CHALMERS

Hydraulic Efficiency in Pond Design

JESPER PERSSON

Department of Hydraulics
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 1999

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Akademisk avhandling som för avläggande av teknisk
Doktorsexamen vid Chalmers tekniska högskola försvaras vid
offentlig disputation den 28 maj 1999,
Klockan 13.00 i sal A2, Sven Hultins gata 6, Göteborg.

Avhandlingen försvars på svenska.
Fakultetsopponent är Dr. Lennart de Maré,
Jordbruksverket, Jönköping.

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ABSTRACT

Today there is a growing interest in constructed ponds to treat agricultural runoff, sewage water and stormwater. But ponds not only remove nitrogen, phosphorus and pollutants such as heavy metals; they can also have ecological, social and esthetic values. Many researchers claim that hydraulic design of surface flow wetland (SFW) systems and ponds cannot be overemphasized, and that short-circuiting is one of the greatest hindrances to successful design. The research questions asked in this thesis are: (i) Is a two-dimensional vertically integrated model able to describe the hydraulic performance of ponds? (ii) How does the design affect hydraulic performance? (iii) What is hydraulic efficiency and how should it be measured? (iv) Which factors determine pond design? By raising these questions the thesis follows a tradition of research on the hydraulic processes in ponds and surface flow wetlands, and on how design can be improved.

The results show that two-dimensional vertically integrated numerical models can, although not without restrictions and experience, be used to simulate hydraulic performance in ponds. Results from simulations of hypothetical ponds indicate, for instance, that a subsurface berm or an island placed in front of the inlet improves the hydraulic performance as regarding short-circuiting, effective volume and amount of mixing. In this thesis it is suggested that hydraulic efficiency can be defined as a product of the effective volume ratio and the amount of mixing. In a case study, seven explicit factors were identified that determine stormwater pond design: site-specific factors, financial resources, esthetic values, demand for pollutant removal and detention, ecological values, and social values. There were also indications that preferences based on academic tradition may act as an implicit factor, affecting the design. Particularly in stormwater pond design, it is suggested that landscape architects should focus on the pond's outer space, while the inner space is primarily a task for engineers and biologists. The shape is, however, of common interest.

Keywords: design, efficiency, environmental science, hydraulics, numerical modeling, pond, preference, performance, tracer study, wetland.

Till Thomas
Tack för goda diskussioner
och hopp om gott fortsatt
samarbete.
Jesper

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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ISBN 91-7197-804-6

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr 1504
ISSN 0346-718X

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Chalmers reproservice
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LIST OF PUBLICATIONS

This thesis is based on the work contained in the following papers and reports, referred to by capital letters in the text.

A Persson, J., 1998, *Utformning av dammar: En litteraturstudie med kommentarer om dagvatten-, polerings- och miljödammar,* andra upplagan, Institutionen för vattenbyggnad, Rapport B:64, Chalmers Tekniska Högskola, Göteborg.

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This is not the end.
It is not even the beginning of the end.
But it is the end of the beginning.

Sir Winston Churchill

HYDRAULIC EFFICIENCY IN POND DESIGN

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SUMMARY

Today there is a growing interest in constructed ponds to treat agricultural runoff, sewagewater and stormwater. But ponds not only remove nitrogen, phosphorus and pollutants such as heavy metals; they can also have ecological, social and esthetic values. This, together with cost-effectiveness in relation to other technological measures for pollutant and flow control, will probably result in a large number of new ponds both in and outside Europe. Many researchers claim that hydraulic design of surface flow wetland (SFW) systems and ponds cannot be overemphasized, and that short-circuiting is one of the greatest hindrances to successful performance. In general, constructed ponds are seen as 'black boxes' whose performance is measured by comparing in- and outgoing concentrations of, for example, nutrients. The fact that a uniform flow condition is often assumed has led to a need for sophisticated descriptions of the hydraulics in ponds and SFW.

The research questions asked in this thesis are: (i) Is a two-dimensional vertically integrated model able to describe the hydraulic performance of ponds? (ii) How does the design affect hydraulic performance? (iii) What is hydraulic efficiency and how should it be measured? (iv) Which factors determine pond design? By raising these questions the thesis follows a tradition of research on the hydraulics in ponds and surface flow wetlands, and on how design can be improved.

The results show that two-dimensional vertically integrated numerical models can, although not without restrictions and experience, be used to simulate hydraulic performance in ponds. Results from simulations of hypothetical ponds indicate that a subsurface berm or an island placed in front of the inlet improves the hydraulic performance as regards short-circuiting, effective volume and amount of mixing. These design elements can therefore be recommended to increase hydraulic efficiency in ponds, without increasing the length-to-width ratio or the velocity of the water. Further, the study showed that a curved pond or an island placed near the side does not lead to lower hydraulic performance, and that the length-to-width ratio and the location of in- and outlets have a considerable impact on the hydraulic performance. Hydraulic efficiency is generally related to the ability to distribute incoming water and to achieve plug flow. In this thesis it is suggested that hydraulic efficiency is defined as a product between the effective volume ratio and the amount of mixing.

In a case study, seven explicit factors were given as determining stormwater pond design: site-specific factors, financial resources, esthetic values, demand for pollutant removal and detention, ecological values, and social values. There were also indications that preferences based on academic tradition may act as an implicit factor, affecting the design. It was, however, found that the interaction between form and performance (addressed in the previous questions) was not taken into account in the design. In none of the investigated cases there was a dialogue between the engineer who sized the pond and the landscape architect who did the design, concerning the interaction between form and hydraulic performance.

Design is, in principle, based on social and esthetic factors, as well as technical and ecological factors. If one looks at a pond as two spaces, an inner and an outer space, it is possible to connect the outer space with the social and esthetic factors, and the inner space with the technical and ecological factors (mainly hydraulics, hydrology and the biochemical environment). Particularly in stormwater pond design, it is suggested that landscape architects should focus on the outer space, while the inner space is primarily a task for engineers and biologists. The shape is, however, of common interest.

ACKNOWLEDGEMENTS

When I began to work as a Ph.D. candidate in environmental science at the Department of Urban Design and Planning at Chalmers, I was to function as a link between engineers and architects. After carrying out research on different environmental topics my interest became focused on pond design in urban and rural areas. This was partly because I saw the potential in ponds and partly because it embraces interactions between academic disciplines. My thesis is based on those last years of research on this topic.

I want to thank Prof. Hans Bjur who made it possible for me to start my studies in environmental science in the first place, and Prof. Lars Bergdahl for enabling me to finish them. Special gratitude goes to Dr. Hans-Bertil Wittgren, director of the VASTRA program, for having the same enthusiasm for ponds as I, but also for standing by and encouraging me during my work. Among my colleagues at the Department of Hydraulics I want to thank my supervisors Dr. Sven Lyngfelt and Prof. Lars Bergdahl, and the Ph.D. candidates Jens-Uwe Friemann and Åsa Adamsson for cooperation, commenting on manuscripts and for stimulating discussions. Also I want to thank Dr. Tony Wong and Ph.D. candidate Nicholas Somes, at Monash University in Australia, for good cooperation and stimulating discussions; and my wife, Ane Kirkegaard, Ph.D. candidate at PADRIGU for commenting on manuscripts. Finally, I want to thank all those who have contributed comments, good questions, field and lab measurements or just encouragement.

For extra financial support I am grateful to the Swedish Council for Building Research (BFR), the Swedish Institute (SI), the Swedish Association of Graduate Engineers (CF), Adlerbertska Foundation, the Nordic Council of Ministers, and the Swedish Water Management Research Program (VASTRA). I also want to thank the Danish Hydraulic Institute (DHI) for letting me use their software package Mike21.

Jesper Persson

STRUCTURE OF THE THESIS

Content

This thesis is based on six papers including two reports (listed in Table 1), with an overviewing text which links these works together. Four papers are written in English, while the reports are in Swedish with English summaries. The outline of the overviewing text is described below.

Chapter 1 consists of three parts. The first part gives a general review of research on pond hydraulics and design. The second part includes the aim of the thesis. The third part is directed toward a Swedish audience, and consists of a discussion on *'miljövetenskap'* (environmental science) as a concept and how this thesis corresponds to the requirements of a degree in environmental science, as established by Chalmers University of Technology and the School of Environmental Science. In Chapter 2, form and performance are discussed. The results are covered in Chapter 3, where report A is to be seen as a general bas is for the thesis, describing terminology, pond functions, and present methods to size and design ponds. Articles B, C, D and E describe and analyze hydraulic efficiency and performance in hypothetical ponds as well as existing ones. Report F is a case study that covers six ponds in three Swedish cities; their focus is on explicit and implicit factors that determine pond design.

Table 1. The six papers on which the thesis is based.

A	Persson, J., 1998, *Utformning av dammar: En litteraturstudie med kommentarer om dagvatten-, polerings- och miljödammar*, andra upplagan, Institutionen för vattenbyggnad, Rapport B:64, Chalmers, Göteborg.
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Chapters 4 and 5 cover a discussion and ideas for further research, while Chapter 6 contains conclusions.

All reports and articles are presented in appendices, at the end of the thesis.

Article D is based on a conference paper: Persson, J., N. Somes & T. Wong, "Hydraulic Efficiency of Constructed Wetlands and Ponds", *6th International Conference on Wetland Systems for Water Pollution Control,* September 27 – October 2, 1998, San Pedro, Brazil.

Article E is based on another conference paper: Persson, J., "The Hydraulic Performance of Surface Flow Wetlands of Various Layouts", *UDM 98 - Fourth International Conference on Developments in Urban Drainage Modelling,* 21-24 September 1998, London, UK.

Division of work

Two of the articles are not written by the author alone. In article B the author has written the 'Tracer study' section, and the 2.5-D part in the 'Theory and numerical methods' section, as well as taking part in the discussion of 'Discussion' and 'Conclusion'. In article D the author has written the sections 'Measures of flow hydrodynamics' and 'Simulations of pond shapes and inlet/outlet configuration influences'.

1. INTRODUCTION

1.1 Why study ponds and pond hydraulics?

Today constructed ponds and surface flow wetlands (SFW) are used to treat agricultural runoff, sewagewater and stormwater. Ponds offer many possibilities to improve the environment. Water from agricultural land that flows into ponds is reduced in nitrogen and phosphorus, and therefore lessens the load on watercourses along our coasts. Ponds also contribute ecological values and offer possibilities for recreation. Further, ponds can be used for the treatment of urban runoff, functioning as detention devices as well as improving the water quality, mostly with respect to capture of particulate matter. Thus, ponds are looked upon as a good complement to other methods used to improve water quality (Leonardson 1994, Moshiri 1993, Reed 1994, Wittgren 1994, Persson 1998, Urbonas & Stahre 1993).

A large part of the research done concerning ponds in Sweden and abroad has been directed towards the chemical processes and the capture of nutrients and suspended matter. Less research has been devoted to hydraulic performance in ponds and the interdependence between hydraulics and water quality processes. This thesis contributes knowledge on pond hydraulics and the connection between form and performance.

The subject of the thesis is ponds in general, which are described as small areas of water, smaller than a lake. By this definition, a pond also fits into the subgroup 'surface flow wetland'. There are many other definitions of a wetland and a pond (which are discussed in part A). Those definitions differ not only between scientific disciplines such as geography, ecology and engineering, but also within these disciplines. In this thesis the term 'pond' is used even when some scientists would use the word 'wetland'. As a generalization, at least among engineers, the difference between surface flow wetland and pond is often related to the amount of vegetation.

1.2 Aim of research

The aim of the research presented in this thesis has been to answer following questions:

1. Is a two-dimensional vertically integrated model able to describe the hydraulic performance in ponds?
2. How does the design affect hydraulic performance?
3. What is hydraulic efficiency and how should it be measured?
4. Which factors determine pond design?

With these questions the thesis follows a tradition of research on the hydraulics in ponds and surface flow wetlands, and on how design criteria can be improved.

1.3 Environmental science[1]

The aim of Sections 1.3 and 1.4 is to place the thesis in a larger context. Environmental science (*miljövetenskap* in Swedish) as a discipline will be discussed in Section 1.3, while the correspondence between the thesis and environmental science will be discussed in Section 1.4. Specific description of how the articles correspond to the field of pond design is given in each of the articles individually.

Environmental science is not equivalent to biology, as becomes clear when reflecting on the concepts of environment and environmental problems. Environment consists, according to the Swedish Parliament, of four items: biodiversity, human health, natural and cultural environment, and sustainable management of natural resources (Proposition 1999/91:90). In other words, disciplines such as chemistry, urban planning and medicine are also connected with environment and environmental problems.

The Swedish National Encyclopedia defines environmental science as the scientific basis for the description and explanation of environmental problems, and for suggestions on measures to avoid or eliminate environmental problems.[2] This definition shows, however, an

[1] This part is based on an article in '*Nordisk Samhällsgeografisk Tidskrift*' (Persson 1997).

[2] "...sammanfattande benämningen på den vetenskapliga basen för beskrivning och förklaring av miljöproblemen samt förslag till åtgärder för att undvika eller eliminera dem".

interesting characteristic feature of environmental science. Since environmental problems are both contextually and historically dependent (Persson 1996), it implies that the scientific foundation, i.e. theory and formulation of research problems, changes constantly. A logical consequence is that *topicality* constitutes, more than in other sciences, a characteristic feature of environmental science. Every scientific discipline is able to carry out environmental science, but environmental science cannot be carried out in all scientific fields (i.e. those which are not linked to environmental problems).

But does not the definition in the Swedish National encyclopedia, include too much of present research as environmental science? Can pollen analysis be considered environmental science as long as the researchs tell something about environmental problems, and is not sanitary engineering then equivalent to environmental science? Such questions point to a need for some characteristic features of environmental science, besides the broad definition in an encyclopedia?

1.4 The context of the thesis

What Aristotle would think of research on ponds

A thesis in environmental science ought to reflect on the different types of knowledge that are needed to understand or overcome environmental problems, as in this example to develop design tools and to construct better ponds and wetlands. Well aware of the amount of research and thinking done in disciplines such as history of science and theory of science and research, and also of modern philosophers such as Kuhn, Popper and Feyerabend, I have chosen Aristotle[3] to place the research on ponds in a larger context.

Mankind by nature desires to know; mankind by nature is also social. A characteristic feature of engineering is the willingness to act. Engineers and technicians are still, since Aristotle days, focusing on creating constructions and artifacts. This capability (or virtue) Aristotle call *techne*, and he sees it in all activities that produce machines, craft or art. *Techne* differs from purely mathematical or logical virtues, which Aristotle calls *episteme,* corresponding to what we today mean by science or scientific knowledge. The third virtue is *phronesis,* which is

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[3] See also Bengt Flyvbjerg's article "Practical Philosophy for Sustainable Development: The Phronetic Imperative" *in Culture, Perception, and Environmental Problems*, Forskningsrådsnämnden Report 96:7, or *The Nichomachean Ethics* by Aristotle.

our capability to value and consider what is right or wrong and good or evil. These three concepts, *techne*, *episteme* and *phronesis*, can in everyday terms be represented by craftsmanship, theoretical knowledge, and conduct of life. It must, however be added that engineering today has become a complex task which often demands scientific knowledge, or what Aristotle would call *episteme*.

Applying Aristotle's concepts to pond design can be fruitful. *Techne* is needed to construct the pond, build in- and outlet configurations and, if desired, manage vegetation and sediment. This is not only carried out by the engineers but is also the work of the landscape architect. *Episteme* is needed to know how vegetation is functioning, how it is established, how the flow can be regulated, and about pond hydraulics. *Phronesis* is needed to decide whether a pond is necessary or if some other construction is better, and to site the pond considering social impacts or local ecological planning strategies. But this capability is also needed by e.g. landscape architects when choosing in which way the natural environment should be shaped and which values the pond is to display. This simple analysis makes clear that all three virtues must be combined to achieve a well-functioning pond, and no discipline alone has all of these virtues.

<u>The thesis in relation to environmental science</u>

Since this thesis is focusing on design of constructed ponds that are used to remove pollutants, it fulfills the basic criteria that have been set up by the School of Environmental Science as associated with environmental science. Further, by studying the correlation between form and performance, the thesis emphasizes the need for cooperation between different academic traditions.

It should be added that the requirements for the doctoral degree include both course-work and a dissertation, which has to correspond to a minimum of three years of full-time work in a specific field of research. The demands on the thesis are: (a) that the result of the research should have a quality such that it can be published in an international journal with a peer-review system; (b) that the work is scientifically stringent and carried out with a high level of independence; and (c) that some part of the research is in the frontier of the research field. The School of Environmental Science at Chalmers has an additional demand for a certain level of cooperation between different research disciplines connected with the research.

The thesis in relation to research on ponds

Even if constructed ponds are becoming popular, not many have been built. However, it is in this situation important to carry out research on how ponds function and how future ponds ought to be designed, since a large number of ponds probably are going to be built both in Europe and elsewhere.

As described in the introduction there are many definitions of a wetland and a pond, often depending on one's perspective. This is also the case with ponds as a topic. Ponds have been discussed in different scientific environments and from different perspectives.

During the last decades, engineers have been studying concrete ponds in sewage treatment plants and urban drainage systems. For civil engineers the focus has been on construction, design, retention capabilities or sedimentation processes, while chemical engineers have focused on removal of nutrients and phosphorus, preferably within the sewage treatment industry. These ponds have often been small basins, and therefore differ in several respects from the ponds studied in this thesis. Ponds addressed in this thesis are generally larger, with some amount of vegetation, and similar to natural ponds as regards topography and shape.

Scientific disciplines such as ecology, biochemistry and limnology study ponds and surface flow wetlands (SFW), but have focused on topics such as plant ecology, nutrient uptake or ecological systems. Here not only constructed ponds and SFW, but also natural and reconstructed SFW, are research objects. Further, researchers in these disciplines do not always have a utilitarian attitude towards ponds and SFWs, in the sense that they see these systems as having the primary task of improving water quality.

In general, both of these clusters of academic traditions have treated constructed ponds and SFW as 'black boxes' where performance is measured by comparing in- and outgoing concentrations of e.g. nutrients. Hydraulics is thus, considered as vital and also one of the most important factors of successful performance. Many authors (Reed et al., 1995; Brown, 1994; WPCF, 1990) claim that the importance of the hydraulic design of SFW systems cannot be overemphasized, and that short-circuiting is one of the greatest hindrances to successful performance of wetland. All of the design models in current use assume uniform flow conditions, and unrestricted opportunities for contact between the incoming water and the organisms responsible for treatment. It is, however, widely known that this is not the case (Reed et al., 1995). Therefore, when it comes to calculating pollutant removal, researchers have asked for more sophisticated models, describing the hydraulics in SFW, than the present models of plug flow and the continuous stirred-tank model (e.g. Wittgren 1994).

Another important research area is the connection between form and performance. Today there are different design criteria, e.g. length-to-width ratio or use of subsurface berms. This, together with an often varying topography, creates a need for a method to compare the hydraulic performance between different ponds and design solutions.

In the thesis these two subjects, concerning a sophisticated description of the hydraulics and the relation between form and function, are highlighted.

2. FORM AND PERFORMANCE

2.1 Function and efficiency

As previously stated in the introduction, there is no unified terminology on ponds that is used between or within different academic disciplines. In this thesis the term 'pond' is used even when some scientists and practitioners would use the word 'wetland'. This is discussed specifically in part A.

Constructed ponds can be divided into three groups: stormwater ponds, ponds receiving treated wastewater and ponds receiving agricultural runoff. The latter ponds are mainly used to remove nutrients and phosphorus as well as for recreation purposes. Stormwater ponds are built along roads and in urban areas and are used to reduce flow events, and to remove nutrients and suspended solids (containing for example heavy metals), but also as an esthetic asset (see part F). Ponds receiving treated wastewater are built downstream of sewage treatment plants and bio-beds, and their main function is to remove nutrients and phosphorus. But these ponds or wetland systems also function as wildlife habitats and are in some cases used for recreation. These three types of ponds receive different waters, are situated in different environments and are exposed to different hydrological conditions. In spite of their differences, they are all ponds with common properties as regards treatment processes and hydraulics (see part A).

There is no sharp line between hydraulic efficiency and hydraulic performance. One way to explain the difference is by saying that performance is a wider concept that embraces more aspects of the flow condition (e.g. short-circuiting and lag-time) and is less value-oriented. Efficiency is often related to (a) hydrological effectiveness, (b) hydraulic efficiency and (c) facilitation and optimization of water quality treatment processes (see parts D and A). The hydrological efficiency is a measure of the available capacity of the wetland to capture inflow. It is defined by the ratio between the accumulated water volume in the pond and the accumulated influent water. The interactions pond volume, residence time and outlet configuration; and interdependency between the inherent variability of the inflow affect the hydrological efficiency. By analyzing the hydrological efficiency for different outlet configurations, the effects on the dry periods and the possibilities for vegetation can be assessed. Hydraulic efficiency describes how the incoming water is distributed in the pond and the amount of mixing taking place. It consists of two components, namely effective volume ratio and the amount of mixing (see part D).

All three points above (a, b and c) are in fact linked together by one common denominator, i.e. residence time. Primarily, the biological processes needed to remove nutrient and pesticides are correlated with residence time. Further, long residence time generally indicates low water velocities, which enhance sedimentation processes. In other words, the efficiency of a pond is based on the biochemical environment and how much time the water particles spend in the pond. To investigate residence time, both hydrology and hydraulics must be considered. Analysis of pond hydrology is preferably done by studying historical flow series, volume and outlet configuration. This will give results in the form of a probabilistic residence time distribution (PRTD) curve, which gives knowledge of the proportion of runoff (%) as a function of residence time. Hydraulic efficiency, on the other hand, is analyzed by tracer studies (see part A). A tracer study gives information about the residence time of incoming water and is represented in a residence time distribution (RTD) curve.

2.2 Design

The following paragraphs are mostly focused on stormwater ponds, but to some extent they can also be applied to ponds receiving wastewater and agricultural runoff.

Today stormwater ponds, around the world as well as in Sweden, are mainly designed by landscape architects. Since many of these ponds are located in urban settlements or along larger roads, their esthetics are unquestionably an important aspect. From an engineering and hydraulic standpoint, a rectangular pond with an in- and outlet placed along the short sides ought to be the best solution. Landowners would, however, accept this in all situations, especially if esthetic values are appreciated. On the other hand, not many landscape architects take engineering aspects into account, and if they do, they generally are not trained for it.

Design is, in principle, based on social and esthetic factors, as well as technical and ecological factors. These factors can be divided in two parts. One part is the inner space and the other part is the outer space, where the bank of the pond indicates the border between the spaces. It can be added that sizing is separated from the design procedure. Sizing a pond involves determining its volume. The pond volume that is needed is based on desired residence time, incoming flow characteristics and outlet configuration.

To design the inner space one has to decide the pond shape and length-to-width ratio, in- and outlet configuration and location, topography, and also the vegetation. All these factors have impact on the hydraulic efficiency and accordingly also on the residence time. The outer space is planned and shaped according to the social and esthetic needs and values. The social need consists of accessibility planning such as tracks, signs and parking places (which depends on size and prominence of the pond). Social values are often related to recreation or seen as an educational asset. The esthetic value of a pond consists of beauty (both as a piece of nature and as art, decorating the urban space), symbolic value, historical value, and sometimes also an expression of 'primitiveness' (which is related to biologically oriented esthetic values). The esthetic value is managed in traditional landscape design.

What I want to emphasize is that the landscape architect traditionally designs both inner and outer spaces, but should be focusing on the outer space, i.e. the social and esthetic factors. The inner space consisting of technical and ecological factors (mainly hydraulics, hydrology and the biochemical environment) is, on the other hand, primarily a task for engineers and biologists. The shape is intermediate between the spaces and therefore of common interest. In this situation cooperation between disciplines is needed, but also knowledge about pond hydraulics and hydrology.

2.3 Form and performance

Length-to-width ratio is generally seen as the most important factor influencing hydraulic performance. Numerous researchers report this and also recommend different ratios to achieve a low degree of mixing (see part A). However, Kadlec & Knight (1996) have stated that '...many SF [surface flow] wetland geometries yield similar tracer responses and that N=3 [number of stirred tanks] is a fair approximation to the tracer data'. Further, they write that even an aspect ratio of 25:1 may be representable by one or two stirred tanks (N=1 to 2), implicitly saying that form does not have much effect on hydraulic performance. Their own explanation of the fact that a pond with aspect ratio of 25:1 has a well-mixed flow is that it was due to windy conditions during the tracer test. However, one may ask what happens if the wind does not blow. The statement above can therefore not be considered as general, considering the results from part B, C and

E. On the contrary, I would claim that geometry to a large extent influences hydraulic performance (see part E).

It is interesting to notice that the result from the case study (part F) indicated that the connection between form and performance is not considered when the design is planned. In none of the cases included in the case study did the engineers discuss with the landscape architects how the form affects the hydraulic performance — their task was only to size the pond.

3 RESULTS

In this chapter the four central questions posed in the introduction are addressed.

1. Is a two-dimensional vertically integrated model able to describe the hydraulic performance of ponds?

Two different ponds were studied to answer this question (see part B). The first is a small and simple pond equivalent to a basin. It has a rectangular geometry with a volume of 115 m^3, and in- and outlet placed on the short sides opposite each other. The second pond is diverse. It has a complex geometry with a volume of 24 300 m^3 and has partly dense vegetation. To study the two-dimensional vertically integrated (2.5-D) model, momentaneous tracer tests were carried out both in the field and with the numerical model. The RTDs were then compared and evaluated. For the rectangular pond the flow patterns were also compared. As an example of a 2.5-D model the commercial code Mike21 was chosen.

For the rectangular geometry with constant water depth the 2.5-D model simulates the general flow pattern reasonably well, with some reservations for the lower velocities. The RTD for 20 and 8 l/s fitted well with the measured RTD for the basin. For 2 l/s the 2.5-D model was acceptable. See further in part D for a more detailed description of the results.

The conclusion drawn from the study of the complex pond is that it is possible to simulate pond hydraulics, in a partly dense vegetated pond with complex topography and unsteady flow, with a 2-D vertically integrated numerical model (see part C). However, experience and extensive measurements are needed to validate and calibrate the model. It was also shown that the period of the tracer measurements was found to be too short. Around one month should have been sampled instead of a week, due to the proportion between incoming water volume and pond volume, and to geometry and vegetation. It was not possible to calculate hydraulic performance in terms of amount of mixing and effective volume ratio. However, mass balance, peak time and the general shape of the RTD (from the outlet) corresponded with the measured field data.

2. How does the design affect hydraulic performance?

To study how the design affects the hydraulic performance, thirteen hypothetical ponds with different layouts were investigated in a 2.5-D model using the Mike21 program (see part E). The ponds differed regarding length-to-width ratio, shape, topography (islands and subsurface berms) and type and location of in-/outlets. The basic shape was a rectangular pond with the length-to-width ratio 2:1. The length-to-width ratio was then changed to 1:1, 4:1 and 12:1. The shape was rectangular in all 13 cases except one, which had an L-shape. In three cases, an island or a subsurface berm changed the topography. In five cases the type and location of in- and outlet were altered.

The results indicate that a subsurface berm or an island placed in front of the inlet improves the hydraulic performance as regards short-circuiting, effective volume and amount of mixing. Further, the study showed that a curved pond or an island placed near the side does not change the hydraulic performance, while length-to-width ratio and location of in- and outlets have a considerable impact on the hydraulic performance.

3. What is hydraulic efficiency and how should it be measured?

How hydraulic efficiency should be measured is one of the central questions in this thesis (part D and E). This question originates from the need to compare ponds and design solutions, so that the hydraulic performance can be optimized or at least become acceptable.

Plug flow is generally considered to be the optimal flow and, from a hydraulic point of view, is the preferred flow regime since all fluid elements reside around the nominal residence time. Moreover, the removal rate of BOD, TSS and TN increases with the loading rate, which therefore makes plug flow desirable. The degree of plug flow is actually a measure of the amount of mixing and is correlated with advection-dispersion processes. A common measure of the degree of plug flow is the number of stirred tanks (N) used in a tank-in-series model. The higher N the more plug flow like the flow is. Measures of N are

$$N = \frac{t_n^2}{\sigma^2} \qquad \text{or} \qquad N = \frac{t_n}{t_n - t_{peak}}$$

where t_n is the nominal residence time (which is defined by the ratio between volume and flow), σ^2 is the variance, and t_p is the peak time of the RTD. But since the variance in real ponds can be larger than the nominal residence time t_n and result in N-values less than 1 (which is not possible in the tank-in-series model), the last equation is preferably used. In real ponds the nominal residence time t_n differs to a great extent from mean residence time t_{mean} and, if the shape of the RTD is in focus, it is more correct to use the latter. This is the reason why t_n is replaced with t_{mean} below.

However, to consider only the degree of plug flow is not sufficient, since the effective volume differs considerably between ponds; i.e. the mean residence time is less than the nominal residence time. The effective volume ratio (e) is defined by

$$e = \frac{t_{mean}}{t_n} = \frac{V_{effective}}{V_{total}}$$

Persson's, Somes' and Wong's suggestion (see part D) is therefore to define the hydraulic efficiency (λ) as a product of the effective volume ratio and a measure of the amount of mixing:

$$\lambda = e\left(1 - \frac{1}{N}\right) \quad \text{or} \quad \lambda = \left(\frac{t_{mean}}{t_n}\right)\left(1 - \frac{t_{mean} - t_p}{t_{mean}}\right) = \frac{t_p}{t_n}$$

To lessen the effect of overestimation of the efficiency due to extremely high N-values, we prefer to use the mixing factor (1 - 1/N) instead of N. This also puts the mixing factor (1 - 1/N) in an interval between 0 - 1. Both terms have, therefore, a range of 0 to 1 providing equal weighting for effective volume ratio and the mixing factor. The resulting expression for hydraulic efficiency is simply the ratio of the time of the peak outflow concentration to the nominal residence time. The measure can thus be readily derived from RTD-functions and does not have the problems associated with deleting or measure the mean residence time.

This method of estimating the hydraulic efficiency has been developed and tested for ponds, but can in principle be used for both subsurface and surface flow wetlands, since the focus is on analyzing residence time in RTDs. Further, it has the advantage of being simple, with two factors in the interval 0-1 and also the advantage of not needing to consider the tail of the RTD.

4. Which factors determine pond design?

The factors that have impact on the design can be divided into technical, economical, ecological, social and esthetic factors. A case study was carried out to investigate which factors determine pond design (part F). Six, relatively new, stormwater ponds were chosen in three Swedish cities. In the case study, seven explicit factors were found to determine stormwater pond design: site-specific factors, economy, esthetic values, demand on pollutant removal and detention, ecological values, and social values.

But in the study there was also a hypothesis that preferences constitute an implicit factor which determines pond design. The study indicates that this may be the case. Engineers' and landscape architects' perception of stormwater ponds can be described in two ways. There seems to be a common perception of the benefits of a pond among these two groups. This shows that the environmental values of a pond are common to society. However, when the question of how a well-functioning pond ought to look was posed, the two groups gave different answers, which indicated the existence of different preferences. To the landscape architects it was important that the pond looks and is placed as if it were natural (i.e. not man-made) except in cases where artistic designs are asked for. Among the engineers, the answers were mixed in the sense that some were of the opinion that regulations and management of the ponds were paramount, while others emphasized the different functions of a pond. To some degree the varying preferences of the actors are rooted in values and attitudes, which may originate from the fact that they were educated in different academic traditions. If this is the case, there is a reason to emphasize cooperation between disciplines to achieve well-functioning ponds.

4. DISCUSSION

The questions that are addressed in this thesis are investigated and discussed individually in each of the articles and reports. This chapter is therefore to be seen as an extract of the discussions found in the separated parts (A-F).

4.1 CFD simulations and verifications

It is worthwhile to emphasize that, even if the 2.5-D model by definition is less precise than a 3-D model, it has some advantages. It cannot consider 3-D affects in the flow, as in vertically stratified flow or in basins with steep slopes. But otherwise it can be assumed to represent the hydraulic conditions well, which is confirmed by the two studies included in this thesis (parts B and C). The advantage of a 2.5-D model compared to a 3-D is that it is less time-consuming, as regards both grid-generating and simulation time, especially when simulating unsteady flow.

After using Mike21 as an example of a 2.5-D model it can be concluded that knowledge and experience are needed to select the Manning number, eddy-viscosity and dispersion coefficients (see parts B and C). It was also shown that there are some difficulties with simulating flow conditions in a pond with complex geometry and vegetation, and where the incoming flow volume is relatively small compared to the pond volume. The major problems are connected with tracer sampling and the selection of roughness on vegetation. But practical difficulties also exist, such as measuring water depth when the bottom is 'soft' or when the vegetation is dense. Ponds with complex geometry and dense vegetation are commonplace, since these circumstances often occur in both constructed and natural ponds.

It would have been better if velocity measurements had been done during the tracer study on pond SN3 in Oxelösund, to obtain flow data. Thus the Manning number and eddy-viscosity coefficient can be calibrated more accurately and then the dispersion coefficient. By such procedure, the hydrodynamics can first be stated and then the advection-dispersion processes. To acquire better knowledge of the hydraulic performance in pond SN3, a new tracer test with a sampling period of one month ought to be carried out. However, to make extensive measurements of flow velocities and tracer tests over a period of one month would need substantial extra time and financial resources.

Part E, which covers several different pond layouts, is limited in respect to the number of chosen cases. Two cases were to investigate the impact of an island. One was placed at the long side of the pond and one close to the inlet. However, only one size of the island was tested and only at these two locations. Further, it is possible that the case with the subsurface berm may include some 3-D effects, which cannot be simulated in the 2.5-D model. Only one height of the berm was tested, and several heights ought to be investigated to cover the relation between berm height/water depth and hydraulic performance.

4.2 Hydraulic efficiency

The formulation of the hydraulic efficiency (part D) was developed as a method to be able to compare ponds and different design solutions, according to hydraulic performance. The development of the hydraulic efficiency factor λ was based on two considerations. The first consideration was to make λ simple and easy to understand, and the second was to lessen the effect of high N-values, so that the efficiency is not overestimated for high N-values. Replacing N with 1 - (1/N) did solve the latter problem, leading to the equation: $\lambda = t_p/t_n$. However, this is based on a number of hypothetical cases and simulations of several modifications of an existing creek. It would therefore be interesting to study how this tool correlates with empirical data on pollutant removal. Only in this way may questions such as 'How good is λ=0.60?' or 'How much better is λ=0.9 in relation to λ=0.3 or 0.7?' be answered. This will, however, lead to new problems and questions such as whether the hydraulic efficiency depends not only on layout but also on amount of flow, or whether and how hydraulic efficiency varies depending on which pollutants are studied.

It is interesting to compare the results of hydraulic efficiency from parts C and D/E. The results from part C show that pond SN3 has the same hydraulic efficiency as the poorest of 13 investigated hypothetical cases (λ=0.10). This case had a rectangular form with a length-to-width ratio of 2:1, and in- and outlet placed close to each other. The other cases that were investigated differed according to form and topography, location of in- and outlet, and length-to-width ratio. This shows the similarities between an existing pond with poor design and the hypothetical ponds simulated; secondly, it shows how large an impact the form has on the hydraulic efficiency. Further, it is notable that a pond designed for water treatment has such low hydraulic efficiency, but also that this is probably often the case, since the form is seldom planned (parts C and F) but rather a result of the existing topography.

4.3 Case study

There are three main problems connected with the case study (part F). The first is that it was difficult to find information about the background of pond designs, due to a lack in documentation in the planning process. This can be overcome if e.g. participant observation during a planning process is used as a research method, instead of focused interviews. The second problem was that no case could be found where a biologist or a sanitary engineer had designed the stormwater pond. This made it impossible to compare design solutions between different disciplines. The third problem was that effects of cooperation between disciplines could not be investigated because the sanitary/civil engineers worked strictly separate from the landscape architects. While one group did the sizing, the other group did the design.

5. FURTHER STUDIES

There are several suggestions for further research projects presented in the different parts (A-F). Among these I would like to emphasize the following:

- Investigate in which cases a 2.5-D model has to be replaced by a 3-D model.
- How to select model parameters when using a 2.5-D model on ponds.
- Further investigation of how the hydraulic efficiency (λ) is related to shape, length-to-width ratio and flow, and also regarding removal of nutrients and phosphorus.
- The hypothesis that preferences are an implicit factor, which determines pond design, ought to be studied further.

6. CONCLUSION

'How should ponds be designed?' is a rather typical question asked by engineers. This thesis, like other theses, is not able to answer that question in full, mainly for the simple reason that there is no universal design. This is partly because ponds are multifunctional and partly because the design must take into consideration site-specific conditions. What we know, and what is described in the case study (part F), is that cooperation between different disciplines should be considered when designing a pond. Further, it is shown that several non-technical factors together with the technical ones determine pond design. Among the technical factors it was found that pond hydraulics is often not considered (parts C and F). Instead, site-specific factors such as topography have a large impact on the design, which can lead to poor hydraulic performance.

Results from simulations of hypothetical ponds indicate that a subsurface berm or an island placed in front of the inlet improves the hydraulic performance as regards short-circuiting, effective volume and amount of mixing (part E). These design elements may therefore be recommended to increase a pond's hydraulic efficiency, without having to increase the length-to-width ratio or the velocity of the water. Further, the study showed that a curved pond or an island placed near the side does not change the hydraulic performance, and that the length-to-width ratio and the location of in- and outlets have a quite large impact on the hydraulic performance.

To compare different ponds and design solutions, regarding hydraulic performance, it is suggested that hydraulic efficiency, λ, be used as a method (part D). The efficiency should be defined as a product of the effective volume ratio and the amount of mixing, resulting in the formula: $\lambda=t_p/t_n$ where t_p is the peak time and t_n the nominal residence time, and where λ varies between 0 and 1.

Moreover, it has been shown that a two-dimensional vertically integrated numerical model can, although not without restrictions and experience, be used for simulate the hydraulic performance of ponds (parts B and C).

BIBLIOGRAPHY

Adamsson, Å., J. Persson & S. Lyngfelt, "Numerical Simulation and Large-Scale Physical Modelling of Flow in a Detention Basin". Accepted to the *8th International Conference on Urban Storm Drainage*, 30 August – 3 September 1999, Sydney, Australia.

Aristotle, *The Ethics of Aristotle: The Nichomachean Ethics* (Book VI on Intellectual Virtues), Penguin Classics, 1976.

Brown, D. S., 1994, "Constructed wetlands in the USA", *Water Qual. Int.*, No. 4, p. 24.

Flyvbjerg, B., 1996, "Practical Philosophy for Sustainable Development: The Phronetic Imperative" in *Culture, Perception, and Environmental Problems*, Forskningsrådsnämnden Report 96:7, Stockholm.

Kadlec, R. & R. Knight, 1996, *Treatment wetlands*, Lewis Publishers, Boca Raton , USA.

Nationalencyklopedin, 1994, Band 13, Bra Böcker, Höganäs.

Persson, J., 1995, "Hållbar utveckling - är vi överens?", *NordRevy*, nr 2.

Persson, J., 1996, *Jakten på MKB: Dokumentstudier kring miljökonsekvensbeskrivningar (MKB) i fysisk planering*, Licentiatuppsats, Institutionen för Stadsbyggnad, Chalmers Tekniska Högskola, Göteborg.

Persson, J., 1997, "Ge miljövetenskap en tydligare identitet", *Nordisk Samhällsgeografisk Tidskrift*, Nr. 24, s. 101-104.

Persson, J., 1998, *Utformning av dammar: En litteraturstudie med kommentarer om dagvatten-, polerings- och miljödammar*, andra upplagan, Institutionen för vattenbyggnad, Rapport B:64, Chalmers Tekniska Högskola, Göteborg.

Persson, J., N.L.G. Somes & T.H.F Wong, 1999, "Hydraulic Efficiency of Constructed Wetlands and Ponds", accepted for publication in *J. of Water, Science and Technology.*

Persson, J., 1999, *Bestämmande faktorer vid dammutformning*, Institutionen för vattenbyggnad, Rapport B:65, Chalmers, Göteborg.

Proposition 1990/91:90, *En god livsmiljö*, Miljödepartementet, Stockholm.

Reed, S.H., R.W. Crites & E. J. Middlebrooks, 1995, *Natural Systems for Waste Management and Treatment*, 2nd edition, McGraw-Hill, New York.

Somes, N.L.G., W.A. Bishop & T.H.F Wong, 1997, "Numerical Simulation of Wetland Hydrodynamics", *Modsim97*, Hobart, Australia, pp. 385-390.

Urbonas, B. & P. Stahre, 1993, *Stormwater: Best management practices and detention for water quality, drainage and CSO management* (Chapter 24), PTR Prentice Hall, Englewood Cliffs, New Jersey, U.S.

Wittgren, H.B., 1994, *Våtmarker som behandlingsmetod för avloppsvatten och dagvatten: Kunskapssyntes och utredning om forskningsbehov*, Naturvårdsverket Rapport 4365, Stockholm.

Water Pollution Control Federation, 1990, *Manual of Practice, Natural systems*, Wetlands Chapter, February 1990, MOP FD-16 WPCF, p. 270.