are shallow vegetated channels used to convey stormwater. Pollutants that are transported with the runoff can partly either be removed by settling or be infiltrated into the soil. However, effective removal of pollutants requires that a swale has a rather low slope and is well drained.

Filter strips and “rain gardens”

To some extent filter strips – also known as vegetated buffer strips – are like grassed swales except that they have rather flat banks. A “rain garden” is a small footprint BMP for storing and percolation of stormwater and can be based around detention basins and swales. The use of deep-rooted perennial plants in such solutions can enhance the infiltration.

Porous pavement

A porous pavement – also named permeable pavements – consist typically of asphalt or concrete through which stormwater is quickly transported into a layer of a high-void materials, e.g. gravel.



The runoff is stored in this layer until it either infiltrates into an underlying soil or is routed through a drain to a stormwater conveyance system or an infiltration trench.

In total, these structural types of BMPs constitute quite different types of techniques. Some are treatment systems that “remove” the pollutants in terms of either degradation or accumulation depending on the nature of the pollutant. An example of this technique is the wet pond. Other methods, e.g. the porous pavement basically tend to reduce the runoff volume by detention and following diversion of the runoff.

7.2. Non-structural Types of BMPs

The list of different scenarios of non-structural BMPs is basically long. The following only outlines some common control measures that tend to reduce the negative impacts from stormwater runoff in urban areas and at highways.

- Public education
- Regulations
- Land use
- Landscaping
- Pesticide and fertilizer management
- Litter and debris control
- Painting and use of metals in constructions
- Road cleaning

Source control measures have in several cases been efficient for reduction of the environmental deteriorating impacts from stormwater runoff. A classical successful example is the regulation of lead in gasoline. The result of this regulation has in several countries reduced the load of lead from stormwater runoff considerably. Other examples of potential source control measures are material replacement for copper roofs, banning the use of copper in brake linings of cars and the use of more environmentally friendly studs in tires and changes in driving pattern reducing the PAH load from road wear (Ahlman et al., 2005).

8. WET POND FOR STORMWATER TREATMENT

Basically two main types of detention ponds exist: the extended detention basin (dry pond) and the wet pond (wet detention pond). In the following, only the wet pond will be dealt with.

8.1. General Principles and Characteristics of Wet Pond Performance

Wet ponds – or wet detention ponds – are designed to collect stormwater and to drain it slowly, often holding it for days. By doing so, “treatment processes” for the inflowing water similar to those that naturally take place in small, shallow lakes may occur, e.g. pollutant accumulation in the pond sediments, transformations of biodegradable substances and uptake of pollutants in the vegetation. The main characteristics of a wet pond receiving stormwater and road runoff are therefore:

- It has a permanent water volume

- It holds the inflowing stormwater and reduces thereby hydraulic effects like erosion of downstream located receiving water systems at the same time pollutant removal processes proceed
- It reduces non-point source loadings of pollutants onto downstream located receiving waters

The main types of pollutant removal processes in such wet ponds are:

- Sedimentation and thereby accumulation of pollutants in the sediment
- Uptake of (soluble) pollutants in the vegetation followed by degradation or accumulation in the sediments when the vegetation dies and decays
- Adsorption of fine particulate (colloidal) material on fixed surfaces, e.g. plants and bottom sediments

To some extent, also degradation of pollutants in the water phase may take place. However, compared with these three types of processes, it is normally less important because of a typical low biodegradability of the incoming organic matter.

A wet pond can in addition to observe hydraulic and pollutant removal purposes also be designed as a “natural” lake and thereby contribute to the recreational value in an urban area. A wet pond is therefore also a potential element of “water in the city” observing dual purposes. A wet pond will over time typically be populated with different plants and animals. It is, however, important to stress that it is a treatment device that should remain as such and that authorities should not convert it to an “ecological system” and define corresponding quality criteria.

In principle, the water volume of a wet pond consists of two parts, a “permanent water volume” that defines a “minimum” dry weather water depth and an overlaying “storage volume” that in principle corresponds to the water volume that has been temporarily accumulated in the pond from the inflowing runoff water, Figure 2. This storage volume is also named “treatment volume”. In practice, a number of phenomena and processes result in modifications of this simple approach. As example, evaporation can further reduce the permanent volume during a long dry weather period and during extreme events, the maximum water level can be further raised or overflow can take place. More correctly, it is the entire complex water balance of the pond and the flow pattern in it that will determine the distribution, mixing and residence time of the pond water.

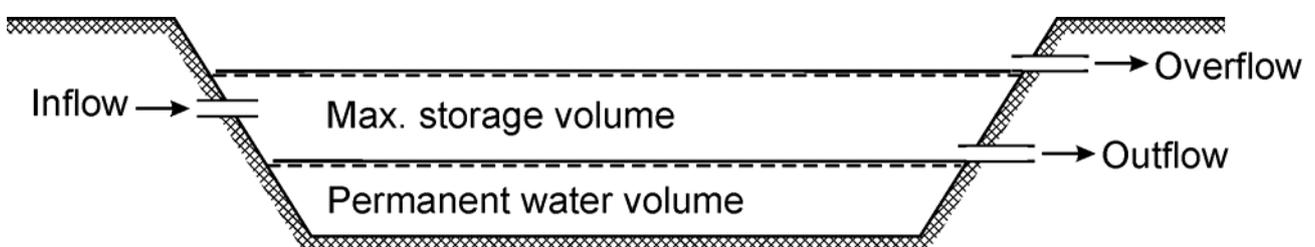


FIGURE 2. Principle of a wet pond showing the permanent water volume and the maximum storage volume for the runoff water, cf. text.

Continuous outflow from a pond will occur as long as the water level exceeds the minimum level. Although mixing between the two parts of the water volume takes place, it is in terms of performance and design important to understand the basic approach of two types of volumes.

Figure 3 shows an example of a wet detention pond receiving highway runoff.



FIGURE 3. A wet pond receiving highway runoff and located in a property development, Fornebu, in Oslo, Norway. The area was until 1998 the airport of Oslo. The “permanent water volume” is in this case compared with the “storage volume” a dominating feature.

8.2. Design Principles for Wet Ponds

There are several ways and concepts for design of a wet pond that observes the objectives and characteristics mentioned in Section 8.1. In Figure 4, two different principles for construction are depicted. Because of risk for clogging of the filter, the type with the horizontal flow is most commonly implemented.

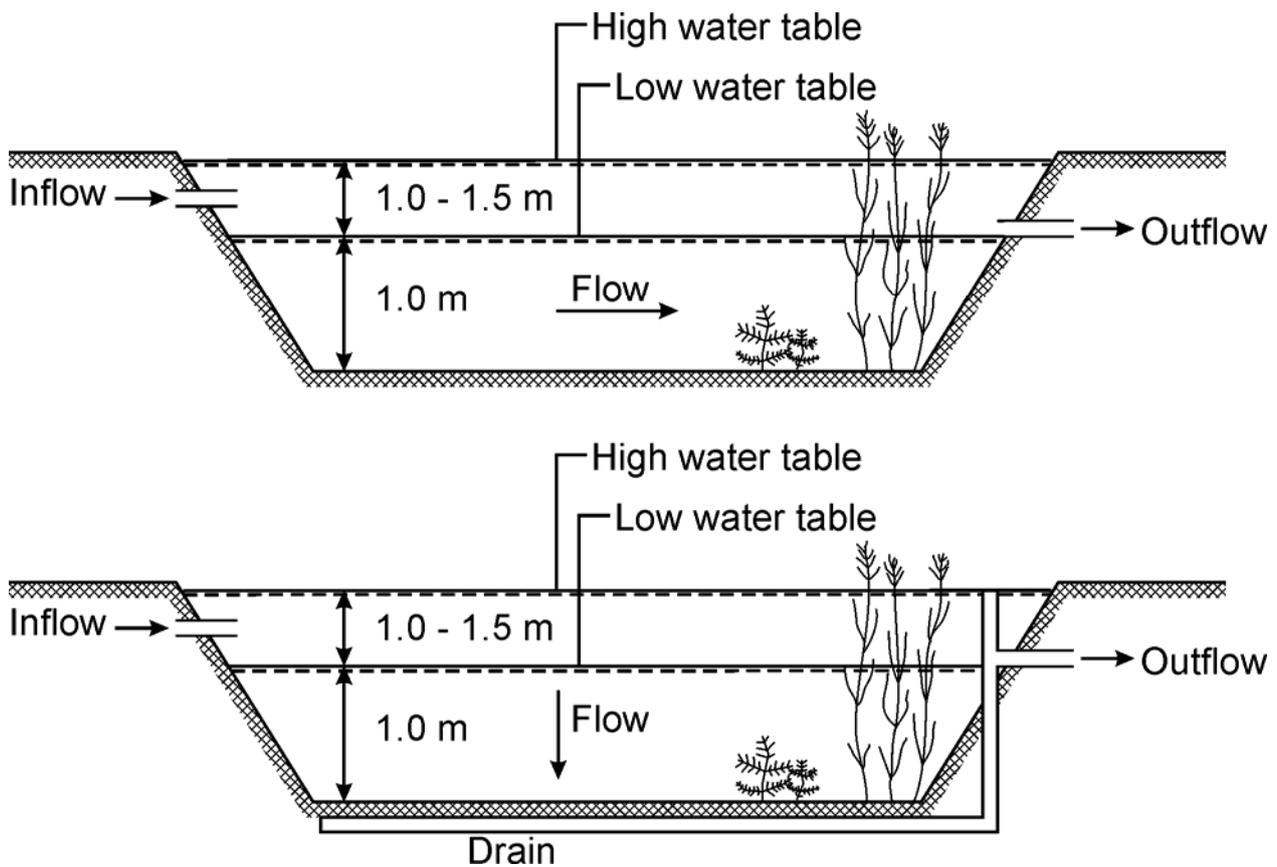


FIGURE 4. Principle of a wet pond with horizontal flow and with vertical flow through a stone filter, respectively. Both submerged plants and marsh plants can be present. Typical high and low water tables are indicated, cf. text.

Further design details are depicted in Figure 5. This figure also shows a flood control volume used for peak discharges.

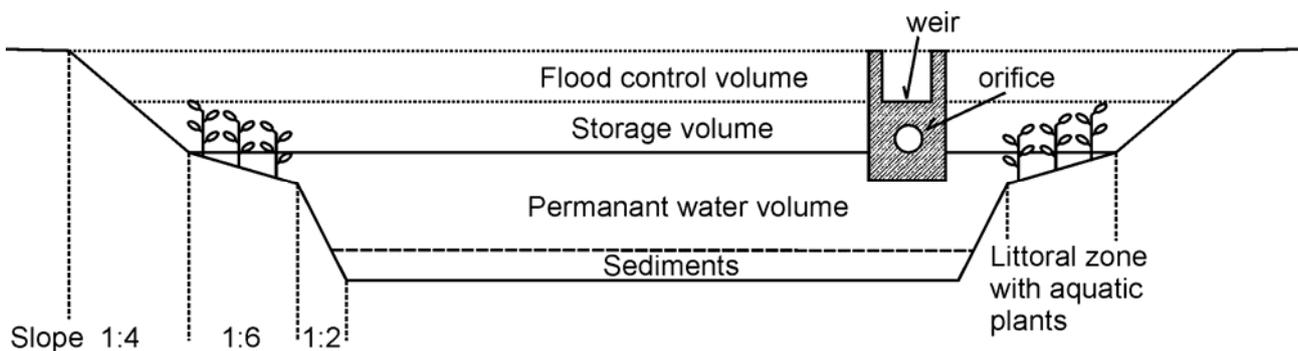


FIGURE 5. Example showing design details of a wet pond, cf. Figures 2 – 4.

In the design phase, it is in addition to the treatment performance important to consider those environmental problems that can occur in wet ponds and of course also those aspects that are related to the operation and maintenance. The following are major environmental problems that are frequently observed in wet detention ponds:



- Eutrophication
- Wet ponds as breeding grounds for mosquitoes and mosquito-borne diseases like the West Nile virus

Furthermore, the following should be considered:

- Occurrence of excessive siltation
- Avoiding areas where more or less permanent stagnant waters exist
- Maintaining aerobic conditions in all parts of the pond
- Design the systems so they draw in e.g. birds and predators like mosquito fish and dragonflies whereby the occurrence of harmful insects can be reduced
- Create as much as possible a “natural” system

Basically, the first step in the design process is to determine the volume of the wet pond. A number of additional criteria should following be considered to observe both process and operational related objectives of the pond. The following four different principles illustrate what normally are applied for determination of the pond volume. In the following Sections 8.2.1 – 8.2.4, these principles will be further illustrated:

1. Design based on the specific pond area in terms of a recommended surface area of a pond per impervious unit area of the contributing catchment, e.g. determined in units of $m^2 ha^{-1}$, cf. Section 8.2.1.
2. Design based on empirical knowledge for the pollutant removal rates in detention ponds versus a dimensionless variable describing the pond volume relative to the runoff volume from the local mean storm event, cf. Section 8.2.2.
3. Design based on a minimum duration of the inter-event dry period between successive storm events and a corresponding return period for exceeding this criterion, cf. Section 8.2.3.
4. Design based on a rainfall-runoff model for the catchment and an empirically based expression for removal of selected pollutants in the detention pond, cf. Section 8.2.4.

Although these design principles are mentioned in order of increasing complexity, they are all based on empirical knowledge. A conceptual description of all the important processes for the performance of a wet pond does not exist at a level where it is realistic and true.

These four principles for determination of the wet pond volume are not exclusively given to illustrate the application of different tools for this specific purpose. The objective is more general by illustrating that the use of quite different empirical approaches can lead to quantification and solution of identical problems. This fact is important because it must be realized that pollution from urban catchments and roads is subject to considerable variability and that one of the implications is that quantification for solution to a problem in general must rely on empirical and not conceptual knowledge. Contrary to apply a conceptually based tool that in case of environmental process engineering typically relies on well-defined theoretical knowledge on the governing processes, an empirical approach as a means to solve a given problem can have different starting points.

Last but not least it is crucial to stress that the volume of water in a wet pond varies considerable, in principle between a minimum value (a permanent pool of water volume) and a “high” value



including both the permanent water volume and the overlaying storage volume. The pond volumes determined by the four design methods must therefore be interpreted by taking this fact into account. Furthermore, changes in the water volume will be affected by the outflow from a wet pond. This outflow can be restricted in case of a potential hydraulic impact onto downstream receiving waters. These aspects will be discussed in Section 8.2.5.

In addition to the determination of the volume of the wet detention pond, there are a number of other design criteria that must be considered. In Sections 8.2.6 and 8.2.7, these aspects will briefly be dealt with.

8.2.1. Size of Wet Ponds based on a Specific Pond Area, Method #1

A rather simple design principle for a wet detention pond is to relate the surface area of the pond to the area of the catchment, i.e. to determine a specific pond area in units of e.g. m^2 per impervious contributing catchment (ha). To some extent this design principle must reflect the hydraulic load of the pond and a recommended value for the pond-catchment area ratio will therefore vary with the rainfall pattern from one region to another. Indirectly, the principle is based in a fixed water depth of the pond, typically varying in the interval 1-1.5 m.

The design principle will be illustrated by an example. Based on measured long-term pollutant removal efficiencies, Pettersson et al. (1999) have studied the importance of the surface area of a wet pond relative to the catchment area. They performed investigations in two pond systems, one that was high loaded and one with a relatively low load. Table 7 and 8 show main results from this study.

The two ponds have average depths of about 1.2 m. The volume of the high loaded and the low loaded pond corresponds to a capacity for detention of the precipitation of about 5 and 30 mm of rainfall at the catchments, respectively.

TABLE 7. Inflow and outflow concentrations of pollutants and corresponding removal efficiencies for a high loaded wet pond with a specific surface area of $40 \text{ m}^2 \text{ ha}^{-1}$ impervious area of the catchment. Because of the high load, an overflow structure at the inlet diverts runoff water directly to the receiving water during heavy storm events. The number of events included is 65.

Pollutant	Inflow SMC	Average outflow concentration	Removal efficiency (%)
TSS (g m^{-3})	55	17	42
VSS (g m^{-3})	16	6	39
Zn (mg m^{-3})	120	83	24
Cu (mg m^{-3})	53	37	24
Pb (mg m^{-3})	13	7	30
Cd (mg m^{-3})	0.55	0.48	12
Tot N (g m^{-3})	2.0	1.9	8
Ortho P (g m^{-3})	0.07	0.04	27



TABLE 8. Inflow and outflow concentrations of pollutants and corresponding removal efficiencies for a low loaded wet pond with a specific surface area of 240 m² ha⁻¹ impervious area of the catchment. The number of events included is 13.

Pollutant	Inflow SMC	Average outflow concentration	Removal efficiency (%)
TSS (g m ⁻³)	153	25	84
VSS (g m ⁻³)	27	6.5	76
Zn (mg m ⁻³)	135	24	82
Cu (mg m ⁻³)	34	9	75
Pb (mg m ⁻³)	26	5	82
Cd (mg m ⁻³)	0.41	0.20	50
Tot N (g m ⁻³)	0.9	0.6	33
Ortho P (g m ⁻³)	0.09	0.02	74

Investigations that have been performed in other wet ponds under similar rainfall conditions and with a specific pond area larger than about 250 m² ha⁻¹ have in general not shown removal efficiencies exceeding what is reported in Table 8. From a practical point of view, this specific area of a wet pond – having a water depth of about 1-1.5 m – is therefore considered an upper limit for the pollutant removal capacity of a simple pond. The results that are shown in Figure 6 illustrate this fact.

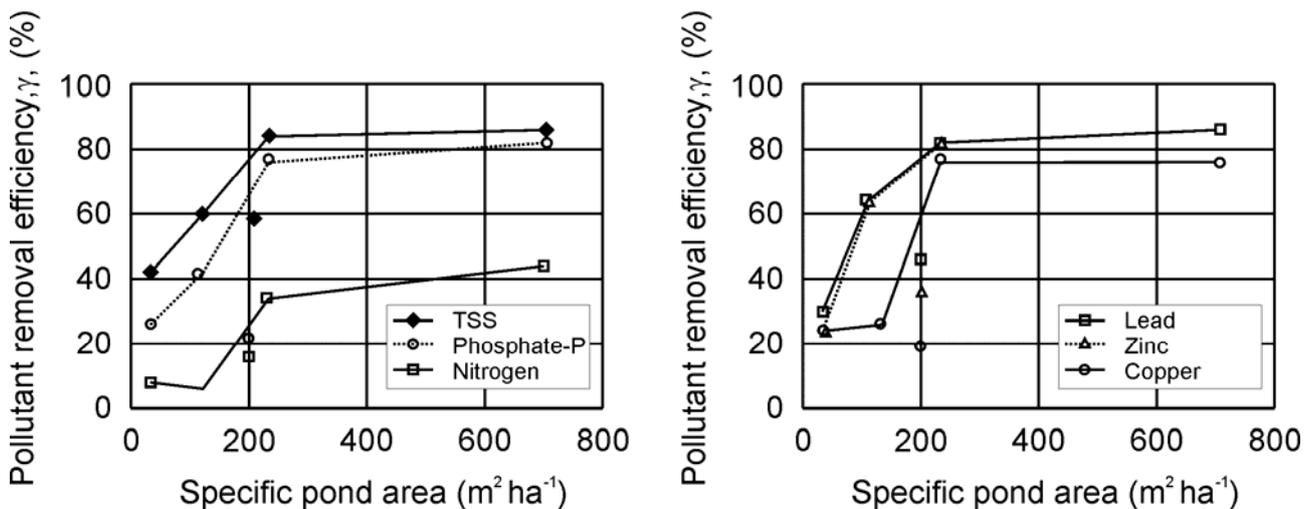


FIGURE 6. Measured and estimated pollutant removal efficiencies for selected heavy metals versus the specific pond area (Pettersson et al., 1999).

8.2.2 Determination of Pond Volume based on Pollutant Removal Efficiency and the Local Mean Storm Event, Method #2

The empirical background for this design principle is based on rather simple information on rainfall characteristics that is combined with knowledge on the pollutant removal efficiency that is observed in wet ponds located at different sites. The following is the information originating from different wet ponds contributing to the design basis:

- The rainfall depth for a mean rainfall event at the site
- The volume of the wet pond
- The pollutant removal efficiency (%) observed for the pond

Compared with the design principle explained in Section 8.2.1 that is based on determination of a specific pond area, the estimation of the pond volume by this method takes into account the local rainfall pattern in a simple way. The following formula defines in this respect a central parameter, n , by combining the volume of the wet pond and information on the local rainfall:

$$n = V/v \tag{2}$$

where:

n = dimensionless pond water volume (-)

V = volume of a wet pond determined per unit area of impervious catchment ($m^3 ha^{-1}$)

v = volume of water for a mean storm event per unit area of impervious catchment ($m^3 ha^{-1}$)

Based on information available from a number of wet ponds, an empirical relationship between the dimensionless pond water volume, n , and the pollutant removal efficiency, γ , can be established, Figure 7.

$$\gamma = f(n) \tag{3}$$

where:

γ = pollutant removal (treatment) efficiency (%)

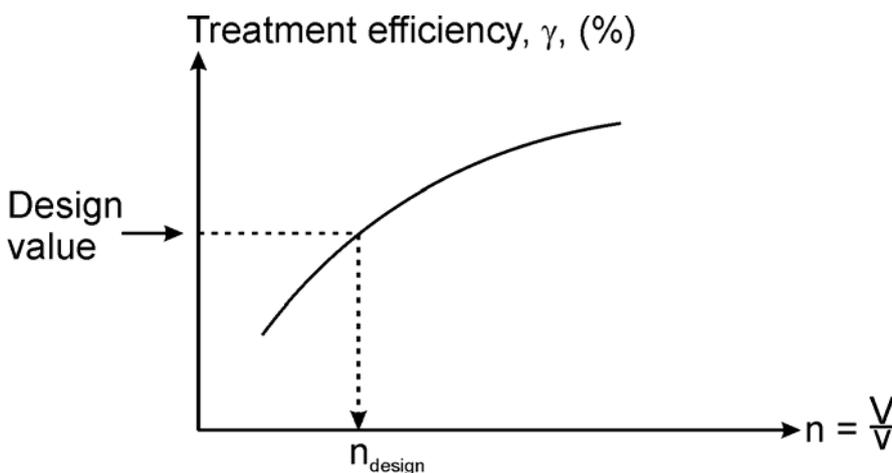


FIGURE 7. Principle for determination of a wet detention pond volume, V , based on the volume of water for a mean storm event, v , and required removal (treatment) efficiency, γ , of a pollutant, cf. text.



The starting point for determining the pond volume is the empirical relationship $\gamma = f(n)$ for a selected pollutant that is considered central and for which a specific removal efficiency should be met, cf. Figure 7. Based on this selected value of γ , a corresponding dimensionless pond water volume, n , is found and following the wet pond water volume, V , according to Equation 3. In case of rainfall conditions for Northern Europe, it is typically observed that an “optimal” value of γ corresponds to a value of n in the interval 6-8.

The principle depicted in Figure 7 is exemplified for total suspended solids (TSS) and total phosphorus (tot. P), Figure 8. The design curves are based on information originating from USEPA (1986), Hvitved-Jacobsen et al. (1987) and Hvitved-Jacobsen et al. (1994).

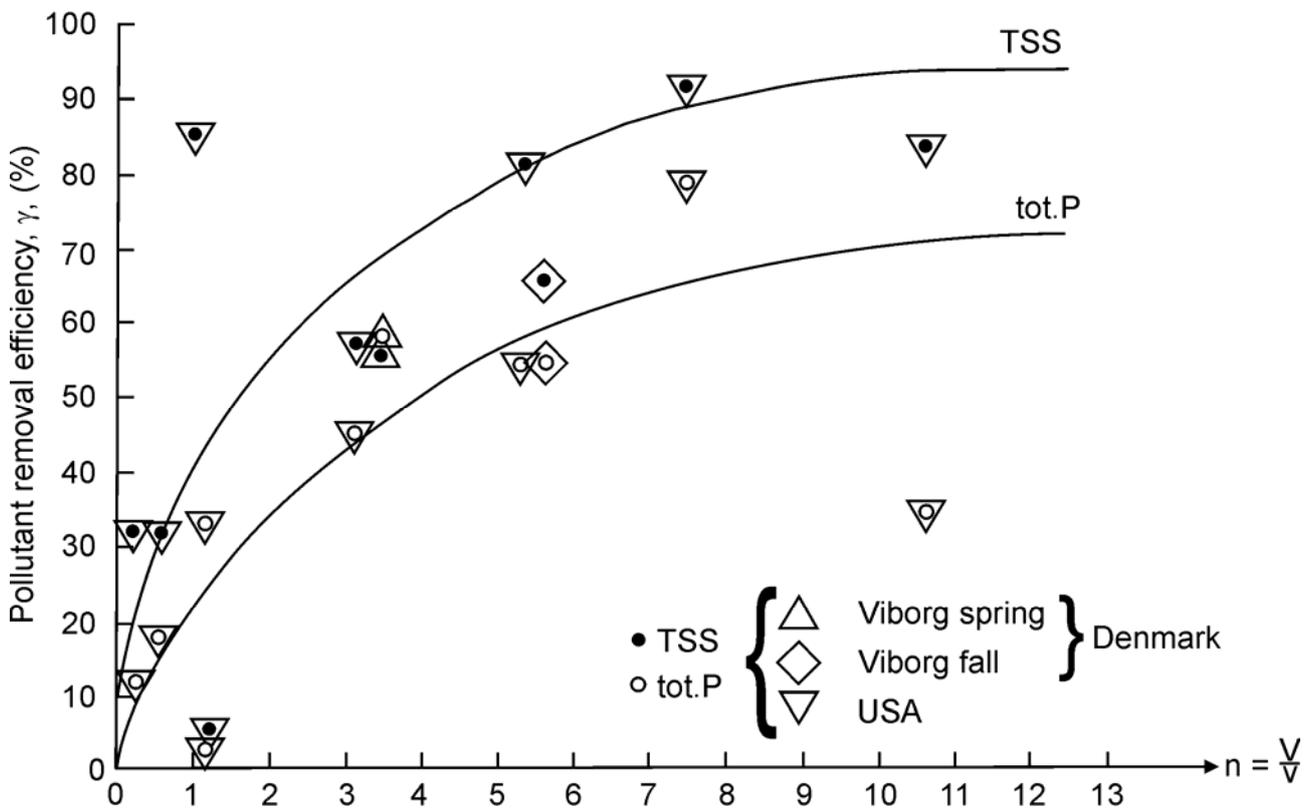


FIGURE 8. Empirical based design curves for determination of a wet pond volume, V , based on required pollutant removal efficiency, γ , and information on the mean rainfall volume, v , for the site. Design curves are shown for total suspended solids (TSS) and total phosphorus (tot. P).

A mean rainfall depth can be defined in different ways. In case of the results shown in Figure 8, this mean value is based on a rainfall series with rainfalls > about 0.4 mm and a minimum inter-event dry weather period of about 1 hour. Because of the empirical nature of the design principle other criteria can be selected as well.

The pond volume, V , must be interpreted in terms of permanent water volume and/or storage volume, cf. Figure 2 and for further details also Section 8.5. This interpretation depends in principle on the type of which underlying data are used for the empirical Equation 3. In case of Figure 8, the wet ponds that were included operated with a rather small storage volume. The results based on this



figure therefore relate to similar conditions and the volume V should basically be interpreted as a permanent water volume.

From Figure 8 it is seen that a removal efficiency, $\gamma = 0.65$ for total P corresponds to a dimensionless pond water volume, $n = 7.5$. Under Northern European conditions with a typical mean storm event, $v = 30 \text{ m}^3 \text{ ha}^{-1}$, the (permanent) water volume is therefore:

$$V = n v = 7.5 \times 30 = 225 \text{ m}^3 \text{ ha}^{-1}$$

8.2.3. *Wet Pond Design based on Inter-event Dry Period Characteristics, Method #3*

The central idea behind this design method is the observation that high pollutant removal efficiency in a wet pond will occur if sufficient residence time is provided and if also conditions with a minimum of mixing in the water phase can be established. The reason is that sedimentation and pollutant uptake in plants and other transformation processes require time to proceed and because optimal sedimentation is supported by quiescent conditions in the water phase. The combination of sufficient residence time, i.e. Hydraulic Residence Time, HRT, and quiescent condition in the water phase can be expressed in terms of the length of the inter-event dry period between two consecutive rainfall (runoff) events.

It has been observed that under temperate climate conditions, 2-3 days of inter-event dry period is typically required to fulfill what can be considered “optimal” pollutant removal efficiency. Such “optimal” conditions means that not just settling of solids will occur but also to some extent biological uptake of soluble species, e.g. nutrients, having lower reaction rates. Observations show that an increase in this period normally only to a minor degree improves the removal of a pollutant, probably because some kind of complex “equilibrium” is established with both uptake and release of accumulated substances.

Applying this design principle, the concept exemplified in Figure 9 can be used for determination of the pond volume. This figure shows the relation between rainfall depth (rainfall volume), inter-event dry period and frequency of the event at low return periods. The curves in this figure are based on statistical analysis of a 33 years rainfall series from the city of Odense, Denmark, and must of course for specific design purposes be replaced by local rainfall statistics.

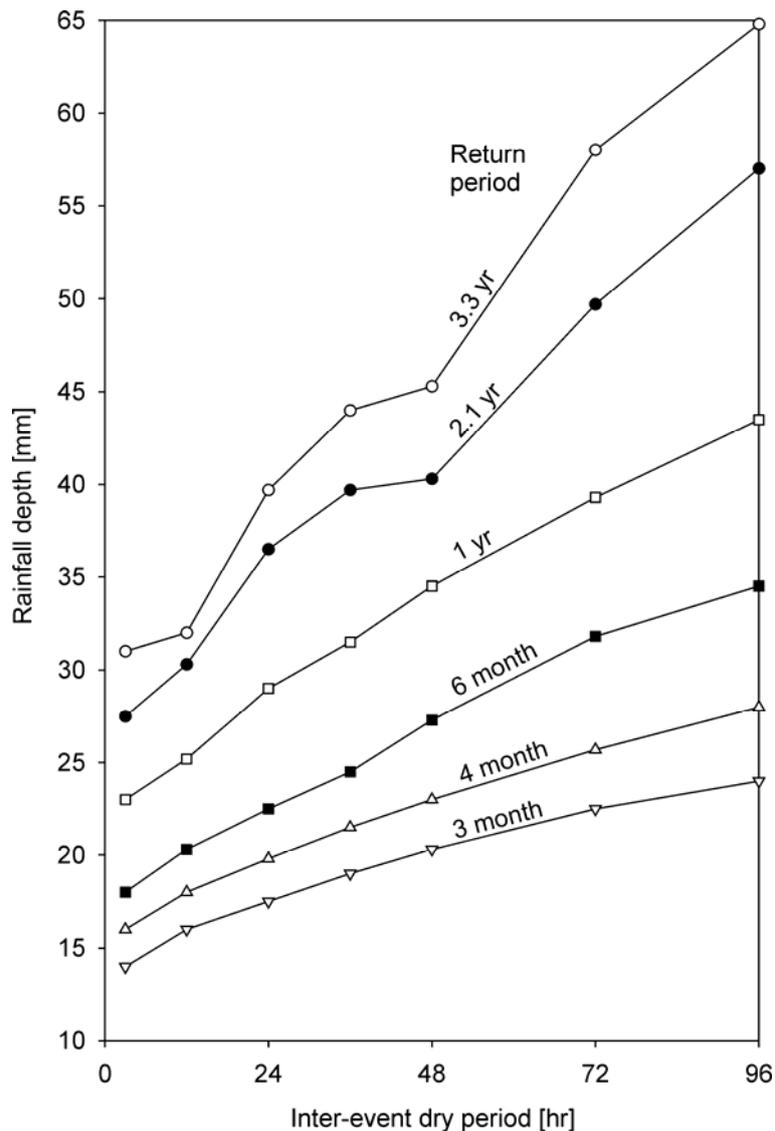


FIGURE 9. Rainfall/inter-event dry period/frequency curves based on a 33 years rainfall record for the city of Odense, Denmark (Hvitved-Jacobsen and Yousef, 1988).

As an example, the following design criteria for determination of the volume of a wet pond volume can be selected:

- A frequency of overflow of untreated runoff water from the pond: 3 yr^{-1} (i.e. a return period of 4 months)
- An inter-event dry period between two consecutive rainfall events equal to 72 hours, i.e. a period where conditions with a minimum of mixing in the water phase can be expected

The example in Figure 9 shows that these two criteria result in a design rainfall equal to 24 mm. If the rainfall and runoff volume from an impervious area are almost equal for such a storm, the volume of the wet pond per unit area of the catchment is:

$$V = 24 \cdot 10^{-3} \cdot 1 \cdot 10^4 = 240 \text{ m}^3 \text{ ha}^{-1}$$



As it was the case for Method #2, this pond volume shall be interpreted in terms of the permanent water volume and/or the storage volume. For this Method #3, one of the criteria for the design concerns the frequency of overflow of untreated runoff water, i.e. outflow of water that has not observed the criterion of sufficient residence time. It is therefore clear that the volume, V , includes the storage volume but also – depending on the hydraulic design of the pond – a portion of the permanent water volume. As will be further discussed in Section 8.2.5, good hydraulic performance of a wet pond will ensure that a portion of the treated permanent water volume will be discharged during a runoff event and replaced by the incoming runoff water.

The result in terms of the wet pond volume is by applying Method #3 highly dependent on the actual rainfall pattern and the criteria selected, i.e. the frequency of overflow and the inter-event dry period. The criteria that are selected in the example resulting in a wet pond volume of $240 \text{ m}^3 \text{ ha}^{-1}$ therefore relate to the climate and process conditions in Denmark that is situated in the northern European temperate zone. If these criteria, as an example, are applied for Florida, USA with a subtropical climate, the wet pond volume turns out to be about 4 times larger (Hvitved-Jacobsen et al., 1989). This is probably not realistic – and not a correct choice – because the criteria should be chosen to observe “optimal” pollutant removal under the conditions that prevail in the actual case. Specific values for these climate depending criteria must therefore be evaluated and carefully selected for each region.

8.2.4. Wet Pond Design based on Model Simulation for Pollutant Removal, Method #4

The physical, chemical and biological processes that take place in a wet pond are as previously mentioned in principle the same as those of a shallow lake. For modeling purposes of wet ponds, the governing pollutant removal processes are in practice not possible to describe in details – particularly not in case the design concerns new systems. This is basically expected because of the complex nature of the pollutant removal processes. As a substitute, a simple 1st order understanding of pollutant removal in a wet pond can be applied (Hvitved-Jacobsen et al., 1994; FHWA, 1996):

$$C = C_0 e^{-kt} \quad (4)$$

where:

C = pollutant concentration at time t (g m^{-3})

C_0 = pollutant concentration of the incoming stormwater (g m^{-3})

t = residence time in the pond (d)

k = 1st order removal rate of the pollutant (d^{-1})

The kinetics shown in Equation 4 can be included in a model for pollutant removal in a wet pond.

Based on results from investigations on pollutant removal in wet ponds, the following values for k were estimated (Hvitved-Jacobsen, 1994):

dissolved phosphorus: $k = 0.1 \text{ d}^{-1}$

particulate phosphorus: $k = 0.35 \text{ d}^{-1}$

total suspended solids (TSS): $k = 0.5 \text{ d}^{-1}$



As an example, Equation 4 was used in a model for prediction of pollutant removal in a wet pond receiving runoff from a highway near Oslo, Norway (Vollertsen et al., 2006). Based on continuous measurements of inflow and outflow from the pond during a year, the pollutant removal rate constant, k , was estimated. In this case the yearly average removal rate constant for TSS ($k = 2.0 \text{ d}^{-1}$) and for total phosphorus ($k = 0.14 \text{ d}^{-1}$) was determined. Because of the variability that basically exists for the runoff phenomena and treatment processes, Equation 4 is not relevant to apply at a time scale corresponding to single runoff events. In case of pollutants with accumulative effects – which in general exist in case of stormwater runoff – this is not a relevant obstacle for the design.

Design Method #4 differs from the three previously described methods #1 - #3 by the fact that it is based on model simulation. It is therefore a methodology appropriate for analysis of different scenarios, cf. Section 8.2.5. Furthermore, the input of both water and pollutants to the model of the wet pond can be described in terms of a runoff model for the catchment. Such a model will typically be based on a historical rainfall series. As an example, the residence time distribution of the inflowing runoff water in the pond is therefore a possible and useful model result (Vollertsen et al., 2006).

Method #4 requires a number of input data, e.g. a starting value of the pond volume determined by one of the methods #1 - #3.

Because Method #4 is a model simulation procedure, the pond volume, V , is basically subdivided into two parts, the permanent water volume and the storage volume.

8.2.5. Integrated Pollutant Removal and Hydraulic performance of Wet Ponds

When implementing the results obtained with the three design methods #1 - #3 for the pond volume, it is important to combine pollutant removal with the hydraulic performance of the actual wet pond. Method #4 dealt with in Section 8.2.4 is as mentioned a simulation methodology. Therefore, this design methodology in principle also includes an analysis for optimal pond performance, i.e. also the hydraulic performance.

The starting point of integrated process design is – after having used one or more of the design methods #1 - #3 – a “pond volume”, i.e. a runoff volume being exposed to treatment. As already discussed to some extent in Sections 8.2.2 and 8.2.3, an important design step is to determine how this volume should be interpreted. In this respect the important question is if the pond volume is a “storage” volume, a “permanent” water volume, the total of these or some other kind of “effective” volume? In the following this question will be further focused on and discussed in terms of the hydraulic performance of the pond.

The pond volume determined by the design methods #1 - #3 is particularly based on which water volume can be exposed to removal of the pollutants. These three methods are empirical and the underlying data originate from real systems where different phenomena, e.g. specific hydraulic characteristics, prevail and are of importance. When implementing the result of the design in practice, the actual hydraulics of the wet pond must be considered, i.e. the flow regime in the pond and the outflow relative to the inflow. Thereby it is particularly important to observe the following two integrated objectives or requirements in the design procedure:



Sufficient residence time of the captured runoff volume in a wet pond must be ensured to support treatment

Hydraulic performance of the wet pond and required protection of downstream receiving waters must be observed.

As a first step it is important that sizing a pond in terms of a detention volume is done to obtain an appropriate treatment performance under extreme runoff conditions, i.e. in a case where a portion of the runoff volume will pass the overflow weir. Under such conditions the point is that a volume of runoff water – including a potential “first flush” volume – is captured by the pond and given sufficient residence time to let treatment processes proceed. Because of that, the pond volume determined by the design Methods #1 - #3 is basically the storage volume under conditions where a rather limited flow out of the pond is to be observed. However, if this is not required and in a hydraulically well-designed pond where plug flow conditions approximately prevail, a portion of the permanent water volume will also contribute to improve the residence time. This is caused by the fact that the incoming water to some extent will push the permanent water volume in a forward direction and thereby let treated water pass through the outlet, cf. Section 8.2.6. The storage volume – or treatment volume – is therefore just a first and rather conservative estimate of the “effective” pond volume.

If no requirements exist for the flow out of the wet pond, e.g. if hydraulic protection of downstream facilities or receiving waters is not needed, the incoming runoff water can to some extent almost simultaneously replace a portion of the treated water from the permanent water volume. In this case the shape of the pond, i.e. the length to width ratio and the water depths at both high and low water tables, affects the size of the pond when interpreting what is the “pond volume”. Rather complex hydraulic models are required for the analysis in such a design case. However, based on results from existing pond systems and as a first and rather crude estimate of the effective pond volume, the following can be recommended:

- a) The pond volume determined by the design methods #1 - #3 is approximately equal to the storage volume in case of limitations in outflow from the pond.
- b) The pond volume determined by the design methods #1 - #3 is approximately equal to the storage volume plus 0.4 - 0.6 times the permanent volume in case that no limitation in the outflow exists and the hydraulic performance of the pond observes the criteria outlined in Section 8.2.6.

In the following Example 1, these two different scenarios for design of wet ponds will be briefly illustrated and commented.

Example 1: Pollutant removal and hydraulic performance of two wet ponds

The two cases, a) and b), are illustrated in Figure 10. Pond a) is a case where a receiving water body sensitive to e.g. erosion is located downstream the outlet from the wet pond whereas this is not the case for pond b). Furthermore, it is particularly expected that pond b) observes good hydraulic performance as further described in Section 8.2.6. In both cases the contributing catchment is 1 ha and design Method #3, Section 8.2.3, is used. Based on results from Figure 9 with criteria of an

inter-event dry period equal to 48 hours and 3 months return period, the design volume of the wet pond is 200 m^3 for each of the two ponds. This volume of water should therefore be detained and treated in the wet ponds in both case a) and b) according to the requirements.

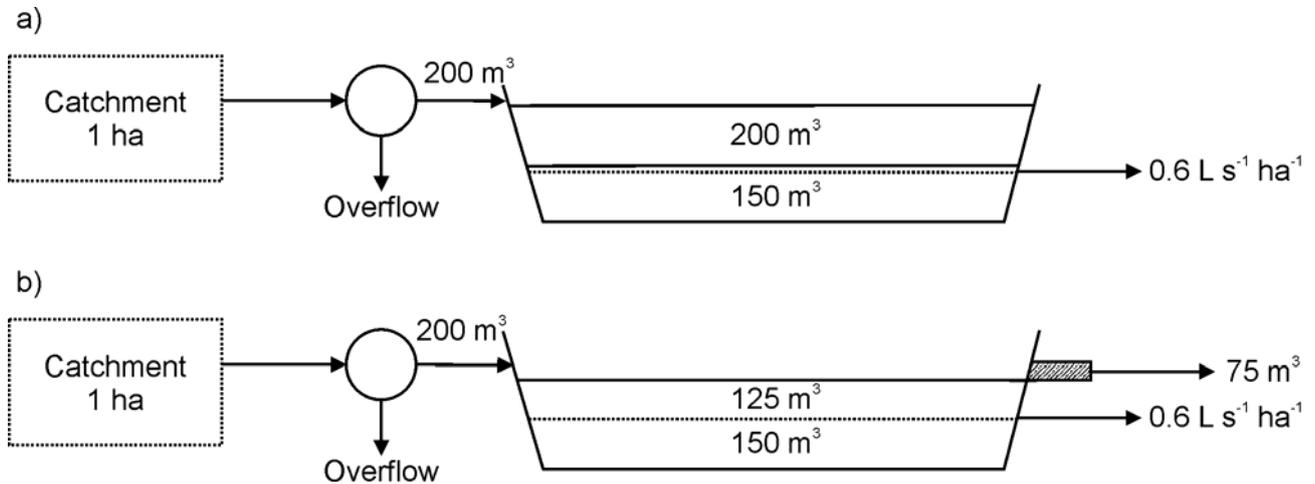


FIGURE 10. Illustration of two different pond design principles, cf. text.

If the dry weather volume – the permanent water volume – in each of the two ponds is 150 m^3 , the need for an overlying storage volume in case a) is 200 m^3 . If it is assumed that 50% of the permanent water volume, i.e. 75 m^3 , can be replaced by the incoming runoff water, the storage volume is in case b) reduced to 125 m^3 . In the latter situation it is expected that 75 m^3 of treated water originating from the permanent water volume is discharged via the outlet from the pond in principle simultaneously with the inflow of the runoff water. In case the detained runoff water in the two ponds is following discharged with a rate of $0.6 \text{ l s}^{-1} \text{ ha}^{-1}$, the pond in case a) will return to the dry weather state in about 3.9 days whereas it in case b) only lasts 2.4 days. As can be seen from Figure 10, the total volume of the wet pond in case b) is 275 m^3 whereas the requirement for hydraulic protection of a downstream located receiving water body in case a) increases the total pond volume to 350 m^3 .

An important point of Example 1 is that the result in terms of the pond volumes determined from the design Methods #1 - #3 should be further assessed addressing both the hydraulic performance of the pond itself and that of the downstream receiving systems. Although the pond designs illustrated in this example for the two cases are based on the same “pond volume” originating from design Method #3, it is readily seen that the detention time of the captured runoff water volume will not turn out to be equal. By applying the simulation Method #4 outlined in Section 8.2.5, further details of the two scenarios can be analyzed, e.g. taking into account inflow according to a historical rainfall series, hydraulic characteristics of the outlet structures and mass balances for both water and selected pollutants.

3.2.6. Hydraulic Function of Wet Ponds

The hydraulic function of a wet pond is important for two main reasons, namely for the efficiency of pollutant removal and because of the hydraulic effect on downstream located receiving waters.



Substances that are associated with particulate matter must be subject to conditions where they can settle and not following be eroded and sufficient residence time for pollutant removal processes to proceed must be observed. Furthermore, the flow out of the pond must be controlled. If possible, an appropriate hydraulic function of a wet pond should in principle be observed without the use of pumps and other types of unit operations that require extensive maintenance, energy consumption and use of manpower.

In brief, the following generally expressed design rules result in an appropriate hydraulic function of a wet detention pond:

- The inlet structure, the pond itself and the outlet must be designed to manage the design flow from the catchment. An overflow structure for extreme runoff events must be an integrated part of the design.
- The inlet structure and flow regime in the pond must allow for sedimentation and protect against erosion.
- “Plug flow” through a pond will result in optimal conditions for settling and residence time of the pollutants in the water phase. A length to width ratio of the pond between 3:1 and 4:1 is typically recommended.
- Flow control out of the pond must observe the requirements for the hydraulic load onto downstream facilities or receiving waters. For sensitive receiving waters a typical recommended flow out of the pond is $0.5\text{-}2\text{ l s}^{-1}\text{ ha}^{-1}$ of the contributing catchment.
- A “natural” flow through the pond and no use of pumps require a location of a pond downstream the contributing catchment and upstream the receiving water.

8.2.7. Specific Design Characteristics for Wet Ponds

In addition to determination of the wet pond volume and the hydraulic function, a number of design characteristics must be observed.

A main requirement is related to maintaining aerobic conditions with a DO concentration typically $>$ about 4 g m^{-3} and not lower than about 2 g m^{-3} . In this case, the redox potential at the sediment-water surface is sufficiently high to establish conditions for retaining e.g. phosphorus and metals. Furthermore, good biological quality can be observed and obnoxious smell caused by degradation under anaerobic conditions is avoided. Although a wet pond is a technical installation, it is also a potential recreational element that in a natural way becomes a kind of wetland and a habitat for several animals including fish. The DO mass balance is therefore also crucial for such reasons. Main processes in the DO balance are the reaeration (the air-water mass transfer), the photosynthesis of the plant community and the total respiration. A simple DO mass balance for a wet pond is shown in Equation 5 (Madsen et al., 2007)

$$dC/dt = K_L a (C_S - C) + P(t) - R - SOD/H \quad (5)$$

where:

C = DO concentration (g m^{-3})
 t = time (d)



K_{La} = overall volumetric mass transfer coefficient between water and air, i.e. reaeration rate coefficient (d^{-1})

C_s = DO saturation concentration ($g\ m^{-3}$)

$P(t)$ = photosynthesis ($g\ m^{-3}\ d^{-1}$)

R = respiration, mainly caused by plants ($g\ m^{-3}\ d^{-1}$)

SOD = sediment oxygen demand ($g\ m^{-2}\ d^{-1}$)

H = pond water depth (m)

In addition to oxygen produced by plants, Equation 5 shows that the reaeration plays a central role for input of oxygen. Madsen et al. (2007) showed that the reaeration rate was particularly affected by the wind speed at the pond water surface and that K_{La} at low – and critical – values of the wind speed was a linear function. A shallow pond – e.g. maximum 1-1.5 m deep during a dry weather period – with a balanced vegetation of rooted plants and, minimal occurrence of stagnant water and phytoplankton will in most cases favor an acceptable DO concentration level.

Another design criterion is related to the water balance in case of a long dry period. A membrane – artificial or produced in clay – is therefore important.

Designed as a shallow lake, a wet detention pond has the potential to become a recreational element that is valuable for the local community. The shape of the pond, its vegetation and ecological quality and the plantation of the surroundings are in this respect important elements. Important for a safe performance is sloping banks and e.g. a possibility to establish reed vegetation at parts of the pond, cf. Figure 5.

In order to avoid siltation of a wet pond, a sediment trap (catch basin) is normally included as an integrated part of the design, cf. Section 9. An efficient removal of sand particles in an inlet structure will considerably reduce the need for sediment removal in the wet pond itself to take place with e.g. 15-30 years of interval.

9. POLLUTANT REMOVAL AND SEDIMENT MANAGEMENT OF WET PONDS

Pollutant removal efficiencies in wet ponds receiving stormwater runoff from urban catchments and roads have been discussed as an integral part of the design methods and particularly exemplified in Section 8.2.1. Further comments will be given in relation to the following Example 2.

Pollutant removal in wet ponds is except for what is degraded closely associated with a corresponding accumulation in the sediments. Removal and management of the sediments from wet ponds are therefore an integral aspect of the operation.

Example 2: Pollutant removal in a wet pond

A wet detention pond located in Oslo, Norway that receives highway runoff from a 2.2 ha impervious area is selected as example (Vollertsen et al., 2006). The pond volume is designed according to the principle described in Section 8.2.3 with a criterion of 72 hours of inter-event dry period and a frequency of 3-4 overflow events per year from the pond. Furthermore, the design characteristics dealt with in Section 8.2.6 and 8.2.7 were taken into account. The wet pond is



therefore designed according to rather pragmatic criteria following what might be considered possible in practice, still observing a potential for “good” removal of pollutants.

This example is selected because the design is well defined and particularly because continuous monitoring at the inlet and the outlet of the pond has been performed during a 1-year period. Totally, 87% of the incoming stormwater during this year has thereby been monitored. Main results from the monitoring program are shown in Table 9:

TABLE 9. The yearly average pollutant removal efficiency and flow weighted yearly average pollutant concentrations in the inlet to the wet pond and the outlet from the pond, cf. text.

Pollutant (unit)	Average inlet concentration (SMC)	Average outlet concentration	Removal efficiency (%)
TSS (g m ⁻³)	246	43	82.5
Total N (g m ⁻³)	1.49	1.05	29.5
Total P (g m ⁻³)	0.674	0.262	61.1
Bioavailable P (g m ⁻³)	0.388	0.146	62.4
Oil and fat (g m ⁻³)	5.0	0.9	82.0
Total PAH (mg m ⁻³)	1.77	0.26	85.3
Pb (mg m ⁻³)	17.1	4.1	76.1
Zn (mg m ⁻³)	272	78	71.3
Cu (mg m ⁻³)	86	36	58.1
Cd (mg m ⁻³)	0.21	0.08	61.9
pH (-)	7.4	7.6	-
Conductivity (mS m ⁻¹)	39	42	-

In general, the results shown in Table 9 correspond in terms of removal efficiencies to what is often observed for well functioning wet detention ponds in Northern and Central Europe and in the USA (Shueler et al., 1992). The results therefore exemplify what is considered possible with this type of BMP.

The efficiency of a BMP is traditionally expressed in terms of a percent reduction of a pollutant concentration relative to the level in the incoming stormwater. However, in a treatment device – including the BMPs dealt with in this chapter – the outcome of the treatment processes in terms of an outlet concentration is more or less constant irrespective of the inlet concentration. The efficiency given as percent pollutant removed is therefore not the best measure for the functioning of a BMP because a high inflow concentration favors a high value of removal efficiency. A mean or median outlet concentration from a BMP receiving stormwater runoff is the most relevant measure for what is possible with a given technology (Strecker et al., 2001). Unfortunately, this fact has not been emphasized in most literature on BMPs for stormwater management.

This example – because the results are based on a whole year of continuous monitoring – illustrates which treatment level of a number of pollutants in terms of outlet concentrations is possible to achieve with a well-functioning wet detention pond.



The sediment removed in the forebay (catch basin) of a wet pond consists mainly of sand and coarse materials. If well operated, only a limited amount of fine particles and thereby associated organic matter and toxic pollutants are therefore found in such sediments.

However, and as intended, the sediments in the wet pond itself are contaminated with micropollutants and therefore pose ecotoxicological risks when disposed of. Basically, the frequency of sediment removal from a wet pond can be determined by its potential toxic impact onto the ecosystem but is mostly determined by loss of storage volume (Heal et al., 2006). When removed, e.g. every 20 to 30 years, such sediments are, however, potentially hazardous waste and should therefore be assessed against local soil and sediment quality guidelines.

The distribution of the concentration of pollutants in the sediments from wet ponds depends on the particle size. This is in Table 10 illustrated based on data reported by Pétavy et al. (2007). In general, the table shows an increase in the concentration of organic matter and micropollutants with decreasing particle diameter. The data therefore also indicate the importance of removing only sand and coarse materials in forebays to allow a following use or disposal without major environmental risk.

TABLE 10. Organic matter, hydrocarbon and heavy metal contents in the sediment from a pond receiving stormwater runoff (Pétavy et al., 2007). It is seen that the concentration vary with the particle size and that the major part of the sediment has a particle diameter < 2 mm.

Sediments; bulk and fractions	TS distribution (%)	Organic matter (%)	Hydrocarbons ($\mu\text{g g}^{-1}$)	Zinc ($\mu\text{g g}^{-1}$)	Copper ($\mu\text{g g}^{-1}$)	Lead ($\mu\text{g g}^{-1}$)	Cadmium ($\mu\text{g g}^{-1}$)
Bulk sediment	100	16	3,500	1180	306	140	1.3
> 30 mm	4	-	-	-	-	-	-
2-30 mm	8	7.5	-	650	125	85	0.4
60-2000 μm	50	2.5	Below d.l.	190	25	60	0.1
< 60 μm	38	25	6,400	2280	500	270	1.6

In an investigation by Marsalek et al. (2006), the concentration levels of heavy metals in sediments from a number of stormwater BMPs were reported. They found that according to local guidelines between 80 and 100% of the samples were marginally-to-intermediately polluted with several heavy metals and noted also severe levels at several facilities, e.g. 100-200 $\mu\text{g g}^{-1}$ TS for Cr and Cu.

10. EXTENDED WET PONDS FOR ADVANCED TREATMENT

Although soluble and colloidal materials to some extent can be removed in wet ponds, e.g. by plant uptake and adsorption, the major process for treatment is sedimentation and following accumulation of particulate bound pollutants in the sediments. Wet ponds may, however, be extended with facilities for advanced treatment, here defined as based on unit processes that enhance removal of dissolved and colloidal pollutants remaining in the water phase after traditional treatment.

Typically advanced treatment of stormwater is of relevance in case of a sensitive receiving water body or the stormwater is to be used as a source for drinking water purposes. In principle, advanced treatment is possible by combining BMP units that in terms of treatment performance are complementary, cf. Section 7. Furthermore, it is in addition to such BMP units possible to apply



well-known technologies from wastewater treatment, e.g. accomplished by chemical addition or filtration (Tchobanoglous et al., 2003).

The selection of chemicals, types of filter materials and layout of systems that can be applied in case of advanced treatment of stormwater is legion. Advanced treatment of stormwater runoff that has been subject to treatment in wet ponds can typically be performed in two different ways, cf. the following two Sections 10.1 and 10.2.

10.1. Chemicals added to Enhance the Removal of Dissolved and Colloidal Pollutants

Chemicals are widely used for both drinking water clarification and wastewater treatment and can be used for lake restoration purposes too. Aluminum salts are particularly common for drinking water clarification and salts of aluminum, calcium and iron are in general used for wastewater treatment. Precipitation, coagulation and flocculation are the central unit processes for the purification.

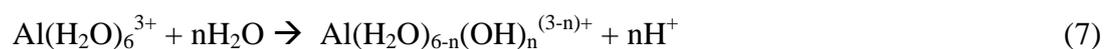
In case of wet ponds, the effect of Al, Ca and Fe salts for the removal of phosphorus, metals and organic micropollutants – including particles like algae – are particularly important. In the following, the mechanisms of these salts will be briefly outlined (Stumm and Morgan, 1996; Cooke et al., 2005).

10.1.1. Aluminum

Aluminum can be added to the runoff water at the pond inlet as e.g. aluminum sulfate (alum), i.e. $\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$, where the aluminum ion is immediately hydrated, in general after few minutes:



Depending on the pH, different hydrated forms of aluminum hydroxide will be formed by liberation of a hydrogen ion:



where

$$n = 1, 2 \text{ or } 3 (-)$$

The different hydrated forms of $\text{Al}(\text{OH})_3$ appear in form of amorphous flocs with characteristics in terms of precipitation, coagulation, adsorption or flocculation of a number of different pollutants and particles. These flocs will following settle and thereby transfer pollutants to the sediments in the pond.

At pH values between 6 and 8, the insoluble $\text{Al}(\text{OH})_3$ will dominate. Above pH 8.5, as could occur during intense photosynthesis, there is a risk for producing the soluble – and toxic – aluminate ion ($\text{Al}(\text{OH})_4^-$) and thereby also a corresponding release of adsorbed pollutants. The $\text{Al}(\text{H}_2\text{O})_6^{3+}$ ion is also toxic but pH values below about 4.5 where this ion is a dominating species will typically not occur in wet ponds. If low alkalinity waters exist, i.e. the water is not well buffered, it cannot be recommended to apply aluminum for pollutant control.

The sorption characteristics of $\text{Al}(\text{OH})_3$ is inert to changes in the redox potential.

10.1.2. Calcium

Calcium can be added at the pond inlet in form of e.g. calcium hydroxide (lime). However, most often Ca is not applied this way but as CaCO_3 in a filter, cf. Section 10.2. Efficient removal of e.g. phosphorus by precipitation of hydroxyapatite ($\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$) requires a relatively high pH value (high alkalinity). The use of lime added for removal of pollutants in wet ponds is therefore – contrary to what is the case for certain types of wastewater treatment plants – in general not appropriate.

10.1.3. Iron

As can be seen from Figures 11 and 12, $\text{Fe}(\text{OH})_3$ is at a relatively high redox potential, i.e. under aerobic conditions, a stable compound in an aqueous system having a low solubility between pH 7 and 10. Although the solubility and stability of $\text{Fe}(\text{OH})_3$ are more complex under the conditions that exist in a wet pond receiving stormwater runoff, these figures depict the real conditions rather well. In general, it is therefore concluded that a major part of iron accumulate in the sediments as $\text{Fe}(\text{OH})_3$ together with other low solubility iron species like $\text{FeO}(\text{OH})$ and FePO_4 . A high redox potential in the upper part of the sediment is crucial for not risking dissolution of Fe(III) as ferrous iron (Fe^{2+}). Furthermore, FeS can be produced if anaerobic conditions in the sediments result in sulfate reduction.

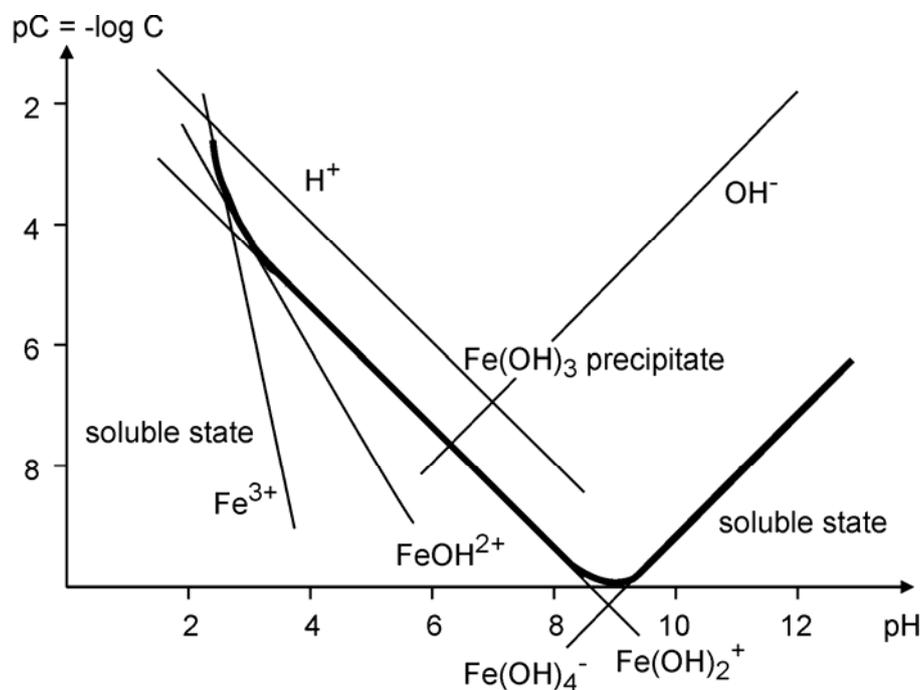


FIGURE 11. Solubility diagram for iron hydroxide in an aqueous system at a high (aerobic) redox potential. The equilibrium conditions for the dissociation of H_2O are indicated in terms of H^+ and OH^- species, cf. text.

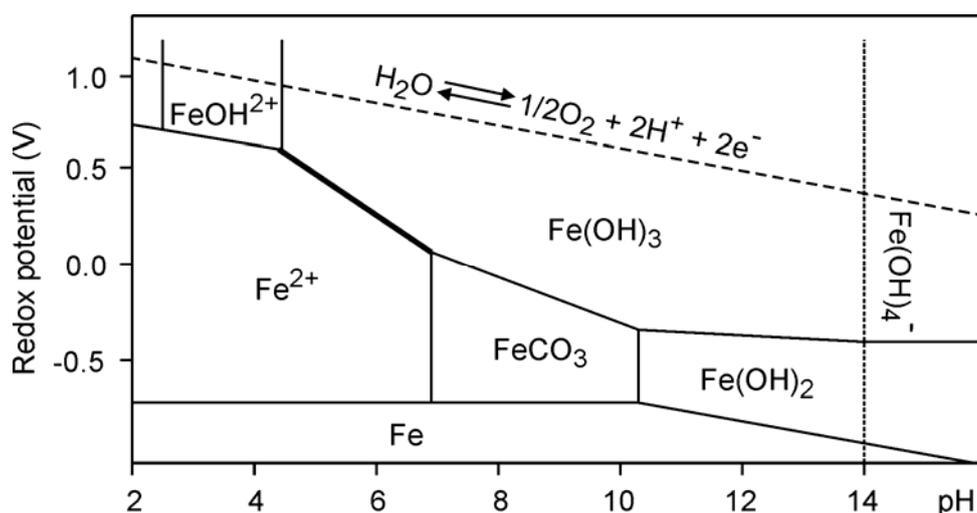


FIGURE 12. Redox potential versus pH for iron species in an aqueous system. The total concentration of soluble iron is $2 \cdot 10^{-3} \text{ mol L}^{-1}$ and the concentration of carbonate is $10^{-3} \text{ mol L}^{-1}$.

The pollutant removal efficiency of iron salts applied for treatment in wet ponds relies on the chemical characteristics of iron mentioned above. In general, $\text{Fe}(\text{OH})_3$ can provide sorption sites for a number of pollutants and $\text{Fe}(\text{III})$ salts can form precipitates or other low solubility complexes with a number of pollutants and thereby accumulate these in the sediments. Aerobic conditions are crucial for two reasons by not risking dissolution of $\text{Fe}(\text{II})$ and by not inactivating iron as FeS .

The entire sequence of chemical and physico-chemical reactions with Fe in an aqueous system are very complex and because of that not possible to quantify in details. The amount of iron required to remove pollutants from the water phase in a wet pond must therefore be determined empirically. In case of phosphorus, investigations have shown that the equilibrium sorption capacity of sediments follows a Langmuir adsorption isotherm, i.e. the relation that exists between the equilibrium P concentration in the water phase and that accumulated in the sediment, Jacobsen (1977). Empirically it is known that these sorption isotherms depend on the sediment composition in terms of its iron content. Figure 13 is an example that originates from analysis of aerobic sediments from a number of shallow lakes (Jacobsen, 1977). As shown in this figure, an increase in the iron content does not cause a proportional increase in the phosphate sorption capacity because the specific area of iron hydroxide will decrease. It can be expected that the similarities between shallow lakes and wet detention ponds makes such relation valid for sediments in wet ponds too.

Figure 13 shows that the iron/phosphate ratio for sediments is a central parameter that determines the capacity for sorption of phosphate and thereby its removal from the water phase. As an example, the figure shows that a reactive iron content (e.g. as $\text{Fe}(\text{OH})_3$ and $\text{FeO}(\text{OH})$) in the sediments of $100 \text{ g Fe (kg TS)}^{-1}$ results in semi-optimal conditions for adsorption of phosphorus. In this case the Fe/P ratio is approximately $17 \text{ g Fe (g P)}^{-1}$. A ratio in the order of $15 - 20 \text{ g Fe (g P)}^{-1}$ in the sediments is therefore considered an appropriate design value when adding iron to the sediments in a wet pond for improved treatment, cf. Example 3. Basically, this design criterion only relates to treatment for phosphorus. However, it is likely that oxides and hydroxides of iron also provide sorption sites for a number of other pollutants, e.g. heavy metals.

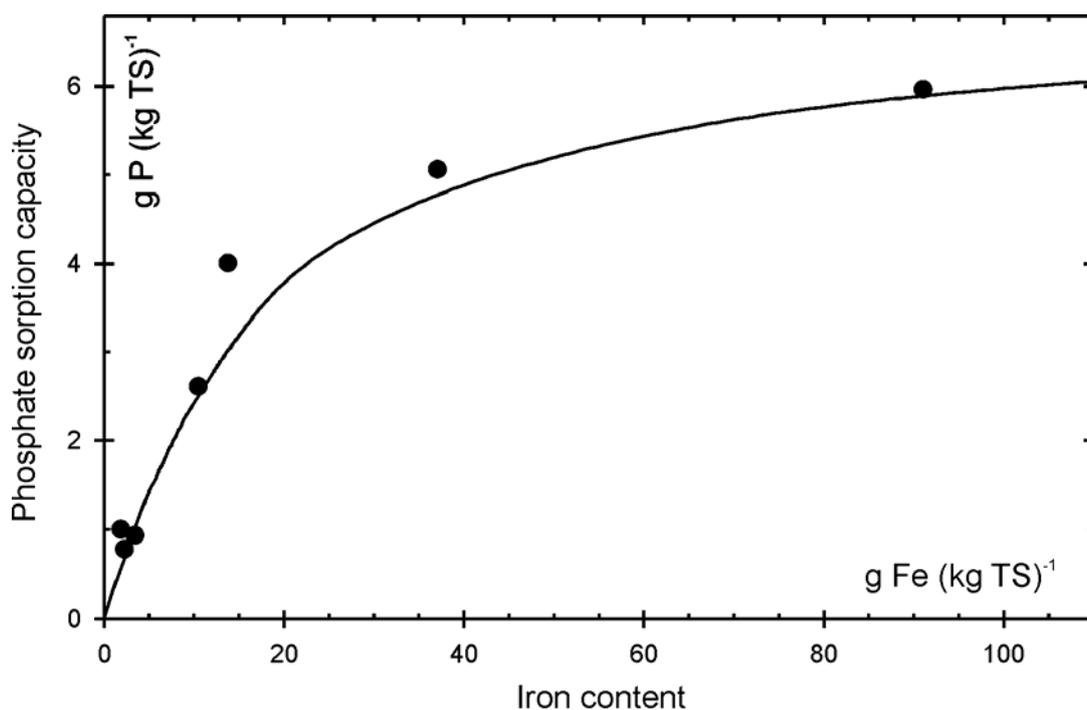


FIGURE 13. Sorption capacity for phosphate versus the iron content of aerobic lake sediments. The results originate from investigation of the upper 5 cm of sediments from 8 shallow Danish lakes (Jacobsen, 1977). Total Fe is determined by extraction with oxalate and therefore represents a measure for reactive iron in terms of e.g. sorption characteristics.

As already mentioned, $\text{Fe}(\text{OH})_3$ has its lowest solubility between pH 7 and 10. Sorption of phosphorus onto its surfaces, however, is optimal at about pH 5-7. In addition, other iron phosphates, e.g. FePO_4 and AlPO_4 , are formed and precipitate. This example illustrates that complex interactions determines the chemical behavior of the entire system.

10.1.4. Solubility of chemicals added

As already dealt with in Sections 10.1.1 – 10.1.3, the pH value plays a central role for the removal of pollutants by the formation of insoluble precipitates or by formation of adsorption sites. As already mentioned, the removal pattern in terms of precipitation or adsorption followed by settling of flocs is complex and not possible to quantify in details. As an example, phosphate may – at high redox potentials – form insoluble precipitates with iron, e.g. as FePO_4 , but also be removed by adsorption to $\text{Fe}(\text{OH})_3$.

By only focusing on hydroxide and inorganic carbon, Figure 14 is a simplification that, however, illustrates the influence of pH on the solubility of Al, Ca and Fe in stormwater. The solubility is calculated at 25°C and assuming a water phase with a total inorganic carbon concentration $C_T = 1 \text{ mM}$ (12 g C m^{-3}). Furthermore, the curves are based on solubility equilibria for relevant species as illustrated for $\text{Fe}(\text{OH})_3$ in Figure 11. The carbonate system plays an essential role in terms of formation of carbonate but also as a buffer. Although Figure 14 is an incomplete description of what happens when applying chemicals in a wet pond, it shows which pH intervals are generally

required to observe minimum of solubility to enhance pollutant removal and also to avoid toxic soluble species of aluminum.

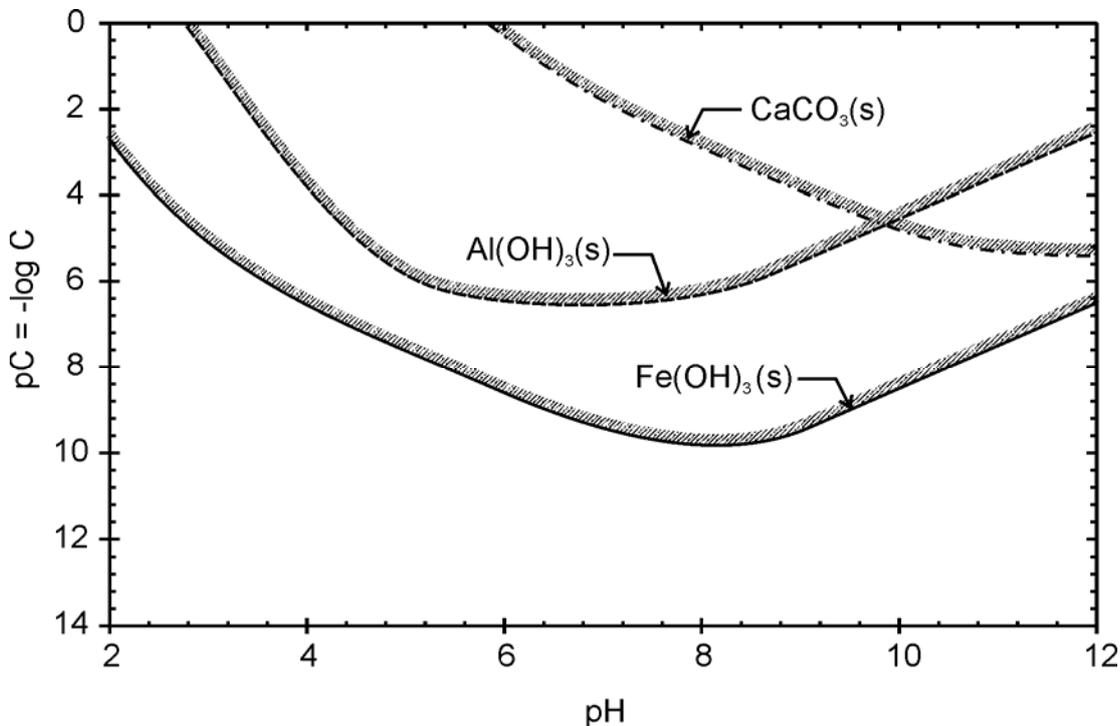


FIGURE 14. Solubility diagram for Al, Ca and Fe at 25°C assuming a concentration of total inorganic carbon $C_T = 1 \text{ mM}$ (12 gC m^{-3}), cf. text.

Example 3: Amount of iron added to the sediments in a wet pond to improve P-removal

It has been decided to improve the sorption capacity for phosphorus in a wet pond receiving stormwater runoff by adding an iron salt to the sediments. The sediment surface area of the pond is 240 m^2 per impervious ha of the contributing catchment with a yearly runoff volume corresponding to 470 mm. The amount of iron salt needed will be dosed by stirring it into the upper about 5 cm of the sediments. It is the intention that the amount of iron salt corresponds with the amount of phosphorus inflow to the pond that is expected transferred to the sediments during a period of 2 years. The removal efficiency of phosphorus in the wet pond is before iron addition 65%, but is expected increased to 90% when improving the sorption capacity. A yearly mean value of phosphorus concentration in the inflowing stormwater is 0.7 g P m^{-3} .

Furthermore, it is assumed that an iron/phosphorus ratio in the sediments of $20 \text{ g Fe (g P)}^{-1}$ is needed to secure the removal efficiency intended. By calculating the amount of iron salt needed, the initial amount of iron and phosphorus in the pond sediments should be taken into account. It is expected that sulfate respiration (H_2S -production) in the sediments will not be a problem, and iron can therefore be added as iron sulfate ($\text{FeSO}_4, 7\text{H}_2\text{O}$).

Analysis of the initial iron content in the sediments is performed based on extraction with oxalate. It can therefore in the following calculations be assumed that it is reactive and has sorption



characteristics as shown in Figure 13. Furthermore, it is assumed that the inflow of iron from the stormwater runoff has no further capacity available for sorption and is therefore not taken into account.

Analysis of the upper 5 cm of the sediments in the wet pond before iron addition:

Total P in dry sediment matter: $0.24 \text{ g P (kg TS)}^{-1}$
 Iron in sediment dry matter: $6 \text{ g Fe (kg TS)}^{-1}$
 Dry matter: $0.58 \text{ g TS (g sediment)}^{-1}$
 Sediment density: $1.7 \text{ g sediment cm}^{-3}$

The initial iron/phosphorus ratio in the sediment is therefore $6/0.24 = 25 \text{ g Fe (g P)}^{-1}$, i.e. $> 20 \text{ g Fe (g P)}^{-1}$. Corresponding to the iron/phosphorus ratio intended, there are free sites expected to be available for sorption. The extent of that can be calculated based on the total amount of both Fe and P in the upper 5 cm of the sediments:

Initial amount of Fe in the upper 5 cm of the sediments:

$$0.05 \text{ 240 (m}^3 \text{ of sediments)} \times 1.7 \text{ 10}^3 \text{ (kg m}^{-3} \text{ of sediment)} \\ \times 0.58 \text{ (kg TS (kg sediment)}^{-1}) \times 6 \text{ 10}^{-3} \text{ (kg Fe (kg TS)}^{-1}) = 71 \text{ kg Fe}$$

Initial amount of P in the upper 5 cm of the sediments:

$$0.05 \text{ 240 (m}^3 \text{ of sediments)} \times 1.7 \text{ 10}^3 \text{ (kg m}^{-3} \text{ of sediment)} \\ \times 0.58 \text{ (kg TS (kg sediment)}^{-1}) \times 0.24 \text{ 10}^{-3} \text{ (kg Fe (kg TS)}^{-1}) = 2.84 \text{ kg P}$$

Amount of iron that is expected available for sorption of phosphorus per 240 m^2 of sediment surface area:

$$71 \text{ (kg Fe)} - 2.84 \text{ 20 (kg Fe)} = 14 \text{ kg Fe}$$

The total inflow of phosphorus during 2 years from a catchment area of 1 ha:

$$0.7 \text{ (g P m}^{-3}) \times 0.470 \text{ (m yr}^{-1}) \times 10^4 \text{ (m}^2 \text{ ha}^{-1}) \times 2 \text{ (yr)} = 6.58 \text{ 10}^3 \text{ g P ha}^{-1}$$

If 90% of P-load is transferred to the sediments, the accumulated amount is:

$$0.9 \text{ 6.58 10}^3 = 5.92 \text{ 10}^3 \text{ g P ha}^{-1}$$

The corresponding required amount of iron per unit area of catchment is:

$$20 \text{ g Fe (g P)}^{-1} \times 5.92 \text{ 10}^3 \text{ g P ha}^{-1} = 1.18 \text{ 10}^5 \text{ g Fe ha}^{-1}$$

The calculated initial amount of iron available for sorption (14 kg) is compared with what is expected required (118 kg) of minor importance. It is, however, concluded that about 100 kg Fe (corresponding to 500 kg of iron sulfate ($\text{FeSO}_4, 7\text{H}_2\text{O}$)) will be needed per 1 ha of catchment area



to improve the removal of phosphorus inflow to the pond during a period of 2 years. This amount corresponds to an added dose of about 420 g Fe m^{-2} of the sediment surface.

It must be noticed that these calculations are based on removal of phosphorus. The sorption capacity for other pollutants in the stormwater inflow is, however, also expected improved by addition of an iron salt. It is therefore worth consideration to increase the amount of iron added.

10.1.5 Dose of Chemicals

An appropriate dose of chemicals added to the stormwater inflow to a wet pond – or a corresponding amount of chemicals to the sediments – is from a theoretical point of view complex. The reason is that the dose basically depends on which pollutants are central, their level of concentration and of course also – as already mentioned in Sections 10.1.1 – 10.1.3 – the alkalinity and the redox potential. Furthermore, the time scale of the control – an immediate removal or long-term inactivation of the pollutants – will play a central role. Determination of an appropriate dose therefore basically relies on experimental procedures, c.f. Cooke et al. (2005) with particularly reference to P removal in lakes.

In order to get an impression which dose amounts have been used for P removal in lakes, the data given in Table 11 refer to what has been typically applied (Cooke et al., 2005). The amounts given in Table 10 do not refer to a well-defined period for which the added amount is effective and therefore only serves the purpose of indicating dose levels applied in practice.

TABLE 11. Amount of chemicals that have been typically used for P removal in lakes, cf. text.

Chemical	Dose	Comments
Al	$5 - 20 \text{ g Al m}^{-3}$	Added to the water phase
Al	$50 - 300 \text{ g Al m}^{-2}$	Added to the sediments
Ca	$10 - 100 \text{ g Ca m}^{-3}$	Added to the water phase
Ca	-	-
Fe	$2 - 5 \text{ g Fe m}^{-3}$	Added to the water phase
Fe	100 g Fe m^{-2}	Added to the sediments

It is important to notice that the amounts given in Table 11 in general refer to lakes. For comparison with what is required in wet ponds, it is important to take into account a quite different flow and residence time pattern of the inflowing stormwater. In this case it might be appropriate to add the chemical directly and flow proportional to the stormwater during the runoff event.

10.2. Filter Materials with Binding Efficiencies and Capacities for Pollutant Removal

Important characteristics for filter materials are their transport properties for water, their kinetics, i.e. reaction rate characteristics, and their capacity for accumulating chemicals. A high sorption rate of a pollutant will reduce the need for residence time in the filter medium and thereby its volume. A high capacity of a filter will reduce the need for volume of the filter material and prolong the lifetime of it.

A main problem in applying filter media for sorption of soluble and colloidal pollutants is the risk for clogging of the filter due to the contents of particles associated with stormwater. To reduce the risk for clogging that otherwise will reduce the flow and ultimately stop it, a pre-filter with e.g. sand is generally recommended. The design of such sand pre-filters will not be dealt with in this respect. General information on filters can be found in e.g. Tchobanoglous et al. (2003) and Shilton (2005). Specific and more detailed knowledge on sand filters related to treatment of stormwater runoff is available in e.g. FHWA (1996).

Figure 15 shows a sketch of a wet pond integrated with sand pre-filter and a filter for sorption of soluble and colloidal pollutants. To reduce the risk for an inconvenient headloss through the filter, equipment for backwash can be installed. For practical purposes, the filter systems will typically be designed to manage only a portion of the water and that overflow of water from the pond that has not been subjected to advanced treatment is accepted in case of extreme events.

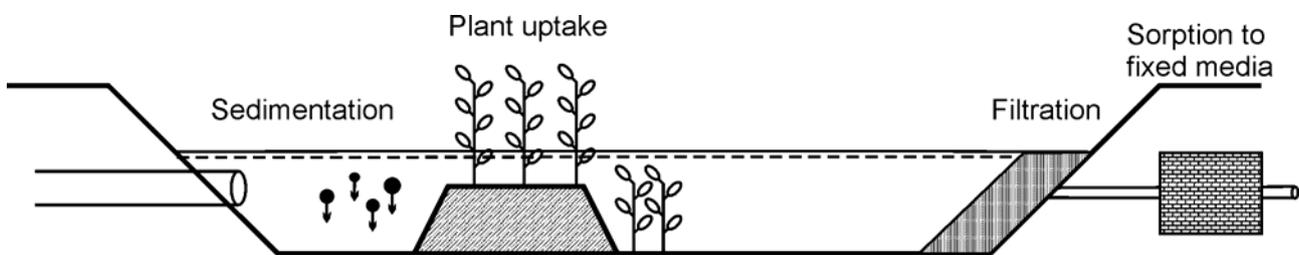


FIGURE 15. Sketch of a wet pond equipped with filters for advanced treatment of stormwater, cf. text.

Several materials have been tested for their potential binding characteristics for soluble and colloidal pollutants (Färm, 2002; Liu et al., 2004; 2005a; 2005b; Westholm, 2006). Both natural filter substrates, modified materials and artificially produced filter media can be used. The following list includes few selected examples of filter materials:

- Materials where the active component is CaCO_3 and/or MgCO_3 , i.e. materials like marble, limestone, dolomite and different types of shells
- Silicon containing rock materials, e.g. zeolite
- Iron oxide-coated sand
- Manganese oxide-coated polymeric media

Different media show different adsorption kinetics and capacity to the different pollutants. As examples, calcium carbonate filters may exert good sorptive characteristics for phosphates whereas manganese oxide-coated polymeric media particularly adsorb metals. In general, the capacity of a filter material is highly depending on both the pH value and the cation exchange capacity (CEC). A filter material that consists of mixed media can get improved pollutant removal characteristics and hydraulic properties compared with the single components.

For practical purposes, the pollutant removal capacity of a filter material relative to the residence time in the filter is crucial. The variability of these properties is high caused by both filter media and stormwater characteristics. It is therefore basically needed that sorption characteristics be determined experimentally in each specific case.



It is crucial to understand that the filter material must observe efficient sorption characteristics at the very low pollutant concentrations that exist in treated stormwater. These sorption characteristics are important for a rather wide range of pollutants. Filter media with a sorption capacity for a pollutant about 200 – 1000 g m⁻³ of filter material (or 0.1 – 0.5 mg g⁻¹ of filter material) must – depending on which pollutant it concerns – be considered acceptable. Furthermore, a rate corresponding to 20-30 minutes of contact time for the stormwater in the filter to obtain this efficiency is as a first estimate considered appropriate for practical use (Barbosa and Hvitved-Jacobsen, 1999; Färm, 2002).

The hydraulic surface load – reflecting the pollutant load – of a filter is a central but also a simple design parameter. A more advanced, and also more relevant, design criterion is in principle based on the hydraulic conductivity of the clogging layer (Vollertsen et al., 2007). It is the silt-like particles that accumulate in the clogging layer and particularly those particles with a diameter < about 5 µm that limit the transport of water through the filter.

11. VEGETATION IN WET PONDS AND THEIR SURROUNDINGS

Rooted plants (macrophytes) contribute to the treatment performance and the recreational value of wet ponds and their surroundings. In this respect, major effects and contributions are as follows:

- Plants have an impact on the flow regime in a wet pond. They can reduce turbulence of the flow and widen the flow throughout the pond. Plants will thereby improve conditions for settling of particles from the runoff water and reduce the risk of erosion.
- Submerged plants will by photosynthesis contribute positively to the DO balance in the pond. Available in excess, however, they may during night cause DO depletion because of respiration.
- Macrophytes are in competition for nutrients with algae (phytoplankton) that are free-living in the water body. The rooted plants – particularly those submerged – may thereby reduce the level of eutrophication in the wet pond.
- Pollutants like nutrients and heavy metals will to some extent accumulate in the plant biomass. When the plants die, part of these pollutants can be transferred to the sediment. Furthermore, plants increase the submerged solid area of the pond and thereby create sites for pollutant adsorption and surfaces for attachment of microorganisms that degrade organic matter.
- Vegetation – e.g. grass and emergent plants – can stabilize sloping banks and protect these against erosion.
- Vegetation in and around a pond will improve the recreational value of a wet pond and its surroundings. Plants in the pond itself and trees and bushes around the pond can add to the overall impression of a natural landscaping.
- Plants are an integral and central part of the entire ecosystem that will develop over time when constructing wet ponds. The habitat value of the system and its surroundings is thereby improved.

The selections of plant species and the extent of plantation should observe such fundamental goals. Furthermore, the choice of species must take into account local climatic conditions and native plant species that can adapt to these conditions should be selected. The type of soil – e.g. a sandy soil type – that is selected as substrate for the plants is an integral part of the plantation.



The water depth and the moisture content of the soil in the pond and at the edge of the pond must be considered when selecting plants for a wet pond and its surroundings. The submerged aquatic plants belong to the deep part of a wet pond whereas the shallow part observes conditions for the emergent aquatic vegetation. At the shoreline where changing moisture content and periodic drying exists, plants that tolerate such conditions must be selected.

12. REFERENCES

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